by
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## DEDICATION

This Work is Dedicated
to all the Universe's Inhabitants

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#### Abstract

The primary topics of this dissertation are (1) target selection for searches for extrasolar life, especially for the Search for Extraterrestrial Intelligence (SETI) and the Terrestrial Planet Finder (TPF) and (2) remote detection of biosignatures, especially with regard to TPF. Chapter 1 gives a brief introduction to the field of astrobiology, and to the search for life on other planets. Chapters 2 and 3 ask, "What are the best places in the Universe to search for Earth-like life?" A class of stars, "habstars," is defined as stellar systems that are potentially habitable to Earth-like complex life. The physical properties of habstars are derived from the biological requirement of habitable zone stability, and these properties are translated into observable characteristics. In Chapter 2, the Catalog of Nearby Habitable Stellar Systems (HabCat), containing ~17,000 "habstars" within 300 parsecs, is presented for use as a new target list for the Search for Extraterrestrial Intelligence with the Allen Telescope Array. In Chapter 3, HabCat is augmented with other targets of interest, including a list of $\sim 250,000$ stars within 1000 parsecs from the Tycho-2 Catalog that are likely to be main-sequence (based on their proper motions) F, G, K and M stars (based on their B-V colors), old open clusters, and the nearest 100 stars.


This work is refined in Chapter 4 for the Terrestrial Planet Finder (TPF), a mission to image and spectroscopically analyze extrasolar terrestrial planets. The TPF Target List Database is presented, and it contains all Hipparcos stars within 30 parsecs plus data that are relevant to planetary habitability and detectability. From this database, a sample of targets is selected and recommended for observation based on suitability for life.

Chapter 5 asks, "What are the spectral signatures of a habitable, or inhabited, planet?" The Earthshine spectrum, from 0.3 to 2.5 microns, is presented and used to illustrate the spatially unresolved spectrum of a planet with abundant water and life. Water vapor, oxygen, ozone, methane, and carbon dioxide are unambiguously detected, while the vegetation signature is less certain. Chapter 6 explores possibilities for extending the earthshine work and submits recommendations for improving the TPF database content and usability.

## 1. INTRODUCTION

The search for extraterrestrial life (ETL), once limited to philosophy and fiction and then relegated to the sidelines of astrophysics, is now at the forefront of NASA's space missions. Yet in this young field, there are so many unanswered questions that nearly everything imaginable seems a legitimate possibility for ETL's form and function. Astrobiologists readily admit that nothing is known of life other than what is represented on our own planet, but we assume that this locally successful model for life could reasonably be found elsewhere. In other words, we are looking for ourselves among the stars.

### 1.1 Approaches to Searching for Extraterrestrial Life

### 1.1.1 Visitations and Human Space Flight

There are at least four ways to search for extraterrestrial life. One tactic is to simply wait for it to come to us, perhaps in the form of a visit from another space-faring civilization, or in the form of meteorites containing viable or fossilized organisms. The former is a topic of much discussion among some "UFOlogy" enthusiasts (Dennett 2001, Hough 1999), but so far the evidence for alien visitations does not lend itself well to scientific scrutiny (Druyan \& Sagan 1997).

The search for signs of past life in meteorites of extraterrestrial origin has also stirred controversy within the scientific community. In 1996, McKay et al. presented evidence that Martian meteorite ALH84001 (1) was, while still on Mars, infiltrated by liquid water (a prerequisite for life), (2) has structures within the cracks in carbonate mineral globules that are similar in shape and size to "nanobacteria," the sub-micron entities found in carbonates in terrestrial rocks (Folk 1993) and possibly involved in biomineralization in animals (Drancourt et al. 2003), and (3) contains, within the carbonate globules, microscopic mineral grains like those produced by bacteria on Earth and polycyclic aromatic hydrocarbons (PAHs, which can form during decomposition of bacteria). However, PAHs and mineral deposits can form non-biologically (Treiman 2003). To make matters more uncertain, the real nature of terrestrial "nanobacteria," is itself still a matter of controversy. Nanobacteria are too small to contain enzymes for DNA replication and amino acid synthesis (Maniloff 1997, Nealson 1997, Psenner \& Loferer 1997). Although they appear to increase in number given the appropriate growth medium, Ciser et al. (2000) found that (1) the biomineralizing activity of nanobacteria was not inhibited by a common respiration inhibitor, (2) molecular analysis of the "cultures" have failed to detect nucleic acid or proteins, and (3) the 16 S rDNA sequences once ascribed to Nanobacterium species (Kajandar \& Çiftçioglu 1998) were indistinguishable from that of a common contaminating microorganism. Thus, even the terrestrial nanobacteria may not be alive.

A second way to search for ETL is to send biologists to other planets to carry out investigations. So far, the Moon is the only extraterrestrial body to host a visit from humans. The Apollo missions returned samples to Earth for analysis, but no amino acids or signs of life were found (Brinton \& Bada 1996, Taylor, Ferguson \& Truby 1970). Interestingly, viable Streptococcus mitis organisms, a common human bacteria, were recovered from the polyurethane insulation inside the Surveyor 3 Camera, which was retrieved by Apollo 12 astronauts after it spent nearly 3 years on the Moon (NASA 1972). Although there is now some question as to whether the insulation samples were analyzed under strictly sterile conditions (Jaffe 1994), that finding inspired panspermia enthusiasts (Klyce 1998) and sparked discussion about planetary protection for future missions to and from other planets, especially Mars and Europa, which could conceivably have existing ecosystems (NRC 2000, NRC 1997). Human travel to Mars may now be on the horizon (White House 2004), but it remains to be seen whether the cost of such a program can be borne by American taxpayers in otherwise trying times (Economist 2004).

### 1.1.2 Probes

Where humans cannot go, biological analysis can sometimes be carried out by probes. In this way, one search for life has been conducted on Mars. In 1976, two Viking spacecraft carried out four experiments aimed at detecting soil microbes: (1) gas exchange (GEX), to detect alterations in the composition of gases in a test chamber as a result of biological
activity, (2) a labeled release experiment (LR), to detect uptake of a carbon-14 labeled nutrient, and (3) a pyrolytic release experiment (PR), to detect the existence of organic materials in soil samples, and (4) a gas chromatograph-mass spectrometer (GC-MS), to determine the chemical composition of the Martian surface (NASA 1984). While GEX, LR and PR all returned positive results, GEX and PR returned positive results even with a heat-sterilized soil sample, indicating that non-biological processes were at work. Only the LR returned negative results with the sterilized sample, but the rate of gas release in the non-sterilized sample plateaued in a manner that was considered inconsistent with biological activity. The GC-MS analysis detected a surprising amount of water, but failed to detect organic compounds, which should have been detected in the presence of carbon-based life. Thus, while there is still some debate as to whether the Viking results might be consistent with the presence soil microbes (Levin \& Staat 1988), no unambiguous evidence for extant life on the Martian surface was found. More recently, the Opportunity rover mission has provided strong evidence that the surface of Mars was once partially covered in standing water (Bell et al. 2004, Squyres et al. 2004). However, the best is yet to come: NASA's plans beyond ~2014 include sample returns and deepdrilling to explore any subsurface water reservoirs, and these missions may be our best opportunities for discovering past and extant extraterrestrial life in the Solar System.

Saturn's largest moon, Titan, is another astrobiologically interesting location that is about to be visited by a human probe. Titan's $\sim 1.5$ bar primarily nitrogen atmosphere makes it unique among moons and could allow for persistent methane lakes and rivers. Although
the temperature on this moon's surface ( $\sim 95 \mathrm{~K}$ ) makes biology unlikely, solar UV photons impinging on its methane-rich atmosphere drive a rich organic chemistry that may provide insights into the prebiotic chemistry on Earth. A photochemical haze surrounding Titan makes study of its surface difficult, but recent observations taken with the $8-\mathrm{m}$ VLT in Chile have pierced the veil and show light and dark regions that may correspond to landmasses and lakes (see Figure 1.1, from L. Close, private communication). In December of 2004, the Cassini mission to Saturn will release the Huygens probe for Titan. As Huygens descends through Titan's atmosphere, it will measure atmospheric temperature and pressure, wind gusts, electromagnetic activity, scattering of sunlight due to suspended particles, gaseous and aerosol composition, and as it nears landing, it will image the surface. In the event of a safe landing (ideally on a forgiving surface such as liquid or snow), Huygens will analyze the surface composition and measure acoustic, thermal, and electrical properties. These experiments are not intended to search for life, but they will shed light on the chemical processes and potentially prebiotic products of organic chemistry in a highly reducing planetary environment. Titan is thought to be more like the very young Earth than any other body in the Solar System (including the current Earth), and perhaps one day it will be a site of habitability under the red giant Sun (Lorenz, Lunine \& McKay 1997).

Perhaps in the next decade, orbiters and/or probes will get a closer look at Europa, which now seems likely to harbor a tidally-warmed salty ocean, about twice the volume of Earth's oceans, beneath a thin frozen crust (Pappalardo et al. 1999). Models of Galileo
gravity data indicate that Europa's interior consists of a metallic core, rocky mantle, and outer ice or water shell $\sim 80-170 \mathrm{~km}$ thick (Anderson et al. 1998). Galileo magnetometer data further revealed that as Europa revolves around Jupiter its induced magnetic field varies in a way that implies a conducting fluid close to the moon's surface, which rules out an entirely frozen crust but is easily explained by an ocean with salinity comparable to the Earth's oceans (Zimmer, Khurana \& Kivelson 2000). Furthermore, high-resolution ( $\sim 54 \mathrm{~m}$ ) Galileo images of apparently mobile or recently mobile "icebergs" imply the wide spread presence of liquid water at depths of a few kilometers or less within the past $10^{7}$ years (Carr et al. 1998). Curving surface cracks and the uniform distribution of impact craters also suggest that the rotation of the ice crust is slightly out of sync with the core/mantle rotation, and therefore that the crust is mechanically decoupled from the mantle (Geissler et al. 1998). Taking all of this together, a salt-water subsurface ocean is a convincing explanation, and if we apply the "where there is water, there is life" maxim that works so well on Earth, the possibility of subsurface ecosystems cannot be ignored. At this distance from the Sun, light may not be a significant energy source for life, but tidally generated hydrothermal activity may provide a habitable environment similar to those around vents at the bottom of our own seas (Chyba \& Phillips 2002). NASA's proposed Jupiter Icy Moons Orbiter would launch in 2012 or later to make more definitive observations to determine the depth of Europa's ocean, and to investigate its potential for sustaining life.

### 1.1.3 Remote Sensing of Habitable Environments and Life

For ETL searches in the entire Universe beyond the Solar System, the only remaining option is that of remote sensing, to which this dissertation is dedicated. One ongoing project, the Search for Extraterrestrial Intelligence (SETI), is dedicated to the discovery of extrasolar civilizations through detection of technological signals in the radio (Backus 2004) and in the optical (Howard et al. 2004). The Terrestrial Planet Finder Coronagraph (TPF-C), planned for 2014, will image the "habitable zones" of nearby stars in search of habitable planets, and if any planets are found, low-resolution spectroscopy will be used to determine whether the planet is habitable, and perhaps even inhabited.

### 1.2 Remote Sensing of Life: Identifying Habitable Environments

### 1.2.1 The Definition of Habitability

Life is presumed to be a planetary (as opposed to a stellar or interstellar) phenomenon. On Earth, the "biosphere" extends to every location where liquid water, organic matter, and an energy source are found. The vast majority of Earth's biomass is likely to be subterranean (Ghiorse, 1997); "oasis" ecosystems have been discovered around deep-sea hydrothermal vents (Schrenk et al. 2003); viable organisms have even been found in ice cores (Priscu et al. 1998). The one location on Earth where a Viking mission would not find life is within the driest part of the Chilean Atacama Desert, where water is simply too scarce for terrestrial organisms (Navarro-Gonzalez et al. 2003); this does not bode
well for extant lifeforms on the surface of Mars, compared to which even the Chilean desert is water-rich.

Although planetary habitability clearly extends to (or, perhaps, starts with) the subsurface regions, the current working definition of a "habitable" planet, for those of us who work in remote sensing, is "a planet that has liquid water on its surface." The circumstellar "habitable zone," then, is "that region around a star where an Earth-like planet is expected to have an atmospheric pressure and temperature capable of supporting liquid water on its surface." The "on its surface" requirement came originally from life's presumed dependence on sunlight; now the requirement is still preferred, because a planet with water on its surface will also have underground reservoirs and is more likely to support habitable niches that are detectable remotely. In the case of SETI, a habitable surface simply seems necessary for organisms that communicate between the stars.

### 1.2.2 The Connection Between Life and Water

The "water" part of habitability comes from the fact all known life requires liquid water to survive. Of all substances, why water? Various unique properties of water are thought to be particularly favorable for biochemistry. Water's relatively high cosmic abundance, combined with (1) the stability of its liquid phase over a wide range of temperatures (thanks to the formation of hydrogen bonds), (2) strong but selective solvent properties (thanks to a strong molecular polarity and the dependence of solubility on hydrogen
bonds), (3) high dielectric constant (which prevents oppositely charged organic products from recombining), (4) neutral pH (which allows for the survival of a diverse array of molecules), and (5) high heat capacity (which helps stabilize organics forming near energy sources like hydrothermal vents) all seem to make it a highly successful medium for the wide range of biochemical products and processes. Because the solubility of a substance depends on the molecule's ability to form hydrogen bonds with water, organic molecules can be classified into "hydrophobic" (non-water soluble) and "hydrophilic" (water soluble) types. Hydrophobic species cluster together, and this determines the geometry and function of large molecular assemblies (such as membranes and proteins). Clay minerals, which are formed by water alteration of silicate minerals, may also have been intimately involved in the origin of life. The global presence of liquid water on Earth is also helped by the unusual fact that ice floats, and insulating ice layers over lakes prevent their complete freezing and/or evaporation, thereby promoting the survival of liquid water reservoirs throughout long periods of sub-freezing surface temperatures.

### 1.2.3 The Characteristics of "Habstars"

Given a rough definition for a habitable environment, the likelihood of ETL discovery by SETI and TPF is proportional to the number of habitable environments searched, and the identification of these environments is the topic of Chapters 2,3 and 4. Both the SETI and TPF missions need target lists. While nothing is known about the presence or habitability of terrestrial planets orbiting even the nearest stars (except in the cases where
a known giant planet rules out the presence of an Earth in the habitable zone), we do know (or can easily observe) the basic characteristics of the stars themselves. In this dissertation, I propose that a "habitable stellar system," or "habstar," is a stellar system with (1) a metallicity that is consistent with the existence of terrestrial planets, and (2) has a circumstellar habitable zone that is static and (3) dynamically stable over biological timescales, given evolutionary stage of the star and the presence of any stellar or giant planet companion.

A key point about this "habstar" definition is that the biological timescale can be specified according to the kind of lifeforms we are interested in, which gives different sets of stars. Equally important, the habstar requirements are translatable into observable parameters indicative of a star's age, evolutionary state, metal content, variability, and, for stars with companions, orbital parameters. For example, a star with near-zero metal content cannot host a habitable zone, because zero metallicity stars form from zero metallicity interstellar clouds, in which there is not enough heavy element content to form terrestrial planets in the first place. The effects of increasing the metallicity of a protostellar cloud on the resulting number and masses of planets is unknown at this time, but we know that there must be some minimum metallicity for making Earth-sized planets, and perhaps there is also a upper limit on metallicity, where the planets formed are of too high a mass.

In Chapters 2 and 3, the biological timescale for SETI is taken to be 3 billion years (a perhaps optimistic timescale for evolving radio telescopes). Thus stars that are younger than 3 billion years, or whose current evolutionary stage does not last at least 3 billion years, are not habstars, because they are changing more quickly than the lifeforms of interest can arise. In the case of a technological civilization, it is imaginable that the lifeforms of interest could travel between planets to survive the dramatic stages between evolutionary stages (e.g., traveling from Earth to Mars to Europa to Titan during the Sun's transition from main sequence to giant phase, Lorenz, Lunine \& McKay 1997), without having to arise anew. This scenario involves so many additional assumptions (that there are several successively habitable planets, that the transition will be smooth, that the technology is far in advance of our own) that, at least in this dissertation, giant stars are not favored targets for SETI or TPF. Nevertheless, in creating the supplemental SETI target list in Chapter 3, where targets are selected by proper motion analysis, we will see that giants inevitably sneak into the list in rough proportion to their numbers in the Galaxy $(\sim 10 \%)$.

Crucial to Chapter 4, the biological timescale for Terrestrial Planet Finder targets is shorter, because the lifeforms of interest are microbes that produce biosignatures by emitting gases that would not normally be present in the planet's atmosphere given the other consituent gases (see Section 1.3). Single-celled organisms can arise on a planet within the first billion years (Schopf 1993), so the primary concern is that the system be old enough that most interplanetary debris has been cleared, both for the sake of the
lifeforms (which probably do not appreciate frequent giant impact events) and for the sake of observing the system with TPF (which gets very difficult if planets are immersed in gas and dust).

### 1.3 Remote Sensing of Life: Detection of Biosignatures

Given a list of good target stars, what remotely observable indications of life should we look for? Good biosignatures are easily observable from afar and are not produced by non-biological processes. For SETI, the biosignature is any signal that is created through technological activity, can travel for kiloparsecs through the interstellar medium without being entirely absorbed, and is not created by any kind of astrophysical object. Narrow band radio signals are one logical signature to look for in a search for technological civilization, because (1) radio waves travel easily through the interstellar medium and are cheap to produce energetically, (2) narrower frequency bands give a better signal-to-noise ratio for a given energy output, and (3) there is no known natural source that produces radio waves in narrow frequency bands. For example, the narrowest observed features in OH masers are $\sim 0.5 \mathrm{kHz}$ (Cohen et al. 1987), and the interstellar $21-\mathrm{cm}$ hydrogen emission line has a typical width of 10 kHz , both of which are fairly broad by the standards of technology. As another example, pulsars produce short, very precisely timed radio signals, which earned them a "little green men" nickname while physicists struggled to understand their true nature, but these pulses are extremely wide-band in nature-a signal that is so energetically costly as to be impractical for a civilization.

An example of a remotely observable non-technological biosignature is that of the leaf reflection spectrum. As discussed further in Chapter 5, plants are distinct from other reflective surfaces because they are highly reflective in the infrared, but chlorophyll pigments are highly absorptive in the optical, and this gives rise to a distinct "red edge" at about 0.7 microns in the reflection spectrum that is observable from space (Woolf et al. 2002, Arnold et al. 2002). Microbial life is also potentially detectable if it produces a gas that is clearly out of equilibrium with the atmosphere's other constituents. For example, Earth's atmosphere contains remotely detectable levels of methane, but the lifetime of methane is very short due to (1) reaction with OH radicals to form water and $\mathrm{CO}_{2}$, and (2) oxidation in soils. This implies that there must be a source of methane production. Volcanic activity is certainly one source, but methane is observed in a much greater proportion to other volcanic gases than is explainable without some additional methane source. That source is methanogenic bacterial metabolism, which anaerobically degrades organic matter and produces methane in rice paddies and cattle digestive systems.

Intriguingly, methane has recently been detected at low levels in the Martian atmosphere, a planet that has long been believed to be tectonically inactive and volcanically dormant (Krasnopolsky, Maillard, \& Owen 2004). Again, reactions with OH radicals and the highly oxidized Martian soil are also expected to deplete methane on a short timescale of $\sim 400$ years. This does not prove that Mars hosts methanogenic bacteria, and a very low
level of geologic activity could be responsible. However, local enhancements of methane could identify the locations of methane sources, and such sites would be attractive landing targets for future probes.

Finally, in Chapter 5 we have observed the signature of an inhabited terrestrial planet: Earth. By observing Earth's light reflected off of the Moon, we are seeing the spectrum as it would appear to us if we were observing from another stellar system. Thus the Moon has once again proved itself to be endlessly valuable, by giving us the opportunity to see our own planet from space without leaving home. Through Earthshine studies, we can ask: How does the spectrum of an Earth-like planet change with the seasons, or with the weather, or the amount of landmass in view? Is it possible to know not only what the atmosphere is made of, but how much of each constituent it contains? Earthshine work is still in its early stages, but it will prove itself to be extremely valuable to TPF in the coming years.

### 1.4 The Philosophy of Searching for ET

The most common criticism of current efforts to search for extraterrestrial life, especially from those who are not engaged in the search, is that we are too conservative in imagining the various forms that life could take and therefore the environments in which it could be found. That, I think, is as obvious as it is unavoidable. When this criticism is aimed at the research presented here, my reply is that our attempts to identify systems
that seem like "homes away from home," are still defining a parameter space that is fairly broad and includes many circumstellar environments (and certainly many planets) that are very different from our own. Even within these criteria, we simply do not have enough data to rule out all "deviant" stars. This does not bother us at SETI, because we, too, want a balance between focus and open-mindedness in our search. For TPF, which is not a survey mission, we will inevitably be strongly biased by instrument limitation. It would not be possible, given the stringent observing constraints, to create an "unbiased" target list for TPF. Scientifically, given a core target list of only 35 stars, it would not be sensible to do so, and I challenge any scientist to come up with an "unbiased" target list of 35 stars that falls within TPF's detectability space or meaningfully answers a useful question in the case of a null result. Lucky for us, as we will see in Chapter 4, the Universe is arranged such that, instrumentally, TPF will be biased in just the way those of us looking for habitable planets would want it to be.


Figure 1.1 Titan as observed with the SDI on the VLT. The image is a composite of images taken outside (brown) and inside (blue) the methane absorption band at 1.6 microns (provided by L. Close, University of Arizona). Surface features are clearly visible, and the dark areas are thought to be methane/ethane oceans.

# 2. TARGET SELECTION FOR SETI: 1. A CATALOG OF NEARBY HABITABLE STELLAR SYSTEMS 

### 2.1 Introduction

### 2.1.1 Target Selection for SETI

In preparation for the advent of the Allen Telescope Array, the SETI Institute has the need to greatly expand its former list of $\sim 2000$ targets compiled for Project Phoenix, a search for extraterrestrial technological signals. In this Chapter we present a catalog of stellar systems that are potentially habitable to complex life forms (including intelligent life), which comprises the largest portion of the new SETI target list. The Catalog of Nearby Habitable Systems (HabCat) was created from the Hipparcos Catalogue by examining the information on distances, stellar variability, multiplicity, kinematics and spectral classification for the 118,218 stars contained therein. We also make use of information from several other catalogs containing data for Hipparcos stars on X-ray luminosity, CaII H\&K activity, rotation, spectral types, kinematics, metallicity, and Strömgren photometry. Combined with theoretical studies on habitable zones, evolutionary tracks and third body orbital stability, these data were used to remove unsuitable stars from HabCat, leaving a residue of stars that, to the best of our current knowledge, are potentially habitable hosts for complex life. While this Catalog will no
doubt need to be modified as we learn more about individual objects, the present analysis results in 17,129 Hipparcos "habstars" near the Sun ( $75 \%$ within 140 pc ), $\sim 2200$ of which are known or suspected to be members of binary or triple star systems.

### 2.1.2 Motivation for HabCat: Project Phoenix and the Allen Telescope Array

The creation of a Catalog of Habitable Stellar Systems (HabCat) was motivated specifically by a need for an expanded target list for use in the search for extraterrestrial intelligence by Project Phoenix of the SETI Institute. Project Phoenix is a privately funded continuation of NASA's High Resolution Microwave Survey (HRMS), a mission to search for continuous and pulsed radio signals generated by extrasolar technological civilizations. HRMS consisted of an All Sky Survey in the 1 to 10 GHz frequency range as well as a Targeted Search of 1000 nearby stars at higher spectral resolution and sensitivity in the 1 to 3 GHz range. Although Congress terminated HRMS in 1993, the SETI Institute raised private funds to continue the targeted portion of the search as Project Phoenix. Project Phoenix now carries out observations at the Arecibo Observatory in conjunction with simultaneous observations from the Lovell Telescope at the Jodrell Bank Observatory in England. The project uses a total of three weeks of telescope time per year and is able to observe $\sim 200$ stars per year.

In the near future, the SETI Institute expects to increase the speed of its search by a factor of 100 or more. In a joint effort by the SETI Institute and the University of CaliforniaBerkeley, the Allen Telescope Array (ATA, known formerly as the One Hectare Telescope) is currently being designed for the Hat Creek Observatory located in northern California. The ATA will consist of 350 dishes, each 6.1 meters in diameter, resulting in a collecting area exceeding that of a $100-\mathrm{m}$ telescope. On its current development and construction timeline, the ATA should be partially operational in 2004 and fully operational in 2005. The construction of the ATA will mark an increase in telescope access and bandwidth capability sufficient to observe thousands to tens of thousands of SETI target stars per year. Hence the observing list for Project Phoenix needs to be greatly expanded from its original scope of about 2000 of the nearest and most Sun-like stars (Henry et al. 1995). The Catalog of Nearby Habitable Stellar Systems (HabCat) presented in this Chapter comprises the largest portion of SETI's new target list (to be discussed fully in a subsequent publication).

### 2.1.3 Defining Habitability

Our goal is to build a catalog of stars that are potentially suitable hosts for communicating life forms. In defining the habitability criteria for SETI target selection, we note that the development of life on Earth required (at the very least) a terrestrial planet with surficial liquid water and certain heavy elements (e.g., phosphorus), plus an energy source (e.g., Sunlight) (Alberts et al. 1994). The basic requirement of terrestrial
planets suggests that there may be a lower limit on stellar metallicity for habitability (discussed in §3.7). Given the possibility of terrestrial planets, the second requirement of liquid water means that the concept of a "habitable zone" (HZ), i.e., that annulus around a star where the temperature permits the presence of liquid water on an Earthlike planet (investigated in detail by Kasting, Whitmire \& Reynolds 1993), is a recurring theme as we evaluate the habitability of stars with different spectral types and also multiple star systems.

An additional requirement for the development of complex life on Earth has been the continuous habitability of the planet over billions of years. Although there is evidence that simple life forms inhabited Earth as early as 0.8 billion years after Earth's formation (Schopf 1993), multicellular life did not appear until after $\sim 4.1$ billion years (McKay 1996) and the emergence of a technological civilization capable of interstellar communication occurred only in the last century. The requirement for a long habitability timescale, $\tau_{\text {hab }}$, strongly impacts the number of stars included in HabCat. All such stars must be older than $\tau_{\text {hab }}$, and their HZ locations must not change by more than the HZ width over that time. However, it is not clear that the 4.6 billion year time to intelligence on Earth is a universal requirement for the appearance of interstellar communication technology (e.g., arguments made by McKay 1996). Here we acknowledge that the determination of a minimum $\tau_{\text {hab }}$ for SETI targets is arbitrary, and we follow the examples of Dole (1964), Hart (1979) and Henry et al. (1995) in setting $\tau_{\text {hab }}=3$ billion years.

Combining these ideas, we define a "habitable" stellar system as a system in which an Earthlike planet could have formed and supported liquid water throughout the last 3 billion years. For convenience, we call the host star of such a system a habstar. Implicit in the definition of a habstar are concerns about metallicity, companions, stellar age and mass, and stellar variability. We expect that the habitability criteria presented below will need to be adjusted as more is learned about the formation of terrestrial planets, the origin and evolution of life on Earth, and the presence of life, if any, on other planets or moons of the Solar System.

### 2.1.4 The Hipparcos Catalogue as a starting point for HabCat

The Hipparcos and Tycho Catalogues (ESA 1997a) meet many of SETI's needs in terms of astronomical data compilation. The Hipparcos mission's typical parallax standard errors of $\sim 1$ milliarcsecond (mas) allow unprecedented accuracy in distance measurements (standard errors of $20 \%$ or less for $\sim 50,000$ stars) and hence vast improvements in luminosity determinations, which is perhaps the most important information we use in determining the habitability of nearby stars. The Catalogue also includes accurate photometry (B-V uncertainties typically less than 0.02 magnitudes; important for determining bolometric corrections and habitable zone locations) and proper motion data (which we use to constrain membership to the Galactic disk), as well as information on variability and multiplicity. All these data contribute to the goal of
creating a sample of well-characterized stars that we believe may provide suitable habitats for complex life forms. However, the data used in this Chapter regarding stellar kinematics, chromospheric activity, rotation, metallicity, multiplicity, etc, are still missing for most stars in the Solar Neighborhood. Therefore our procedure was to begin with the entire Hipparcos Catalog and eliminate stars for which currently available data indicate non-habitability.

### 2.1.5 The Creation of HabCat

The creation of HabCat was carried out in two phases. First, the Celestia 2000 program published on CD-ROM by the European Space Agency (ESA 1997b) was used to query the Hipparcos database and exclude undesirable stars using the flags present in the Hipparcos Catalogue itself. Celestia 2000 allows the user to specify many criteria and combine them to generate a subset of stars. The resulting subset can be output in machine-readable format with all of the information available from the Hipparcos Input Catalogue, the Hipparcos Catalogue and the Tycho Catalogue. We refer to this subset generated with our habitability criteria as the "Celestia sample." In the second phase of target selection, stars were removed from the Celestia sample using information from external databases or other calculations, so as to keep only stars which appear to be potential habstars based on spectral type, age, variability, metallicity or stellar/substellar companions.

In Section 2 of this Chapter we present the criteria used for the creation of the initial Celestia sample, and in Section 3 we describe additional cuts made by matching these Hipparcos stars with data from other databases. In Section 4 we present the resulting Catalog of Nearby Habitable Stellar Systems.

### 2.2. The Celestia Sample

### 2.2.1 Minimal Data Requirements and Uncertainty Limits

In order to do any assessment of the habitability of Hipparcos stars, we require some estimate of luminosity and temperature. Therefore we have only included stars for which B and V photometry and parallax were obtained, and we did not include stars whose parallax measurements were less than zero (due to large uncertainties). Additionally, the quoted fractional parallax uncertainties (the mean standard error in the mean) $\sigma_{\pi} / \pi$ were limited to $30 \%$, which corresponds to a range of -0.77 mag to +0.57 mag around the calculated $\mathrm{M}_{\mathrm{v}}$. This uncertainty in visual luminosity is acceptable because we expect a solar mass star to increase in brightness by $\sim 1$ mag between the zero-age main sequence and the Hertzsprung gap on the HR-diagram, so we can still determine whether or not our stars are on the main sequence. The uncertainty in locating stars to the main sequence is dominated by that of the parallaxes measurements, and photometric uncertainties are generally small for the vast majority of stars in the Hipparcos Catalogue (median precision 0.06 mag in $\mathrm{V}, 0.07$ mag in B$)$.

### 2.2.2 Variability Detected by Hipparcos

What about variable stars? We know that all stars are variable at some level, but how much fluctuation is tolerable to life, or to complex life? The most well-studied variation of the Sun is the 11 year Sunpot cycle (also called the Schwabe cycle), and during Solar Minimum the Sun's total irradiance fluctuates by only $\sim 0.02 \%$. During Solar Maximum, the Sun's output appears to increase both in total irradiance (by $\sim 0.1 \%$, corresponding to a global terrestrial tropospheric temperature increase of $0.5-1.0^{\circ} \mathrm{C}$ ) and in stochastic variability (to $\sim 0.15 \%$ ) (Willson \& Hudson 1991; Lean 1997 and references therein). The Solar wind, UV and X-ray fluxes, and coronal mass ejection events also increase in intensity during Maximum, and the resulting geomagnetic storms, drop in cosmic-ray fluxes, and change in ozone production impact terrestrial atmospheric circulation, temperatures and weather (Haigh 1996, Cliver 1995, Tinsley 1998). There appears to be a longer and more pronounced variation cycle superimposed on the Schwabe cycle (the ~200 year "Suess wiggles", Damon \& Sonnett 1991), and the most recent minimum in this cycle occurred between 1645 and 1715 AD (the Maunder Minimum) with Solar irradiance levels dropping by $0.22-0.55 \%$ from the current quiet Sun (Baliunas \& Jastrow 1990; Wigley \& Kelly 1992). This decrease in Solar irradiance coincides with the coldest years of the Little Ice Age of 1550-1700 AD. Likewise, the Medieval Maximum of sunspot activity ( 1100 to 1250 AD ) coincides with a warm interval on Earth known as the Medieval Warm Period. These Solar variations were not deleterious to
complex biology, nor did they prevent the emergence of technological civilization. However, given that these extremely small fluctuations did have noticeable impacts on global climate, we have taken the view that stellar variability greater than $\sim 1 \%$ in luminosity would be a significant concern for habitability.

The Hipparcos mission was able to detect flux variations of $\sim 3 \%$ in the Hp bandpass during the four year mission, a level of variability at least 5 times greater than the Sun's change in output since the Maunder Minimum and possibly beyond the limit of variability tolerated by complex life forms. However, the fluctuations detected by Hipparcos are on a much shorter timescale than those of the Sun and thus may not be completely analogous (e.g., the thermal inertia of a planet's atmosphere and oceans may filter out short period fluctuations so that only the average luminosity is relevant to climate). Erring on the conservative side, we have chosen to remove all stars with detected variability: "unsolved" variables (flagged as " $U$ " in column H52 or " $R$ " in H52 and " 2 " in H53), "microvariables" (flagged as "M" in H52), "variability-induced movers" (flagged as "V" in field H59), and stars included in the Variability Annex Part C ("C" flag in H54, non-periodic or unsolved variables) were omitted during the Celestia query. As for periodic variables (flagged as " P " in H52), stars classified as cataclysmic, eruptive, pulsating, rotating or X-ray variables were eliminated, but variables identified as eclipsing binaries were retained for analysis in §3.8.

### 2.2.3 Multiplicity in the Hipparcos Catalogue

Approximately $20 \%$ of the Hipparcos stars are known or suspected to be members of a multiple star system. There are undoubtedly many more multiple systems in the Hipparcos Catalogue that have not been identified, and studies of the Solar Neighborhood suggest that the fraction of Solar-type stars in binary or multiple systems is closer to $2 / 3$ (Abt \& Levy 1976, Duquennoy \& Mayor 1991). The presence of more than one star in a stellar system places limitations on where planets can form and persist in stable orbits. In order for a multiple system to be habitable to life, stable planetary orbits must coincide with the habitable zone. In the creation of HabCat, we have examined multiple systems individually for habitability by matching HZ location calculations with planetary stability zone locations (discussed in §3.8). Eclipsing binaries, spectroscopic binaries, astrometric binaries, and visual binary and multiple systems where no more than 2 components were resolved in each associated Hipparcos entry were retained for this analysis. We excluded from the Celestia sample entries containing more than 2 resolved components (indicated in field H58). Stars with "stochastic" astrometric solutions (flagged as "X" in H59) are likely to be astrometric binaries with periods less than $\sim 3$ years, and they were also excluded from the Celestia sample.

### 2.2.4 The Celestia Query and Resulting Sample

The Celestia query resulted in a total of 64,120 stars out of the original 118,218 . In Table 1, we show the exact criteria specified in the Celestia query. Figure 2.1 shows the resulting color-magnitude diagram. For a given star, the B- and V-band photometry listed in the Hipparcos Catalogue (and plotted in our Figures) represents either groundbased measurements (collected from the literature), the converted Hipparcos mission measurements (where the Hp magnitude was converted to Johnson-Cousins V magnitude) or the converted Tycho measurements (where $\mathrm{B}_{\mathrm{T}}$ and $\mathrm{V}_{\mathrm{T}}$ were converted to Johnson-Cousins B and V magnitudes). While the quoted photometric uncertainties are small (less than 0.02 mag in B-V for 75\% of Celestia sample stars), Bessell (2000) has noted that the published converted Tycho measurements differ slightly from JohnsonCousins measurements by up to 0.05 magnitudes, and that the residuals are a slowly varying function of $\mathrm{B}-\mathrm{V}$. Despite this, the uncertainty in position on the color-magnitude diagram is dominated by the uncertainty in distance for $98 \%$ of Celestia stars and the photometric errors do not affect the analysis carried out below.

From the color-magnitude diagram presented in Figure 2.1 it is obvious that there are many giants present in the Celestia sample, a few white dwarfs, and many stars of early spectral type (O-A) on the main sequence. In the analysis below we use our timescale for habitability, $\tau_{\text {hab }}$, to define a "locus of habitability" on the color-magnitude diagram.

After removing stars outside this locus and applying other cuts we will look at the final distribution of spectral types in HabCat.

Another noticeable feature of the Celestia color-magnitude diagram is the enhanced number of objects located inside the region $1.55<\mathrm{B}-\mathrm{V}<1.75$ and $6.5<\mathrm{M}_{v}<9.5$. The initial concern was that these are pre-main sequence stars, which would certainly violate our $\tau_{\text {hab }}$ criterion for minimum age. Rather, this scatter above the lower main sequence is caused primarily by objects that had no available photometry at the time of the creation of the Hipparcos Input Catalog and were below the detection threshold for Tycho photometry. These objects appear systematically too red and are likely to be main sequence K stars. We have drawn our "terminal-age main sequence" cut in $\S 3.1$ so as to include these stars in the sample.

Finally, we note that many stars in the Celestia sample are known or suspected members of a multiple system on the basis of one or more indicators: 9421 are associated with a Catalog of Components of Double and Multiple systems (CCDM) identifier, 1986 required an astrometric acceleration term, 201 have orbital astrometric solutions, 414 have an eclipsing binary-type light curve, and 1856 are associated with a "suspected nonsingle" astrometric solution quality flag. These non-exclusive categories affect a total of 12,958 Hipparcos entries. Although our query specified that the number of resolved stellar components within one entry was not to exceed 2 , there are some systems with more than 2 components contained in the sample where separate entries are related via
the same CCDM identifier. The analysis of all binary/multiple systems for habitability is described in §3.8.

### 2.3 CRITERIA FOR HABITABILITY: NON-HIPPARCOS DATA

### 2.3.1 Habitability on the color-magnitude diagram

With $\tau_{\text {hab }}=3$ billion years, HabCat is limited to low mass stars on the main sequence. As stars evolve off the zero-age main sequence toward luminosity class IV, the HZ moves slowly outward and may encompass planets that were previously too cold to be habitable (e.g. Lorentz, Lunine \& McKay 1997). Meanwhile, planets that were once in the star's habitable zone will suffer runaway greenhouse effects and lose any liquid water present (see Kasting et al. 1993). One can imagine that an advanced civilization could relocate to a more temperate world and persist throughout a star's main sequence lifetime. Therefore we consider a habitable system to remain habitable from 3 Gyr until it reaches the "terminal-age" main sequence, even though the HZ may move more than its own width during that total time (as is true for the Sun). We define the "terminal age" of the main sequence (TAMS) to be at the Hertzsprung gap in the color-magnitude diagram, where the lack of stars is due to large changes in effective temperature (and stellar radius) over timescales much shorter than $\tau_{\text {hab }}$. In order to determine what range of masses is acceptable for HabCat, we have used the TYCHO stellar evolution program (described by Young et al., 2001) to evolve Solar metallicity models of stellar masses between 1 and
$2 \mathrm{M}_{\S}$. We computed stellar age starting from the onset of core hydrogen burning, and a star that reaches the TAMS before 3 billion years is not considered habitable. With TYCHO models we find that a star of $\sim 1.5 \mathrm{M}_{\S}$ (spectral type $\sim \mathrm{F} 5$ ) is just habitable and that stars of this mass reach a maximum absolute brightness of $\mathrm{M}_{\boldsymbol{v}} \sim 2.5$ before approaching the TAMS.

Using this information we have applied two cuts to the Celestia sample: (1) a cut based on color-magnitude data and (2) a cut based on spectral types listed in the literature. The first cut removed all stars that are located above the TAMS drawn in Figure 2.1 (longdashed curve, described by $\mathrm{M}_{\mathrm{v}} \leq-10((\mathrm{~B}-\mathrm{V})-1.4)^{2}+6.5$, plus a $\mathrm{B}-\mathrm{V}<1.75$ requirement), all stars brighter than $\mathrm{M}_{\mathrm{v}}=2.5$, or below the main sequence (short-dashed line, $\mathrm{M}_{\mathrm{v}} \geq 28(\mathrm{~B}-\mathrm{V})+5.8$ for $\mathrm{B}-\mathrm{V}<-0.1 ; \mathrm{M}_{\mathrm{v}} \geq 4.8(\mathrm{~B}-\mathrm{V})+3.5$ for $-0.1<\mathrm{B}-\mathrm{V}<1.28$; $M_{V} \geq 17(B-V)-12.2$ for $\left.B-V>1.28\right)$. To apply a cut on spectral types, we matched each Celestia star to its corresponding two-dimensional MK spectral type (where available) in the catalogs of Houk and collaborators (Houk \& Cowley 1975; Houk 1978; Houk 1982; Houk \& Smith-Moore 1988; Houk \& Swift 1999). When a spectral type was not available from these catalogs, the spectral type listed in the Hipparcos Input Catalog was used. We then removed stars with undesirable spectral types, including spectral types earlier than F5, stars with noticeable emission lines, nebulous lines, weak lines, variable lines and shell stars. Stars with spectral types containing the following characters were removed: O, B, A, D, C, F0, F1, F2, F3, F4, II, III, Ia, Ib, VI, delta, sd, sh, W, e, var, R, N, S, w, v, or n. The $\sim 2 \%$ of Celestia stars that did not have spectral
types listed in our sources were examined only according to color-magnitude location. These two cuts resulted in the removal of $64 \%$ of the stars from the Celestia sample (leaving 23,246).

### 2.3.2 The Habitability of F Stars

There are $\sim 8600 \mathrm{~F}$ stars in the remaining list. In addition to concerns about main sequence lifetime, the distribution of a star's spectral energy output is relevant to the evolution of Earth-like biology. Biological molecules, including nucleic acids (found in DNA and RNA), amino acids (proteins) and lipids (cell membranes), absorb strongly at ultraviolet wavelengths (see Cockell 1999 and references therein), and each absorption event has the potential to disrupt the molecule. Even with the sophisticated repair mechanisms commonly employed at the cellular level, the Sun's UV output would be fatal to complex life were it not for the Earth's protective ozone layer. For F5V stars with effective temperatures near 6800 K and luminosities of $\sim 4 \mathrm{~L}_{8}$, UVC (200-280 nm) emissions can be $\sim 10$ times that the Sun, depending on the extent of metal-line blanketing (see IUE spectra in Heck et al. 1984). Given the biological sensitivity to these wavelengths, this raises the question of whether additional limits on spectral type should be imposed.

Kasting, Whittet and Sheldon (1996) addressed this issue and showed that, since ozone formation is initiated by the splitting of $\mathrm{O}_{2}$ by ultraviolet photons, Earth-like planets
orbiting F-stars may have thicker ozone layers and receive even less UV radiation at their surfaces than does the Earth. For K stars the amount of UV radiation and hence ozone production is less, but the lack of incident radiation more than compensates for the lack of ozone shielding, and in fact it may be G-type stars that are the least habitable to complex life forms in terms of ultraviolet radiation. Yet even G stars are capable of supporting technological civilizations. Therefore we have not culled our Habitable Systems Catalog on the basis of stellar UV emissions.

### 2.3.3 The Habitability of M Stars

There are also $\sim 600 \mathrm{M}$ stars on our remaining list. Although this is a small fraction of the total list $(\sim 2.5 \%)$, the habitability of M dwarfs is of general interest to SETI because these stars may account for more than $70 \%$ of the stars in the Galaxy (Henry et al., 1999). Previous SETI target lists did not include M dwarfs for several reasons. The first concern was that the fully convective interiors and rapid rotation of some $M$ stars give rise to highly energetic flaring events and that the ultraviolet emissions from these flares could be harmful to lifeforms in the nearby HZ. However, Doyle et al. (1991) assert that M star flares would generate large amounts of ozone in the upper atmosphere of a planet, which would in turn protect the planetary surface from the intensified UV radiation. Furthermore, they point out that the total amount of UV radiation from flares even at this small distance from the star is still less than the Solar UV radiation flux on Earth. Therefore we have not explicitly excluded M stars on the basis that some of them are
flare stars. However, we note that we tried to avoid frequently flaring stars by excluding non-periodic variables in the Celestia query, and by excluding in $\S 3.1$ spectral classifications flagged with "e" (indicating the presence of Balmer emission lines which is generally associated with chromospheric activity, e.g. Mauas et al. 1997) in Houk's catalogs.

A second consideration for fainter stars is that of habitable zone width. Because of the inverse-square fall-off of radiation, the distance at which a planet in thermal equilibrium with its parent star will be at a given temperature goes as the square root of the stellar luminosity. Thus the total width of the habitable zone also goes as $L^{0.5}$ and the HZ narrows as we consider later spectral types. Kasting, Whitmire \& Reynolds (1993, hereafter K93) estimate the HZ width (from "runaway greenhouse" to "maximum greenhouse") for the Sun to be $\sim 0.83 \mathrm{AU}$, but for an M0 star the instantaneous HZ width is only $\sim 1 / 3$ of this and would seem to be $1 / 3$ as likely to host a habitable planet. On the other hand, their long main sequence lifetimes suggest that a planet orbiting within an M dwarf HZ is more likely to eventually develop complex (and potentially communicating) life. To make a meaningful comparison of stars of different spectral types we need to factor in both HZ time and area by using K93's concept of the continuously habitable zone (CHZ), defined as the annulus that is continuously habitable over a specified amount of time. For $\tau_{\text {hab }} \sim 3$ billion years, G stars have the largest $\mathrm{CHZs}(\sim 0.5 \mathrm{AU})$, M0 stars have CHZs of just under half this width, and CHZs disappear altogether for spectral
types earlier than our F5 cutoff. In these terms, M stars appear to be reasonable locations for the appearance of life.

The location of M star HZs may be a concern for habitability in that Earth-mass planets may not usually form at this small distance from the star (Wetherill 1996). Furthermore, K93 note that the CHZs of M stars are located within the tidal lock radius (and would therefore be synchronous rotators). They suggested that planets orbiting within the CHZ would have one side of the planet perpetually dark and cold enough to freeze out any atmosphere. Haberle et al. (1996) and Joshi et al. (1997) explored this issue and calculated that a $\mathrm{CO}_{2}$ atmosphere of only 0.1 bars would be enough to circulate heat from. the illuminated side of the planet and prevent atmospheric collapse, while 1.5 bars of $\mathrm{CO}_{2}$ would allow temperatures compatible with the existence of liquid water over much of the surface of the planet.

Many questions remain regarding the habitability of $M$ dwarf systems. The spectral energy distribution of these stars may have negative consequences for photosynthesis, and the thicker atmospheres required to prevent atmospheric collapse in synchronously rotating planets may interfere with the transmission of photosynthetically useful radiation over much of the planet's surface. Thus these stars may indeed be less attractive targets, but the potential problems are not necessarily insurmountable. Given the small number of M stars found in the Hipparcos Catalogue (and hence the small amount of telescope
time devoted to them), we opt at this time to include them in HabCat, except where they fail the habstar criteria applied to all spectral types.

### 2.3.4 Stellar Age Indicators: Chromospheric Emission

As part of a minimum age cut for HabCat, we have already removed from our target list those stars of spectral types known to have lifetimes shorter than the required 3 Gyr. But for stars of later spectral types, habitability determination on the basis of age is less straightforward. Henry et al (1995) proposed using the Ca II H and K line chromospheric activity indicator for age determination of potential SETI targets (as described in Noyes, Weiss \& Vaughan 1984). Due to periodic activity cycles (like the 11 year Solar cycle), typical 1-o uncertainties for stars with $\mathrm{B}-\mathrm{V}>0.6$ are about 0.4 to 0.5 dex in $\log ($ age $)$ (Lachaume et al. 1999). This translates into an uncertainty of $+/-3$ Gyr for a 5 billion year old star. Over the past 400 years, the chromospheric activity of the Sun has ranged from $\log \mathrm{R}^{\prime}{ }_{\mathrm{HK}} \sim-5.1$ during the Maunder Minimum (corresponding to an estimated age of $\sim 8 \mathrm{Gyr}$ ) to $\log \mathrm{R}^{\prime}{ }_{\mathrm{HK}} \sim-4.75$ during Solar Maximum (corresponding to an estimated age of $\sim 2$ Gyr) (Baliunas et al. 1995a, Baliunas et al. 1995b). Nevertheless, it seems that stars which show activity cycles always remain on either the "active" or "inactive" side of $\log R^{\prime}{ }_{H K} \sim-4.75$ (Henry et al. 1996). Thus it should be possible to tell from only one observation on which side of this line a star will continue to reside. According to the relation from Donahue (1993),

$$
\log \tau=10.725-1.334 \mathrm{R}_{5}+0.4085 \mathrm{R}_{5}^{2}-0.0522 \mathrm{R}_{5}^{3},
$$

where $\tau$ is the age in years and $R_{5}$ is defined as $\log R^{\prime}{ }_{H K} \times 10^{5}$. The value $\log R^{\prime}{ }_{H K}=$ -4.75 corresponds to an age of $\sim 2.2$ Gyr. Thus for our purposes, we can rule out all stars with activity index $\log \mathrm{R}_{\mathrm{HK}}>-4.75$. Figure 2.2 shows the distribution in $\log \mathrm{R}^{\prime}{ }_{\mathrm{HK}}$ for the 1408 stars in the sample resulting from $\S 3.1$ in comparison with Donahue's ageactivity relation (R'HK data from T. J. Henry and D. R. Solderblom 2002, private communication). With these data 425 more objects were identified as "young" and cut, leaving 22,821 stars.

### 2.3.5 Stellar Age Indicators: X-ray Luminosity

Another indicator of age is X-ray luminosity. Pre-main-sequence stars tend to emit Xrays in excess of that expected from the blackbody temperature deduced from their optical spectra, and these emissions steadily decrease with age. Güdel et al. (1997) investigated X-ray emissions for nine Sun-like stars of ages 70 Myr to 9 Gyr and found that

$$
\mathrm{L}_{\mathrm{x}} \sim 2.1 \times 10^{28} \boldsymbol{\tau}^{-1.5}\left[\mathrm{ergs} \mathrm{~s}^{-1}\right]
$$

where $L_{x}$ is the total luminosity in the $0.1-2.4 \mathrm{keV}$ energy range (i.e., the energy range observed by the ROSAT Position-Sensitive Proportional Counter (PSPC) instrument) and $\tau$ is the stellar age in Gyr. In the ROSAT All Sky Survey (RASS), young active late-type stars ( F through M) were found to account for $85 \%$ of the soft X-ray sources detected in the Galactic plane (Motch et al. 1997). Guillout et al (1999, hereafter G99) performed a cross-correlation of the RASS with the Hipparcos and Tycho Catalogues and found 6200
matches with Hipparcos entries. The X-ray/Optical offset was required to be less than 30 arcseconds, a separation for which the authors calculate a $\sim 7 \%$ spurious match rate. In Figure 2.3 of G99 the PSPC count rate as a function of exposure time is shown for all of the RASS-Tycho matches. From this Figure we can see that most of the X-ray sources were detected at an exposure time of $\mathrm{t}_{\mathrm{exp}} \sim 450 \mathrm{~s}$, which corresponds to a detection threshold of $\mathrm{S}_{\text {thr }} \sim 0.015$ counts $/ \mathrm{s}$. Combining this with the result above from Güdel et al. (1997), the detectable X-ray luminosity as a function of distance and age is then

$$
\mathrm{L}_{\mathrm{x}}=4 \pi \mathrm{~d}^{2} \mathrm{~S}_{\mathrm{thr}} \times E C F=2.1 \times 10^{28} \tau^{-1.5}\left[\mathrm{ergs} \mathrm{~s}^{-1}\right],
$$

where ECF is the counts-to-energy conversion factor. The ECF is a function of spectral hardness and interstellar absorption, but G99 found a value of $10^{-11} \mathrm{erg} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$ per count $\mathrm{s}^{-1}$ to be a good average conversion factor for the RASS-Tycho and RASS-Hipparcos matches. Using this value, we calculate the maximum distance at which a star of a given age should be detectable to ROSAT:

$$
\mathrm{d}_{\max }(\mathrm{pc})=34 \times \tau(\mathrm{Gyr})^{-0.75} .
$$

This function is plotted in Figure 2.3 and the 3 Gyr detection limit of 14.8 pc is marked. Superimposed on Figure 2.3 is the normalized histogram for the 2127 RASS sources matched to the stars in our remaining sample. From this plot we can see that the detection limits of ROSAT PSPC allow us to probe distances up to $\sim 200 \mathrm{pc}$ for late spectral-type stars younger than 100 Myr . The vast majority of these detections are beyond $\sim 15 \mathrm{pc}$ and hence, according to the above calculations, younger than 3 Gyr , and we have removed all of them from our sample. The 120 stars that were detected at smaller distances are not necessarily this young, and they have been retained. Thus

20,814 stars remain in HabCat after cutting 2007 RASS sources. We note that the above age- $\mathrm{L}_{\mathrm{x}}$ relation was derived for G dwarfs, and lower mass stars may in fact take longer to decrease in X-ray luminosity (due to a longer spin-down time, see Soderblom et al. 1993) so that in terms of $\mathrm{L}_{\mathrm{x}} / \mathrm{L}_{\text {bolometric }}$ they will appear younger than their Solar-mass counterparts of the same age. However, lower mass stars also put out less total luminosity, and in terms of detectability this offsets their larger fractional X-ray fluxes (see Figure 7 of G97).

### 2.3.6 Stellar Age Indicators: Rotation

Ultimately, the X-ray emissions and chromospheric activity are associated with stellar rotation. Stars are born with relatively high rotation velocities ( $\sim 100 \mathrm{~km} / \mathrm{sec}$ ) but lose angular momentum through magnetically driven winds (Soderblom et al. 1993). The rotation slows with time, leading to decreased X-ray emissions and chromospheric activity. Since the magnetic dynamo depends on the depth of the convective envelope, the relationship between rotation period and age also depends on stellar mass. Lachaume et al. (1999) combined the period-age-mass relation found by Kawaler (1989) and Barry (1988) with evolutionary tables from Bertelli et al. (1994) to obtain an estimate of stellar age as a function of rotation period, $\mathrm{B}-\mathrm{V}$ color, and $[\mathrm{Fe} / \mathrm{H}]$. However, Tables A 1 and A 2 of Lachaume et al. show that this formula consistently gives ages that are lower than ages derived from Bertelli's isochrones by 2.5 Gyr or more. In light of this discrepancy we used rotation velocities only to exclude those stars that are unambiguously young. In
order to avoid throwing out old stars (like $v$ And, $\tau_{\text {isochrone }} \sim 3$ Gyr from Lachaume et al. 1999, $v \sin i \sim 9 \mathrm{~km} \mathrm{~s}^{-1}$ from Glebocki et al. 2000), we have chosen to make a single cut in rotation velocity at $v \sin i=10 \mathrm{~km} \mathrm{~s}^{-1}$, consistent with ages much less than 1 Gyr (at least for G-type stars and later spectral types, Soderblom et al. 1993). Data were taken from the Glebocki et al. (2000) catalog of projected rotational velocities for 4865 Hipparcos stars, of which 426 stars remain in our list. Of these, 49 rotationally young stars were identified and eliminated, leaving a sample of 20,765 potential habstars.

### 2.3.7 Habitability and Metallicity

### 2.3.7.1 Introduction

Although the presence of terrestrial planets has yet to be demonstrated for any main sequence star other than the Sun, stellar metallicity may indicate whether terrestrial planets are possible. Certainly there must be a lower limit in metallicity below which there are not enough heavy elements to build an Earth-mass planet during the system's formation. Recent work by Reid (2002b) shows that the frequency of detected planetary systems is clearly correlated with stellar metallicity. The Sun itself is typical in metallicity amongst G-type disk dwarfs within 25 pc (Reid, 2002b) but it is less metalrich than $\sim 2 / 3$ of the stars with close-orbiting giant planets (Lineweaver 2001, Santos et al. 2001, Reid 2002a). If it is the case that metallicity is an indicator not only of planet occurrence but also of planet mass then there may be a limited range of metallicities
where low mass (terrestrial) planets exist (Lineweaver 2001), which would necessitate both minimum and maximum metallicity cuts. As extrasolar planet detections accumulate we will be able to explore more thoroughly any relationship between metallicity and planet mass (and other parameters such as semimajor axis or eccentricity), but at this time there is no clear case for a correlation between planet mass and stellar metallicity (see data and analysis in Reid 2002a). Consequently, we conclude that a minimum metallicity cut is justified, but we chose not to impose an upper limit in metallicity.

The exact value in $[\mathrm{Fe} / \mathrm{H}]$ that is theoretically too low for planet formation is difficult to estimate because of the many variables involved and uncertainties remaining in star and planet formation theory (e.g., whether a more massive circumstellar disk could compensate for lower metallicity, how disk parameters are correlated with stellar mass, and to what extent giant planet mass and position can alter terrestrial planet mass, number, and position (see Wetherill 1996)). We can get a rough estimate of minimum metallicity by assuming (1) that the total terrestrial planet mass scales linearly with the abundance of the initial star-forming cloud (which is reflected in the abundance of the observable central star), (2) that the mass of terrestrial planet material in the Solar System is typical for Solar metallicity, and (3) that one Earth mass is the minimum amount of material necessary to create a habitable planet. Then the Solar System's total terrestrial planet mass ( $\sim 2$ Earth masses) implies a minimum metallicity for habitability of $[\mathrm{Fe} / \mathrm{H}] \sim$
-0.3. In the next Section we describe an observationally convenient metallicity cut that is consistent with this estimate.

### 2.3.7.2 Kinematics as an indicator of low metallicity

One tactic for identifying low-metallicity stars is to make use of kinematics data and the kinematics-age-metallicity relationship. Older generations of stars tend to be lower in metallicity and therefore they are expected to be less likely to harbor terrestrial planets. For stars in the galactic disk, a connection between metallicity and kinematics also exists because older stars are also more likely to have undergone gravitational encounters with other stars at some point during their lifetimes, and thus they tend to exhibit larger velocities relative to the local standard of rest (LSR). Stars that formed as part of the halo have even higher velocities and are thought to be the oldest existing population in the Galaxy, with near zero metallicity (see Binney \& Merrifield 1998, Chapter 10 and references therein).

To find general trends in metallicity vs. kinematics, we use the data presented by Edvardsson et al. (1993, hereafter E93) for 189 nearby F and G disk dwarfs. Figure 2.4 shows the $\mathrm{U}, \mathrm{V}$ and W Galactic velocities as a function of $[\mathrm{Fe} / \mathrm{H}]$ for the E 93 stars ( U increases away from Galactic center, V increases along Galactic rotation, and W increases towards the North Galactic Pole). The marked increase in V and W velocity dispersion at $[\mathrm{Fe} / \mathrm{H}] \sim-0.4$ makes this a convenient choice for a kinematical cut-off, and
from our calculations above we believe this metallicity is an acceptable lower limit for Solar System-like planet formation. (This metallicity is also chosen by Binney \& Merrifield (1998) as the division between the "thin" and "thick" disk populations.) From E93, we find that for the 131 stars with $[\mathrm{Fe} / \mathrm{H}]>-.4$, the average velocities and dispersions in Galactic coordinates are:

$$
\begin{gathered}
<\mathrm{U}>=1.0+/-3.0 \mathrm{~km} / \mathrm{sec}, \sigma_{\mathrm{u}}=34.3 \mathrm{~km} / \mathrm{sec}, \\
<\mathrm{V}>=-12.5+/-2.0 \mathrm{~km} / \mathrm{sec}, \sigma_{\mathrm{v}}=21.5 \mathrm{~km} / \mathrm{sec}, \text { and } \\
<\mathrm{W}>=-1.7+/-1.6 \mathrm{~km} / \mathrm{sec}, \sigma_{\mathrm{w}}=17.9 \mathrm{~km} / \mathrm{sec},
\end{gathered}
$$

where the velocities have been transformed to the local standard of rest (LSR) by accounting for the Solar velocity, $(\mathrm{U}=-10.0+/-0.4, \mathrm{~V}=5.3+/-0.6, \mathrm{~W}=7.2+/-0.4)$ $\mathrm{km} / \mathrm{sec}$ (Denhen \& Binney 1998). We have used these mean values plus and minus three times the velocity dispersions as maximum and minimum velocity limits for potential habstars. The resulting ellipsoid of space velocities included in HabCat is then described by:

$$
\begin{gathered}
(\mathrm{U}-1 \mathrm{~km} / \mathrm{sec})^{2} /(3 \times 34.3 \mathrm{~km} / \mathrm{sec})^{2}+ \\
(\mathrm{V}+12.5 \mathrm{~km} / \mathrm{sec})^{2} /(3 \times 21.5 \mathrm{~km} / \mathrm{sec})^{2}+ \\
(\mathrm{W}+1.7 \mathrm{~km} / \mathrm{sec})^{2} /(3 \times 17.9 \mathrm{~km} / \mathrm{sec})^{2} \leq 1
\end{gathered}
$$

To calculate $U, V$ and $W$ space velocities for our list of potential habstars, we have used coordinates, proper motions and parallaxes from the Hipparcos Catalog and radial velocities from Barbier-Brossat \& Figon (2000, hereafter BBF). Only data where $\left|v_{\mathrm{rad}}\right|>$ $3 \sigma_{\text {vad }}$ were used, and 1339 stars from the BBF catalog were thus matched to our remaining list of 20,765 stars. For stars without radial velocity data, $v_{r a d}$ was assumed to
be zero, and the U, V and W velocities calculated are lower limits. We did not attempt to correct for Galactic rotation because all of our stars are within $\sim 300 \mathrm{pc}$, and recent determinations of the Oort constants (e.g., Feast \& Whitelock 1997, $A=14.8+/-0.8$ $\mathrm{km} / \mathrm{sec} / \mathrm{kpc}, \mathrm{B}=-12.4+/-0.6 \mathrm{~km} / \mathrm{sec} / \mathrm{kpc}$ ) imply that the total variation in the velocity of the local standard of rest over this space is only on the order of a few $\mathrm{km} / \mathrm{sec}$, a small fraction of our velocity ellipsoid.

Thus we have separated our stars into two populations: "kinematically high metallicity" (hereafter KHM) stars and "kinematically low metallicity" (hereafter KLM) stars. The velocity space occupied by KHM stars (black points) and KLM stars (red points) is shown in Figures 2.5 a and 2.5 b (as above, the velocities are corrected for Solar motion), and using this criterion we have removed 1917 additional stars from HabCat (leaving 18,848).

We can test whether our kinematic cut is in fact removing low metallicity stars by looking at the cut for stars that have both radial velocity data and metallicity data. Figure 2.6 shows, for 699 KHM stars and for 209 KLM stars (all of which have radial velocity measurements), the distribution of metallicities derived from either spectroscopic or photometric measurements (described in the next §3.7.3). We find that, as expected, there is an offset in mean metallicity for the two groups $(<[\mathrm{Fe} / \mathrm{H}]\rangle=-0.13$ for the "high metallicity" sample and $\langle[\mathrm{Fe} / \mathrm{H}]\rangle=-0.64$ for the "low metallicity" sample), and that the KLM sample includes many objects at extremely low metallicities.

However, we also find that the KHM group includes 68 stars with measured metallicities below our desired cutoff at $[\mathrm{Fe} / \mathrm{H}]=-0.4$ (vertical dashed line), and there are 83 stars in the KLM group with $[\mathrm{Fe} / \mathrm{H}] \geq-0.4$. Therefore we expect that less than $10 \%$ of the stars predicted to be high metallicity will in fact have $[\mathrm{Fe} / \mathrm{H}]<-0.4$. We have also chosen to remove those 68 KHM stars that we know fail the metallicity cut in the next Section. For the 83 high metallicity stars with large Galactic velocity components, we point out that there may be a second reason to exclude from HabCat stars which have high velocities relative to the local standard of rest (LSR), regardless of metallicity: the LSR is believed to be nearly in co-rotation with the Galaxy's spiral pattern (Lépine et al. 2001, Balázs 2000). The co-rotation zone in the Milky Way has been proposed to give rise to a "Galactic Belt of Life," where stars near the Sun's Galactocentric radius with low velocities relative to the LSR will encounter spiral arms perhaps only once in several billion years (Balázs 2000, Marochnik \& Mukhin 1988, Doyle \& McKay 1991). The velocities of KLM stars depart significantly from that of the LSR and these stars are likely to be on elliptical orbits that bring them into more frequent spiral arm-crossings, where they encounter biologically damaging radiation fluxes perhaps $10^{7}$ times that currently received by the Earth (Clark et al. 1977, Doyle \& McKay 1991). This criterion deserves further consideration as more is learned about the true structure of the Galaxy. For now, we have chosen not to include KLM stars, even where they are known to have $[\mathrm{Fe} / \mathrm{H}]>-0.4$.

### 2.3.7.3 Spectroscopic and Photometric Measurements of Metallicity

We have also used direct spectroscopic measurements of stellar metallicity (Cayrel de Strobel et al. 2001, with data for 352 stars in our remaining sample) and metallicity estimates from Strömgren uvby photometry (Olsen 1983, Olsen \& Perry 1984, Olsen 1993, Olsen 1994a, Olsen 1994b, with data for 6272 additional stars in our remaining sample) to identify and cut low metallicity stars. In keeping with the above Sections we have set $[\mathrm{Fe} / \mathrm{H}]=-0.4$ as the lower metallicity limit for HabCat. We used Schuster \& Nissen's (1989) calibrations for F stars $(0.22<(b-y)<0.375)$ and G stars $(0.375<(b-y)$ $<0.59$ ) to estimate metallicities from Strömgren photometry. Stars with b-y colors outside this range were not considered. To check that the photometric metallicity estimates ( $[\mathrm{Fe} / \mathrm{H}]_{\text {phot }}$ ) were close to the spectroscopically determined metallicities $\left([\mathrm{Fe} / \mathrm{H}]_{\text {spec }}\right)$, we compared the $[\mathrm{Fe} / \mathrm{H}]$ estimates for 602 Hipparcos stars included in both the Cayrel de Strobel et al. and Olsen et al. catalogs. Figure 2.7 shows that while the photometrically determined metallicities depart from the spectroscopic measurements at very low metallicities $\left([\mathrm{Fe} / \mathrm{H}]_{\text {spec }}<-2\right),[\mathrm{Fe} / \mathrm{H}]_{\text {phot }}$ is generally good enough to identify stars with $[\mathrm{Fe} / \mathrm{H}]<-0.4$. Use of these catalogs has eliminated an additional 841 low metallicity stars from HabCat.

To test whether our metallicity cut is serving the purpose of eliminating stars which are not likely to host planetary companions, we have compared our lists of high and low metallicity stars to the list of stars known to host extrasolar planets. At the time of this
writing, 80 Hipparcos stars are confirmed candidates for hosting extrasolar planetary systems based on radial velocity variations (http://www.exoplanets.org). Of these, 4 stars have metallicities below our $[\mathrm{Fe} / \mathrm{H}]$ cutoff (HIP 5054, 26381, 64426, 64459). One explanation for low metallicity, giant exoplanets may be that they were formed by gravitational instabilities, rather than by core accretion and subsequent addition of a dense atmosphere (Boss 2002). In that case, these low metallicity systems are unlikely to harbor terrestrial planets or giant moons suitable for complex life. Furthermore, the analysis of planet-bearing stars by Reid (2002b) shows that the frequency of currently detectable planets drops from $\sim 50 \%$ at $[\mathrm{Fe} / \mathrm{H}]=0$ to $\sim 2 \%$ at $[\mathrm{Fe} / \mathrm{H}]=-0.4$. This means that adjusting our cuts to include the lowest metallicity of planet-candidate stars (HIP 64426, $[\mathrm{Fe} / \mathrm{H}] \sim 0.7$ from Cayrel de Strobel et al.'s 2001 catalog) would add fewer than 50 planetary systems to HabCat while increasing the number of stars in the catalog by $\sim 2500$. At this time we opt not to alter our bulk metallicity cut, even for cases in which low metallicity stars are known to harbor giant planets. This decision will be revisited if future observations provide evidence of terrestrial planets in low metallicity systems.

As a result of applying the low metallicity cut at $[\mathrm{Fe} / \mathrm{H}]=-0.4,18,007$ potential habstars remain. The 55 remaining exoplanetary systems are assessed for dynamical habitability in Section 2.3.8.4 of this Chapter.

### 2.3.8 Habitability and Stellar Multiplicity

### 2.3.8.1 Introduction

In terms of habitability, binary and multiple star systems are especially interesting because there is the potential for a habitable zone surrounding each star in the system as well as a circumbinary habitable zone. It is clear that, at least in certain configurations, planets can form and persist for billions of years in binary systems without being ejected or accreted (e.g., planets orbiting in double systems $16 \mathrm{Cyg} \mathrm{B}, 55 \mathrm{Cnc}, \tau \mathrm{Boo}$, v And, and triple system HD 178911). However, not all binary orbits will permit dynamically stable habitable zones. Even if a dynamically stable HZ does exist, a planet orbiting there may receive wildly varying levels of radiation due to the constantly changing distance of the second star. Given that $\sim 2 / 3$ of stars are in binary or multiple systems (Abt \& Levy 1976, Duquennoy \& Mayor 1991), these issues are important to the overall habitability of the Galaxy. In the following Section we describe the analysis of habitability for Hipparcos binary and multiple systems in detail.

After all of the cuts described in the previous Sections, there remain 3507 unique entries in the HabCat that are known or suspected members of multiple star systems. This includes 2433 entries that are associated with an identifier from the Catalog of Components of Double and Multiple Stars (the "CCDM" category), 19 known eclipsing binaries ("EB"), 49 known spectroscopic binaries ("SB," data provided by D. Pourbaix,
private communication), 627 entries flagged as suspected non-single stars ("SNS"), 37 orbital astrometric binaries with full or partial orbital solutions listed in the Hipparcos Double and Multiple Systems Annex ("O"), and 542 entries whose astrometric solutions required "acceleration" terms ("G"). Inventories for these non-exclusive multiplicity categories are listed in Table 2.

Before the dynamical and radiation variability analyses were performed, the list of binary/multiple systems was prepared as follows:

1. Hipparcos parallax and proper motion measurements were compared for the visual doubles/multiples where both components remain on our list of potential habstars. In this manner we identified CCDM visual doubles that are not physical binaries as evidenced by Hipparcos parallax measurements. However, we note that the analysis of parallax and proper motion data was not always carried out when Hipparcos observed only one component, or when only one CCDM component remained on our list of potential habstars. Therefore the cuts of this Section have likely excluded from HabCat a few single stars on erroneous grounds.
2. Wherever a CCDM identifier was associated with more than one Hipparcos entry, all components were removed if one or more components failed any of the criteria applied in the above Sections.
3. Stars whose astrometric solution quality was flagged as "suspected non-single" were removed, because we require an estimate of semimajor axis or period in order to assess habitability. Stars whose astrometric solutions required acceleration terms were not removed, as they are probably wide binaries (with periods much longer than the Hipparcos mission duration) whose orbits are unlikely to interfere with the habitable zones lying within a few AU of either star. The unseen component is assumed to be a main sequence star that is fainter than Hipparcos' detection limits. Eclipsing binaries, of which the longest period is 6.7 days, also do not affect their surrounding habitable zone, so none of these systems were cut.
4. Stars without angular separation measurements listed in either the CCDM or Hipparcos catalogs were removed from the list.
5. Each entry was examined by hand to identify visual triple systems. The CCDM catalog often lists only two components, while Hipparcos in fact resolved one of those CCDM components into two stars, resulting in a known triple system. There were no such known quadruple stars.
6. For relative simplicity, systems having more than two components were eliminated, except in the cases where (a) one component of a wide binary was resolved into two stars by Hipparcos, (b) one component of a visual double is an eclipsing binary, or (c) the visual double has a long period component as evidenced by astrometric acceleration
terms. In case (a), all three components were taken into account when assessing the dynamical stability of the HZs as described in §3.8.2.
7. Each system was matched with V-band magnitudes and angular separations from the CCDM catalog. When the CCDM and Tycho photometry did not agree, Tycho photometry was used. Where Tycho photometry was available for only one component of a binary, the CCDM magnitude differences were used to calculate the magnitude of the second component. Where Tycho photometry represents the combined light of two components, the CCDM magnitudes were used to deconvolve the Tycho photometry into two magnitudes. For triples, V magnitudes for the third components (usually not observed by Hipparcos) were likewise calculated by using the CCDM magnitude differences. Where one component was resolved into two stars the separation was taken from the Hipparcos Catalogue, but V-band photometry for the individual components was generally not available in any catalog. In this case, individual V magnitudes were estimated from the Hp magnitude difference.

The above preparations removed 410 Hipparcos entries. For the remaining stars, habitable zones of visual double/triples were assessed for both dynamical stability and irradiance variations (2.3.8.2), while spectroscopic and astrometric binaries were assessed only for dynamical stability because the magnitude of the secondary star is not known (2.3.8.3). When one entry was associated with more than one multiplicity category, the star was assessed for habitability independently in each category.

### 2.3.8.2 Visual Doubles/Multiples

Stable planetary orbits for a binary star can take two forms: S-type orbits, in which the planet orbits as a "satellite" to one of the stars, or P-type ("planetary") orbits, in which the planet orbits the whole binary. The question of habitability for these systems depends on whether the habitable zone set up by either an individual star or the binary as a whole resides within a region of dynamical stability. Figures 2.8 a and 2.8 b show the possible configurations of dynamically stable habitable zones of double and triple star systems, respectively. The dashed lines denote the "critical" semimajor axes for planets orbiting the primary and secondary, inside of which a planet will be dynamically stable, while the solid line denotes the critical semimajor axis for a planet orbiting the entire binary, outside of which a planet will be dynamically stable. The location of each critical distance depends on binary mass ratio, eccentricity and separation. For a binary to be habitable, one of the three possible HZs must be dynamically stable. We note that while the Figures portray several dynamically stable habitable zones, it is never true that circumstellar and circumbinary habitable zones simultaneously exist (i.e., as we move two stars closer together, their HZs eventually merge and become one circumbinary HZ ).

We begin our analysis by locating the habitable zone for each system. For the outer edge of the HZ we have chosen to use the "maximum greenhouse limit" from Kasting, Whitmire, \& Reynolds (1993, K93), which is the maximum distance from the star where
a cloud-free $\mathrm{CO}_{2}$ atmosphere can maintain a surface temperature of 273 K . Beyond this distance, additional $\mathrm{CO}_{2}$ does not further warm the planet because the atmosphere is already entirely opaque in the infrared and the additional $\mathrm{CO}_{2}$ serves to raise the planetary albedo through increased Rayleigh scattering. However, the maximum greenhouse limit may be conservative, because $\mathrm{CO}_{2}$ clouds are expected to condense interior to this radius, and (unlike water clouds) their net effect would be to warm the planetary surface through a scattering greenhouse effect, thereby increasing the distance of the outer HZ boundary (Forget \& Pierrehumbert 1997). In this analysis, the inner habitable zone limit was not needed, because even the closest visually resolved binaries had separations of more than a few $A U$, so circumbinary habitable zones were never possible.

Using these criteria, the outer limit of the Sun's HZ is $\sim 1.67 \mathrm{AU}$ with an atmospheric $\mathrm{CO}_{2}$ partial pressure of $\sim 10$ bars. For stars of different spectral types, the radiation field will differ in total energy flux and in wavelength distribution, both of which have effects on the habitable zone limits. For a main sequence star more massive than the Sun the increase in stellar luminosity pushes the habitable zone outward, but the shifting of the spectrum towards the blue lessens this effect somewhat because the $1 / \lambda^{4}$ dependence of Rayleigh scattering increases the effective planetary albedo. For a main sequence star less massive than the Sun, the smaller luminosity causes the $H Z$ to move inward, but the shifting of radiation towards the red lessens this effect in two ways: (1) Rayleigh scattering is decreased thereby lowering the effective planetary albedo, and (2) the
amount of starlight absorbed by the planet is further enhanced by high opacities in the near-infrared due to atmospheric $\mathrm{H}_{2} \mathrm{O}$ and $\mathrm{CO}_{2}$. K93 included these effects in calculating HZ boundaries for stars of spectral types M0, G2 and F0. We corrected K93's HZ locations based on updated luminosity estimates for their listed effective temperatures (main sequence luminosities taken from $\operatorname{Cox} 2000$ ). We then interpolated by eye for spectral types between F 0 to M 0 and extrapolated by eye down to our faintest stars at $\mathrm{M}_{\mathrm{v}}$ $\sim 18$. We fit polynomials to the resulting data to obtain the approximate location of the habitable zone outer limit in terms of $\mathrm{M}_{\mathrm{v}}$ :
$M_{v}<3.46:$
$\mathrm{a}_{\text {out }}=23.21-19.41 \times \mathrm{M}_{\mathrm{v}}+12.49 \times \mathrm{M}_{\mathrm{v}}{ }^{2}-5.165 \times \mathrm{M}_{\mathrm{v}}{ }^{3}+1.051 \times \mathrm{M}_{\mathrm{v}}{ }^{4}-0.07996 \times \mathrm{M}_{\mathrm{v}}{ }^{5}$
$\mathrm{Mv} \geq 3.46$ :
$\mathrm{a}_{\text {out }}=6.959-1.896 \times \mathrm{M}_{\mathrm{v}}+0.2283 \times \mathrm{M}_{\mathrm{v}}{ }^{2}-0.01433 \times \mathrm{M}_{\mathrm{v}}{ }^{3}+0.0004473 \times \mathrm{M}_{\mathrm{v}}{ }^{4}-5.393 \times$ $10^{-6} \times \mathrm{M}_{\mathrm{v}}{ }^{5}$

The next step in identifying habitable binaries is to calculate for each system where stable planetary orbits are located. Holman \& Wiegert (1999, hereafter H99) have investigated planetary stability in binaries with numerical simulations for a range of binary mass ratios and eccentricities. Our estimates of critical semimajor axes, $a_{\text {crit }}$, are very rough, as we do not have any direct measurement of mass ratios, orbital eccentricity, inclination or semimajor axis for visual binaries/triples. We estimated stellar mass ratios from V-band photometry, and for eccentricity we used $\mathrm{e}=0.67$, the average value for binaries with
periods greater than 1000 days (Duquennoy \& Mayor 1991). We also took the observed linear separation to be the semimajor axis. The distance $\mathrm{a}_{\text {out }}$ was then required to be less than $\mathrm{a}_{\text {crit }}$ for at least one star in order for a double system to be habitable.

As is shown in Figure 2.8b, the situation is slightly more complicated for triple systems. There is now an additional circumbinary radius outside of which planets will not be stable due to the presence of the third star, and this may eliminate the possibility of circumbinary stable orbits and interfere with S-type orbits inside the close pair. With the observed separations and our assumption of $\mathrm{e}=0.67$, there was no situation where a circumbinary or circumtriple habitable zone was possible.

In doing this HZ stability analysis we eliminated 310 Hipparcos entries, leaving 1387 entries that are associated with visual binary systems and 115 entries associated with visual triple systems or visual doubles where one component is an eclipsing, spectroscopic or astrometric binary. In Figure 2.9 we plot absolute V-band magnitude verses linear separation for the components of our remaining double/triple systems as compared to the outer HZ location. We note that in this plot, the binary components have brightnesses and separations that seem to avoid interference with the $H Z$, but this is an observational effect. Brighter objects are on average further away and therefore are not visually resolved at small separations, and spectroscopically detected binaries tend to "fill in" the space overlapping and interior to the HZ .

In order to assess the level of radiation variability within each habitable zone due to the constantly changing distance of a second star, we first calculated maximum and minimum distances of the second star to the habitable zone in question by again assuming a binary eccentricity of 0.67 and a semimajor axis as given by the observed linear separation. The fractional change in total HZ irradiance from maximum to minimum stellar separation was then calculated and systems where the HZ irradiance varies by more than $3 \%$ (the limit imposed in Section 2.2 .2 for single variable stars) were eliminated. The largest binary separation that was cut during this part of the analysis was 86 AU. For triples, it was always the case that the third star was more than $\sim 90 \mathrm{AU}$ away from the close pair, so radiation variations were not a concern for this distant companion. Thus we eliminated 101 more Hipparcos entries from HabCat, and these systems are also shown in Figure 2.9.

One effect that we have not accounted for in this Section is that of terrestrial planet orbital eccentricity induced by the presence of a second star. For example, Mazeh, Krymolowski, \& Roenfeld (1997) have suggested that the high eccentricity of the giant planet orbiting $16 \mathrm{Cyg} \mathrm{B}(\mathrm{e}=0.63, \mathrm{a}=1.6 \mathrm{AU})$ is caused by the presence of 16 Cyg A even given the wide separation of the pair (projected binary separation $\sim 800 \mathrm{AU}$, mass ratio $\sim 1$, eccentricity similar to our assumption above, Cochran et al. 1997, Romanenko 1994). Recent work by Williams \& Pollard (2002) suggests that Earths on fairly eccentric orbits might still be habitable, as long as the average stellar flux received over an entire orbit is comparable to that received by a planet on a circular orbit within the HZ. The expected
planet eccentricity in binary systems (which will presumably be a function of the secondary mass, orbital eccentricity and inclination relative to the planet orbital plane) remains an outstanding question at this time.

### 2.3.8.3 Spectroscopic and Astrometric Binaries

After all of the above cuts on binary stars, the remaining list contained 17,190 Hipparcos stars. From this list we identified 47 binaries with spectroscopically or astrometrically determined orbits. For each system a mass ratio of 0.23 (the average value according to Duquennoy \& Mayor 1991) was assumed unless the system was a double-lined spectroscopic binary, in which case the mass ratios were calculated from the maximum velocity amplitudes of the two components. The eccentricities were directly available for spectroscopic binaries, and for astrometric binaries the eccentricity was assumed to be 0.67 as in the previous Section. For spectroscopic binaries the mass of the primary was estimated from the V-band magnitude of the system and the semimajor axis was then calculated from the period, while for astrometric binaries the projected semimajor axis was used. Outer HZ limits were calculated as above, and the inner HZ limits were estimated by subtracting an HZ width that is proportional to $L_{*}^{0.5}$ (where bolometric corrections were taken from Flower 1996) and equal to 0.81 AU for a $1 \mathrm{~L}_{\S}$ star. The entire HZ was required to be dynamically stable for a binary to be included in HabCat. Thus 12 SBs (all with periods less than 45 days) were found to have stable circumbinary habitable zones but none were found to have stable circumstellar HZs. Of the 29
astrometric binaries, only 9 were found to be dynamically habitable (with semimajor axes up to 0.5 AU ), all of which support circumbinary habitable zones. Three stars had both spectroscopic and astrometric orbits, and they were required to be habitable according to all the observations. A total of 27 objects were removed in the Section.

### 2.3.8.4 Extrasolar Giant Planets

Of the 17,163 stars remaining in HabCat, there are 55 stars known to host 65 total planets. With the smallest minimum planet mass of 0.12 Jupiter masses (HD 49674), all of these planets are likely to be gas giants and are thus unlikely to support Earth-like life. However, these planetary systems may still be habitable if (a) the giant planet does not interfere with the dynamic stability of the HZ , or (b) the giant planet occupies the HZ throughout its orbit, giving rise to potentially habitable moons. The potential habitability of moons is questionable, considering the high-radiation environment of a giant planet, possible gravitational focusing of large impactors by the giant planet, and the large eccentricities of most known extrasolar giant planets. Williams, Kasting \& Wade (1997) have shown that the effects of radiation could be avoided if the moon has an Earth-like magnetic field, and work by Williams \& Pollard (2002) suggests that planets in eccentric orbits will still be habitable, as long as the stellar flux averaged over one year at the moon's surface is comparable to that of a circular orbit (as was also mentioned in §3.8.2). The question of whether impact rates could remain high enough after a few billion years to prevent the appearance of complex life remains to be addressed.

In order to assess the dynamical habitability of these systems, we have located the inner and outer HZ limits as in the previous Section, and we have demanded that no giant planet come within three Hill radii of the habitable zone at any time during its orbit (hereafter referred to as the "Hill criterion"). At a separation of one Hill radius, the gravitational interaction between the giant planet and a terrestrial planet is approximately the same as that between either planet and the central star. This distance is calculated by:

$$
\mathrm{R}_{\mathrm{H}}=\mathrm{a}\left(\mathrm{M}_{\mathrm{p}} / 3 \mathrm{M}_{*}\right)^{1 / 3}
$$

where $M_{p}$ is the mass of the known giant planet, $M_{*}$ is the mass of the star, and $\alpha$ is the giant planet's semimajor axis. Stellar masses were calculated by:

$$
\log \left(\mathrm{M} / \mathrm{M}_{\S}\right)=0.48-0.105 \mathrm{M}_{\mathrm{bol}},
$$

where $\mathrm{M}_{\mathrm{bol}}$ is the bolometric magnitude (bolometric corrections taken from Flower 1996). The data used in our calculations and habitability results (star name, mass, luminosity, planet mass, planet semimajor axis, inner HZ limit, outer HZ limit, and whether the system is habitable) are shown in Table 3.

In previous work, Jones et al. (2001) used the Hill criterion in addition to demanding that a terrestrial planet survive in the HZ for $10^{8}$ to $10^{9}$ years in numerical integrations for four exoplanetary systems, and Noble et al. (2002) have performed numerical integrations for three exoplanetary systems at higher time resolution but shorter total times. We have not performed any numerical integration, but we have used the Hill criterion to look at all of the 55 otherwise habitable exoplanetary systems. Figure 2.10 shows the location of
habitable zones compared to the radial excursion of known planetary companions. Also indicated is the area falling within three times the giant planet's Hill radius. From this analysis we found that 17 of the known exoplanetary systems could host terrestrial planets in the habitable zone, 4 have giant planets orbiting completely within the HZ and could host habitable moons (HIPs $86796,17096,20723$, and 8159 ), and we ruled out the other 34. For those "habitable" systems with giant planets interior to 1 AU , we note that although the HZ is stable, the giant planet probably would have migrated through the HZ on its way to its current location. This would not bode well for the existence of terrestrial planets in the HZ. However, terrestrial planet formation in the HZ after giant planet migration may not be impossible, and other (so far undetected) giant planets in the HZ could have habitable moons, so for now, we have opted to keep these systems on our target list.

Where our list of exoplanetary systems overlaps with the objects analyzed by Jones et al. (2001, rho Crb, ups And, 47 UMa, Gliese 876) and Noble et al. (2002, HD 210277, 51 Peg, 47 UMa ), we find that in every case our analysis reaches the same conclusions as the numerical integrations. We note that in this Chapter, for a system to be considered "habitable" the entire HZ must be stable, so we have not included 47 UMa in HabCat, although we agree with both authors that there are likely to be stable orbits in the inner HZ . We also find that the triple planetary system 55 Cnc is habitable, in agreement with work done by Marcy et al. (2002). After cutting these last 34 stars from our list, HabCat contains 17,129 habstars.

### 2.4. Summary of Chapter 2

To briefly restate our criteria for habitability, a "habstar" must: (1) be at least 3 Gyr old, (2) be non-variable, (3) be capable of harboring terrestrial planets, and (4) support a dynamically stable habitable zone (defined by that annulus where an Earth-like planet could support liquid water on its surface). We have used those criteria to trim the list of 118,218 stars in the Hipparcos Catalogue down to the 17,129 stars in the Catalog of Nearby Habitable Stellar Systems (HabCat). HabCat will serve as the list of preferred targets for targeted searches carried out by the SETI Institute from the Allen Telescope Array.

Despite the broad array of data used to assemble this catalog, this exercise has forced us at every turn to admit that we are defining "habitability" from a position of considerable ignorance. A complete characterization of all the stars within a few hundred (or even a few tens of) parsecs, including their masses, ages, variability, and whether they have stellar companions or planetary systems (including terrestrial planets), is simply not realizable at this time. Additionally, many theoretical questions remain regarding the effects of metallicity on planet formation, the kinematics of stars and whether spiral arm crossings are truly deleterious to life forms, the effects of stellar variability (including timescales of hours, days and decades) on planet climate, the effect of stellar/giant planet companions on terrestrial planet orbital eccentricity, the effect of the stellar spectral
energy distribution on the evolution of plants and other life forms, the suitability of giant planet moons for life (given expected impact rates, tidal heating, and particle radiation), etc. For SETI, this humbling situation is amplified when we consider that we have no indisputable definition for "life" itself, to say nothing of the precise conditions that are necessary and sufficient for life to evolve into a technological civilization detectable by a SETI search program. HabCat reflects the state of our current knowledge and will evolve as we learn more about Galactic structure, the Solar Neighborhood, planets, life in the Solar System, and the evolution of intelligence on Earth.

Figure 2.11 shows habstar distances as a function of spectral type as well as the cumulative distribution for all spectral types. Distances have been corrected for the LutzKelker bias using the method outlined in Hanson (1979) and the parameters specific to the Hipparcos sample as determined by Reid (1997). The Allen Telescope Array (ATA) will have access to the 12,319 habstars north of $-34^{\circ}$ in declination. With predicted ATA sensitivities, we will be able to place upper limits of $1.2 \times 10^{13}$ Watts EIRP (comparable to the Arecibo planetary radar power) on ETI transmissions at a distance of 300 pc . As can be seen in Figure 2.12, the Hipparcos limiting magnitude and our cut on early-type stars have conspired to create a list comprised mostly of late F and G stars ( $44 \% \mathrm{~F}, 39 \%$ G, $14 \% \mathrm{~K}$, and $3 \% \mathrm{M}$ stars). The list of Hipparcos stars contained in HabCat is available in the electronic version of Turnbull \& Tarter (2003) and via email from M. Turnbull.

Table 1

## The Celestia Query

| Query Parameter | Specification | Number of |
| :--- | :---: | :---: |
| 1. Hipparcos Stars | All entries | 118,218 |
| 2. Photometry | $-1.037<$ B-V $<5.460$ | 116,937 |
| 3. Parallax | $\pi>0$ mas | 113,710 |
| 4. Parallax Uncertainty | $\sigma_{\pi} / \pi<0.3$ | 69,301 |
| 5. Coarse Variability | $<0.06$ mag | 4112 |
| 6. Coarse Variability | 0.06 to 0.6 mag | 6351 |
| 7. Coarse Variability | $>0.6$ mag | 1099 |
| 8. Variability Annex | Unsolved variables (2) | 5542 |
| 9. Variability Annex | Light curve (not folded) (C) | 827 |
| 10. Variability Type (1 Letter) | Microvariable (M) | 1045 |
| 11. Variability Type (1 Letter) | Unsolved variables (U) | 7784 |
| 12. Multiplicity Annex | Variability induced movers (V) | 288 |
| 13. Multiplicity Annex | Stochastic solution (X) | 1561 |
| 14. Resolved Components | 3 or 4 | 135 |
| 15. Variability Type (5 Letters) | E, EA, EB, EW | 986 |
| 16. Combined Criteria | 1 AND 2 AND 3 AND 4 | 69,014 |
| 17. Combined Criteria | NOT 14 AND (4 OR 5 OR 6) | 10,576 |
| 18. Combined Criteria | 1 AND NOT (7 OR 8 OR 9 OR 10 | 64,120 |

## Table 2

Hipparcos Binary/Multiple Stars

| Multiplicity Type | EB | CCDM | SB | SNS | 0 | G |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| EB.................... | $19$ | ... | ... | ... | ... | ... |
| CCDM................ | $3$ | $2433$ | ... | ... | ... | ... |
| SB | $4$ | $32$ | $49$ | ... | ... | ... |
| SNS | $1$ | $122$ | $2$ | $627$ | ... | ... |
| O...................... | $0$ | 7 | $6$ | 0 | $37$ | ... |
| G...................... | 0 | 25 | 3 | 0 | 0 | 542 |

Table 2.3
Extrasolar Giant Planet Data

| Star parameters |  |  |  |  | Planet parameters |  |  | HZ parameters |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| HP | Other | $\mathrm{M}_{\mathrm{v}}$ | $\begin{aligned} & \mathrm{M}_{*} \\ & \mathrm{M}_{8} \end{aligned}$ | $\begin{aligned} & \mathrm{L}_{*} \\ & \mathrm{~L}_{\$} \end{aligned}$ | $\underset{M_{j}}{M \sin i}$ | $\begin{gathered} \mathrm{a} \\ \mathrm{AU} \end{gathered}$ | e | $\begin{aligned} & \mathrm{a}_{\text {out }} \\ & \mathrm{AU} \end{aligned}$ | $\begin{aligned} & \mathrm{a}_{\mathrm{in}} \\ & \mathrm{AU} \end{aligned}$ | HAB1 ${ }^{1}$ | HAB2 ${ }^{2}$ |
| 522 | HD142 | 3.66 | 1.25 | 2.77 | 1.36 | 0.98 | 0.37 | 2.46 | 1.09 | NO | NO |
| 1931 | HD2039 | 4.23 | 1.11 | 1.75 | 5.10 | 2.20 | 0.69 | 2.07 | 0.99 | NO | NO |
| 3502 | HD4203 | 4.24 | 1.13 | 1.86 | 1.64 | 1.09 | 0.53 | 2.07 | 0.95 | NO | NO |
| 6643 | HD8574 | 3.90 | 1.19 | 2.28 | 2.23 | 0.76 | 0.40 | 2.29 | 1.05 | NO | NO |
| 7513 | Ups And | 3.45 | 1.31 | 3.36 | 0.68 | 0.06 | 0.01 | 2.60 | 1.10 | YES | NO |
| 7513 | Ups And | 3.45 | 1.31 | 3.36 | 1.94 | 0.83 | 0.25 | 2.60 | 1.10 | NO | NO |
| 7513 | Ups And | 3.45 | 1.31 | 3.36 | 4.02 | 2.54 | 0.31 | 2.60 | 1.10 | NO | NO |
| 8159 | HD10697 | 3.71 | 1.27 | 2.94 | 6.08 | 2.12 | 0.11 | 2.42 | 1.01 | YES ${ }^{3}$ | YES ${ }^{3}$ |
| 9683 | HD12661b | 4.58 | 1.04 | 1.31 | 2.30 | 0.82 | 0.35 | 1.87 | 0.93 | NO | NO |
| 9683 | HD12661c | 4.58 | 1.04 | 1.31 | 1.56 | 2.56 | 0.20 | 1.87 | 0.93 | NO | NO |
| 12048 | HD16141 | 4.05 | 1.16 | 2.07 | 0.22 | 0.35 | 0.00 | 2.18 | 1.00 | YES | YES |

[^0]|  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |


| Star parameters |  |  |  |  | Planet parameters |  |  | HZ parameters |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| HIP | Other | $\mathrm{M}_{\mathrm{v}}$ | $\begin{aligned} & \mathrm{M}_{*} \\ & \mathrm{M}_{\mathrm{s}} \end{aligned}$ | $\begin{aligned} & \mathrm{L}_{*} \\ & \mathrm{~L}_{\mathbf{g}} \end{aligned}$ | $\begin{gathered} M \sin i \\ M_{J} \end{gathered}$ | $\begin{gathered} \mathrm{a} \\ \mathrm{AU} \end{gathered}$ | e | $\begin{aligned} & \mathrm{a}_{\text {out }} \\ & \mathrm{AU} \end{aligned}$ | $\begin{gathered} \mathrm{a}_{\mathrm{in}} \\ \mathrm{AU} \end{gathered}$ | HAB1 ${ }^{1}$ | $\mathrm{HAB}_{2}{ }^{2}$ |
| 86796 | HD160691 | 4.20 | 1.13 | 1.83 | 1.74 | 1.48 | 0.31 | 2.09 | 0.98 | YES ${ }^{3}$ | YES ${ }^{3}$ |
| 89844 | HD168443b | 4.03 | 1.18 | 2.19 | 7.64 | 0.30 | 0.53 | 2.20 | 0.98 | YES | NO |
| 89844 | HD168443c | 4.03 | 1.18 | 2.19 | 16.96 | 2.87 | 0.20 | 2.20 | 0.98 | NO | NO |
| 90004 | HD168746 | 4.78 | 0.99 | 1.09 | 0.24 | 0.07 | 0.00 | 1.77 | 0.91 | YES | YES |
| 90485 | HD169830 | 3.10 | 1.42 | 4.62 | 2.95 | 0.82 | 0.34 | 2.89 | 1.12 | NO | NO |
| 96901 | 16 Cyg B | 4.60 | 1.02 | 1.25 | 1.68 | 1.69 | 0.68 | 1.86 | 0.95 | NO | NO |
| 97336 | HD187123 | 4.43 | 1.06 | 1.46 | 0.54 | 0.04 | 0.01 | 1.96 | 0.97 | YES | YES |
| 98714 | HD190228 | 3.33 | 1.40 | 4.36 | 5.01 | 2.25 | 0.43 | 2.70 | 0.98 | NO | NO |
| 101806 | HD196050 | 4.14 | 1.14 | 1.91 | 2.81 | 2.41 | 0.20 | 2.13 | 0.99 | NO | NO |
| 104903 | HD202206 | 4.75 | 1.00 | 1.12 | 14.68 | 0.77 | 0.42 | 1.78 | 0.91 | NO | NO |
| 108859 | HD209458 | 4.29 | 1.09 | 1.60 | 0.63 | 0.05 | 0.02 | 2.04 | 1.00 | YES | YES |
| 109378 | HD210277 | 4.90 | 0.97 | 1.02 | 1.29 | 1.12 | 0.45 | 1.71 | 0.88 | NO | NO |
| 111143 | HD213240 | 3.76 | 1.23 | 2.61 | 4.49 | 2.02 | 0.45 | 2.38 | 1.05 | NO | NO |
| 113020 | GJ876c | 11.80 | 0.27 | 0.01 | 0.56 | 0.13 | 0.27 | 0.27 | 0.20 | YES | NO |
| 113020 | GJ876b | 11.80 | 0.27 | 0.01 | 1.89 | 0.21 | 0.10 | 0.27 | 0.20 | NO | NO |
| 113137 | HD216437 | 3.92 | 1.20 | 2.32 | 2.09 | 2.38 | 0.34 | 2.27 | 1.02 | NO | NO |
| 113357 | 51 Peg | 4.52 | 1.04 | 1.35 | 0.46 | 0.05 | 0.01 | 1.91 | 0.95 | YES | YES |
| 113421 | HD217107 | 4.70 | 1.01 | 1.20 | 1.29 | 0.07 | 0.14 | 1.81 | 0.91 | YES | YES |
| 116906 | HD222582 | 4.57 | 1.03 | 1.28 | 5.20 | 1.36 | 0.76 | 1.88 | 0.95 | NO | NO |



Figure 2.1. The color-magnitude diagram for the Celestia sample, showing evolutionary tracks up to 3 Gyr for a 1.4 Solar mass star (yellow) and a 1.6 Solar mass star (cyan) with Solar metallicity. Also shown are the cuts applied below the main sequence and at the Hertzsprung gap, and a maximum luminosity cut at $\mathrm{M}_{\mathrm{v}}=2.5$ (described in §3.1). The shaded area of the color-magnitude diagram was excluded from HabCat.


Figure 2.2. The distribution of calcium H\&K activity for 1408 stars in our sample (left axis). The vertical dashed line indicates our cutoff for "young" stars at $\log \mathrm{R}^{\prime}{ }_{\mathrm{HK}}=-4.75$, and the dotted line indicates the CE-age relation from Donahue (1993) in gigayears (right axis) as a function of $\log \mathrm{R}^{\prime}$ нк. The Sun's excursion in $\log \mathrm{R}^{\prime}{ }_{\mathrm{HK}}$ from Maunder Minimum ( -5.1 ) to Solar Maximum ( -4.75 ) is also shown.


Figure 2.3. The number of RASS detections as a function of distance (left axis). The dotted line indicates the maximum age star detectable to ROSAT (right axis) at the given distance, based on the $\mathrm{L}_{\mathrm{x}}$-age relation from Güdel et al. (1997). The vertical dashed line indicates the distance within which detected stars may be older than 3 Gyr .


Figure 2.4. (a) U, V and W velocity components (circles, squares, and triangles, respectively) as a function of metallicity for the 189 stars in Edvardsson et al. (1993). The vertical dashed line at $[\mathrm{Fe} / \mathrm{H}]=-0.4$ denotes the minimum metallicity cutoff applied to HabCat.


Figure 2.5. (a) The V and U components of galactic space velocity for 20,765 potential habstars resulting from the cuts of §3.6. Stars with 3-dimensional space velocities that indicate "low" metallicity are black, and kinematically "high" metallicity stars are indicated in gray. (b) The same, for V and W components of galactic space velocity. V is along the direction of galactic rotation, $U$ is positive toward the galactic anti-center, and $W$ is perpendicular to the galactic plane.


Figure 2.6. The metallicity distributions of kinematically low metallicity stars (KLM, filled histogram) and kinematically high metallicity stars (KHM, open histogram). The metallicities were derived either from spectroscopic data or photometry (described in $\S 3.7 .3$ ), and the vertical dashed line denotes the minimum metallicity cutoff applied to HabCat.


Figure 2.7. Spectroscopically determined metallicities ( $[\mathrm{Fe} / \mathrm{H}]_{\text {spec }}$, from Cayrel de Strobel et al. 2001) compared to photometrically determined metallicities using Strömgren uvby photometry ( $[\mathrm{Fe} / \mathrm{H}]_{\text {phot }}$, see Olsen et al. references) for 602 Hipparcos stars. $[\mathrm{Fe} / \mathrm{H}]_{\text {phot }}$ agrees well enough with $[\mathrm{Fe} / \mathrm{H}]_{\text {spec }}$ for use in coarsely assigning stars to "low" $([\mathrm{Fe} / \mathrm{H}]<$ -0.4 ) and "high" ( $[\mathrm{Fe} / \mathrm{H}] \geq-0.4$ ) metallicity categories. The dashed lines denote the minimum metallicity cutoff applied to HabCat.


Figure 2.8. The location of possible habitable zones (shaded area) and stable planet orbits for (a) a binary system and (b) a triple system (not to scale). Stable S-type (circumstellar) orbits exist interior to the dotted lines, and stable P-type (circumbinary) orbits exist exterior to the solid lines. Note that while the Figure illustrates both circumbinary and circumstellar HZs, in reality a circumbinary HZ can only exist when two stars are so close together that neither could support a circumstellar HZ.


Figure 2.9. The location of the outer HZ limit as a function of absolute V magnitude (dashed line), compared to the separations of the binaries (squares) and triple systems (stars) of $\S$ 3.8.2. Black symbols denote systems that were cut due to dynamical instability of the HZ , magenta symbols denote systems that were cut due to radiative variations in the HZ of greater than $3 \%$, and cyan symbols denote systems that were kept in HabCat.


Figure 2.10. The location of the HZ (shown in magenta) as a function of absolute V magnitude for stars known to harbor extrasolar giant planets, compared to the total orbital excursions of the exoplanets (solid black line) and the orbital excursion plus three times the Hill sphere (cyan dashed line).


Figure 2.11. The number of HabCat stars as a function of distance for M stars (solid histogram), K stars (dark-hatched histogram), G stars (light-hatched histogram), F stars (horizontal-lined histogram), and all stars (open histogram). The furthest star in HabCat is at $\sim 300 \mathrm{pc}$, and transmitter powers comparable to the Arecibo planetary radar will be detectable to the ATA at this distance.


Figure 2.12. The number of HabCat stars as a function of B-V color. Our spectral type cutoff at $\sim$ F5 and the Hipparcos limiting magnitude result in a sample that contains primarily late F- and early G-type stars.

# 3. TARGET SELECTION FOR SETI: II. TYCHO-2 DWARFS, OLD OPEN CLUSTERS, AND THE NEAREST 100 STARS 

### 3.1 Introduction

In Chapter 2, we described in detail the Catalog of Nearby Habitable Stellar Systems (HabCat), which consists of 17,129 stars selected from the Hipparcos Catalog according to considerations of age, variability, spectral type, metallicity, and multiplicity. Subject to observational limitations and gaps in our understanding of life, this catalog contains "habstars" that may host planetary systems that are habitable to complex lifeforms. The radio search for extraterrestrial technological signals currently in progress at the SETI Institute will concentrate its observing time on these stars for the remaining observations at the Arecibo Observatory and for the first few years of observations at the Allen Telescope Array (ATA, formerly the One-hectare Telescope or 1 hT ), currently under construction at the Hat Creek Observatory in Northern California. In this Chapter, we present the remainder of the assembled target list, with the expectation that other SETI projects may find it useful.

The primary reason for augmenting HabCat with additional subsets of targets is that the ATA will speed up the current rate of target searching by more than two order of magnitude, observing more than 10,000 stars per year in the full $0.5-11 \mathrm{GHz}$ range (Welch \& Dreher 2000). Therefore there will be opportunity to observe many more stars than the 17,129 included in HabCat. The unique construction of the ATA will permit
observation of a minimum of three targets simultaneously, using each target as an "off source" reference for the other two in order to mitigate against terrestrial radio frequency interference (RFI). Identifying three stellar targets within the primary field of view (PFOV) of the array necessitates a much bigger target list than HabCat. The expanded target list also allows (1) exploration of the possibility that dramatically different forms of advanced life may thrive in environments humans consider hostile and (2) an increase in observing efficiency by including suitable stellar clusters.

In Section 3.2 of this Chapter we briefly describe the capabilities of the ATA, which motivates us to expand our target list from HabCat. Section 3.3 presents the "Tycho" subset of $\sim 250,000$ dwarf stars selected from the Tycho- 2 Catalog of $\sim 2.5$ million stars. Section 3.4 describes the "Nearest 100 " list of targets, which includes the closest (known) 100 stars regardless of age, spectral type, metallicity, multiplicity or variability. Section 3.5 discusses a subset of old, metal rich open clusters included in our target list to enhance observing efficiency, and Section 3.6 presents an algorithm for prioritizing these objects in terms of their interest to SETI.

### 3.2 Capabilities of the Allen Telescope Array

The ATA is a joint effort by the SETI Institute and the University of California-Berkeley currently under construction at the Hat Creek Observatory located in northern California. The ATA will consist of 350 dishes, each 6.1 meters in diameter, resulting in a collecting
area exceeding that of a $100-\mathrm{m}$ telescope. The current development and construction timeline calls for the first 32 antennas to be operational in 2004 and the full array to come online in 2007.

The unique architecture of the ATA permits simultaneous imaging of a very large primary field of view (PFOV) for traditional radio astronomy and targeted observations of up to 16 dual-polarization synthesized beams within the PFOV for SETI, as illustrated in Figure 3.1. Four intermediate frequency (IF) processors provide four independently tunable frequency channels for simultaneous observation, each with a 100 MHz bandwidth. The signal from each IF processor can feed an imaging correlator, a summing network that provides four dual-polarization beams on the sky, or both. Thus a total of sixteen spatially independent beam-pairs can be synthesized (and hence up to 16 SETI targets observed) at a maximum of four different frequencies while an image of the PFOV is simultaneously being generated. Finding 16 stars within every ATA PFOV would require catalogs of $\sim 400,000$ stars (at 1 GHz ) and 4 million stars (at 11 GHz ) north of $-34^{\circ}$ declination.

Initially, SETI observations will have access to three dual-polarization beams. As processing becomes more affordable and larger star catalogs (e.g. from the GAIA mission) become available, observing efficiency will increase by making use of all sixteen possible simultaneous SETI target and frequency combinations. The initial goal is to maintain a minimum of three spatially separated beams in operation at all times to
enable an efficient filter against RFI by utilizing two of the target stars as "off source" measurements for the third, and discarding signals detected from more than one target. While all three beams do not have to contain SETI stars for filtering of interfering signals, here we strive for three SETI targets in every PFOV.

Figure 3.2 illustrates how the decreasing size of the PFOV at increasing frequencies demands larger target lists for simultaneous SETI and radio astronomy observing. SETI observations will begin at the lowest frequencies where the ATA PFOV is largest. The 13,256 habstars visible from Hat Creek will permit simultaneous SETI and radio astronomy observations (i.e. there is, on average, at least one target star in any PFOV) at frequencies below $\sim 1.2 \mathrm{GHz}$. The solid line in Figure 3.2 shows the average number of HabCat stars per beam from 0.5 GHz to 11 GHz .

For stars in the Tycho-2 catalog (which extend to much larger distances), concentration toward the Galactic plane causes the number of stars per area to be diminished at the Galactic poles by a factor of $\sim 2.5$ from the surface density averaged over the whole sky (see Høg et al. 2000a and 2000b for an overview of Tycho-2). The dotted line in Figure 3.2 shows there is always more than one star (at the Galactic poles) per PFOV up to 6.8 GHz with a target list of 250,000 stars and below 2.3 GHz , there will be more than 3 stars per PFOV. A target list of 1 million stars (dashed curve) makes simultaneous SETI and radio astronomy observing possible at all frequencies and over the whole sky with the ATA, with 3 stars per beam at frequencies below 9 GHz . In the next Section we present
a large list of main sequence stars identified in the Tycho-2 catalog, which we will use to supplement HabCat with as many reasonable SETI targets as possible.

### 3.3 Identification of Dwarf Stars in the Tycho-2 Catalog

3.3.1 Tycho-2 Data

The Tycho-2 Catalog of 2.5 million stars can provide targets for observation when fewer than 3 HabCat stars are present in the ATA PFOV. Due to a general lack of information about the Tycho-2 stars (including age indicators, spectral types, metallicities and multiplicity data), this list will not be as "refined" as HabCat in terms of the habitability requirements we outlined in Chapter 2. However, the Tycho-2 list should be comprised of late type, main sequence stars, to the extent that they can be separated them from the giants.

Tycho-2 lacks the parallax data necessary to determine absolute magnitudes, but the catalog contains $\mathrm{B}_{\mathrm{T}}$ and $\mathrm{V}_{\mathrm{T}}$ photometry and accurate proper motions (standard errors $\sim 3.5$ milliarcseconds/yr) for the complete sample of stars brighter than $V \sim 11$. As explained in detail by Gould \& Morgan (2003), the reduced proper motion (RPM) vs. $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}$ diagram can be used to separate dwarfs from giants in much the same way as a color magnitude diagram (CMD). Here we define reduced proper motion as the quantity $H_{V}=V_{T}+5 \log$ $\mu-5$, where $\mu$ is the proper motion in arcsec $\mathrm{yr}^{-1}$.

### 3.3.2 Identifying Dwarf Stars by Reduced Proper Motions

To establish RPM criteria for excluding Tycho-2 giants, we start with the Hipparcos Catalogue, where we have both Tycho photometry, $\mathrm{V}_{\mathrm{T}}$ and $\mathrm{B}_{\mathrm{T}}$, and parallax data. Figure 3.3 shows the CMD in the Tycho bandpasses for Hipparcos stars with $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}$ photometric uncertainties less than 0.015 mag, fractional parallax uncertainties less than 0.1 , fractional proper motion uncertainty less than 0.5 , and no catalog flag denoting "combined photometry" in Field H48. We define in this Figure the portion of the diagram that we ultimately want to keep (which is similar to that kept for HabCat). The stars in this region (displayed in black) were used to define reduced proper motion cuts in Figure 3.4. To remove short-lived early type main sequence stars, we applied minimum $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}$ and $\mathrm{M}_{\mathrm{v}}$ limits, and to remove evolved stars (and extremely low metallicity main sequence stars) we applied cuts above and below the length of the main sequence. Thus stars in Figure 3.3 not meeting the following criteria were removed:

$$
\begin{gathered}
\mathrm{M}_{\mathrm{V}} \geq 2.5 \mathrm{mag} \\
\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \geq 0.4 \mathrm{mag}
\end{gathered}
$$

For $0.4<\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \leq 1.4 \mathrm{mag}: 3.3\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)+3.5 \leq \mathrm{M}_{\mathrm{V}} \leq-9\left(\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-1.4\right)^{2}+5.8$
For $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \geq 1.4 \mathrm{mag}: 10\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-5.9 \leq \mathrm{M}_{\mathrm{V}} \leq 5\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-1.2$

In Figure 3.4, the RPM diagram for the desirable targets is shown, and cuts in RPM- $\left(\mathrm{B}_{\mathrm{T}}-\right.$ $\mathrm{V}_{\mathrm{T}}$ ) space are defined to include only these stars. These are the RPM cuts used in
selecting stars from the Tycho-2 catalog. Stars not meeting the following criteria were removed:

$$
\begin{gathered}
\mathrm{HV}_{\mathrm{V}} \geq 4 \mathrm{mag} \\
\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \geq 0.4 \mathrm{mag} \\
\text { For } 0.4 \leq \mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}<0.9 \mathrm{mag}: \mathrm{H}_{\mathrm{V}} \geq 18\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-7.5 \\
\text { For } 0.9 \leq \mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}<1.6 \mathrm{mag}: \mathrm{H}_{\mathrm{V}} \geq 3.5\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)+5.55 \\
\text { For } \mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \geq 1.6 \mathrm{mag}: \mathrm{HV} \geq 18\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-17.65 \\
\text { For } 0.4 \leq \mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}<0.8 \mathrm{mag}: \mathrm{H}_{\mathrm{V}} \leq 9\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)+5 \\
\text { For } 0.8 \leq \mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}<1.5 \mathrm{mag}: \mathrm{H}_{\mathrm{V}} \leq 2.3\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)+10.36 \\
\text { For } \mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \geq 1.5 \mathrm{mag}: \mathrm{H}_{\mathrm{V}} \leq 19\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-14.7
\end{gathered}
$$

Stars from the Hipparcos catalog satisfying these RPM cuts inhabit the color-magnitude space shown in Figure 3.5a. Clearly this is an extremely effective way of eliminating giants (which are separated from the desired sample in both $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}$ and $\mathrm{H}_{V}$ ), but bright main-sequence stars are harder to remove because they are separated from fainter dwarfs only in $\mathrm{H}_{\mathrm{V}}$. The fraction of stars in Figure 3.5 that fall outside the desired zone of acceptance is $11 \%$. Nearly all of these contaminants are early-type main sequence stars, with only $1 \%$ of RPM-selected stars falling in the post-main sequence region. Figure 3.5b shows the CMD for Hipparcos stars which were rejected by the RPM cuts; approximately $8 \%$ of "good" main sequence stars were falsely rejected.

The proper motion accuracies in Hipparcos and Tycho-2 are similar, but the Hipparcos sample differs from the Tycho-2 sample in that (a) distant giants were preferentially removed by the parallax uncertainty cut, and (b) the median photometric precisions ( $\sigma_{V_{T}} \sim 0.006 \mathrm{mag}, \sigma_{B_{T}} \sim 0.006 \mathrm{mag}$ ) are significantly better than those in the Tycho-2 sample, especially in $\mathrm{B}_{\mathrm{T}}$ ( $\sigma_{V_{T}} \sim 0.05 \mathrm{mag}, \sigma_{B_{T}} \sim 0.07 \mathrm{mag}$ at $\mathrm{V}_{\mathrm{T}}=10-11 \mathrm{mag}$, increasing to $\sigma_{V_{T}} \sim 0.11 \mathrm{mag}, \sigma_{B_{T}} \sim 0.17 \mathrm{mag}$ at $\mathrm{V}_{\mathrm{T}}=11-12 \mathrm{mag}, H ø \mathrm{~g}$ et al. 2000 a ). While the larger number of bright, distant giants in the Tycho-2 sample is unlikely to make a significant impact on the resulting contamination rate (those stars will primarily reside in the far upper-right of the RPM diagram and be easily removed with Tycho-2 proper motion data), we must still account for the reduced photometric precision.

### 3.3.3 Contamination Rates in an RPM Selected Sample of Stars

To estimate the contamination and false exclusion rates we expect to have for an RPMselected set of stars from the Tycho-2 catalog, we added artifical noise to the B and V photometry of the same set of Hipparcos stars used above. For each star we randomly selected a number, $x$, from a gaussian distribution centered on zero and having a standard deviation $\sigma_{x}=1$. This number was used to create a scatter term, $x N \sigma_{l}$, where $N$ is an integer determining the magnitude of uncertainty enhancement and $\sigma_{I}$ is the quoted photometric standard error for the star. This scatter term (which can be positive or negative) was then added to the quoted B or V magnitude for that star, giving a new
standard error $\sigma_{2}=\sigma_{1} \sqrt{N^{2}+1}$. The factor $N$ was adjusted to give new B and V magnitudes with precisions comparable to those for stars in Tycho-2, and contamination and false exclusion rates (defining desirable and undesirable stars using the CMD for non-scattered data) were determined using the same process as above.

Table 1 shows the expected contamination and false exclusion rates for several ranges of $\mathrm{V}_{\mathrm{T}}$ magnitude and the corresponding median standard errors in the Tycho-2 catalog. The primary effect of increasing photometric uncertainty is to scatter "good" stars out of the RPM-selected sample (the false exclusion rate, $\mathrm{f}_{\mathrm{FE}}$, reached $60 \%$ in the noisiest sample). The fractions of selected stars that are of early-type main sequence ( $\mathrm{f}_{\mathrm{EMS}}, \mathrm{MV}_{\mathrm{V}} \leq 2.5$ ) and giant stars ( $\mathrm{f}_{\mathrm{G}}$ ) increase less dramatically, reaching $21 \%$ and $12 \%$, respectively, in the worst case. These numbers are slight overestimates, because the fainter magnitude limit of Tycho-2 endows the catalog with proportionately fewer bright stars than Hipparcos (both because more faint stars are included in the sample and because the brightest stars are seen out to distances from the Galactic plane where their space densities decrease). Thus for Tycho-2, $\sim 48 \%$ of stars are rejected by our RPM cuts, but for the Hipparcos sample with similar (artificially increased) uncertainties, $\sim 58 \%$ of stars are rejected. Therefore the true contamination and false rejection rates may be lower than the values listed in Table 1 by a factor of $\sim 0.8$.

### 3.3.4 The Tycho-2 Supplemental Target List for SETI

We applied the derived RPM cuts to the $\sim 500,000$ Tycho- 2 stars with proper motion uncertainties less than $50 \%$, no position flag (in field 2 ), proximity flag $\geq 999$, $\sigma_{V_{T}}<0.2 \mathrm{mag}, \sigma_{B_{r}-V_{T}}<0.1 \mathrm{mag}$, and $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \geq 0.4$. The result is a supplemental target list of 256,610 stars with median uncertainties $\sigma_{V_{T}}<0.06 \mathrm{mag}$, and $\sigma_{B_{T}}<0.06 \mathrm{mag}$, giving an expected giant star fraction of $8-10 \%$. When fewer than 3 stars from HabCat are present in the PFOV, additional targets will be selected for observation from this Tycho-2 subset. This list will allow continuous all-sky SETI observing below 7 GHz (and 3 targets per beam below 2.3 GHz ) with the ATA. The distributions of spectral types and apparent magnitudes are shown in Figure 3.6. Thus our cuts in proper motion uncertainty and $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}$ combined with the Tycho-2 limiting magnitude for completeness have given us a list containing mostly late F- and early G-type dwarf stars within $\sim 250 \mathrm{pc}$ (assuming $\mathrm{M}_{\mathrm{V}} \sim 4$ for $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}} \sim 0.6$ ), a spectral distribution similar to that in HabCat (shown in Figures 2.11 and 2.12) but at three times the average distance and with 15 times as many stars. Figure 3.7 shows the approximate distribution of distances assuming a transformation $\mathrm{M}_{\mathrm{V}}=2.9\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)+2$ (a by-eye approximation to the Hipparcos data for RPM-selected stars), compared to the Lutz-Kelker corrected distances of all stars in HabCat. In the following Sections, the SETI target list is augmented by three more subsets of stars that complement HabCat.

### 3.4. The Nearest 100 Stars

### 3.4.1 SETI in the Solar Neighborhood

The Hipparcos Catalogue was the starting point for creating HabCat because it is the largest collection of accurate parallax measurements in existence, and stellar distances are crucial in determining whether individual stars meet many of the habitability criteria applied in Chapter 2. However, the mission's magnitude limit for completeness introduced an observational bias that excluded many of the systems nearest to the Sun, a population dominated by faint M and K dwarf stars.

The "Near 100 " subset, a list of the nearest 100 star systems prepared by the Research Consortium on Nearby Stars (RECONS, http://www.chara.gsu.edu/RECONS, updated January 1, 2003), plus the third nearest system recently discovered by Teegarden et al. (2003), includes 144 total stars, of which about a third are not found in the Hipparcos Catalog. Table 2 lists these systems, with spectral types taken from RECONS except the "e," "sd," and "var" flags, which were taken from the Michigan Spectral Survey catalogs (Houk 1978, Houk 1982, Houk \& Cowley 1975, Houk \& Smith-Moore 1988, Houk \& Swift 1999). The sample includes 9 white dwarfs, 27 double systems, 7 multiple systems, 3 brown dwarf companions (GJ 845B, GL 229B and GJ 570D), and 2 known planetary systems ( $\varepsilon$ Eri and GJ 876B). Of the 100 stars found in the Hipparcos Catalog, 75 were rejected from HabCat in Chapter 2 based on habitability criteria (e.g., white dwarfs, A- and F-type stars, emission-line stars, and dynamically unfavorable multiple
systems/extrasolar planet systems). However, we have added the Near 100 objects to the SETI target list, as they provide an opportunity to explore diverse environments that could give rise to unexpected forms of complex life at distances where we are most likely to detect them.

The distance of the furthest star in the Near 100 sample, GJ 809 , is $\sim 7 \mathrm{pc}$. Our sensitivity limit at that distance corresponds to a transmitter with 3.1 GW equivalent isotropic radiated power (EIRP) using the Arecibo dish and 0.7 Hz resolution after a 300 second observation (13.5 GW EIRP with the ATA with the same resolution and integration time). Such a signal is much less powerful than many terrestrial radars, but more than a thousand times stronger than commercial TV and radio broadcasts.

### 3.4.2 The expected habitability of the nearest stars

Seventy-five percent of the Hipparcos stars in the nearest 100 systems were rejected from HabCat. Table 2 indicates which objects were cut, and in the following paragraphs we briefly outline the reasons for their exclusion.

Alpha Centauri. One system in particular, $\alpha$ Centauri, seems like an interesting system to SETI, both because of its proximity and because the primary of this triple system is Sun-like. However, the $\alpha$ Cen A and B orbit likely rules out the presence of habitable planets. Endl et al. (2001) have ruled out the presence of planets with masses greater
than $\sim 2$ Jupiter masses interior to 4 AU around either star (assuming orbits coplanar with the binary), but simulations by Holman \& Wiegert (1999), Marzari \& Scholl (2000) and Quintana et al. (2002) suggest that terrestrial planet formation is possible interior to $\sim 3$ AU of $\alpha$ Cen A. The eccentricity of the binary $(e=0.5179$, Pourbaix et al. 2002) means that over the course of one binary orbit the separation between the two stars varies from 11 AU to 36 AU , causing a non-periodic variability in insolation at the primary's habitable zone of $\sim 3 \%$ (Hale 1996). This may not be enough to make the system uninhabitable (our insolation variability cut-off for HabCat was $3 \%$, the variability detection limit for Hipparcos), but Quintana et al. (2002) also predict eccentric planet orbits (typically between 0.05 and 0.2 for planet orbits co-planar with the binary, up to $\sim 0.4$ for planet-forming disks inclined at $45^{\circ}$ ). This would cause annual insolation variations of $20 \%$ to $125 \%$ (compared to $7 \%$ for the Earth's eccentricity of 0.016 ). Planets in eccentric orbits also received an increased time-averaged flux over one orbit, and thus increased global mean surface temperatures (from $15^{\circ} \mathrm{C}$ for Earth to $23^{\circ} \mathrm{C}$ for e $=0.3$ ), and annual global temperature variations of 9 degrees for $\mathrm{e}=0.3$, with more pronounced variations on land masses (Williams \& Pollard, 2002). Williams \& Pollard also find that such variations probably don't rule out habitability (in terms of water loss during the hottest parts of the year), depending on the planet's inventory of volatiles, which serves to moderate climactic extremes. However, as suggested by Quintana et al. (2002), the secondary star may prevent the initial delivery of volatiles to terrestrial planets from further out in the planetary system (as envisioned by Morbidelli et al. 2000, Robert 2001). Thus planets in the habitable zone could be dry (which would rule out
water-based life) or severely depleted in volatiles (in which case seasonal temperature variations could be much more extreme than those expected for an Earth-like planet, thereby ruling out water-based life). We maintain that the $\alpha$ Cen system does not belong in HabCat (and thus it will not have the priority given to HabCat objects in §5), but it will be observed as a Near 100 object.
$\delta$ Pav and Other Near 100 G Stars. All but one of the main-sequence G stars in the Near 100 sample were excluded from HabCat. $\tau$ Ceti and $\varepsilon$ Eri were removed on the basis of low metallicity $([\mathrm{Fe} / \mathrm{H}]<-0.4)$ according to spectroscopic data from Cayrel de Strobel, Soubiran, \& Ralite (2001, hereafter CSR), $\eta$ Cas was detected as an unsolved variable by the Hipparcos mission, and $\xi$ Boo was identified as a BY Drac type variable. The G8 IV/V star, $\delta$ Pav (HIP 99240), is SETI's most attractive target in the nearest 100 subset. This single star is metal-rich $([\mathrm{Fe} / \mathrm{H}] \sim+0.3, \mathrm{CSR})$ and has thin disk kinematics $(\mathrm{U}=44 \mathrm{~km} / \mathrm{sec}, \mathrm{V}=-10 \mathrm{~km} / \mathrm{sec}, \mathrm{W}=-11 \mathrm{~km} / \mathrm{sec}$, Eggen 1998). It is chromospherically quiet according to the Ca II $\mathrm{H} \& \mathrm{~K}$ activity indicator (Henry et al. 1996), was not detected as a ROSAT All Sky Survey X-ray point source (Guillout et al. 1999), has a small projected rotational velocity of $3.2+/-0.2 \mathrm{~km} / \mathrm{sec}$ (Reiners \& Schmitt 2003), and resides slightly above the main-sequence. These data all suggest that the star is the Sun's age or older (see Section 2.3.4 in Chapter 2 for a discussion of age indicators), and Ibukiyama \& Arimoto (2002) derive an age of $\sim 11$ Gyr by isochrone fitting. Although the SIMBAD database designates this object as a "variable star" based on inclusion in the New Suspected Variables catalogue (Kukarkin \& Kholopov, 1982), no recent photometry
suggests variability, and Hipparcos photometry confirms its stability. Six years of radial velocity measurements with the Anglo-Australian Telescope showed no variations above the $3.0 \mathrm{~m} / \mathrm{s}$ uncertainties, implying that there is no planet having a mass of 0.5 Jupiter masses or more within 5 AU , and no Saturn-mass planet within 2 AU (G. W. Marcy, private communication). Therefore the habitable zone of HIP 99240 is dynamically stable for terrestrial planets unless there is a giant planet outside of 5 AU with orbital eccentricity greater than 0.5 (see Table 3 of Holman \& Wiegert 1999). This star $(\delta=$ $-66^{\circ}$ ) was observed by Project Phoenix from the Parkes Radio Observatory in April and May of 1995, and no technological signal in the frequency range $1.2-2.8 \mathrm{GHz}$ stronger than the 15 Jy detection limit was detected. Such a signal would require an omnidirectional transmitted power of 65 GW , or for a $70-\mathrm{m}$ directional antenna, 84 kW of power into the transmitter (P. Backus, private communication); for example, NASA's Goldstone $70-\mathrm{m}$ antenna and 420 kW transmitter, pointed toward Earth, would be easily detectable at the distance of $\delta$ Pav. Although it will not be visible to the ATA, $\delta$ Pav should continue to be a high priority target for SETI programs operating in the southern hemisphere. In $\S 5$ we discuss the top priority targets for SETI at the ATA.

Non-Solar Type Stars. One-third (30) of the M dwarfs in the nearest 100 systems are not found in the Hipparcos Catalogue and were therefore not included in HabCat, although 7 of those stars are part of multiple systems whose primaries were included. Many of these non-Hipparcos (mostly M) stars, however, would have been excluded from HabCat due to flaring activity. GJ 752 A , an M3 dwarf, was excluded based on an
erroneous spectral type (M2III) given in the Houk \& Swift (1999) catalog and has been re-introduced into HabCat. GJ 338 A and B have also been re-introduced, as they are part of a habitable double system, not a quadruple system as listed in the Catalog of Components of Double and Multiple Systems (CCDM) catalog. Initially, all 19 of the K dwarfs in the Near 100 sample were excluded from HabCat for reasons such as variability detected by Hipparcos (including the known planetary system $\varepsilon$ Eri), youth indicated by Ca II H\&K line activity (Noyes, Weiss, \& Vaughan, 1984, Henry et al. 1996, Donahue 1993), kinematics suggestive of halo membership, or dynamical instability of the habitable zone in binary systems (see Chapter 2 for a detailed description of all these criteria). However, GJ 380 (K3V, excluded due to erroneous listing as a member of a binary system in the CCDM catalog) has been re-introduced into HabCat. The white dwarfs and main sequence stars earlier than F5 were all excluded from HabCat based on a 3 Gyr habitability timescale for the development of complex lifeforms, as explained in Chapter 2. An updated list of HabCat stars (with merits as assigned in Section 3.6 of this Chapter) can be obtained by email from M. Turnbull.

### 3.5 Old Open Clusters

The primary field of view (PFOV) for the ATA is very large ( 3.31 degrees at 1 GHz ), and as many as 16 independent synthesized beams can be used to simultaneously observe target stars anywhere within that field. Clusters are therefore of interest to SETI because they allow us to search for signals from many stellar systems of a chosen age and
metallicity in a single observation. Globular clusters have the highest concentration of stars in the Galaxy and they meet the minimum 3 Gyr age requirement for habstars, but their very low metallicities and extremely high stellar densities (leading to photoevaporation and gravitational disruption of planet-forming disks) make the presence of planetary systems unlikely (Armitage 2000, Davies \& Sigurdsson 2001). This is borne out by the failure to detect planetary transits in observations carried out by Gilliland et al. (2000). Globular clusters have the added disadvantage that their large distances from Earth (from $\sim 2 \mathrm{kpc}$ for $M 4$ out to $\sim 28 \mathrm{kpc}$ for $M 54$ ) require more powerful ETI transmitters to produce signals that will be detectable on Earth.

On the other hand, open clusters are relatively nearby, they tend to have metal abundances closer to solar (Dias et al. 2002), and computations suggest that the stellar densities of open clusters are not prohibitive to planet formation (Scally \& Clarke 2001, Bonnell et al. 2001, Smith \& Bonnell 2001, de la Fuente Marcos \& de la Fuente Marcos 1997). While most open clusters are far too young to be of interest to SETI, the literature does contain a subset of $\sim 20$ clusters that are older than the 3 Gyr timescale for habitability required for habstars in Chapter 2. These fascinating objects are found near or outside of the solar circle in the Galaxy and at larger distances from the Galactic plane than very young clusters but generally with $\mathrm{z}<1 \mathrm{kpc}$ (Janes \& Phelps 1994, see Friel 1995 for an overview of old open cluster properties). The known old open clusters have heliocentric distances ranging from $\sim 800 \mathrm{pc}$ (Ruprecht 46, Dias et al. 2002) to $\sim 8 \mathrm{kpc}$ (Berkeley 20, MacMinn et al. 1994), ages as high as $\sim 10$ Gyr (e.g., Berkeley 17, Carraro,

Girardi, \& Chiosi 1999, Phelps 1997), and metallicities ranging from $\sim 25 \%$ solar (e.g. Berkeley 20 at $[\mathrm{Fe} / \mathrm{H}] \sim-0.61$, Friel et al. 2002), to more than six times solar (e.g., NGC 6253 at $[\mathrm{Fe} / \mathrm{H}] \sim+0.8$, Twarog, Anthony-Twarog, $\&$ De Lee 2003). So far, two searches for transiting planets in old open clusters have been published. Mochejska et al. (2002) discovered 47 new, low amplitude variables in NGC 6791, and Street et al. (2003) report 11 transit-like events in the field of NGC $6819(\tau \sim 2.5 \mathrm{Gyr},[\mathrm{Fe} / \mathrm{H}] \sim 0.07)$, but these studies are still in progress.

Once the stars in a cluster become old enough to support complex lifeforms, we expect the total habitability of the cluster (in terms of number of habitable stars) to diminish with time as the more massive stars leave the main sequence. This could be mitigated if newly inhabited systems around low mass stars arise at a rate similar to their loss, but de la Fuente Marcos \& de la Fuente Marcos (2003) suggest that as clusters age the range of stellar masses that is potentially habitable shrinks, because massive stars leave the main sequence faster than planets orbiting lower mass stars can become habitable (e.g., through building up protective ozone atmospheres for land-based lifeforms, with a timescale dependent upon UV flux, Livio 1999). However, considering the variety of potential evolutionary paths for terrestrial planets of different masses and compositions orbiting stars of different spectral types, our foremost concerns are (a) that the clusters be old enough for the emergence of complex life, and (b) that the metallicity be high enough for terrestrial planet formation.

Table 3 presents data taken from Chaboyer, Green \& Liebert (1999, NGC 6791 data), Dias et al. (2002), and Chen, Hou \& Wang (2003) for 14 open clusters that are roughly 3 Gyr or older in age, and have metallicities greater than $[\mathrm{Fe} / \mathrm{H}] \sim-0.4$ (the same metallicity cut-off applied to stars in HabCat ). The large angular sizes (as large as 25 arcmin for M67) of many of these clusters can still be accommodated by the large PFOV of the ATA, even at the highest frequency now being considered for SETI observations (11 GHz). For observations with the ATA, the entire PFOV will be observed with an imaging correlator using the best spectral resolution $(\sim 1 \mathrm{kHz})$, at the same time that individual stars within the cluster are being observed with up to 16 synthesized beams using the SETI signal processors. At the lower frequencies it will also be possible to select only those antennas whose spacings are short enough to form a synthesized beam that more nearly matches the angular size of the cluster; all stars in the cluster will be searched, but at a reduced sensitivity. The smallest clusters with diameters $\sim 3 \operatorname{arcmin}$ could be observed with the a subarray comprised of 145 antennas at $\lambda .21 \mathrm{~cm}$. One cluster (Berkeley 17, $\sim 7$ arcmin diameter) at +31 degrees declination will be observable to the Project Phoenix observing program at Arecibo, but it will require a mosaic of 7 single dish beams to include the entire cluster at 1 GHz . Three of the clusters in Table 3 will be unobservable with the ATA ( $\delta<-40$ degrees), but they have been included to make this list useful to observers at facilities in the Southern Hemisphere.

The clusters in Table 3 vary substantially in terms of membership numbers, from the fairly sparse Ru 46 (the existence of which as a true cluster has been questioned, e.g. Carraro \& Patat, 1995) to the much more populous clusters M 67 , NGC 6819 and NGC 6791 (with $\sim 10^{3}$ members or more). Although observing more stars per observation is generally an advantage for SETI, the dynamics of the richest objects may be less favorable for habitable worlds, so this variety in cluster richness is desirable for the SETI target list.

With an average distance of $\sim 3 \mathrm{kpc}$, these objects represent the most distant SETI targets. At this distance a signal comparable to the high gain Arecibo Planetary Radar ( $2 \times 10^{13}$ W EIRP) would be just detectable to Project Phoenix at Arecibo $\left(9 \times 10^{13}\right.$ W EIRP with the ATA), if that signal were aimed at Earth. An omni-directional beacon would require $10^{7}$ times more power to be detectable. The proximity of these clusters to the Galactic plane, however, means that at 1 GHz we expect to capture $\sim 10^{7}$ foreground stars in each observation.

### 3.6 Prioritization of SETI Targets

In the previous Sections and Chapter 2, we have assembled a total of $\sim 274,000$ targets for SETI, including the Catalog of Nearby Habitable Stellar Systems (HabCat), the Near 100, Old Open Clusters, and Tycho-2 dwarfs. In this Section we present a prioritization
algorithm for SETI targets, so that those targets which are the most interesting from a habitability standpoint and the nearest to Earth are observed first and most often.

### 3.6.1 HabCat Targets and the "Top 25" Habstars

The most favorable targets are those included in HabCat, and the two factors we have used in determining "merit" (i.e., priority) are location on the color-magnitude diagram (CMD) and distance. The "spectral" merit is a 2-dimensional Gaussian in B-V and $\mathrm{M}_{\mathrm{v}}$ which peaks at the Sun's location on the CMD (corresponding to a merit of 1.0 ). The distance merit falls off as the inverse-square of distance, according to the detectability of a given transmitter power. Distance merit was chosen to dominate HabCat merits out to the distance of 50 light years ( $\sim 15 \mathrm{pc}$, a sphere encompassing 215 habstars), where responses to the first terrestrial signals of $\sim 100$ years ago could be reaching us now (e.g. Marconi's transatlantic communications with the broadband Poldhu spark transmitter in 1901, which may have radiated a fraction of its power through the ionosphere at $v>7$ MHz , Ratcliffe 1974). The spectral and distance merits were added together to create the spectral-distance merit:

$$
\begin{gathered}
\mathrm{M}_{\text {HabCat }}=\mathrm{M}_{\text {spec }}+\mathrm{M}_{\text {dist }} \\
\text { where } \\
\mathrm{M}_{\text {spec }}=e^{-\left[\left(M_{v}-4.78\right)^{2} / 2 \sigma_{M v}\right]} \times e^{-\left[((B-V)-0.65)^{2} / 2 \sigma_{B-V}\right]}, \\
\sigma_{M v}=5, \sigma_{B-V}=0.25,
\end{gathered}
$$

and

$$
\mathrm{M}_{\mathrm{dist}}=(15 p c)^{2} /(\text { distance }, \mathrm{pc})^{2}
$$

Figure 3.8 shows the total merit for HabCat stars as a function of distance, color-coded according to spectral merit for the 1000 best (i.e., most Sunlike) stars in green, 1001 through 5000 in red, 5001 through 10000 in blue, and 10001 through 17,133 in black. The total merit values range from 0.11 (for distant, non-Sunlike stars) to 26 (for the nearest HabCat star, HIP 57548, an M4.5V dwarf).

Looking at spectral merit alone, the 25 most interesting HabCat targets within 25 pc are listed in Table 4 (sorted by distance). The Table shows an age estimate based on isochrone fitting (from Ibukiyama \& Arimoto, 2002) or, if this was unavailable, a "chromospheric age" calculated using Donahue's (1993) chromospheric activity-age relation and Ca II H\&K line activity data from T. J. Henry and D. R. Soderblom (2002, private communication) or G. W. Marcy (2003, private communication). The isochrone ages have uncertainties of $\sim 0.12$ dex ( $\sim 1 \mathrm{Gyr}$ uncertainty at a 3 Gyr age estimate), while the chromospheric ages have larger uncertainties (0.4-0.5 dex) due to their dependence on stellar activity cycles, but stars tend to stay on the "active" or "inactive" side of $\log \mathrm{R}^{\mathrm{HK}}$. $\sim-4.75$ (Henry et al. 1996), which corresponds to an age estimate of 2.2 Gyr. The $[\mathrm{Fe} / \mathrm{H}]$ metallicities shown were taken from CSR, otherwise they were estimated from Strömgren uvby photometry (Olsen 1983, 1993, 1994a, 1994b; Olsen \& Perry 1984; or

Eggen 1998, in the case of HIP 30503). These 25 neighbors are billions of years old, with no variability detected in Hipparcos photometry, and with Sunlike luminosities and temperatures. Four stars are either listed in the CCDM catalog or have "acceleration solutions" in Hipparcos photometry indicating probable widely separated companions, but their circumstellar habitable zones are dynamically stable according to the calculations we did in Chapter 2 (Section 2.3.6.2). Twenty-three of these stars are included in the Doppler planet search project at the Keck and Lick Observatories (Butler et al. 1996, Nidever et al. 2002, marked as "KLO" in Table 4) or at the Anglo-Australian Telescope (Tinney et al. 2001, marked "AAT"), with the other two being excluded due to nearby optical or astrometric companions. Of these twenty-three, 51 Peg is the only star that has been found to have a giant planet companion (Mayor \& Queloz, 1995), but at 0.05 AU , this planet does not affect the dynamical stability of the habitable zone. The other "KLO" and "AAT" stars likely do not have any giant planet within $\sim 2$ AU (G. W. Marcy, private communication), with the exception of HIP 52369. That star was added to the planet search list in 2003 (C. McCarthy, private communication), so no statement can be made about the presence or absence of planets at this time. All of the "Top 25 " stars show thin disk kinematics and have metallicities greater than $40 \%$ solar (see Chapter 2, Section 2.3.5). Eight of these objects are listed as solar analogues by Cayrel de Strobel \& Friel (1998), including solar twin candidate 18 Sco (Porto de Mello \& da Silva, 1997). Twenty of these objects will be observable from the ATA. Given their distances ( $8-25 \mathrm{pc}$ ), these stars may also be prime targets for other astrobiological studies, especially the Terrestrial Planet Finder mission.

### 3.6.2 The Near 100, Old Open Clusters, and Tycho-2 Targets

Near 100 stars have merits determined solely by distance, and numerically they range from 0.1 (for Proxima Centauri) to 0.0003 according to:

$$
\mathrm{M}_{\mathrm{N} 100}=0.1 \times(1.3 \mathrm{pc})^{2} /(\text { distance }, \mathrm{pc})^{2}
$$

The next "level" of merits were given to old open clusters (also determined by inversesquare of distance, $3 \times 10^{-4}$ to $4 \times 10^{-6}$ ):

$$
\mathrm{M}_{\mathrm{cluster}}=3 \times 10^{-4} \times(752 \mathrm{pc})^{2} /(\text { distance }, \mathrm{pc})^{2} .
$$

Finally, the Tycho-2 stars were assigned the lowest merits, and these were based on $\mathrm{B}_{\mathrm{T}^{-}}$ $\mathrm{V}_{\mathrm{T}}$ color, a 1-dimensional Gaussian centered on the Sun's $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}$ color, 0.72 (converted from Cousins-Johnson $\mathrm{B}-\mathrm{V}=0.65$ using Table 1 of Bessel, 2000):

$$
\begin{gathered}
\mathrm{M}_{\mathrm{Tycho}}=4 \times 10^{-6} e^{-\left[\left(\left(B_{T}-V_{T}\right)-0.72\right)^{2} / 2 \sigma_{B_{T}-V_{T}}\right]} \\
\text { where } \sigma_{B_{T}-V_{T}}=0.25
\end{gathered}
$$

### 3.7. Concluding Remarks

HabCat has now been augmented with subsets of targets that include some non-Sunlike environments (i.e., the nearest 100 stars and stars in clusters) and improve the ATA
observing efficiency (by providing one or more HabCat or Tycho-2 targets within every possible PFOV). This target list of $\sim 300,000$ stars will allow us 3 targets per beam from 0.5 to $\sim 3 \mathrm{GHz}$, and one target per beam up to $\sim 8 \mathrm{GHz}$ over the whole sky, with the situation improved somewhat close to the Galactic plane. Our most crucial need, both for improving the SETI target list and for the overall study of the biological habitability of the Solar Neighborhood, is measurement of the distances, metallicities, variability, masses, age indicators and multiplicities for late $F, G$ and $K$ stars in the nearest $\sim 100 \mathrm{pc}$ (i.e., a complete sample down to $\mathrm{V} \sim 14$ for stars with $0.4<\mathrm{B}-\mathrm{V}<1.0$ ). The detailed study of stars near the Sun has been largely neglected up to this point, but the growing field of astrobiology is creating a demand for these data, especially with regard to SETI, NASA's Terrestrial Planet Finder mission, and ESA's Darwin mission. Survey programs with undersubscribed meter-class telescopes could potentially enlist the talents of amateur astronomers to provide intermediate-band photometry (for metallicity estimates) and monitor stellar variability for many thousands or even millions of nearby stars. Otherwise, we eagerly await the SIM and GAIA missions as contributors to this repertoire of necessary, basic data.

## Table 1

Contamination Rates for RPM-selected Stars in the Tycho-2 Catalog

| $\mathrm{V}_{\mathrm{T}}$ | $\sigma_{V_{T}}$ | $\sigma_{B_{T}}$ | $\mathrm{f}_{\mathrm{EMS}}(\%)$ | $\mathrm{f}_{\mathrm{G}}(\%)$ | $\mathrm{f}_{\mathrm{FE}}(\%)$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $<7$ | 0.010 | 0.015 | 9.2 | 3.9 | 9.0 |
| $7-8$ | 0.011 | 0.016 | 9.0 | 4.2 | 9.3 |
| $8-9$ | 0.014 | 0.020 | 8.9 | 4.7 | 10.2 |
| $9-10$ | 0.023 | 0.033 | 10.0 | 5.0 | 13.0 |
| $10-11$ | 0.050 | 0.068 | 12.3 | 6.5 | 23.3 |
| $11-12$ | 0.114 | 0.173 | 18.1 | 9.5 | 47.0 |
| $>12$ | 0.198 | 0.248 | 21.1 | 12.0 | 60.3 |

Table 2
The Nearest 100 List

| N | ID | HIP | $\mathrm{d}(\mathrm{pc})$ | Spectype | Name | HabCat | Note |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | GJ 551 | 70890 | 1.30 | M5.5 Ve | Proxima Cen | No | Flare star |
| 1 | GJ 559 A | 71683 | 1.34 | G2 V | Alpha Cen A | No | $\begin{gathered} \text { Binary, } a=23.5 \mathrm{AU}, \\ \mathrm{e}=0.51 \end{gathered}$ |
| 1 | GJ 559 B | 71681 | 1.34 | K0 V | Alpha Cen B | No | $\begin{gathered} \text { Binary, } a=23.5 \mathrm{AU}, \\ \mathrm{e}=0.51 \end{gathered}$ |
| 2 | GJ 699 | 87937 | 1.83 | sdM4.0 V | Barnard's Star | No | subdwarf |
| 3 | $\begin{gathered} \text { SO } 025300.5 \\ +165258 \end{gathered}$ | - | 2.4 | M6.5 | - | No | Teegarden et al. 2003 |
| 4 | GJ 406 | - | 2.4 | M6.0 V | Wolf 359 | NA | - |
| 5 | GJ 411 | 54035 | 2.54 | M2.0 V | Lalande 21185 | No | halo kinematics |
| 6 | G. 244 A | 32349 | 2.63 | A1 V | Sirius | No | var 0.06-.06 mag |
| 6 | GJ 244 B | - | 2.63 | DA2 | Sirius B | NA | - |
| 7 | GJ 65 A | - | 2.68 | M5.5 V | - | NA | - |


| N | ID | HIP | $\mathrm{d}(\mathrm{pc})$ | Spectype | Name | HabCat | Note |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 7 | GJ 65 B | - | 2.68 | M6.0 V | UV Ceti | NA | - |
| 8 | GJ 729 | 92403 | 2.97 | M3.5 Ve | Ross 154 | No | Flare star |
| 9 | GI 905 | - | 3.16 | M5.5 V | Ross 248 | NA | - |
| 10 | GJ 144 | 16537 | 3.23 | K2 V | epsilon Eri | No | HIP microvariable, 1 planet |
| 10 | GJ 144 P1 | - | 3.23 | ------ | - | No | $\begin{gathered} >0.92 \mathrm{M}_{\mathrm{H}}, 3.4 \mathrm{AU}, \\ \mathrm{e}=0.4 \end{gathered}$ |
| 11 | GJ 887 | 114046 | 3.29 | M1.5 V | Lacaille 9352 | No | Halo kinematics |
| 12 | GJ 447 | 57548 | 3.35 | M4.0 V | Ross 128 | Yes | - |
| 13 | GJ 866 A | - | 3.45 | M5.0 V | EZ Aquarii | NA | - |
| 13 | GJ 866 B | - | 3.45 | ------ | - | NA | - |
| 13 | GJ 866 C | - | 3.45 | ------ | - | NA | - |
| 14 | GJ 280 A | 37279 | 3.50 | F5 IV-V | Procyon | No | Binary w/WD |
| 14 | GJ 280 B | - | 3.50 | DA | - | NA | - |
| 15 | GJ 820 A | 104214 | 3.50 | K5.0 V | 61 Cygni A | No | var $>0.6 \mathrm{mag}$ |
| 15 | GJ 820 B | 104217 | 3.50 | K7.0 V | 61 Cygni B | No | var 0.06-0.6 mag |
| 16 | GJ 725 A | 91768 | 3.53 | M3.0 V | - | No | $[\mathrm{Fe} / \mathrm{H}]<-0.4$ |
| 16 | GJ 725 B | 91772 | 3.53 | M3.5 V | - | No | $[\mathrm{Fe} / \mathrm{H}]<-0.4$ |
| 17 | GJ 15 A | 1475 | 3.56 | M1.5 V | - | No | var $<0.06 \mathrm{mag}$ |
| 17 | GJ 15 B | - | 3.56 | M3.5 V | - | NA | - |
| 18 | GJ 845 A | 108870 | 3.63 | K5 Ve | epsilon Indi | No | Ca II H\&K var |
| 18 | GJ 845 B | - | 3.63 | T2.5 | - | NA | $\begin{gathered} \text { Brown dwarf, } 1450 \\ \text { AU } \end{gathered}$ |
| 19 | GJ 1111 | - | 3.63 | M6.5 V | DX Cancri | NA | - |
| 20 | GJ 71 | 8102 | 3.64 | G8 Vp | tau Ceti | No | $[\mathrm{Fe} / \mathrm{H}]<-0.4$ |
| 21 | GJ 1061 | - | 3.68 | M 5.5 V | RECONS 1 | NA | - |
| 22 | GJ 54.1 | 5643 | 3.72 | M4.5 Ve | YZ Ceti | No | Flare star |
| 23 | GJ 273 | 36208 | 3.79 | M3.5 V | Luyten's Star | Yes | - |


| N | ID | HIP | $\mathrm{d}(\mathrm{pc})$ | Spectype | Name | HabCat | Note |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 24 | GJ 191 | 24186 | 3.92 | M1.5 V | Kapteyn's Star | No | var 0.06-0.6 mag |
| 25 | GJ 825 | 105090 | 3.95 | M0.0 V | AX Micro | Yes | - |
| 26 | GJ 860 A | 110893 | 4.03 | M3.0 V | Kruger 60 | No | 8 AU Binary w/flare star |
| 26 | GJ 860 B | 110923 | 4.03 | M4.0 V | - | No | var 0.06-0.6 mag |
| 27 | $\begin{gathered} \text { DEN 1048- } \\ 3956 \end{gathered}$ | - | 4.03 | M9.0 V | RECONS 2 | NA | - |
| 28 | GJ 234 A | 30920 | 4.09 | M4.5 Ve | Ross 614 | No | Flare star |
| 28 | G. 234 B | - | 4.09 | ------ | - | NA | - |
| 29 | GJ 628 | 80824 | 4.24 | M3.0 V | - | Yes | - |
| 30 | GJ 35 | 3829 | 4.31 | DZ7 | - | No | evolved star |
| 31 | GJ 1 | 439 | 4.36 | M3.0 V | - | No | Halo kinematics |
| 32 | GJ 473 A | - | 4.39 | M5.5 V | Wolf 424 | NA | - |
| 32 | GJ 473 B | - | 4.39 | - | - | NA | - |
| 33 | GJ 83.1 | - | 4.45 | M4.5 V | - | NA | - |
| 34 | LHS 288 | - | 4.49 | M5.5 V | - | NA | - |
| 35 | GJ 687 | 86162 | 4.54 | M3.0 Vvar | - | No | Flare star |
| 36 | LHS 292 | - | 4.54 | M6.5 V | - | NA | - |
| 37 | GJ 674 | 85523 | 4.54 | M3.0 V | - | Yes | - |
| 38 | GJ 1245 A | - | 4.54 | M5.5 V | G 208-44A | NA | - |
| 38 | GJ 1245 B | - | 4.54 | M6.0 V | G 208-45 | NA | - |
| 38 | GJ 1245 C | - | 4.54 | ------ | G 208-44B | NA | - |
| 39 | GJ 440 | 57367 | 4.62 | DQ6 | - | No | evolved star |
| 40 | GJ 1002 | - | 4.69 | M 5.5 V | - | NA | - |
| 41 | GJ 876 A | 113020 | 4.70 | M3.5 V | - | No | 2 planets, unstable HZ |
| 41 | GJ 876 A Pl | - | 4.70 | ------ | - | No | $\begin{gathered} >1.89 \mathrm{M}_{\mathrm{H}}, 0.2 \mathrm{AU}, \\ \mathrm{e}=0.1 \end{gathered}$ |
| 41 | G] 876 A P2 | - | 4.70 | ------ | - | No | $\begin{gathered} >0.56 \mathrm{M}_{\mathrm{J}}, 0.13 \mathrm{AU}, \\ \mathrm{e}=0.3 \end{gathered}$ |


| N | ID | HIP | d(pc) | Spectype | Name | HabCat | Note |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 42 | GJ 412 A | 54211 | 4.85 | M1.0 Vvar | - | No | Flare star |
| 42 | GJ 412 B | - | 4.85 | M5.5 V | WX UMa | NA | - |
| 43 | GJ 380 | 49908 | 4.86 | K7.0 V | - | Yes ${ }^{4}$ | Erroneous CCDM entry |
| 44 | GJ 388 | 50583 | 4.89 | M3.0 V | - | No | var $<0.06 \mathrm{mag}$ |
| 45 | GJ 832 | 106440 | 4.93 | M3.0 V | - | Yes | - |
| 46 | LP 944-020 | - | 4.97 | M9.0 V | - | NA | - |
| 47 | GJ 682 | 86214 | 5.01 | M4.5 V | - | Yes | - |
| 48 | GJ 166 A | 19849 | 5.03 | K1 Ve | omicron 2 Eri | No | Flare star |
| 48 | GJ 166 B | - | 5.03 | DA4 | - | NA | - |
| 48 | GJ 166 C | - | 5.03 | M4.5 V | - | NA | - |
| 49 | GJ 873 | 112460 | 5.05 | M3.5 Ve | EV Lac | No | Flare star |
| 50 | GJ 702 A | 88601 | 5.10 | K0 V | - | No | Variable star, 8 AU binary |
| 50 | GJ 702 B | 88601 | 5.10 | K5 Ve | - | No | Flare star |
| 51 | GJ 768 | 97649 | 5.13 | A7 IV-V | Altair | No | Early type |
| 52 | GJ 1116 A | - | 5.23 | M5.5 V | - | NA | - |
| 52 | GJ 1116 B | - | 5.23 | -- | - | NA | - |
| 53 | G 099-049 | - | 5.37 | M3.5 V | - | NA | - |
| 54 | GJ 445 | 57544 | 5.38 | M3.5 V | - | No | Halo kinematics |
| 55 | GJ 1005 A | 1242 | 5.38 | M4.0 V | - | No | HIP mult annex X |
| 55 | GJ 1005 B | - | 5.38 | ------ | - | NA | orbit $<2$ " |
| 56 | GJ 526 | 67155 | 5.43 | M1.5 V | - | Yes | - |
| 57 | LHS 1723 | - | 5.47 | M3.5 V | RECONS 3 | NA | - |
| 58 | LP 816-060 | 103039 | 5.49 | M V | - | Yes | - |
| 59 | GJ 169.1 A | 21088 | 5.54 | M4.0 V | Stein 2051 | No | evolved companion |
| 59 | GJ 169.1 B | - | 5.54 | DC5 | - | NA | - |

[^1]| N | ID | HIP | $\mathrm{d}(\mathrm{pc})$ | Spectype | Name | HabCat | Note |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 60 | GJ 251 | 33226 | 5.57 | M3.0 V | - | Yes | - |
| 61 | GJ 754 | - | 5.71 | M4.5 V | - | NA | - |
| 62 | GJ 205 | 25878 | 5.71 | M1.5 V | - | Yes | - |
| 63 | GJ 764 | 96100 | 5.76 | K0 V | - | No | Halo kinematics |
| 64 | GJ 229 A | 29295 | 5.77 | M1.0 V | - | Yes | - |
| 64 | GJ 229 B | - | 5.77 | T6.0 V | - | NA | Brown dwarf |
| 65 | GJ 693 | 86990 | 5.82 | M4.0 V | - | Yes | - |
| 66 | GJ 752 A | 94761 | 5.85 | M3.0 V | - | Yes ${ }^{5}$ | Erroneous Houk giant |
| 66 | GJ 752 B | - | 5.85 | M8.0 V | van Biesbroeck 10 | NA | - |
| 67 | GJ 213 | 26857 | 5.87 | M4.0 V | - | No | Halo kinematics |
| 68 | GJ 300 | - | 5.89 | M3.5 V | - | NA | - |
| 69 | GJ 570 A | 73184 | 5.89 | K5 Ve | - | No | Ca II H\&K var |
| 69 | GJ 570 B | 73182 | 5.89 | M1.0 V | - | Yes | - |
| 69 | GJ 570 C | - | 5.89 | ------ | - | NA | - |
| 69 | GJ 570 D | - | 5.89 | T8.0 V | - | NA | Brown dwarf |
| 70 | GJ 908 | 117473 | 5.93 | M1.0 V | - | No | Halo kinematics |
| 71 | GJ 34 A | 3821 | 5.94 | G3 V | eta Cassiopeiae | No | var $<0.06$ mag |
| 71 | GJ 34 B | - | 5.94 | K7.0 V | - | NA | - |
| 72 | GJ 588 | 76074 | 5.94 | M3.0 V | - | Yes | - |
| 73 | GJ 285 | 37766 | 5.97 | M4.0 V | - | No | var 0.06-0.6 mag |
| 74 | GJ 663 A | 84405 | 5.97 | K1 Ve | - | No | Flare star |
| 74 | GJ 663 B | - | 5.97 | K1 Ve | - | NA | - |
| 74 | GJ 664 | 84478 | 5.97 | K5 Ve | - | No | Ca II H\&K var |
| 75 | GJ 783 A | 99461 | 6.05 | K3 V | - | No | Halo kinematics |
| 75 | GJ 783 B | - | 6.05 | M4.0 V | - | NA | - |

[^2]| N | ID | HIP | $\mathrm{d}(\mathrm{pc})$ | Spectype | Name | HabCat | Note |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 76 | GJ 139 | 15510 | 6.06 | G5 V | - | No | $[\mathrm{Fe} / \mathrm{H}]<-0.4$ |
| 77 | GJ 1221 | - | 6.07 | DXP9 | - | NA | - |
| 78 | GJ 780 | 99240 | 6.11 | G8 IV/V | $\delta \mathrm{Pav}$ | Yes | Best SETI target |
| 79 | GJJ 268 A | 34603 | 6.14 | M4.5 Ve | - | No | Flare star |
| 79 | GJ 2688 | - | 6.14 | ------ | - | NA | - |
| 80 | GJ 555 | 71253 | 6.14 | M 3.5 V | - | Yes | - |
| 81 | GJ 338 A | 45343 | 6.17 | M0.0 V | - | Yes ${ }^{1}$ | erroneous CCDM $\mathrm{N}=4$ |
| 81 | GJ 338 B | 120005 | 6.17 | K7.0 V | - | Yes ${ }^{1}$ | erroneous CCDM $\mathrm{N}=4$ |
| 82 | GJ 2130 A | 86961 | 6.18 | M2 V | - | No | Triple system |
| 82 | GJ 2130 B | 86963 | 6.18 | M2 V | - | No | below main sequence |
| 82 | GJ 2130 C | - | 6.18 | ------ | - | NA | $<12 \mathrm{AU}$ |
| 83 | GJ 784 | 99701 | 6.20 | M0.0 V | - | Yes | - |
| 84 | GJ 581 | 74995 | 6.28 | M2.5 V | - | Yes | - |
| 85 | GJ 896 A | 116132 | 6.34 | M3.5 Ve | - | No | Flare star |
| 85 | GJ 896 B | - | 6.34 | M4.5 V | - | NA | - |
| 86 | GJ 661 A | 84140 | 6.40 | M3.0 V | - | Yes | - |
| 86 | GJ 661 B | - | 6.40 | ------ | - | NA | - |
| 87 | LHS 3003 | - | 6.40 | M7.0 V | - | NA | - |
| 88 | G 180-060 | - | 6.41 | Dm ${ }^{+}$ | - | NA | - |
| 89 | GJ 223.2 | - | 6.45 | DZ9 | - | No | evolved star |
| 90 | G. 643 | 82809 | 6.45 | M3.5 V | - | No | 5 component system |
| 90 | G. 644 A | 82817 | 6.45 | M2.5 V | - | No | 5 component system |
| 90 | GJ 644 B | - | 6.45 | ------ | - | NA | $<13 \mathrm{AU}$ |
| 90 | GJ 644 C | - | 6.45 | M7.0 V | van Biesbroeck 8 | NA | 1425 AU |
| 90 | GJ 644 D | - | 6.45 | ------ | - | NA | $<13 \mathrm{AU}$ |


| N | ID | HIP | $\mathrm{d}(\mathrm{pc})$ | Spectype | Name | HabCat | Note |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 91 | GI 892 | 114622 | 6.52 | K3 V | - | No | Flare star |
| 92 | GJ 1156 | - | 6.54 | M5.0 V | - | NA | - |
| 93 | GJ 625 | 80459 | 6.59 | M1.5 V | - | Yes | - |
| 94 | GJ 408 | 53767 | 6.66 | M2.5 V | - | Yes | - |
| 95 | GJ 829 A | 106106 | 6.75 | M3.5 V | - | Yes | - |
| 95 | GJ 829 B | - | 6.75 | ------ | - | NA | - |
| 96 | GJ 566 A | 72659 | 6.78 | G8 Ve | $\xi$ Boo | No | var $<0.06 \mathrm{mag}$ |
| 96 | GJ 566 B | - | 6.78 | K 4 Ve | - | NA | - |
| 97 | GJ 402 | 53020 | 6.80 | M4.0 V | Wolf 358 | No | HIP mult annex X |
| 98 | GJ 299 | - | 6.84 | M 4.0 V | - | No | Post-MS |
| 99 | LP 771-095 A | 14101 | 6.86 | M3 | RECONS 4 | No | HIP mult annex X |
| 99 | LP 771-095 B | - | 6.86 | ------- | - | NA | - |
| 99 | LP 771-096C | - | 6.86 | ------ | - | NA | - |
| 100 | GJ 880 | 113296 | 6.86 | M1.5 V | - | Yes | - |

Table 3

## Old Open Clusters

| Name | $\begin{gathered} \mathrm{RA} \\ (\mathrm{~J} 2000) \end{gathered}$ | $\begin{gathered} \text { Dec } \\ (\mathrm{J} 2000) \end{gathered}$ | $\mathrm{d}(\mathrm{pc})$ | $\begin{aligned} & \text { Age } \\ & \text { (Gyr) } \end{aligned}$ | [ $\mathrm{Fe} / \mathrm{H}$ ] | $\mathrm{Z}(\mathrm{pc})$ | D (') | $\mathrm{R}_{\mathrm{g}}(\mathrm{kpc})$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Ruprecht 46 | 0802 | -1928 | 752 | 4.0 | -0.2 | 77 | 3 | 8.9 |
| M67 | 0851 | +1148 | 908 | 4.0 | 0 | 565 | 25 | 9.1 |
| NGC 6253 | 1659 | -52 43 | 1510 | 5.0 | +0.36 | -165 | 4 | 7.1 |
| NGC 188 | 0047 | +8515 | 2047 | 4.3 | -0.1 | 783 | 14 | 9.6 |
| Collinder 261 | 1238 | -68 22 | 2190 | 8.9 | -0.16 | -215 | 9 | 7.5 |
| Berkeley 17 | 0521 | +3036 | 2700 | 12.0 | -0.33 | 172 | 7 | 11.1 |
| NGC 6819 | 1941 | +4011 | 2754 | 2.5 | $+0.07$ | 350 | 9.5 | 8.1 |
| Berkeley 12 | 0445 | +4241 | 3160 | 4.0 | +0.07 | -109 | 4 | 11.5 |


| Berkeley 70 | 0526 | +4154 | 4170 | 4.0 | -0.32 | 260 | 6 | 12.5 |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| NGC 1193 | 0306 | +4423 | 4300 | 7.9 | -0.29 | -907 | 3 | 12.2 |
| Melotte 66 | 0726 | -4740 | 4313 | 2.8 | -0.35 | -1065 | 14 | 10.1 |
| Berkeley 39 | 0747 | -0436 | 4780 | 7.9 | -0.26 | 837 | 7 | 12.3 |
| Berkeley 18 | 0522 | +4524 | 5800 | 4.3 | +0.02 | 507 | 12 | 14.1 |
| NGC 6791 | 1921 | +3746 | 4830 | 8.0 | +0.4 | 914 | 10 | 7.8 |

## Table 4

Top 25 Habstars Within 25 Parsecs

| HIP | Dec | Spec. <br> Type | $\mathrm{d}(\mathrm{pc})$ | [ $\mathrm{Fe} / \mathrm{H}$ ] | $\begin{aligned} & \text { Age } \\ & \text { (Gyr) } \end{aligned}$ | Age Ref | Name | Notes |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 61317 | +4121 | G0V | 8.37 | -0.21 | 4.05 | Iso | $\beta \mathrm{CVn}$ | Solar Analog, KLO |
| 7918 | +4237 | G2V | 12.64 | -0.05 | 5.91 | Iso | HD 10307 | Solar Analog, astrometric binarv |
| 110109 | -5338 | G3V | 13.61 | -0.31 | 3.3 | Chrom | HD 211415 | CCDM: $3^{\prime \prime}$ |
| 79672 | -08 22 | G5V | 14.03 | 0.01 | 4.8 | Chrom | 18 Sco | CCDM: 26", Solar Twin. KLO |
| 113357 | +2046 | G2.5V | 15.36 | 0.15 | 6.34 | Iso | 51 Peg | Solar Analog, giant vlanet. KLO |
| 27435 | -04 06 | G3V | 15.56 | -0.24 | 3.19 | Iso | HD 38858 | KLO |
| 100017 | +6651 | G3V | 17.57 | -0.21 | 5.55 | Iso | HD 193664 | Solar Analog, KLO |
| 70319 | +01 15 | G5V | 17.60 | -0.35 | 5.2 | Iso | HD 126053 | KLO |
| 98959 | -67 19 | G3V | 17.71 | -0.3 | 7.99 | Iso | HD 189567 | Solar Analog, AAT |
| 34017 | +29 20 | G4V | 19.09 | -0.16 | 6.68 | Iso | HD 52711 | Solar Analog, KLO |
| 85042 | -02 23 | G5V | 19.46 | 0.01 | 5.07 | Iso | HD 157347 | KLO |
| 50505 | +4403 | G5V | 20.64 | -0.27 | 4.3 | Chrom | HD 89269 | CCDM: 144", KLO |
| 7339 | +6857 | G6V | 20.99 | 0.03 | 5.61 | Iso | HD 9407 | KLO |
| 41484 | +4539 | G5V | 21.79 | -0.14 | 6.65 | Iso | HD 71148 | KLO |
| 30503 | -2847 | G2V | 22.04 | 0.03 | 4.12 | Iso | HD 45184 | KLO |
| 36210 | -51 24 | G5V | 22.51 | 0.05 | 4.7 | Chrom | HD 59468 | AAT |
| 89474 | +4513 | G2V | 22.69 | -0.05 | 7.02 | Iso | HD 168009 | KLO |


| HIP | Dec | Spec. <br> Type | $\mathrm{d}(\mathrm{pc})$ | $[\mathrm{Fe} / \mathrm{H}]$ | Age <br> $(\mathrm{Gyr})$ | Age Ref | Name | Notes |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 29432 | +0647 | G4V | 23.12 | -0.03 | 4 | Chrom | HD 42618 | KLO |
| 9829 | +2420 | G2V | 23.18 | -0.23 | 3.1 | Chrom | HD 12846 | KLO |
| 19233 | -6413 | G3V | 23.19 | -0.2 | 7.88 | Iso | HD 26491 | AAT |
| 52369 | -1347 | G2/3V | 23.40 | -0.17 | 1.46 | Iso | HD 92719 | KLO |
| 93185 | +3011 | G0V | 23.43 | -0.27 | 2.05 | Iso | HD 176377 | KLO |
| 1499 | -0803 | G5V | 23.44 | 0.2 | 5.75 | Iso | HD 1461 | Solar Analog, KLO |
| 33537 | +2229 | G5V | 24.24 | -0.33 | 2.3 | Chrom | HD 51419 | KLO |
| 64550 | -4511 | G2V | 24.47 | -0.14 | 3.9 | Chrom | HD 114853 | AAT |



Figure 3.1. Sixteen simultaneously synthsized beam-pairs will be available to SETI and other targeted observations within the primary field of view (PFOV, 3.31 degrees at 1 $\mathrm{GHz})$ of the ATA. Each dual polarization beam ( 109 arcsec at 1 GHz ) can be tuned to one of four frequencies within the 0.5 to 11 GHz range, with a bandwith of 100 MHz . (Image used with permission from Paul Signorelli, Las Brisas Observatory.)


Figure 3.2. The number of stars contained in the ATA primary field of view as a function of frequency for HabCat stars (solid curve), 250,000 Tycho-2 stars (short-dashed curve), and 1 million stars (long-dashed curve). The dashed curves are for observations at the Galactic poles and thus represent the minimum number of stars per beam. The vertical lines indicate the highest frequency at which simultaneous SETI and radio astronomy observations are routinely possible.


Figure 3.3. The CMD for Hipparcos stars, in Tycho bandpasses. The desired region of the CMD is outlined and those stars (in black) were used to determine RPM cuts in Figure 3.4.


Figure 3.4. The RPM diagram for Hipparcos stars selected according to the CMD criteria applied in Figure 3.3. The solid lines indicate RPM cuts used to select Tycho-2 stars.


Figure 3.5. (a) The resulting CMD for Hipparcos stars selected according to the RPM cuts defined in Figure 3.4, showing contamination of the RPM-selected sample by earlytype stars and giants. Giants were easily removed, and early type main sequence stars are the largest source of contamination. (b) The resulting CMD for Hipparcos stars that were rejected by the RPM cuts, showing false rejections.


Figure 3.6. $\mathrm{V}_{\mathrm{T}}$ magnitudes (cross-hatched histogram, top axis, 0.1 mag bins) and $\mathrm{B}_{\mathrm{T}-}-\mathrm{V}_{\mathrm{T}}$ colors (open histogram, bottom axis, 0.03 mag bins) for Tycho-2 dwarf stars selected according to reduced proper motion data. Approximate ranges for F and G stars are shown in $\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}$.


Figure 3.7. The approximate distance distribution for RPM-selected dwarfs in Tycho-2 (open histogram), compared to the distances of stars in HabCat (solid histogram), which have been corrected for the Lutz-Kelker bias.


Figure 3.8. Total merit as a function of distance, color-coded by spectral merit. The 1000 most Sunlike stars are in green, 1001 through 5000 in red, 5000 through 10,000 in blue, and 10,001 through 17,133 in black. The total merit is dominated by distance interior to 15 pc , the response distance for Earth's first radio transmissions.

## 4. HABSTARS WITHIN 30 PARSECS: TARGETS FOR TPF

### 4.1. TPF and Habitable Stellar Systems

### 4.1.1 The Terrestrial Planet Finder

Are there habitable extrasolar planets in the Solar Neighborhood? This is one question in the modern field of Astrobiology that has hope for finding an answer in the next few years. NASA's Terrestrial Planet Finder (TPF) space telescopes will use starlight suppression in order to directly image terrestrial planets with diameters larger than about $70 \%$ that of Earth orbiting in the "habitable zones" of nearby stars. The coronagraphic version of TPF, "TPF-C," is currently scheduled to launch around 2014 and will operate at visible wavelengths ( $0.5-0.8$ microns required, $0.5-1.05$ microns desired). In collaboration with ESA, NASA will launch a formation-flying interferometric design in ~2019. TPF-I will operate in the mid-infrared (6.5-13 microns required, 6.5-17 microns desired). Upon discovery, TPF-C will commence with low-resolution spectroscopy $(\mathrm{R} \sim 70)$ to determine the main constituents of the planet atmospheres (especially $\mathrm{O}_{2}$ and $\mathrm{H}_{2} \mathrm{O}$ ) and whether the planets might be habitable.

The planning of TPF has begun to revive the detailed study of nearby stars. TPF's scientific "minimum" mission is to search at least 35 core stars of $\mathrm{F}, \mathrm{G}$ and K spectral
type, while the "full" mission is to search at least 165 such stars. An "extended" sample of stars consisting of stars of any spectral type with partially observable habitable zones is also desireable; it has been suggested by members of the TPF Science Working Group that targets in the extended sample could be used as "controls" on various parameters that might influence the frequency of terrestial planet formation. For instance, stars that have extremely low metallicity or stellar companions within several AU could serve that purpose.

### 4.1.2 The Immediate Need for a TPF Target List

Although launch is not planned for another 10 years, a list of target stars for the full mission is needed early on in the development of TPF instrumentation. The targets chosen will inform the instrument design by setting requirements on the sensitivity, null width, and field of view. Conversely, it may be that all of our favorite stars are simply not observable with a single telescope design, and the star list will have to be adjusted accordingly. In designing a TPF target list, the obvious questions are: what makes a "good" TPF target star, in a scientific sense? How many "good" scientific targets are there within 30 pc ? Given minimal constraints on brightness and null width, how many of these targets are actually observable?

### 4.1.3 Habstars as "Good" TPF Targets

While the TPF mission is not a search for life itself, it is a search for planets that are potentially habitable to Earth-like life. This is TPF's primary purpose, and much of the mission will be spent looking for biologically interesting spectral signatures coming from any detected planets. There is no reason for observing, as core targets, stars that, because of activity, age, or low metallicity, would not likely allow for the habitable conditions we know on Earth, even if these stars are traditional "favorites" because of spectral type or constellation membership. In this work we do not entertain creative hypotheses that some kind of unknown life will be able to take hold even in conditions much different from those on Earth. Our goal is to identify those stars that, given the data at hand, seem to allow for conditions that are suitable for the kind of complex life we are familiar with.

In this work, we again rely on the usual definition of habitability: liquid water is the universal requirement for all known life, and a habitable planet is one that has liquid water on the surface. The circumstellar habitable zone (HZ), where TPF intends to search, is the location around a star where the flux received by an Earth-like planet will support surface temperatures that allow for the presence of liquid water (Kasting et al. 1993).

How do we apply these definitions to the selection of target stars? At the time of TPF's launch, we will know little or nothing about which stars do have terrestrial planets in their
habitable zones. However, we can guess at which ones do not have terrestrial planets, for example, by looking at the star's metallicity and the orbits of any companion stars. Choosing stars whose properties indicate that the habitable zone is spatially static on timescales comparable to the appearance of global biosignatures (e.g., oxygen) is consistent with the mission goals; otherwise, there is no compelling reason to design TPF to search the habitable zone and detect biosignatures. We define a "habstar" as a star that has (1) a habitable zone that is spatially static and dynamically stable on a timescale comparable to the timescale of global biosignature production, $\mathrm{t}_{\text {bio }}$, and (2) a metal content that is high enough to be consistent with the formation of terrestrial planets. The question addressed in this paper then becomes, "given minimal instrument observing constraints on planet brightness and background levels, are there enough habstars within 30 parsecs to satisfy the TPF science requirements?"

### 4.1.4 The Purpose of the "Sun Life" Target List

The target list in this paper has come to be known to the TPF Science Working Group as the "Sun Life" list, and it has three purposes: (1) to find out if limiting the core TPF targets to potentially habitable stellar systems leaves us enough targets within 30 pc to meet the full mission goals (especially given unavoidable observational constraints), (2) to shine a spotlight on those stars, especially those among the traditional "favorites," that might not be ideal TPF targets, and (3), to demonstrate the process of target selection as a
logical subset from the full 30 parsec sample, such that all proposed target lists are recreatable given a set of clearly stated criteria. This last point may be particularly important for TPF, because communication between scientists and mission architects who wish to experiment with creating different target lists will be crucial in determining which stars are truly the best in terms of both science goals and engineering requirements.

We hope that another spin-off of this work will be a heightened awareness regarding the absence of TPF-relevant data for the nearest stars in the universe. Of particular concern is that metallicity and age data are missing for the vast majority of stars within 30 parsecs. Furthermore, there are still theoretical unknowns; e.g., the interpretation of age indicators (e.g., Ca II H- and K-line activity and X-ray luminosity) for F- and K-type stars is still unclear.

Finally, a major by-product of this work is a database containing all Hipparcos stars within 30 parsecs, with data from several other catalogs and calculations which are potentially relevant to TPF. Such a database could be made sortable and searchable through a web interface for instant visual display of available spectra, spectral energy distributions, and background sources as well as habitable zone locations and companion orbits as compared to the null width and field of view. Allowing the definition of selection criteria through the same interface would make easy work of identifying candidate targets and/or stars that need additional data. The "proto-database" created
here, which we call the "TPF Stellar Database," is discussed in Section 4.

### 4.1.5 The Creation of the "Sun Life" Target List and 30 Parsec Database

Although much of the logic is the same for creating the SETI and "Sun Life" target lists, the creation of the final database and list of candidate stars involves a different process. Rather than throwing away stars we deem undesirable, we now wish to keep all of our starting candidate targets and build a database of habitability indicators that can be used to select or deselect stars for the final list. This would have been impractical for the SETI target list, which started from the full Hipparcos and Tycho 2 Catalogues ( $\sim 120,000$ and 2 million stars, respectively). For TPF, the final target list is only 165 stars for the full mission, and there are only 2350 Hipparcos stars within 30 parsecs.

Thus our starting point in creating the Sun Life target list and the TPF Stellar Database is the full list of 2350 stars in the Hipparcos Catalogue whose parallaxes are greater than or equal to 33.3 arcseconds. We take all of the Hipparcos data for these stars, and add updated spectral types, habitability indicators, and other potentially useful data to create the "TPF Stellar Database." From this database, we select those stars that pass all of our criteria to create the "Sun Life" target list.

### 4.1.6 Calculation of Johnson B and V from Hipparcos Photometry

Before carrying out any of the analysis below, the Hipparcos $H_{p}$, and Tycho $B_{T}$ and $V_{T}$ magnitudes for each star were converted to Johnson B and V magnitudes using Bessel's (2000) recalculation of the Hipparcos and Tycho passbands. The fits to Bessel's data are:

$$
\begin{aligned}
& \text { (1) } V-H_{p}=-0.0378\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{6}+0.1886\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{5} \\
& -0.3025\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{4}+0.1336\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{3} \\
& +0.1556\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{2}-0.2811\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-0.0098 \\
& \text { (2) For } \mathrm{V}-\mathrm{I}<2.5: \quad \mathrm{V}-\mathrm{H}_{\mathrm{p}}=0.0338(\mathrm{~V}-\mathrm{I})^{6}-0.242(\mathrm{~V}-\mathrm{I})^{5} \\
& +0.6187(V-I)^{4}-0.6809(V-I)^{3} \\
& +0.4037(\mathrm{~V}-\mathrm{I})^{2}-0.2788(\mathrm{~V}-\mathrm{I})-0.0127 \\
& \text { (3) } \mathrm{V}-\mathrm{V}_{\mathrm{T}}=-0.02\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{3}+0.0549\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{2} \\
& -0.1334\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)+0.001 \\
& \text { (4) } \quad \Delta(\mathrm{B}-\mathrm{V})=(\mathrm{B}-\mathrm{V})-\left(\mathrm{B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right) \\
& =0.0527\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{6}-0.3531\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{5} \\
& +0.9079\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{4}-1.0714\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{3} \\
& +0.4733\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)^{2}-0.1265\left(\mathrm{~B}_{\mathrm{T}}-\mathrm{V}_{\mathrm{T}}\right)-0.0062
\end{aligned}
$$

All residuals between these fits and the Bessel calculations are less than 0.01 magnitudes. The ground-based (B-V) measurement listed in the Hipparcos Catalogue was kept when the uncertainty in that measurement was smaller than that of the $\left(B_{T}-V_{T}\right)$ measurement. Some stars had no Tycho photometry, but they do have ground-based V-I photometry, in which case Equation (2) was used. Equation (1) or (3) was used to calculate Johnson V
magnitude, depending on which of the $H_{p}$ or $\left(B_{T}-V_{T}\right)$ uncertainties was smaller. Equation (4) was then used to calculate the Johnson B magnitude.

We have also used the bolometric corrections as a function of B-V color from Flower (1996) to include luminosity and effective temperature calculations for the stars in our 30 parsec database. The bolometric corrections were fit to a polynomial in terms of (B-V), given as:

$$
\begin{gathered}
\text { B.C. }=-2.6703(\mathrm{~B}-\mathrm{V})^{6} \\
+11.92(\mathrm{~B}-\mathrm{V})^{5}-21.088(\mathrm{~B}-\mathrm{V})^{4} \\
+18.552(\mathrm{~B}-\mathrm{V})^{3}-9.1981(\mathrm{~B}-\mathrm{V})^{2} \\
+2.1958(\mathrm{~B}-\mathrm{V})-0.1494
\end{gathered}
$$

With this fit to Flower's (1996) data, stars with $0.3<\mathrm{B}-\mathrm{V}<1.4$ have residuals $\mid \mathrm{BC}_{\text {fit }}$ $\mathrm{BC}_{\text {Flower }}<0.01$ magnitudes. The effective temperature fit used is:

$$
\begin{gathered}
T_{\text {eff }}=-1479.8(\mathrm{~B}-\mathrm{V})^{5}+6430.7(\mathrm{~B}-\mathrm{V})^{4} \\
-11452(\mathrm{~B}-\mathrm{V})^{3}+12106(\mathrm{~B}-\mathrm{V})^{2} \\
-10182(\mathrm{~B}-\mathrm{V})+9413.2
\end{gathered}
$$

The residuals between this fit and Flower's calculations are less than 50 K for $0.3<\mathrm{B}-\mathrm{V}$ <1.4. However, the user should note that a proper conversion from B-V data to effective temperature and luminosity would make use of metallicity data in addition to B-V color.

### 4.2 Criteria for Selecting TPF Habstars

### 4.2.1 Timescale for Biosignature Production

As in Chapter 2, we have determined a habitability timescale to determine the appropriate ages and evolutionary stages of targets. For TPF, the biosignatures of interest can be produced by single-celled organisms, so the relevant timescale for habitability is shorter than would required be for biosignatures of interest to, say, SETI (Turnbull \& Tarter, 2003). One of the most detectable and reliable biosignatures is that of oxygen, which has potentially observable bands at $6870 \AA$ and $7620 \AA$ (for $\mathrm{O}_{2}$ ) and at $5900 \AA$ and 9.6 mm $\left(\mathrm{O}_{3}\right)$ (Des Marais et al. 2002). On Earth, $\sim 10^{8} \mathrm{~kg} / \mathrm{yr}$ of oxygen is produced abiotically by UV dissociation of water in the upper atmosphere, but oxygen is taken out of the atmosphere through the oxidation of rock and volcanic gases at a rate of about $-10^{11}$ $\mathrm{kg} / \mathrm{yr}$. The ozone and molecular oxygen signatures on Earth are entirely due to the presence of photosynthesizing life, which has a production rate of about $10^{14} \mathrm{~kg} / \mathrm{yr}$. In principle, then, a planet could have an oxygen signature that was entirely abiotic, but only if the planet were too small to be volcanically active, yet massive enough to retain an atmosphere and store of water vapor. For example, small amount of oxygen is produced in Mars' atmosphere by the photolysis of water vapor, and because the removal of oxygen from Mars' atmosphere is so slow (volcanic activity and weathering are both extremely low), oxygen is now at the 0.1 percent level. As another example, Venus may once have had an even stronger oxygen signature than Earth currently does, if it experienced rapid water loss to space as a result of a runaway greenhouse process.

However, cases like these should be discernable from temperature and water vapor information in the planet's spectrum, and it seems that a strong oxygen signature on an Earth-sized planet within the habitable zone is most likely a sign of life.

Given a biogenic oxygen signature, what is the timescale for its production? Such a timescale would have to include the time it takes to form oxygen-producing organisms as well as the time for the oxygen levels to accumulate to detectable levels. Vigorous geological processes during the early phases of planetary evolution, including frequent impacts (which probably limits the proliferation of surface organisms), weathering, and high levels of volcanism probably lengthen this timescale. On Earth, stromatolite formations created by primitive photosynthesizers appear in the rock record at 3.5 billion years ago (Gya), and the appearance of redbeds indicates that the atmospheric oxygen levels increased sharply to $\sim 1 \%$ of present atmospheric levels by about 2-2.2 Gya. From this information we approximate the biosignature generation time, or habitability timescale, $\mathrm{t}_{\text {hab }}$, to be $\sim 2$ Gyr.

### 4.2.2 Stellar Age

The first consequence of setting this timescale is that no star on our final list should have an age less than 2 billion years. To rule out stars younger than this, we use the same tactics as are outlined in Section 2.3. Chromospheric emission, X-ray luminosity, and rotation are all useful age indicators.

In particular, chromospheric emission (Section 2.3.4) is probably the single most useful indicator of whether a star is too young to be a good TPF target. CE data are easily obtainable, and ideally for TPF, a natural division in activity levels between young active stars and older quiet stars occurs at a derived age of $\sim 2$ Gyr. To elaborate, the age derived from CE data for a given star will vary from measurement to measurement by about 0.4 to 0.5 dex in $\log (a g e)$ over the course of a stellar cycle (Lachaume et al. 1999), but even with this excursion, stars always remain on either the "active" or "inactive" side of an activity level that corresponds to an age of 2.2 Gyr (Henry et al. 1996, Donahue 1993).

In the TPF Stellar Database (hereafter, TSD), we provide CE data in the form of $\mathrm{R}^{\prime}{ }_{\mathrm{HK}}$ values, the traditional indicator of chromospheric emission within the Ca II absorption lines, wherever they are available from our sources (J. Wright, 2003 private communication, T. J. Henry, and D. R. Soderblom, 2002 private communication; see also Wright et al. 2004). Donahue (1993) gives us the age relation:

$$
\log \tau=10.725-1.334 \mathrm{R}_{5}+0.4085 \mathrm{R}_{5}{ }^{2}-0.0522 \mathrm{R}_{5}{ }^{3},
$$

where $\tau$ is the stellar age in years and $R_{5}$ is defined as $\log \mathrm{R}^{\prime}{ }_{H K} \times 10^{5}$, and for the Sun Life target list, we rule out all stars with $\log \mathrm{R}^{\prime}{ }_{\mathrm{HK}}>-4.75$.

X-ray data from the ROSAT All Sky Survey were also used to identify young stars. Using the formula derived in Section 2.3.5,

$$
\mathrm{d}_{\max }(\mathrm{pc})=34 \times \tau(\mathrm{Gyr})^{-0.75},
$$

we find that stars beyond $\sim 20$ parsecs that are detectable to ROSAT are too young to be good TPF targets. Thus all ROSAT-detected Hipparcos stars (cross-correlation done by Guillout et al. 1999) beyond 20 parsecs are ruled out of the Sun Life target list.

Finally, we used rotation periods (J. Wright 2003, private communication; Wright et al. 2004) and $v \sin i$ measurements (Glebocki et al. 2000) to conservatively identify very young stars. We set the maximum allowable limit for $v \sin i$ at $10 \mathrm{~km} \mathrm{~s}^{-1}$, and the minimum rotation period for TPF habstars is set at 5 days, values that are consistent with ages much less than 1 Gyr for solar type stars (Soderblom et al. 1993).

### 4.2.3 Instantaneous, Continuous, and Traveling Habitable Zones

The second consequence of our minimum timescale for habitability is that no star should change in brightness so much that the inner edge of the habitable zone $(\mathrm{HZ})$ moves more than the HZ starting width over the course of 1 billion years. As in Chapter 2, this requirement determines a "region of habitability" on the color-magnitude diagram, which sets limits on both stellar mass (which determines the main sequence lifetime) and on evolutionary stage. For our TPF target selection, we simply used the region shown in Figure 4.1, drawn by eye during the TPF Science Working Group's Target Selection subgroup meeting (November, 2003) to include the main sequence only. The limit below the main sequence can be describe as:

$$
\begin{aligned}
\text { For } \mathrm{B}-\mathrm{V} & <0.74: \mathrm{M}_{\mathrm{V}}<6(\mathrm{~B}-\mathrm{V})+1.8 \\
0.74<\mathrm{B}-\mathrm{V} & <1.37: \mathrm{M}_{\mathrm{V}}<4.3(\mathrm{~B}-\mathrm{V})+3.05 \\
\mathrm{~B}-\mathrm{V} & >1.37: \mathrm{M}_{\mathrm{V}}<18(\mathrm{~B}-\mathrm{V})-15.7
\end{aligned}
$$

The limit above the main sequence can be described as:

$$
\begin{aligned}
\mathrm{B}-\mathrm{V} & <0.87: \mathrm{M}_{\mathrm{V}} \leq-8((\mathrm{~B}-\mathrm{V})-1.35)^{2}+7.0 \\
0.87 & <\mathrm{B}-\mathrm{V}<1.45: \mathrm{M}_{\mathrm{V}}<5(\mathrm{~B}-\mathrm{V})+0.81 \\
\mathrm{~B}-\mathrm{V} & >1.45: \mathrm{M}_{V}<18(\mathrm{~B}-\mathrm{V})-18.04
\end{aligned}
$$

Because the Sun Life target list is meant to present candidates for the TPF "core" target list, we also imposed a requirement of $0.3<\mathrm{B}-\mathrm{V}<1.4$, which includes only $\mathrm{F}, \mathrm{G}$ and K stars.

However, a more thoughtful analysis of habitability on the HR diagram is certainly possible. For example, using stellar evolutionary tracks (P. Young, private communication; see also Young et al. 2001) we have estimated the time for which stars of different masses remain habitable. There are three ways in which to think of habitable zones around stars: (1) the "instantaneous" habitable zone (IHZ), which we define as 0.95 to 1.37 AU for one solar luminosity and, for stars on the main sequence, scaled as the square root of stellar luminosity (Kasting, Whitmire \& Reynolds, 1993), (2) the "continuous" habitable zone (CHZ), defined as the annulus around a star that remains habitable from the zero-age main sequence until some specified time, and (3) the "traveling" habitable zone (THZ), defined as the region around a star which is currently habitable and has been habitable for a specified time. For example, the Sun's
instantaneous habitable zone currently extends from 0.95 to 1.37 AU , but 4.5 billion years ago the Sun was about $30 \%$ fainter, and its IHZ then extended from about 0.8 to about 1.17 AU . Therefore the Sun's continuously habitable zone currently extends from 0.95 (the current inner HZ ) to 1.17 AU (the outer HZ during the final phases of planet formation), and this is the only location that has been continuously habitable for the entire history of the Solar System. The Sun's CHZ will disappear when the inner edge of the zero-age IHZ reaches 1.17 AU , at an age of about 9.3 billion years.

However, if we are only concerned about locations that are habitable for 2 billion years at a time, this ever-expanding two billion year traveling habitable zone extends from the inner edge of today's IHZ ( 0.95 AU ) to the outer edge of the IHZ at 2 billion years ago (1.25 AU). This is the location that is most interesting to TPF; as long as the Sun does not change in luminosity so fast that the inner edge of the IHZ is beyond the outer edge of the IHZ of 2 billion years prior, this 2 Gyr THZ will continue to move outward and terrestrial planets (or moons) found within the THZ are potentially habitable to organisms that TPF can detect. The Sun's luminosity changes will remain gradual enough to accommodate the existence of a 2 Gyr THZ until it begins to ascend the giant branch, at about 11.7 billion years.

To map this out more clearly for the Sun and stars of other masses, in Figures 4.2 and 4.3 we compare the locations of the inner and outer edges of the IHZ (solid red and blue lines), the width of the IHZ (textured black), the outer edge of the 2 Gyr THZ (solid
green), and the rate of HZ movement in AU per 2 Gyr (dotted white line) as a function of time for stars of 0.5 to $2.0 \mathrm{M}_{\S}$. When considering stars that are not necessarily on the main sequence, we note that the location of the instantaneous habitable zone depends on effective temperature as well as luminosity, due to the differences in planetary albedo at infrared and optical wavelengths. Rayleigh scattering in the blue and strong absorption $\mathrm{H}_{2} \mathrm{O}$ and $\mathrm{CO}_{2}$ bands in the near-infrared cause the HZ to be slightly further out for red stars than blue stars of the same luminosity. We interpolated a curve as a function of temperature and luminosity from the calculations of Kasting, Whitmire \& Reynolds (1993) for different spectral types (after correcting their luminosities and scaling their HZ locations by the square root of luminosity) as follows:

$$
\begin{aligned}
& \mathrm{HZ}_{\text {inner }}(\mathrm{AU})=\left(-7.4 \times 10^{-5} \mathrm{~T}_{\text {eff }}+1.26\right) \mathrm{L}^{1 / 2} \\
& \mathrm{HZ}_{\text {outer }}(\mathrm{AU})=\left(-1.26 \times 10^{-4} \mathrm{~T}_{\text {eff }}+2.39\right) \mathrm{L}^{1 / 2}
\end{aligned}
$$

For the Sun (Figure 4.2), we see that: (1) after 7 billion years the Earth at 1 AU is no longer in the HZ , (2) Mars (1.5 AU) enters the HZ at about that same time and remains in the HZ until the Sun becomes a red giant at 12 billion years, (3) continuous habitability of any location in the Solar System ends when the inner HZ reaches the original outer HZ at 1.37 AU , at $\sim 9.5$ billion years, and (4) the 2 billion year "traveling" habitability ends only when the Sun ascends the red giant branch, at almost 12 billion years, when the rate of change per 2 billion years exceeds the instantaneous HZ width.

For lower mass stars, evolution slows and the trend is toward longer continuous and traveling habitability. In Figure 4.3, the traveling and instantaneous HZs are nearly
identical for $0.5 \mathrm{M}_{\S}$, and stars of this mass remain habitable for longer than the current age of the Universe. The two billion year habitability requirement is barely met for stars of $1.7 \mathrm{M}_{\S}$, which evolve into red giants at age $\sim 2$ Gyr. A $1.7 \mathrm{M}_{8}$ star corresponds approximately to a spectral type F0 for main sequence stars, and no star more massive than this is a TPF habstar.

We can use data like these to map out the effective temperatures and luminosities where stars of different masses cease to have 2 Gyr THZs, and we have plotted this "region of habitability" on the HR diagram in Figure 4.4. The region of habitability (drawn in black) includes all of the area between the 2 Gyr isochrone and the line where the 2 Gyr THZs disappear for stars of various masses. No star in the Universe below $\sim 0.8 \mathrm{M}_{\S}$ has yet evolved off the main sequence, so the area included in the region of habitability is simply meant to include all of the main sequence below $\mathrm{L}^{*} \sim 10 \mathrm{~L}_{\S}$. Stars falling outside the region of habitability on the HR diagram are not good TPF targets.

The calculated evolutionary tracks used in Figure 4.4 depart significantly from the main sequence for lower mass stars, so we have traced out the main sequence by hand below $\log \left(\mathrm{T}_{\text {eff }}\right) \sim 3.8$ (dotted line), where the 2 Gyr isochrone is observationally indistinguishable from the zero-age main sequence. However, it is important to note that, even ignoring uncertainties in theoretical and observational data, this region has "fuzzy" boundaries because of the degeneracies in luminosity and temperature of stars with slightly different masses and ages. For example, our 1.6 M star (yellow) is habitable
from 2 Gyr of age until it ascends the red giant branch, but it appears in the Figure to leave the region of habitability briefly during the phase of core contraction and before the onset of shell burning. During this time, its location on the HR diagram overlaps with younger, higher mass stars that are not habitable. This situation is exacerbated by the observational and theoretical uncertainties.

### 4.2.4 Stellar Variability

As discussed in Section 2.2.2, the level of stellar variability detected by Hipparcos ( $\sim 3 \%$ ) is about 30 times greater in amplitude than the typical stochastic variability of the Sun $(\sim 0.1 \%)$, and 10 times greater in amplitude than the Sun's variation since the Little Ice Age of the late $1600 \mathrm{~s}(<0.5 \%)$. To date, no assessment of the impact of stochastic stellar variability on planetary climates has been carried out. One can imagine that there is likely a range of variability amplitudes and timescales that will have no impact on an Earthlike planet due to the thermal inertia of oceans. For now, we err on the side of caution and eliminate stars detected by Hipparcos to be variable, as was done in Section 2.2.2.

### 4.2.5 Stellar Multiplicity

For TPF, the primary concerns regarding multiple stars are: (1) the effect of scattered light from nearby companion sources on the ability to detect planets, and (2) the
dynamical stability of the habitable zone. The TPF Science Working Group has set a minimum separation of 10 arcseconds for multiple stars to be observable. That requirement may change, but a 10 -arcsecond separation for stars within 30 parsecs entirely eliminates any concern about the dynamic stability of planets in the habitable zone. Thus for this work we do not need to carry out an analysis like that in Section 2.3.8.

To date, the most complete compilation of the orbits and separations of nearby multiple systems is the Washington Double Star (WDS) survey, carried out and recently updated by Sean Urban and collaborators at the United States Naval Observatory (Urban, private communication, 2003; this work includes and/or supercedes Mason \& Wycoff 2001, Hartkopf, Mason \& Wycoff 2001, Hartkopf \& Mason 2001, Pourbaix 2003, and Mason, Wycoff \& Hartkopf 2001). We include this compilation in our database, and we have ruled out stars with known companions within 10 arcseconds from the "Sun Life" TPF target list.

### 4.2.6 Known Giant Exoplanets

The presence of giant planets (GPs) may not be good for the presence of terrestrial planets in the traditional circumstellar habitable zone, but GPs are desirable targets for two reasons: (1) giant planets, in cases where their orbits are outside of the HZ , may set up their own habitable zones through tidal interactions with moons, which serve to warm
the moons' interiors and could give rise to subsurface liquid water as in the case of Europa, and (2) these objects represent our only chance to test TPF on planets we know should be visible. In Section 2.3.8.4 and Table 2.3, we identified giant planet systems (HIP 86796, HIP 8159, HIP 17096, HIP 20723) whose orbits are always within the circumstellar habitable zone, and these systems should be considered high priority TPF targets. TPF will be designed to detect planets at exactly their location, and giant planets should be "guaranteed" detections. These objects could also have habitable moons, but such moons will fall inside the giant planet's point spread function and will not be detectable by TPF.

Given these considerations, we have not ruled out any star from the Sun Life TPF target list based on the presence of giant planets. However, all candidate TPF targets should, prior to the mission, be included in the radial velocity giant planet search campaigns to identify the orbital parameters of any giant planets within 5 AU . As has been pointed out by Derek Richardson and John Chambers (private communication 2004), such planets not only affect whether there are any stable orbits within the habitable zone, but even if the HZ is dynamically stable, giant planets may affect whether planets can form in the habitable zone. The asteroid belt between Mars and Jupiter is an example of "failed" planet formation, where orbits are stable, but coagulation into a single body was prevented by perturbations from Jupiter, which continually "stir up" the relative velocities between asteroids. The locations of strong resonances, which depend on the
mass and eccentricity of the giant planet in question, should be mapped out for all giant planet systems before the start of the TPF mission.

### 4.2.7 Stellar Metallicity and Galactic Kinematics

Our final requirement for habstars is that they have a metallicity that is compatible with the presence of planets. Logically, there must be a lower limit in metallicity below which there are not enough heavy elements to build an Earth-mass planet during the system's formation. Recent work by Reid (2002b) shows that the frequency of detected planetary systems is clearly correlated with stellar metallicity. The Sun itself is typical in metallicity amongst G-type disk dwarfs within 25 pc (Reid, 2002b) but it is less metalrich than $\sim 2 / 3$ of the stars with close-orbiting giant planets (Lineweaver 2001, Santos et al. 2001, Reid 2002a). If it is the case that metallicity is an indicator not only of planet occurrence but also of planet mass, then there may be a limited range of metallicities where low mass (terrestrial) planets exist (Lineweaver 2001), which would necessitate both minimum and maximum metallicity cuts. At this time, however, there is no clear case for a correlation between planet mass and stellar metallicity (see data and analysis in Reid 2002a). Therefore, we conclude that a minimum metallicity cut is justified, but we chose not to impose an upper limit at this time.

As discussed in Section 2.3.7.1, we can get a very rough estimate of minimum metallicity by assuming (1) that the total terrestrial planet mass scales linearly with the abundance of
the initial star-forming cloud (which is reflected in the abundance of the observable central star), (2) that the mass of terrestrial planet material in the Solar System is typical for Solar metallicity, and (3) that one Earth mass is the minimum amount of material necessary to create a habitable planet. Then the Solar System's total terrestrial planet mass ( $\sim 2$ Earth masses) implies a minimum metallicity for habitability of half solar, or $[\mathrm{Fe} / \mathrm{H}] \sim-0.3$.

So far, the observations appear to support the idea of including a metallicity cut in habstar selection. The occurrence of planets with $\mathrm{M}>1 \mathrm{M}_{\text {Jup }}$ and $\mathrm{P}<3$ years is correlated with metallicity (Fischer, Valenti \& Marcy 2004), with as many as $20 \%$ of stars with $[\mathrm{Fe} / \mathrm{H}]>$ 0.25 having planets and less than $5 \%$ of stars with $[\mathrm{Fe} / \mathrm{H}]<-0.25$ having planets. As there is no trend in metallicity with stellar mass for planet-bearing stars, this correlation does not appear to be caused by the "pollution" of stellar envelopes by accretion of planets (Santos, Isrealian \& Mayor 2003; Pinsonneault et al. 2001). As the time baseline for planet searches increases, we will see if that correlation continues to hold even for planets at several AU semi-major axes; meanwhile, we take the observed trend at face value. For $[\mathrm{Fe} / \mathrm{H}]=-0.3$, the fraction of stars with detected giant planets drops to just a few percent, and this is the minimum metallicity for stars included in the Sun Life target list.

As for Galactic kinematics, we apply the same criteria used in Section 2.3.7.2 to rule out stars whose velocities clearly depart from thin disk kinematics. As in that Section, we find a correlation between kinematics and metallicity. Of our 72 non-thin disk stars with
metallicity data, $\sim 8.3 \%$ have $[\mathrm{Fe} / \mathrm{H}]>0$, and $65 \%$ have $[\mathrm{Fe} / \mathrm{H}]$ below our cut-off of -0.3 . For our 588 thin disk stars with metallicity measurements, $24 \%$ have $[\mathrm{Fe} / \mathrm{H}]>0$, and $19 \%$ are below our -0.3 cut-off. All stars known to be metal poor were ruled out of the Sun Life TPF list even if they are thin disk stars. However, as in Section 2.3.7.2, we have chosen not to include non-thin disk stars even if they are known to be high metallicity. Stars whose velocities depart significantly from that of the local standard of rest cannot be in co-rotation with the Galactic disk and are likely to be on elliptical orbits that bring them into more frequent, potentially biologically and climatologically disastrous spiral arm-crossings (Balázs 2000, Marochnik \& Mukhin 1988, Doyle \& McKay 1991, Clark et al. 1977).

### 4.3 Results: The Final TPF "Sun Life" Target List

Applying all of the criteria discussed so far, we obtain a subset of $162 \mathrm{~F}, \mathrm{G}$ and K habstars within 30 parsecs that we consider to be excellent candidates for the Terrestrial Planet Finder. Here we describe the characteristics of this set of stars and the implications for TPF.

### 4.3.1 Astrophysical Characteristics of "Sun Life" Stars

Table 4.1 shows the final Sun Life target list, and Figure 4.5 shows the color-magnitude diagram for these stars. The stars range in luminosity from $0.01 \mathrm{~L}_{\S}$ to $12 \mathrm{~L}_{\S}$,
corresponding to Earth-equivalent insolation distances of 0.1 to 3.5 AU . According to the Washington Double Star survey, a third of these stars are known binaries with separations given in the "Sep (arcsec)" column, a third appear to be single from high resolution imaging (noted as "-1" in the separation column), and a third do not have any indication of binarity but have not been searched with high resolution imaging. Metallicities for this sample range from half to almost 3 times the solar value (Figure 4.6), with an average metallicity for the sample that is slightly less than solar. These stars are all, to the best of our current knowledge, older than $\sim 2$ billion years and nonvariable.

### 4.3.2 Traditional "Favorites"

By asking colleagues which stars they would expect to be high priority TPF targets, we composed a short list of stars that astronomers sometimes think of as "good" targets for TPF based on brightness, sunlikeness, or proximity. Stars considered "traditional favorites" that are not on our target list include: eta Cas A (ruled out for unsolved variability), tau Ceti (low metallicity, $[\mathrm{Fe} / \mathrm{H}] \sim-0.66$ ), kappa Ceti (variable star), eps Eri (younger than $\sim 2$ billion years according to chromospheric activity; microvariability), zeta Dor (youth indicated by $v \sin i$ ), beta Leo (main sequence lifetime less than 2 billion years: type A3Vvar star), 70 Vir (not main sequence), 36 Oph A (youth incidated by chromospheric activity; companion at $\sim 5$ arcseconds separation), Barnard's Star (nonthin disk kinematics; non-main sequence; companion within 1 arcsecond), 70 Oph A (companion within 5 arcsec; variability), Vega (type A star; unsolved variability;

Hipparcos suspected non-single), sigma Dra (non-thin disk kinematics), Altair (main sequence lifetime less than 2 billion years; variability), 61 Cygni $A$ and $B$ (unsolved variability), 16 Cygni A (component B is on the target list, but component A has a companion or background star at $\sim 3$ arcseconds), gamma Pav (low metallicity, -0.92 ; non-thin disk kinematics), eps Indi (youth indicated by chromospheric activity), and alpha PsA (acceleration in proper motion indicates unseen companion within a few arcseconds; main sequence lifetime less than 2 billion years).

Traditional favorites that are on our Sun Life list include: alpha Cen A and B (although, as discussed in Section 3.4.2), this system may be only marginally habitable for dynamical reasons), delta Pav, beta Hyi, 61 Vir, gamma Lep A, iota Per, gamma Ser, 55 Cancri, 15 Aur, ups And, 18 Sco, $47 \mathrm{UMa}, 51$ Peg, 16 Cygni B, 19 Pup, and rho Ind.

### 4.3.3 Implications for the TPF Mission

The most important conclusion of this work is that the Terrestrial Planet Finder, as a mission to search for Earth-like planets in the habitable zones of stars within 30 parsecs, has a scientifically attainable goal with a single instrument. In other words, given the fairly stringent target selection requirements outlined above and observational requirements on brightness, (1) there are just enough candidate stars for TPF to meet the full mission requirements, and (2) the angular stellar radii of the brightest stars are a factor of $\sim 10$ smaller than the angular habitable zone sizes of the faintest stars.

To address imaging requirements, Figure 4.7 shows the distribution of angular stellar and habitable zone sizes. We note that the angular size of the habitable zone can be approximated as a simple function of V magnitude, and the following equation can be used as a rule-of-thumb for the Earth-insolation equivalent distance:

$$
\theta_{\oplus}(\mathrm{mas})=10 \exp -[\mathrm{V} / 5]
$$

where $\theta_{\oplus}$ is the angular distance at which a planet would receive the same insolation as the Earth, and V is the apparent visual magnitude. The absence of any distance effect in this relation comes from the $1 /$ distance decrease in HZ angular size, combined with the (distance) ${ }^{2}$ increase in the intrinsic luminosity (and therefore the linear increase in HZ size with distance). Using this relation, we find that an inner working angle of $\sim 40$ milliarcseconds will allow at least a partial search of the habitable zones of all the stars presented here, but observing the habitable zones of stars fainter than $V \sim 7$ will require the capability to suppress starlight at smaller angular distances. The largest stellar angular radii for our candidate TPF target stars are less than $\sim 5$ mas (for Alpha Cen A), while the smallest outer HZ radius is $\sim 50$ mas and the largest HZ radius extends from $\sim 730$ mas inner radius to $\sim 1460$ mas outer radius. An angular search zone of 40 mas inner working angle to 1 arcsecond outer working angle is adequate to search the full habitable zones for planets around 93 habstars and partial habitable zones for the remaining 69 habstars within 30 parsecs.

### 4.4 The 30 Parsec Stellar Database and Future Work

The 30 Parsec Stellar Database, including all of the data mentioned above as well as flags noting our requirements for habitability, can be obtained electronically from Turnbull. Versions of the database are also available online in Excel, ASCII, and IDL formats at http://sco.stsci.edu/tpf_tldb, and the companion "readme" file describing the data included can be found in the Appendix of this dissertation. The TPF 30 Parsec Stellar Database will be managed and updated by the Information Processing and Analysis Center at the California Institute of Technology.

Updates to this database are needed as more information on metallicities, giant planets, and age indicators becomes available (indeed, many updates could already be made as of this writing), but with a few functional improvements, this database has the potential to contribute usefully to all of stellar astrophysics research and teaching. Three specific recommendations are:
(1) User Interface: The data itself should be "hidden" (i.e. write-protected) behind a shared web interface that allows users to select available criteria by which to sort and select stars. S. Heap and collaborators at NASA Goddard have already begun work on a user-friendly front end for the database.
(2) Visual Representations: Within the same interface, easily accessible images of the sky immediately surrounding each star, plots of the spectral energy distribution from

Hipparcos, 2MASS, and IRAS data, and a higher resolution UV and optical spectra should be made available for each star.
(3) Nearby Stars Observing Campaign: Some of the fields that are currently blank for various data can be filled in now by a more thorough perusal of the existing literature, but for the most part, metallicities and age indicators simply do not exist. These data are not likely to be obtained if the task is left to professional astronomers or students. Rather, a coordinated program of amateur observers on undersubscribed 1-meter class telescopes could quickly collect all of the missing data, while at the same time engaging a very capable and willing segment of the public in voluntary help.


Figure 4.1 The color-magnitude diagram for Hipparcos stars within 30 parsecs. Stars located between the blue lines were selected for the "Sun Life" target list.


Figure 4.2 Habitable zone movement due to stellar evolution of a $1 \mathrm{M}_{\S}$ star. The region of interest to TPF is the two billion year traveling habitable zone, located between the solid red and green lines.


Figure 4.3 The same as Figure 4.1, but for a $0.5 \mathrm{M}_{8}$ star.


Figure 4.4 The "region of habitability" on the HR diagram, superimposed on evolutionary tracks for stars of $0.5 \mathrm{M}_{8}$ to $1.7 \mathrm{M}_{8}$. This region is bounded below by the 2 Gyr isochrone (solid line), and it is bounded above where stars of various masses cease to have 2 Gyr THZs (dashed line), at the start of the red giant branch. Figure 4.2 Evolution of the habitable zone for a 1 M star.


Figure 4.5 The color-magnitude diagram for Sun Life target stars.


Figure 4.6 The distribution of metallicities of the 162 TPF habstars with $\mathrm{V}<7$.


Figure 4.7 The angular sizes of stellar radii and habitable zones for 162 TPF habstars with $\mathrm{V}<7$.

TABLE 4.1 Sun Life TPF Candidates Stars.

| HIP | NAME | V | $\begin{gathered} \mathrm{d} \\ \mathrm{pc} \end{gathered}$ | $\begin{gathered} L_{*}^{*} \\ \text { Lsun } \end{gathered}$ | Earth <br> AU | $\begin{aligned} & \mathrm{Hz}_{\mathrm{in}} \\ & \text { mas } \end{aligned}$ | $\mathrm{Hz}_{\mathrm{out}}$ mas | $\begin{gathered} R_{*} \\ \text { mas } \end{gathered}$ | $\begin{gathered} \rho \\ \operatorname{arcsec} \end{gathered}$ | [ $\mathrm{Fe} / \mathrm{H}]$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 71681 | alf Cen B | 1.4 | 1.3 | 0.34 | 0.57 | 380.9 | 753.6 | 2.6 | 13.3 | 0.14 |
| 71683 | alf Cen A | 0.0 | 1.3 | 1.35 | 1.15 | 733.4 | 1460.1 | 4.3 | 13.3 | 0.10 |
| 105090 |  | 6.7 | 3.9 | 0.01 | 0.11 | 26.1 | 51.1 | 0.2 | DVAR |  |
| 49908 |  | 6.5 | 4.9 | 0.02 | 0.15 | 29.8 | 58.4 | 0.3 | 149.8 |  |
| 99240 | del Pav | 3.6 | 6.1 | 1.02 | 1.00 | 141.9 | 282.1 | 0.9 |  | 0.28 |
| 2021 | bet Hyi | 2.8 | 7.5 | 3.24 | 1.78 | 199.2 | 398.1 | 1.1 |  | -0.28 |
| 64924 | 61 Vir | 4.7 | 8.5 | 0.68 | 0.82 | 82.3 | 163.8 | 0.5 | 352.9 | -0.03 |
| 23311 |  | 6.2 | 8.8 | 0.14 | 0.37 | 38.6 | 76.1 | 0.3 |  | 0.28 |
| 99825 |  | 5.7 | 8.8 | 0.26 | 0.50 | 50.9 | 100.8 | 0.3 |  | -0.09 |
| 27072 | gam Lep A | 3.6 | 9.0 | 2.43 | 1.55 | 137.8 | 277.1 | 0.7 | 97 | -0.14 |
| 64394 | bet Com | 4.2 | 9.2 | 1.33 | 1.14 | 103.2 | 206.5 | 0.6 | 85.8 | -0.05 |
| 68184 |  | 6.5 | 10.1 | 0.14 | 0.37 | 34.0 | 67.1 | 0.3 | -1 |  |
| 29271 | alf Men | 5.1 | 10.1 | 0.70 | 0.83 | 70.4 | 139.9 | 0.4 |  |  |
| 58345 | - | 7.0 | 10.2 | 0.08 | 0.29 | 26.3 | 51.8 | 0.2 |  | 0.16 |
| 14632 | iot Per | 4.0 | 10.5 | 2.08 | 1.43 | 113.1 | 226.0 | 0.6 | 146.2 | 0.03 |
| 57757 | bet Vir | 3.6 | 10.9 | 3.47 | 1.85 | 138.9 | 278.4 | 0.7 | 305.3 | 0.10 |
| 88972 |  | 6.4 | 11.1 | 0.22 | 0.47 | 37.7 | 74.6 | 0.3 | -1 | -0.16 |
| 3093 | 54 Psc | 5.9 | 11.1 | 0.37 | 0.60 | 47.8 | 94.8 | 0.3 | 164 | -0.02 |
| 78072 | gam Ser | 3.9 | 11.1 | 2.94 | 1.70 | 121.7 | 245.0 | 0.6 | 220.3 | -0.22 |
| 12777 | tet Per A | 4.1 | 11.2 | 2.36 | 1.52 | 108.8 | 218.7 | 0.5 | 20.5 | -0.04 |
| 77952 | bet TrA | 2.8 | 12.3 | 9.62 | 3.07 | 184.5 | 375.7 | 0.8 | 155 |  |
| 43587 | 55 Cnc | 6.0 | 12.5 | 0.42 | 0.64 | 45.9 | 90.9 | 0.3 | 83 | 0.29 |
| 40693 | - | 5.9 | 12.6 | 0.47 | 0.68 | 46.9 | 93.1 | 0.3 |  | -0.03 |
| 24813 | 15 Aur | 4.7 | 12.6 | 1.65 | 1.27 | 84.5 | 168.7 | 0.5 | 29.1 | -0.08 |
| 58576 | - | 5.5 | 12.9 | 0.72 | 0.84 | 56.7 | 112.5 | 0.4 |  | 0.14 |
| 91438 | - | 5.9 | 13.0 | 0.58 | 0.75 | 49.3 | 98.2 | 0.3 |  | -0.23 |
| 7513 | ups And | 4.1 | 13.5 | 3.36 | 1.82 | 109.9 | 220.3 | 0.6 | 114 | -0.03 |
| 16852 | 10 Tau | 4.3 | 13.7 | 2.88 | 1.68 | 101.0 | 202.2 | 0.5 |  | -0.13 |
| 79672 | 18 Sco | 5.5 | 14.0 | 0.95 | 0.97 | 58.4 | 116.5 | 0.3 | 25.8 | 0.01 |
| 53721 | 47 Uma | 5.0 | 14.1 | 1.49 | 1.21 | 72.0 | 143.8 | 0.4 | -1 | -0.12 |
| 59199 | alf Crv | 4.0 | 14.8 | 4.65 | 2.14 | 107.8 | 219.3 | 0.5 |  |  |
| 49081 | 20 Lmi | 5.4 | 14.9 | 1.17 | 1.07 | 61.3 | 122.2 | 0.4 | -1 | -0.11 |
| 28103 | eta Lep | 3.7 | 15.0 | 6.43 | 2.51 | 124.6 | 253.4 | 0.5 |  | -0.13 |
| 5862 |  | 5.0 | 15.1 | 1.86 | 1.35 | 74.0 | 148.1 | 0.4 |  | 0.08 |
| 86796 |  | 5.1 | 15.3 | 1.55 | 1.23 | 69.1 | 137.7 | 0.4 |  | 0.16 |
| 113357 | 51 Peg | 5.4 | 15.4 | 1.18 | 1.08 | 59.5 | 118.6 | 0.3 | -1 | 0.05 |


| HIP | NAME | V | $\begin{gathered} \mathrm{d} \\ \mathrm{pc} \end{gathered}$ | $\begin{gathered} \text { L* } \\ \text { Lsun } \end{gathered}$ | Earth AU | $\mathrm{Hz}_{\mathrm{in}}$ mas | $\begin{gathered} \mathrm{Hz}_{\text {out }} \\ \text { mas } \end{gathered}$ | $\begin{gathered} \mathrm{R}_{*} \\ \text { mas } \end{gathered}$ | $\begin{gathered} \rho \\ \operatorname{arcsec} \end{gathered}$ | [ $\mathrm{Fe} / \mathrm{H}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 3909 | 19 Cet | 5.2 | 15.5 | 1.67 | 1.28 | 66.7 | 134.0 | 0.3 |  | -0.20 |
| 95319 |  | 6.4 | 15.5 | 0.47 | 0.68 | 38.5 | 76.3 | 0.2 | -1 | 0.08 |
| 27435 | - | 6.0 | 15.6 | 0.76 | 0.87 | 46.7 | 93.3 | 0.3 |  | -0.24 |
| 107649 |  | 5.6 | 15.6 | 1.13 | 1.06 | 56.1 | 112.1 | 0.3 | 72.7 | -0.15 |
| 50954 |  | 4.0 | 16.2 | 5.70 | 2.37 | 110.5 | 224.2 | 0.5 |  |  |
| 32480 | 56 Aur | 5.2 | 16.5 | 1.74 | 1.31 | 65.0 | 130.3 | 0.3 | 31.6 |  |
| 116085 | - | 6.8 | 16.9 | 0.38 | 0.61 | 32.0 | 63.5 | 0.2 |  |  |
| 38784 |  | 6.6 | 17.0 | 0.50 | 0.70 | 35.6 | 70.8 | 0.2 | -1 | -0.14 |
| 43726 | - | 6.0 | 17.1 | 0.88 | 0.93 | 46.1 | 91.9 | 0.3 |  | -0.02 |
| 93858 | - | 6.2 | 17.2 | 0.75 | 0.86 | 43.0 | 85.5 | 0.3 |  | 0.01 |
| 33277 | 37 Gem | 5.8 | 17.3 | 1.17 | 1.07 | 51.6 | 103.2 | 0.3 | DVAR | -0.17 |
| 7978 | - | 5.5 | 17.4 | 1.51 | 1.22 | 57.1 | 114.5 | 0.3 |  |  |
| 76829 | g Lup | 4.6 | 17.5 | 3.60 | 1.88 | 83.0 | 167.8 | 0.4 |  |  |
| 100017 | - | 5.9 | 17.6 | 1.05 | 1.01 | 47.9 | 95.8 | 0.3 |  | -0.21 |
| 98819 | 15 Sge | 5.8 | 17.7 | 1.18 | 1.08 | 50.8 | 101.5 | 0.3 | 83.7 | -0.01 |
| 55846 |  | 6.5 | 17.7 | 0.55 | 0.73 | 36.4 | 72.3 | 0.2 | 28.5 | 0.16 |
| 98959 | - | 6.1 | 17.7 | 0.90 | 0.94 | 44.6 | 89.1 | 0.3 |  | -0.30 |
| 17651 | 27 Eri | 4.2 | 17.9 | 5.56 | 2.34 | 101.6 | 205.1 | 0.5 |  | 0.01 |
| 83389 | - | 6.8 | 18.1 | 0.47 | 0.68 | 32.4 | 64.5 | 0.2 |  | -0.03 |
| 83541 | - | 6.6 | 18.1 | 0.51 | 0.71 | 34.7 | 68.7 | 0.2 |  | 0.09 |
| 40843 | 18 Cnc | 5.1 | 18.1 | 2.42 | 1.54 | 67.5 | 135.9 | 0.3 | -1 | -0.28 |
| 79248 | 14 Her | 6.6 | 18.1 | 0.49 | 0.70 | 34.1 | 67.6 | 0.2 |  | 0.45 |
| 26394 | - | 5.7 | 18.2 | 1.43 | 1.19 | 54.1 | 108.1 | 0.3 |  | -0.02 |
| 61174 | eta Cry | 4.3 | 18.2 | 5.42 | 2.31 | 96.7 | 196.0 | 0.4 |  |  |
| 48113 | 15 Lmi | 5.1 | 18.4 | 2.44 | 1.55 | 70.3 | 140.4 | 0.4 | -1 | 0.04 |
| 4151 |  | 4.8 | 18.6 | 3.36 | 1.82 | 80.2 | 160.6 | 0.4 | 135.6 | -0.04 |
| 71957 | 107 Vir | 3.9 | 18.7 | 8.39 | 2.87 | 117.8 | 238.6 | 0.5 |  |  |
| 34017 |  | 5.9 | 19.1 | 1.21 | 1.09 | 47.5 | 94.9 | 0.3 | -1 | -0.16 |
| 29860 |  | 5.7 | 19.3 | 1.53 | 1.23 | 52.9 | 105.7 | 0.3 | 180.6 | -0.08 |
| 97675 | 54 Agl | 5.1 | 19.4 | 2.70 | 1.63 | 68.7 | 137.7 | 0.4 | 14.4 | 0.03 |
| 100925 | - | 6.6 | 19.4 | 0.62 | 0.78 | 34.6 | 68.9 | 0.2 |  | 0.01 |
| 85042 | - | 6.3 | 19.5 | 0.88 | 0.93 | 40.5 | 80.8 | 0.2 |  | -0.02 |
| 29800 | 74 Ori | 5.0 | 19.6 | 3.12 | 1.75 | 69.5 | 140.5 | 0.3 | 29.7 | -0.06 |
| 59072 | eta Cru | 4.1 | 19.7 | 7.34 | 2.68 | 102.6 | 208.3 | 0.4 | 44 |  |
| 67620 | - | 6.4 | 19.9 | 0.79 | 0.88 | 37.8 | 75.3 | 0.2 |  | -0.11 |
| 114924 |  | 5.6 | 20.3 | 1.94 | 1.38 | 55.5 | 111.3 | 0.3 | 129.3 | -0.02 |
| 110649 |  | 5.3 | 20.5 | 2.36 | 1.52 | 63.2 | 126.0 | 0.4 | 81.2 | -0.18 |
| 50505 |  | 6.6 | 20.6 | 0.72 | 0.84 | 34.3 | 68.4 | 0.2 | 145.2 | -0.27 |
| 7339 | - | 6.5 | 21.0 | 0.81 | 0.89 | 36.3 | 72.3 | 0.2 |  | 0.03 |


| HIP | NAME | V | $\begin{aligned} & \mathrm{d} \\ & \mathrm{p} \end{aligned}$ | $\begin{gathered} \text { L* } \\ \text { Lsun } \end{gathered}$ | Earth AU | $\begin{aligned} & \mathrm{Hz}_{\mathrm{in}} \\ & \text { mas } \\ & \hline \end{aligned}$ | $\begin{gathered} \mathrm{Hz}_{\text {out }} \\ \text { mas } \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{R}_{*} \\ \mathrm{mas} \end{gathered}$ | $\rho$ arcsec | [ $\mathrm{Fe} / \mathrm{H}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 102040 |  | 6.4 | 21.0 | 0.92 | 0.95 | 37.9 | 75.7 | 0.2 | 93.7 | -0.22 |
| 109378 | - | 6.5 | 21.3 | 0.78 | 0.88 | 35.8 | 71.0 | 0.2 |  | 0.22 |
| 65530 |  | 6.5 | 21.3 | 0.83 | 0.90 | 36.5 | 72.6 | 0.2 | -1 | 0.09 |
| 96901 | 16 Cyg B | 6.2 | 21.4 | 1.14 | 1.06 | 41.9 | 83.5 | 0.2 | 39.8 |  |
| 41484 |  | 6.3 | 21.8 | 1.09 | 1.03 | 39.7 | 79.4 | 0.2 | -1 | -0.14 |
| 950 | tet Scl | 5.2 | 21.8 | 3.19 | 1.77 | 63.6 | 128.3 | 0.3 |  | -0.14 |
| 61053 |  | 6.2 | 21.9 | 1.26 | 1.11 | 41.6 | 83.4 | 0.2 | -1 | -0.13 |
| 30503 | - | 6.4 | 22.0 | 1.06 | 1.02 | 38.9 | 77.7 | 0.2 |  |  |
| 75809 |  | 6.6 | 22.1 | 0.87 | 0.92 | 35.5 | 70.7 | 0.2 | 31.7 | -0.29 |
| 3979 | - | 7.0 | 22.1 | 0.60 | 0.77 | 29.4 | 58.6 | 0.2 |  | -0.19 |
| 50921 | - | 6.9 | 22.1 | 0.62 | 0.78 | 29.9 | 59.7 | 0.2 |  | -0.28 |
| 86620 | 31 Dra B | 5.8 | 22.3 | 1.91 | 1.37 | 49.8 | 100.0 | 0.3 | 30.2 | -0.08 |
| 40035 | 18 Pup | 5.5 | 22.5 | 2.55 | 1.58 | 56.3 | 113.2 | 0.3 | 80.5 | -0.09 |
| 36210 | - | 6.7 | 22.5 | 0.77 | 0.87 | 33.1 | 65.9 | 0.2 |  | 0.05 |
| 89474 |  | 6.3 | 22.7 | 1.19 | 1.08 | 40.2 | 80.2 | 0.2 | -1 | -0.07 |
| 110712 |  | 6.1 | 23.0 | 1.49 | 1.21 | 43.5 | 87.1 | 0.2 | 20.6 | -0.21 |
| 29432 | - | 6.9 | 23.1 | 0.74 | 0.85 | 31.0 | 61.8 | 0.2 |  | -0.03 |
| 9829 |  | 6.9 | 23.2 | 0.72 | 0.84 | 30.6 | 61.1 | 0.2 | -1 | -0.23 |
| 19233 | - | 6.4 | 23.2 | 1.17 | 1.07 | 38.9 | 77.6 | 0.2 |  | -0.28 |
| 39780 | 10 Cnc | 5.3 | 23.3 | 3.17 | 1.77 | 63.6 | 127.0 | 0.4 |  | 0.04 |
| 52369 | - | 6.8 | 23.4 | 0.82 | 0.90 | 32.0 | 64.0 | 0.2 |  | -0.17 |
| 93185 | - | 6.8 | 23.4 | 0.82 | 0.90 | 31.9 | 63.7 | 0.2 |  | -0.27 |
| 1499 | - | 6.5 | 23.4 | 1.07 | 1.02 | 37.2 | 74.2 | 0.2 |  | 0.20 |
| 70873 |  | 6.4 | 23.6 | 1.18 | 1.08 | 39.1 | 77.9 | 0.2 | -1 | 0.05 |
| 74273 | - | 6.3 | 24.1 | 1.38 | 1.16 | 40.3 | 80.5 | 0.2 |  | -0.11 |
| 64550 | - | 6.9 | 24.5 | 0.78 | 0.87 | 30.0 | 60.0 | 0.2 |  | -0.15 |
| 114570 | 7 And | 4.5 | 24.5 | 7.95 | 2.79 | 84.0 | 171.1 | 0.3 | -1 |  |
| 74975 | 5 Ser | 5.0 | 24.7 | 4.70 | 2.15 | 70.8 | 142.0 | 0.4 | 11.4 | -0.15 |
| 73100 |  | 5.6 | 24.8 | 2.80 | 1.66 | 54.0 | 108.4 | 0.3 | -1 | -0.03 |
| 24786 |  | 6.0 | 24.9 | 2.05 | 1.42 | 46.9 | 93.9 | 0.2 | 45.5 | -0.25 |
| 94981 |  | 6.3 | 25.2 | 1.48 | 1.20 | 40.6 | 80.8 | 0.2 | -1 | 0.02 |
| 74605 |  | 5.2 | 25.3 | 4.50 | 2.10 | 67.6 | 135.6 | 0.3 |  | -0.10 |
| 27075 | - | 6.3 | 25.5 | 1.51 | 1.22 | 39.2 | 78.6 | 0.2 |  |  |
| 39710 |  | 6.8 | 25.6 | 0.98 | 0.98 | 31.8 | 63.7 | 0.2 | -1 | -0.24 |
| 96258 | - | 5.7 | 25.6 | 2.78 | 1.65 | 51.6 | 103.8 | 0.3 |  | -0.18 |
| 6405 |  | 7.0 | 25.6 | 0.83 | 0.91 | 29.6 | 59.2 | 0.2 | -1 | -0.20 |
| 2711 | - | 5.6 | 25.6 | 3.22 | 1.78 | 55.0 | 110.7 | 0.3 |  | 0.04 |
| 74500 |  | 6.5 | 25.7 | 1.27 | 1.11 | 37.2 | 74.0 | 0.2 | -1 | 0.25 |
| 30104 |  | 6.6 | 25.7 | 1.14 | 1.06 | 34.8 | 69.5 | 0.2 | -1 | 0.13 |


| HIP | NAME | V | $\begin{gathered} \mathrm{d} \\ \mathrm{pc} \end{gathered}$ | $\begin{gathered} \text { L* } \\ \text { Lsun } \end{gathered}$ | Earth AU | $\mathrm{Hz}_{\mathrm{in}}$ mas | $\begin{gathered} \mathrm{Hz}_{\text {out }} \\ \text { mas } \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{R}_{*} \\ \text { mas } \end{gathered}$ | $\begin{gathered} \rho \\ \operatorname{arcsec} \end{gathered}$ | [ $\mathrm{Fe} / \mathrm{H}$ ] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 36795 |  | 4.4 | 25.7 | 9.05 | 2.98 | 93.7 | 188.1 | 0.5 | -1 | -0.18 |
| 11783 | 76 Cet | 4.7 | 25.8 | 7.10 | 2.64 | 80.3 | 162.0 | 0.4 |  | -0.30 |
| 24332 |  | 6.5 | 26.0 | 1.40 | 1.17 | 36.6 | 73.5 | 0.2 | 16.7 | -0.23 |
| 97420 | - | 6.9 | 26.0 | 0.91 | 0.95 | 30.7 | 61.2 | 0.2 |  | -0.12 |
| 1444 |  | 6.5 | 26.2 | 1.34 | 1.15 | 36.4 | 72.8 | 0.2 | -1 | -0.01 |
| 64150 |  | 6.8 | 26.3 | 1.01 | 1.00 | 32.2 | 64.2 | 0.2 | -1 | 0.06 |
| 28908 |  | 6.1 | 26.4 | 1.94 | 1.38 | 43.5 | 87.0 | 0.2 | 146.1 | -0.24 |
| 10505 |  | 6.8 | 26.4 | 0.98 | 0.98 | 31.8 | 63.4 | 0.2 | -1 | 0.14 |
| 103682 |  | 6.2 | 26.5 | 1.78 | 1.32 | 41.9 | 83.7 | 0.2 | -1 | 0.11 |
| 22336 |  | 5.8 | 26.5 | 2.68 | 1.62 | 51.3 | 102.5 | 0.3 | -1 | 0.14 |
| 113137 | rho Ind | 6.0 | 26.5 | 2.05 | 1.42 | 45.3 | 90.3 | 0.3 | -1 | 0.10 |
| 60729 |  | 6.3 | 26.7 | 1.70 | 1.29 | 41.1 | 81.9 | 0.2 | -1 | 0.10 |
| 74653 |  | 6.9 | 26.9 | 0.95 | 0.96 | 30.9 | 61.5 | 0.2 | -1 |  |
| 101875 |  | 6.8 | 26.9 | 1.12 | 1.05 | 32.4 | 64.9 | 0.2 | 16.9 | -0.14 |
| 40283 |  | 6.7 | 27.0 | 1.19 | 1.08 | 33.4 | 66.7 | 0.2 | 14.8 | 0.24 |
| 40438 |  | 6.6 | 27.1 | 1.31 | 1.13 | 34.4 | 69.0 | 0.2 | -1 | -0.19 |
| 85268 |  | 6.5 | 27.2 | 1.49 | 1.21 | 37.1 | 74.1 | 0.2 | -1 | -0.13 |
| 10031 |  | 6.6 | 27.3 | 1.41 | 1.18 | 35.1 | 70.3 | 0.2 | -1 | -0.22 |
| 31660 |  | 6.8 | 27.4 | 1.02 | 1.00 | 31.6 | 62.8 | 0.2 | 56.3 | 0.13 |
| 55779 |  | 5.2 | 27.4 | 5.29 | 2.28 | 66.5 | 133.8 | 0.3 |  |  |
| 47007 |  | 6.5 | 27.5 | 1.43 | 1.18 | 36.1 | 72.1 | 0.2 | -1 | 0.32 |
| 42291 |  | 6.5 | 27.5 | 1.45 | 1.19 | 36.0 | 72.1 | 0.2 | -1 | -0.01 |
| 97767 |  | 6.2 | 27.7 | 2.02 | 1.41 | 42.8 | 85.4 | 0.2 | 90.5 | -0.20 |
| 117880 |  | 6.0 | 27.9 | 2.42 | 1.54 | 45.5 | 91.1 | 0.2 | -1 | 0.12 |
| 28066 |  | 6.6 | 28.0 | 1.37 | 1.16 | 35.0 | 69.8 | 0.2 | 76 | -0.13 |
| 99572 | 2 Cap | 5.8 | 28.1 | 3.00 | 1.72 | 48.7 | 98.0 | 0.2 | 83.5 | -0.27 |
| 33719 |  | 6.3 | 28.1 | 1.91 | 1.37 | 40.1 | 80.4 | 0.2 | -1 | 0.21 |
| 71530 |  | 6.0 | 28.2 | 2.52 | 1.57 | 44.8 | 90.1 | 0.2 | 34.1 |  |
| 90223 |  | 6.5 | 28.2 | 1.65 | 1.27 | 37.4 | 74.8 | 0.2 | -1 | -0.17 |
| 23852 | 13 Ori | 6.2 | 28.3 | 2.12 | 1.44 | 42.6 | 85.2 | 0.2 | 123.4 |  |
| 28634 | - | 6.5 | 28.4 | 1.63 | 1.26 | 36.5 | 73.1 | 0.2 |  | -0.20 |
| 69090 |  | 6.0 | 28.7 | 2.55 | 1.58 | 45.5 | 91.2 | 0.2 | -1 | -0.05 |
| 24205 | - | 7.0 | 28.7 | 1.04 | 1.01 | 29.2 | 58.4 | 0.2 |  | -0.14 |
| 92270 |  | 6.2 | 28.7 | 2.28 | 1.49 | 41.7 | 83.8 | 0.2 | -1 | -0.19 |
| 94757 |  | 6.9 | 28.8 | 1.12 | 1.05 | 29.9 | 59.9 | 0.2 | 44.9 | -0.06 |
| 27244 | - | 6.6 | 28.8 | 1.47 | 1.20 | 34.4 | 68.9 | 0.2 |  | -0.17 |
| 78955 |  | 6.3 | 28.9 | 1.89 | 1.36 | 39.8 | 79.4 | 0.2 | -1 | 0.23 |
| 25662 |  | 6.7 | 28.9 | 1.34 | 1.15 | 32.8 | 65.6 | 0.2 | 101.2 | -0.22 |
| 43177 |  | 6.3 | 28.9 | 1.93 | 1.38 | 39.2 | 78.5 | 0.2 | -1 | 0.28 |


| HIP | NAME | V | d <br> pc | $\mathrm{L} *$ <br> Lsun | Earth <br> AU | $\mathrm{Hz} z_{\text {in }}$ <br> mas | $\mathrm{Hz}_{\text {out }}$ <br> mas | $\mathrm{R}_{*}$ <br> mas | $\rho$ <br> $\operatorname{arcsec}$ | $[\mathrm{Fe} / \mathrm{H}]$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 6.5 | 29.0 | 1.78 | 1.32 | 36.8 | 73.8 | 0.2 | -1 | - |
| 60816 |  | 6.7 | 29.1 | 1.34 | 1.15 | 32.6 | 65.3 | 0.2 | -1 | -0.06 |
| 44901 | 15 Uma | 4.5 | 29.3 | 12.26 | 3.47 | 87.1 | 177.6 | 0.4 |  |  |
| 81800 |  | 6.5 | 29.4 | 1.81 | 1.33 | 36.9 | 74.1 | 0.2 | -1 | -0.03 |
| 7276 | - | 5.8 | 29.7 | 3.37 | 1.82 | 51.6 | 103.0 | 0.3 |  | 0.09 |
| 5985 |  | 6.5 | 29.7 | 1.72 | 1.30 | 35.9 | 72.0 | 0.2 | -1 | -0.14 |
| 60353 |  | 6.5 | 29.8 | 1.87 | 1.35 | 37.2 | 74.5 | 0.2 | 20.8 | - |
| 20800 |  | 6.7 | 29.8 | 1.36 | 1.16 | 33.1 | 66.0 | 0.2 | -1 | 0.15 |
| 30711 |  | 6.1 | 29.9 | 2.73 | 1.64 | 44.5 | 89.3 | 0.2 | 41.2 |  |

## 5. Spectrum of a Living Planet: Earthshine from 0.5 to 2.3 Microns

### 5.1 Introduction

One of the key areas of research that will assist in the interpretation of extrasolar terrestrial planet spectra collected by TPF is the study of the spectrum of planet Earth. The best way to study the light of planet Earth is currently through observing earthshine, which is is light reflected from the sunlight-illuminated Earth onto the dark side of the moon and back again to Earth and into our telescopes. Spectra taken via satallite observations are not adequate for viewing the globally integrated optical and nearinfrared spectrum of Earth because satellites (1) observe only small patches of the Earth at one time and (2) usually observe in narrow wavelength bandpasses that contain information about specific components of the reflection spectrum (e.g., the hydration level of vegetation, or the presence of forest fires and resulting aerosols). The Earthshine spectrum, however, includes the disk-averaged spectrum of the illuminated Earth as seen from the Moon, with no spatial information, and we can smooth this spectrum to arbitrary spectral resolution.

Figure 5.1 illustrates the light paths involved in extracting the Earth's spectrum as seen from space. Path 1 (yellow) originates with the Sun, travels through the Earth's atmosphere, reflects off the Earth's surface, travels again through the Earth's atmosphere, reflects off the dark side of the Moon, and after a final pass through Earth's atmosphere,
lands in our telescope. Path 2 (red) orginates with the Sun, reflects off the bright limb of the Moon, and after a pass through Earth's atmosphere, lands in our telescope. Each time the light interacts with an atmosphere or surface, the spectrum intensity at each wavelength is multiplied by the absorption or reflectance spectrum of the atmosphere or surface. Therefore, ignoring for the moment the effect of scattered light in our atmosphere from the bright Moon, the spectrum of the Earth as seen from outer space can be obtained simply by dividing the spectrum observed at the dark Moon location by the spectrum observed at the bright Moon location. This spectrum, which contains no spatial information about Earth, is very similar to what TPF, if orbiting another star and peering back at us, would see.

### 5.2 Previous Optical Observations

In June of 2001, Woolf et al. (2002) obtained earthshine spectra in the spectral range from 4800 to $9200 \AA$, with a resolution of about $600(\Delta \lambda \sim 8 \AA)$. Thie view of the Earth from the Moon during the observations is shown in Figure 5.2, and it is the sunlit portion of the Earth that is represented in their final spectrum. In this Figure we see that their view was of a water-covered world, with only about $1 / 3$ of the visible area covered by land.

The spectrum Woolf et al. (2002) obtained is shown as the uppermost black line in Figure 5.3, along with the model fit to the data superimposed on the data in red. The model is a
least-squares fit to the data of several independent spectral components, including a wavelength-indepent "high cloud" layer (assumed to be spectrally featureless at these wavelengths), a 100 km cloud-free atmosphere of $\mathrm{O}_{2}, \mathrm{O}_{3}$, and $\mathrm{H}_{2} \mathrm{O}$ (red line labeled as "clear"), Rayleigh scattering (blue, "ray"), reflection off of land plants (green, "veg"), and much smaller amounts of reflection off of ocean water (blue, "ocn"), and ocean pigments (green, "pig"), and aerosol scattering (red, "aer"). The cloud-free atmosphere can also be considered to contain the spectrum of the ground and ocean, which are nearly spectrally featureless.

Pretending for a moment that we know nothing about the planet whose spectrum is shown in Figure 5.3, this spectrum sheds some light on what kind of planet we are seeing. The increase in reflectivity toward shorter wavelengths, due to Rayleigh scattering, indicates the total amount of atmosphere, and atmospheric water absorption bands indicate that this planet may be habitable. The oxygen absorption is strongly suggestive of biological processes, especially combined with the vegetation signal, representated by a jump in reflectivity from 7000 to 8000 angstroms.

As a direct detection of surface life forms, the vegetation signal is of particular interest. In Figure 5.4 (from Clark, 1999), we see that the pigments in leaves are strongly absorptive at all optical wavelengths. Indeed, there is only a small decrease in the absorption of chlorophyll pigments at about 5000 angstroms. The resulting bump in reflectivity to a mere $10 \%$ at that wavelength gives rise to the green color of leaves.

However, looking at Figure 5.4, we see that leaves are about 15 times more reflective in the near infrared than in the optical, with reflectance increasing to about $70 \%$ at 0.8 microns.

Although the view of Earth for the optical earthshine observations was dominated by water (Figure 5.2), the vegetation signal appears to be present at a small level in the June 2001 observations. An earlier earthshine study (Arnold et al. 2002) at lower resolution with a more land-filled view of Earth also appears to have detected the vegetation signal at a small level. The TPF-C wavelength range will overlap the vegetation signal, but unless we find a planet totally covered with plants and nearly cloud-free (an unlikely combination, given that plants grow best in the rainiest environments), such a detection is extremely unlikely. One reason why plants can be difficult to detect is that they grow most densely and have the sharpest "red edge" (i.e., they are most hydrated) in regions that get large amounts of rain and are often cloud-covered. However, the model fit shown in Figure 5.3 does not account for the full intensity in the observations just longward of the red edge, and this could potentially be accounted for by adding more plants and using a more realistic cloud reflectivity (which, due to water vapor between cloud droplets, would decrease in the water bands at 8200 and 9000 angstroms).

Because there is such a dramatic difference in reflectivity between ocean water and either plant-covered or plant-free land, we can use the absolute reflectances for vegetation and soil in Figure 5.4 to estimate, from the contributions of different model components in

Figure 5.3, what fraction of the planet's visible area is covered by land and ocean. From the model spectrum, we see that the clear atmosphere (which contains reflection off of the ground and ocean) and vegetation signals together account for $51.5 \%$ of the total signal at 8600 angstroms (a relatively featureless part of the spectrum). We assume that the area of land is half covered by plants, and that Earth's absolute albedo at 8600 angstroms is $\sim 0.3$. We also take the absolute reflectances for soil and plants from Figure 5.4 to be $\sim 0.25$ and $\sim 0.7$, respectively, at this same wavelength. Assuming an index of refraction of $n=1.33$, the reflectivity of water is $[(n+1) /(n-1)]^{2}=0.02$. We then write:

$$
\mathrm{f}_{\text {signal }} \times 0.3=\mathrm{f}_{\text {veg }} \times 0.7+\mathrm{f}_{\text {soil }} \times 0.25+\mathrm{f}_{\text {ocn }} \times 0.02
$$

where $f_{\text {veg }}, f_{\text {soil }}$, and $f_{\text {ocn }}$ are the fraction of the visible area covered by plants, vegetationfree soil, and ocean, respectively, and $f_{\text {signal }}$ is the fraction of the total earthshine signal that is represented by these components. Assuming that $f_{\text {veg }}=f_{\text {soil }}=f_{\text {and }} / 2$ and that whatever is not covered by vegetation or soil is covered by ocean, we can reduce this to:

$$
\mathrm{f}_{\text {signal }} \times 0.3=\left(\mathrm{f}_{\text {land }} \times 0.7+\mathrm{f}_{\text {land }} \times 0.25\right) / 2+\left(1-\mathrm{f}_{\text {land }}\right) \times 0.02
$$

Solving this for $\mathrm{f}_{\text {land }}$, we find that $30 \%$ of the visible area of this planet is covered either by plants or soil, and $70 \%$ is covered by water. Looking again at Figure 5.2, we see this is reasonable. However, the reflectances we have used could vary signiciantly, depending on plant species and hydration level, soil type and hydration level, ice/snow cover, water surface roughness, and the degree to which we have accurately represented the reflection spectrum of the different model components. If we arbitrarily change the reflectances used for ground cover, we find that an increase or decrease in the "land" reflectivity of $20 \%$ causes the fractional area of the ground to decrease or increase by
$\sim 10 \%$. Carrying this analysis out at a different wavelength, e.g. 6800 angstroms, we calculate a land fraction of $76 \%$, and an ocean fraction of $24 \%$, which are still reasonable values.

### 5.3 Near-Infrared Observations

### 5.3.1 Observations and Reductions

To expand our wavelength coverage of the Earth's spectrum, we have obtained earthshine data in the near infrared. Here we present Earthshine observations taken in November of 2003 in the spectral region 0.7 to 2.3 microns at resolution $\sim 300$ with the Cornell Massachusetts Slit Spectrograph (CorMASS) on the $1.8-\mathrm{m}$ Vatican Advanced Technology Telescope at the Mount Graham International Observatory in southeast Arizona. CorMASS, described in detail by Wilson et al. (2001), is low-resolution $(\mathrm{R} \sim 300)$, cross-dispersed, and operates in the near-infrared, from about 0.75 to $2.5 \mu \mathrm{~m}$. A remotely operated flip mirror permits the $256 \times 256 \mathrm{HgCdTe}$ NICMOS3 detector to function as a slit viewer to assist object placement into the $2 " \times 15$ " slit. The wavelength coverage is dispersed into eight orders on the array (see Figure 5.5), decreasing in wavelength from top to bottom, and the edges of each order lie within the atmospheric water absorption bands where the signal drops dramatically. We note, however, that for our observations the signal does not drop to zero at these wavelengths; Mount Graham, with an elevation of 11,000 feet and very dry conditions in the late fall, has an
atmospheric transmission in the water bands that is comparable to Mauna Kea, with only $1-3 \mathrm{~mm}$ precipitable water vapor (Lloyd-Hart 2000). Thus the atmospheric transmission is $\sim 20 \%$ at 1 micron, and $\sim 10 \%$ at 1.9 microns. As we will see in Section 5.3.2, repeatable features of the Earthshine spectrum are indeed visible at these wavelengths.

An image of the Moon on 18 November 2003, the night when we captured nine consecutive sets of dark moon, bright moon and sky observations, is shown in Figure 5.6. As is depicted, the dark side of the Moon is illuminated by sunlight reflected off the Earth, and this light contains the spectral imprint of the Earth's atmospheric and surface features. We were not able to activate the lunar tracking rates on the telescope, so we generally positioned the slit and allowed it to trail across the Moon or sky during the observation, but the amount of total drift for each observation was quite small compared to the size of the Moon. Figure 5.6 shows the effective slit length given the motion of the Moon relative to our non-tracking slit, and the slit positions are numbered according to our observing procedure:

1. Observe the bright limb of the moon (typical exposure times of 1 second or less for our observations, usually taking groups of 10 images)
2. Observe the sky near the dark side of the moon (typical exposure time $\sim 200$ seconds)
3. Observe the dark side of the Moon ( $\sim 200$ seconds)
4. Observe the sky near the dark side of the moon ( $\sim 200$ seconds)

To obtain the Earthshine spectrum, then, we need to subtract the sky (which contains scattered light coming from the bright limb) from the dark side of the Moon and divide
the resulting spectrum by the bright limb spectrum. No sky was subtracted from the bright limb, as this contribution was negligible in such a short integration. Dividing by the bright limb serves three purposes: 1. to flat-field the data (remove any nonuniformities in detector response), 2. to divide out the solar spectrum, 3. to divide out the lunar spectrum, and 4. to divide out the effect of the extra pass through the Earth's atmosphere from the dark moon to our telescope.

Initial data processing required a rather complicated procedure for removing the variable bias level, also referred to as the "NICMOS shading" or "reset decay pattern." This shading is shown in Figure 5.7, a vertical cut of Figure 5.5 at column 50. The level and shape of the NICMOS shading depends upon the time since last read and is thus different from image to image. For each image, a "shading blank image," approximated to the background shading without the orders, was created using sections of each image that were not illuminated by the slit or "ghost" images caused by internal reflections. This model of the bias was then subtracted from the image.

After shading subtraction, there was still a discontinuity between the upper and lower half of each image that was proportional to the amount of light contained in the brightest orders. We concluded from this that the lower half of the detector is more susceptible to scattered light contamination than the upper half. To remove this offset, a "step blank" was made using pixels between the brightest orders above and below the middle row. In reality, the shape of the scattered light background was more complicated than a simple
step function between the upper and lower half of the image, but our primary concern was simply to remove any sharp discontinuities.

After this initial processing, one-dimensional spectra were extracted using the standard IRAF packages for correcting bad pixels, defining the location of each order on the images, summing along the slit and extracting the one dimensional spectra, and wavelength-calibrating the data using emission lines in planetary nebula NGC 7027. The extracted spectra of the dark Moon, bright Moon, and sky were then used to extract the spectrum of the Earth as seen from outer space. As outlined above, our procedure for extracting the Earthshine spectrum is to subtract sky from the dark side of the Moon and divide the resulting spectrum by the bright limb. The formula containing all of the spectral terms shown in Figure 5.1 is:

$$
\begin{aligned}
\mathrm{ES} & =\left[\left(\text { Solar } * \text { Earth }_{\mathrm{atm}} * \text { Earth }_{\mathrm{gud}} * \text { Earth }_{\mathrm{atm}} * \text { Moon } * \text { Earth }_{\mathrm{atm}}+\text { Sky }\right)-\text { Sky }\right] / \mathrm{BM} \\
& =\text { Earth }_{\mathrm{atm}} * \text { Earth }_{\mathrm{gnd}} * \text { Earth }_{\mathrm{atm}}=\text { view of Earth from space } \\
\mathrm{BM} & =\text { Solar } * \text { Moon } * \text { Earth }_{\mathrm{atm}}
\end{aligned}
$$

where "ES" is the earthshine spectrum, and "BM" is the spectrum of the bright limb.

However, there are several complications with scattered light ("sky") subtraction, firstly, because the scattered light level falls off dramatically and changes in wavelength dependence with distance from the bright limb, and therefore the scattered light spectrum observed off the dark limb of the moon is slightly different from the true scattered light spectrum at the location of the dark Moon observation. A direct subtraction of the
observed sky from the observed dark Moon would then undersubtract the total scattered light level as well as introduce wavelength-dependent errors. Secondly, the thermal component of the sky spectrum (beyond $\sim 2.3$ microns) does not change in position, so scaling of the observed sky to the correct overall level at the dark Moon location would over-subtract the thermal component. It was necessary to remove the thermal component from both the sky and dark Moon before subtracting the sky from the dark side of the Moon. We did obtain dome flats, from which we originally tried to estimate the thermal component, however the dome was both warmer and at a much higher optical depth than the sky, thereby giving a very different thermal spectrum. Therefore we first created a model of the thermal contribution to the spectrum by hand and subtracted this separately from the dark Moon and sky spectra. Then, to correct the sky to the position of the dark Moon, we used spectra at positions "Near" and "Far" from the limb of the dark Moon. The "true" sky at the dark Moon position was then estimated by arithmetic on these spectra:
(Near - Far) / Near,
which gives us the fractional change in scattered light level between the "Near" and "Far" observations, as a function of wavelength. We fit a straight line to the resulting spectrum, as is shown in Figure 5.8. This was then divided by the number of arcseconds between the "Near" and "Far" positions to give the increase in flux per arcsecond separation from the sky to the dark Moon observation positions, as a function of wavelength. This is our "Sky_Slope" spectrum, which has units of counts per arcsecond as a function of
wavelength. The observed sky level was then corrected to the "actual" sky level at the location of the dark Moon observation by the following equation:

$$
\text { Sky }_{\text {Actual }}=\text { Sky_Slope }^{*} \Delta \mathrm{RA} *\left(\text { Sky }_{\text {Observed }}-\text { thermal }\right)+\left(\text { Sky }{ }_{\text {Observed }}-\text { thermal }\right),
$$ where $\triangle \mathrm{RA}$ is the difference in position, in arcseconds, between the sky observation and the dark Moon observation. The (thermal subtracted) dark Moon and Sky Actual were then both divided by the bright limb spectrum, and the divided sky was then subtracted from the divided dark Moon to create the sky-subtracted, bright limb divided, dark Moon spectrum (which contains both the earthshine spectrum and the lunar phase function discussed below):

$$
\text { earthshine } * \mathrm{f}_{\text {lunar }}=[(\mathrm{DM}-\text { thermal }) / \mathrm{BM}]-\left[\left(\mathrm{Sky}_{\text {Actual }}-\text { thermal }\right) / \mathrm{BM}\right],
$$

where $\mathrm{f}_{\text {lunar }}$ is the lunar reflectance phase function (discussed below).

The Sky $_{\text {Actual }}$ spectrum, after dividing by the bright limb spectrum to remove solar features, is shown in Figure 5.9. Clearly, a slight mis-subtraction of this spectrum will strongly affect the resulting flux in the shortest wavelengths. We found that the formula above slight undersubtracted sky, and as a result, the Earthshine spectrum had a very steep slope increasing into the optical. This wavelength region is also covered in the optical observations discussed above, and such a slope is not seen. We were not able to uncover any explanation for this other than that the sky was under-subtracted, and this is probably due to a non-linear fall-off of scattered light with distance from the bright limb. Figure 5.10 shows the result of subtracting variable amounts of the sky spectrum shown
in Figure 5.9, and we find that by subtracting an extra $10 \%$ of the Sky $_{\text {Actual }}$ Spectrum calculated above, we were able to remove the steep slope at the shortest wavelengths.

However, this is still not the final Earthshine spectrum, because the Moon itself has a phase function, which tends to redden reflected light at steeper angles. As Figure 5.1 shows, the Sun-Moon-Earth angle is very large, near 175 degrees at the time of our observations. Thus the spectrum from the bright limb, by which we divided our spectrum, is slightly skewed toward the red, and as a result, our dark Moon spectrum is slight skewed to be brighter in the blue. We used USGS reflectance data for the Moon from the Robotic Lunar Observatory (ROLO) disk-integrated reflectance between 0.7 and 2.4 microns at Sun-Moon-Earth angles of 2, 32, 62 and 92 degrees (Tom Stone, USGS, private communication) to extrapolate the spectral dependence of the reflectance at 175 degrees. This extrapolation is shown in Figure 5.11. At this very large Sun-Moon-Earth angle, the Moon is more reflective at 2.4 mm than at 0.7 mm by a factor of $\sim 1.7$. The final step was to multiply this dark Moon spectrum by the lunar phase function (which is equivalent to dividing the bright Moon spectrum by the phase function before we divide by the bright Moon), and the final Earth-from-space spectrum is shown in Figure 5.12. For comparison, we also show the atmospheric transmission spectrum for the altitude $(4200 \mathrm{~m})$ and water column ( 1.2 mm ) of Mauna Kea. The differences between the two spectra are due to (1) Earth's surface reflectance and (2) the fact that in the earthshine data we are simultaneously seeing along many different paths through the atmosphere. As expected, we see more absorption at all wavelengths in the earthshine spectrum. The
water lines at 1.4 and 1.9 microns in the earthshine spectrum are likely saturated for many parts of the visible Earth, hence the lines are significantly broader, but not much deeper, than in the UKIRT transmission spectrum. However, the Earth is not "black" at these wavelengths, as reflection from high clouds and very dry areas of ground are still contributing to the spectrum there.

### 5.3.2 Analysis and Discussion

The views of the Earth from the Moon on 18 November 2003 are shown in Figure 5.13 (start of observations) and Figure 5.14 (end of observations). There are a variety of terrains in view, including desert, rainforest and ocean. We used a simple box model, described in detail in Traub \& Stier (1976), including independently calculated components of clouds, plants, ocean, and plant-free ground (which we approximate to be spectrally featureless at these wavelengths), to generate a least-squares fit the earthshine data. Major atmospheric species for the model included $\mathrm{O}_{2}, \mathrm{O}_{3}, \mathrm{CO}_{2}, \mathrm{H}_{2} \mathrm{O}$ and $\mathrm{CH}_{4}$. We included two spectra with different water levels to represent desert and rainforest conditions. We also expect some contribution from clouds, as the GEOS infrared water vapor image from this night shows (Figure 5.15, obtained from the Space Science and Engineering Center, University of Wisconsin). At near IR wavelengths, clouds cannot be approximated by a flat reflection spectrum as they were with the optical data. We included two clouds types in the model: (1) "cirrus" ice particle clouds at an altitude of 12 km , for which we used the observed reflection spectra for laboratory ice clouds from

Barkey et al. (2000) shown in Figure 5.16, and (2) "cumulus" water vapor clouds, for which we used the calculated spectra from Vanderbilt (private communication, 2004) shown in Figure 5.17, for an effective droplet radius of 16 microns. We also included an average of coniferous and decidous trees, similar to the green plant spectrum shown in Figure 5.4 from Clark (1999).

The resulting fit to the spectrum is shown in Figure 5.18. Given the uncertainties in sky subtraction and cloud reflectance, it is somewhat surprising that we were able to fit the spectrum as well as we did. We find that the major contributors are the wet and dry atmosphere components, with trees, Rayleigh scattering, and clouds coming in a much lower levels. It is worth noting, however, that vegetation and clouds have very similar spectra at these wavelengths and it may not be informative to model them separately. The features seen at the bottom of the water bands are reproducible from night to night, and they do match features in the calculated spectra, showing that the Mount Graham sky is not totally saturated at those wavelengths.

From the components of this model spectrum, we can again estimate what fraction of land and ocean areas are visible. Noting that the "wet" and "dry" atmosphere components (solid magenta and dashed blue) include the ground reflection and account for about $65 \%$ of the signal (ocean and vegetation were insignificant), we follow the same line of reasoning used in Section 5.2. We see from Figure 5.18 that the Earth's albedo at 1.05 microns is very similar to the optical albedo of $\sim 0.3$. Taking absolute
reflectances at this wavelength of $70 \%$ for plants and $25 \%$ for soil, and assuming equal areas of plant- and soil-covered ground, we find a land mass area of $\sim 40 \%$, and an ocean area of $\sim 60 \%$. From Figures 5.13 and 5.14 we see that this is close to reality.

In Figure 5.19 we show both the NIR (black) and optical spectra (red) smoothed to a spectral resolution of $R \sim 50$, which is a more realistic representation of what TPF would see. Although the 1-2.5 micron wavelength range is not currently under consideration for TPF, from this plot we can see that at this resolution, NIR wavelengths may in fact be more useful in terms of unambiguously detecting the sine qua non of life: water. The signal in the water feature at 1.4 microns drops by $80 \%$ from the continuum at 1.25 microns, while in the optical data, the depth of the water features is only about $15 \%$. The oxygen absorption at 1.27 microns is also visible, although only at the $\sim 10 \%$ level, while in the optical the 7600 angstrom oxygen A band appears slightly stronger, at the $15 \%$ level.

Given the strength of the water and oxygen features in the visible $(\sim 10 \%)$, we can calculate the integration time that would be required to detect these signatures with a 10 meter diameter TPF. For a signal that drops $10 \%$ from the nearby continuum, a signal-tonoise ratio of $\sim 33$ is required for a 3-sigma detection, which corresponds to $\sim 1111$ counts per pixel. The Earth's absolute V-band magnitude is $\sim 30$, and the Johnson V bandpass is equivalent to $\sim 8$ of our 0.011 micron pixel width for $\mathrm{R}=50$ at the V -band central wavelength of 0.55 microns. For 8 pixels, we need to collect a total of $\sim 9100$ counts.

Given that a $V=0$ object is, by definition, a 3640 Jy source, our planet is a factor of $10^{-12}$ as bright, which corresponds to 0.0088 photons $\sec ^{-1} \mathrm{~m}^{-2}$ in this bandpass. Assuming a 10 -meter circular primary mirror, and a throughput of $10 \%$ for the whole instrument, this rate becomes 0.276 photons/second, and collecting the necessary 9100 counts will take $\sim 33,000$ seconds, or ten hours, of integration time. However, if we assume that the finite null depth and exozodiacal light combine to give a background level that is comparable to the signal from the planet, then our oxygen and water signals become half as strong, and we must integrate 4 times longer (or 40 hours) to get the same 3 -sigma detection. Looking to the near infrared, the water signal is at least 8 times stronger, so we need to integrate $\sim 1 / 64$ as long, or about 40 minutes. To see the 1.25 -micron oxygen or 2 -micron carbon dioxide signals, however, we would need closer to 50 hours for a 3-sigma detection.

At R~20 (Figure 5.20), the optical water and oxygen/ozone signals are now only about $5 \%$ below the continuum. This implies 160 hours of integration time for a 3-sigma detection, making the same assumptions as in the previous paragraph. The oxygen and carbon dioxide signals in the near infrared have all but disappeared at this resolution, although the Rayleigh scattering is still near the $20 \%$ level. The near IR water bands are still $\sim 70 \%$ deeper than the continuum, and this would give an integration time of under an hour for a 3-sigma detection, taking the assumptions above. The combination of the four water lines at $0.9,1.14,1.4$ and 1.9 microns give us an unambiguous discovery of water on planet Earth.

### 5.5 Future Work in Earthshine Studies

In this chapter, we have demonstrated that the fractional area of land and water can be estimated using our models of earthshine data. We have also shown that the near infrared wavelengths are extremely useful, even at very low spectral resolution, for detecting atmospheric water. For the Earth, the 1.4 - and 1.9 -micron water bands are saturated for at least some lines of sight through the visible illuminated Earth's atmosphere, so these lines are quite broad. The water and oxygen signals in the optical data, however, will be much more challenging for TPF to detect, and it will require at least 50 times longer integration times for the same detection of water. Currently, the coronagraph version of TPF is slated to operate in the optical, but the author recommends that the TPF Science Working Group consider 1-2 micron wavelengths.

Observationally, the two lines of work that need a better understanding for interpreting Earthshine data are (1) a more rigorous study of the scattered light sky spectrum and the way in which it changes as one looks further away from the bright moon, and (2) a better understanding of the spectra of different types of clouds. However, based on the earthshine spectra shown in this Chapter, the author feels that the near IR region of the spectrum is much more interesting from the standpoint of discovering water-bearing planets. In the optical, Rayleigh scattering is also detectable at the $20 \%$ level, and there
is likely an easily detectable (near $100 \%$ ) cut-off at 3000 angstroms due to ozone absorption.

Many other interesting questions, regarding Earth's spectral signature, eminate from the question of change over time. Diurnal changes due to the planet's rotation could be used to create a map of fractional land and ocean area as a function of longitude. Seasonal changes, and even changes associated with atmospheric chemistry shifts in response to the Solar Cycle, are interesting topics that may be relevant to the interpretation of terrestrial exoplanet spectra and would also contribute to our understanding of the EarthSun system. Monitoring the Earth's spectrum for long periods of time may help shed some light on atmospheric changes in response to human activity, and on how those effects might be mitigated. We suggest that a long-term monitoring campaign be started to map out the variability and periodic or long-term trends now unfolding regarding the Earth's atmospheric and surface characteristics. As suggested by W. Traub (private comm), such a campaign could very successfully be carried out from the South Pole, where the Sun is below the horizon, and earthshine can be regularly observed, for months at a time.


Figure 5.1 Diagram showing the light paths involved in extracting Earth's spectrum. The spectrum of the Earth as seen from outer space can be obtained by dividing the spectrum observed at the dark Moon location by the spectrum observed at the bright Moon location.


Figure 5.2 The view of Earth from the Moon as seen at the time of optical observations in June, 2001. This view is akin to that of a "water world." Because the observations were taken during the "young" crescent Moon (seen in the evening early in the lunar cycle), the view is to the West of the observing location in Arizona. No image showing the amount of cloud cover and water vapor present in the atmosphere at this time was available.


Figure 5.3 The earthshine spectrum obtained in June 2001 by Woolf et al. (2002), drawn in black. The components of the model fit to the data are shown individually and include high clouds (no wavelength dependence), cloud-free atmosphere (with contributions from $\mathrm{O}_{2}, \mathrm{H}_{2} \mathrm{O}$, and $\mathrm{O}_{3}$ ), Rayleigh scattering, ocean reflection, vegetation and aerosols. A CCD fringing pattern between 7250 and 9000 angstroms (shown in black beneath the earthshine spectrum) was subtracted before fitting the data. (Figure from Woolf et al. 2002)


Figure 5.4 The reflection spectrum of vegetation between 4000 angstroms and 2.5 microns. Note the sharp increase in reflectivity longward of 7000 angstroms, a distinct signature of plant life. (Figure from Clark, 1999)


Figure 5.5 The dark Moon spectrum on 18 November 2003 showing the intensity of each pixel of the $256 \times 256$ array. A variable bias level, dropping in count level with increasing row for both upper and lower quadrants, as well as an offset between the upper to lower quadrants, are both present.


Figure 5.6 The Moon on 18 November 2003, showing the position of the CorMASS slit for one set of earthshine observations. The overall procedure in extracting an earthshine spectrum is to subtract the average spectrum from positions 2 and 4 from the spectrum at position 3, and divide the result by the spectrum at position 1. This subtracts scattered light and divides out the solar spectrum, lunar spectrum, and extra pass through the Earth's atmosphere, leaving only the spectrum of the Earth as seen from space.


Figure 5.7 A vertical cut through all rows along column 50 of the image shown in Figure 5.6, clearly showing, in counts per pixel, the gradual decrease in the bias level for the CorMASS NICMOS3 detector (also referred to as the "reset decay pattern" or "NICMOS shading") with increasing row number in both the upper and lower quadrants. The amplitude of this pattern depends on the time since the last detector read and is therefore variable from image to image. This bias was modeled separately for each image and subtracted.


Figure 5.8 The observed change in scattered light level, in units of counts per arcsecond, as a function of wavelength between the "Near" and "Far" sky observations off the dark limb of the Moon. Given the low signal levels in both the "Near" and "Far" sky observations, we opted simply to fit a straight line to the spectrum above, and call this our "slope" spectrum.


Figure 5.9 The scattered light spectrum resulting from dividing the sky by the bright moon, showing the steep increase in scattered light level at the shortest wavelengths. The subtraction of this scattered light strongly affected the resulting spectrum shortward of 1 micron.


Figure 5.10. The effect of subtracting different levels of scattered Moonlight (see Figure 5.9) from the dark Moon spectrum. The amount of scattered light subtracted ranges from the Sky Actual Spectrum calculated in Section 5.3.1 to twice that value. We subtracted 1.1 times the calculated Sky $_{\text {Actual }}$ (black), which results in a nearly flat spectrum at the shortest wavelengths and a rough match to the optical data.


Figure 5.11 Lunar Phase function, reflectance as a function of wavelength for a phase angle (Sun-Moon-Earth) of 175 degrees. The lunar surface looks redder at higher phase angles, and our earthshine data was divided by the above function. (T. Stone, private communication)


Figure 5.12 The final Earthshine spectrum (black) as compared to atmospheric transmission data for Mauna Kea (red) (obtained from the UKIRT IRTANS4 program). The differences are due to (1) the reflectance of the ground in the earthshine spectrum, and (2) the integration of many paths through the atmosphere in the earthshine spectrum. As expected, we see more absorption at all wavelengths in the earthshine spectrum. The water lines at 1.4 and 1.9 microns in the earthshine spectrum are likely saturated for many parts of the visible Earth, hence the lines are significantly broader, but not much deeper, than in the UKIRT transmission spectrum. However, the Earth is not "black" at these wavelengths, as reflection from high clouds and very dry areas of ground are still contributing to the spectrum there.


Figure 5.13 The Earth as seen from the Moon at the the start of our 18 November 2003 earthshine observations. Because these near-infrared observations were taken using the "old" crescent Moon (seen in the mornings late in the lunar cycle), the view is to the East of our observing location in Arizona.


Figure 5.14 The view of the Earth from the Moon at the end of our earthshine observations on 18 November 2003.


Figure 5.15 Infrared water vapor image of Earth on 18 Nov 2003, roughly showing the visible illuminated area of Earth as seen from the Moon. There was substantial cloud cover over South America and the equatorial regions of the Atlantic.


Figure 5.16 Ice cloud reflectance data from Barkey et al. 2000.


Figure 5.17 Water droplet cloud reflectances (V. Vanderbilt, private communication 2004). We used the data for $r_{c}=16$ microns.


Figure 5.18 The Earthshine spectrum (black) and model (dashed red), in relative reflectance vs. wavelength in microns. Components of the model are also drawn separately and the major contributors include 100 km atmosphere with $\mathrm{O}_{2}, \mathrm{O}_{3}, \mathrm{CO}_{2}, \mathrm{H}_{2} \mathrm{O}$ and $\mathrm{CH}_{4}$ (magenta), the same but with very little water (dashed blue), 12 km cirrus (solid red), 6 km cumulus clouds (dashed black), and trees (dashed green).


Figure 5.19 The Earthshine spectrum in the optical (red) and near-infrared (black), smoothed to a resolution of R $\sim 50$ and scaled to 1 at 0.76 microns. For TPF observations, this is a more realistic representation of the Earth's spectrum. In the optical, oxygen and water features are relatively weak ( $\sim 10 \%$ ), and would require an integration time of about 40 hours, assuming a $10-\mathrm{m}$ telescope and a throughput of $10 \%$, background level of $100 \%$ of the planet signal. Water is much more easily detectable in the near-infrared, and weak oxygen and carbon dioxide features are also seen in the NIR. The Earth's albedo at 1 micron is similar to that in the optical, but decreases to about $80 \%$ of that value at 1.7 microns.


Figure 5.20 The same as 5.17 , but smoothed to $\mathrm{R} \sim 20$. This is still an unambiguous discovery of water on planet Earth in the near infrared. Now the oxygen and water features in the optical are not distinguishable from one another, although the ozone gives a signal of $\sim 5 \%$, and Rayleigh scattering is probably detectable, with about a $20 \%$ signal depth from 0.5 to 0.6 microns. The near IR water bands are still plainly visible, with a depth of $\sim 70 \%$ from 1.25 to 1.4 microns. This would be detectable in about an hour for an Earth at 10 parsecs, with a $10-\mathrm{m}$ TPF, $10 \%$ throughput, and $100 \%$ background as above.

## 6. Future Directions in Stellar Astrobiology and Preparations for TPF

SETI research and the planning of the Terrestrial Planet Finder mission are driving research in the area of Solar Neighborhood and Galactic habitability. Even within the scope of this dissertation, many questions have been raised. How do we interpret the traditional stellar age indicators for stars of F, K and M spectral types? How does stellar metallicity reflect the initial composition of its parent interstellar cloud vs. the migration and accretion of giant planets? How does the composition of a proto-stellar cloud affect the resulting masses and/or numbers of terrestrial and giant planets? Is there a limited zone in the Galaxy where kinematics and metallicities are within the appropriate ranges for habitable terrestrial planets? How does stellar variability, expressed in terms of amplitude and timescale, affect the climate of terrestrial planets orbiting within the average location of the habitable zone? How much can a planet's spectrum vary according to daily weather, or the view of continents and oceans? How might the timescale for the appearance of a detectable biosignatures vary between two similar planets? Is it possible to unambiguously interpret such biosignatures?

In addition to these theoretical questions, there is much work to be done regarding collection of data for stars in the Solar Neighborhood. Our study of the stars has reached a point where it would be extremely useful to have a complete database of stars, at minimum to 30 parsecs distance (and more usefully to 1 kpc or more) for stars of $0.5 \mathrm{M}_{\S}$ and greater, which includes data on metallicities, ages, masses, companions,
activity/variability, Galactic kinematics and moving group memberships, and the presence or absence of giant planets. While contributing to a deeper understanding of the different stellar populations of the Galaxy and the Galactic evolution of metallicity and kinematics, such a database would place the study of life in a context that extends far beyond the Solar Neighborhood. Because of the sheer volume of data that is necessary, this work is too great a task for the small number of interested professional astronomers and their students. It would be invaluable to the state of astrobiology and the study of the Solar Neighborhood to enlist capable and enthusiastic amateur astronomers in collecting uniformly calibrated data on stellar ages, metallicities, and variability through the use of 1-m class telescopes that are, increasingly, undersubscribed. Ultimately, the study of life in the Universe is an endeavor that will engage wide swaths of human society, and it will propel us in directions heretofore undreamed.

## APPENDIX

This file created by M. Turnbull, 25 Nov. 2003, as a result of discussions with the TPF target list group, 18-19 Nov, 2003. Questions to turnbull@as.arizona.edu. Contents of Directory:

Contents of TPF_STARS folder:

1. README SOURCE.txt - This file, a description of 30PC_SOURCE.xls.
2. 30PC_SOURCE.xls - Microsoft Excel spreadsheet, source file for TPF target list, includes all HIPPARCOS stars within 30 parsecs plus data on age indicators, multiplicity, kinematics, and spectral type, plus data from 2MASS and IRAS. Also includes several columns of flags indicating potential problems for TPE targets.
3. README SHORTLIST.xls - Description of fields in TPF_SHORTLIST.xls
4. TPE_SHORTIIST.xls - Subset of stars in 30PC SOURCE.xls, chosen according to age, data quality, metallicity, multiplicity, variability, and other criteria.

Description of HIP_30PC.xls Columns:
NOTE 1: Columns A through BR were exported directly from theHIPPARCOS Catalogue using the Celestia $2000 \mathrm{CD}-\mathrm{ROM}$, and are explained in more detail in the Hipparcos Catalogue Vol 1.
NOTE 2: Underscores (___) should be interpreted as blanks.
Col Header Description (with HIP Col)


G VSRC (H7) Source of V magnitude in Column $E:$| $G$ | $=$ ground-based measurement |
| ---: | :--- |
| $H$ | $=$ derived from $H p$ bandpass |
| $T$ | $=$ derived from $V T$ and $B T$ bandpasses |

MAIN MISSION ASTROMETRY:
Col Header Description (with HIP Col)

| H | RAdeg | (H8) RA in degrees, epoch J1991.25, ICRS (eqnx J2000) |
| :---: | :---: | :---: |
| I | DECdeg | (H9) DEC in degrees, epoch J1991.25, ICRS (eqnx J2000) |
| J | REFFLG | (H10) Astrometric parameters refer to this component of a double/multiple system: <br> A, B,...: Specific component <br> *: Photocenter of system <br> + : Center of Mass of system |
| K | PARX | (H11) Parallax in milliarcseconds (mas), distance $(\mathrm{pc})=1000 /$ parallax (mas) |
| L | PMRA | (H12) Proper Motion in RA, mas/yr, epoch J1991.25, ICRS |
| M | PMDEC | (H13) Proper Motion in DEC, mas/yr, epoch J1991.25, ICRS |
| N | SIGRA | (H14) Std Error in RA (mas), epoch J1991.25, ICRS |
| 0 | SIGDEC | (H15) Std Error in DEC (mas), epoch J1991.25, ICRS |
| P | SIGPX | (H16) Standard Error in parallax (mas) |
| Q | SIGPMRA | (H17) Std Err Proper Motion in RA (mas/yr), ep. J1991.25, ICRS |
| R | SIGPMDEC | (H18) Std Err Proper Motion in DEC (mas/yr), ep. J1991.25, ICRS |

(Fields H19 - H28 CORRELATION COEEFICIENTS can be accessed from the HIPPARCOS Catalogue)

| $S$ | \%REJECT | (H29) Percentage of Rejected Data for Astrometric <br> Solution |
| :--- | :--- | :--- |
| F FGOOD | (H30) Goodness of Fit of Astrometric Solution |  |

## TYCHO PHOTOMETRY AND COLOR INDICES:

| U | BT | (H32) Mean magnitude in the Tycho BT bandpass |
| :--- | :--- | :--- |
| V SIGBT | (H33) Std Err in the BT magnitude |  |
| W | VT | (H34) Mean Magnitude in the Tycho VT bandpass |
| X SIGVT | (H35) Std Err in the VT magnitude |  |
| Y BVTCOMP | (H36) Reference flag for BT, VT photometry of |  |
|  |  |  |
|  |  | double/multiple systems: |
|  |  | A, B, . S Specific Component |




| BA | RHO | (H64) Angular Separation in arcseconds (J1991.25) |
| :--- | :--- | :--- |
| BB SIGRHO | (H65) Std Error in Angular Separation (arcsec, |  |
|  |  | J1991.25) |
| BC dM | (H66) Magnitude difference of Components |  |
| BD SIGdM | (H67) Standard Error of Magnitude difference |  |
|  |  |  |
| Miscellaneous Catalogue Data |  |  |


| BE | SURVEY | Flag indicating 'survey' star |
| :--- | :--- | :--- |
| BF CHART | Flag indicating ID chart |  |
| BG | NOTE | Flag indicating a Note |

## Identifiers

| BH | HD | Henry Draper identifier |
| :--- | :--- | :--- |
| BI | BD | Bonner Durchmusterung identifier |
| BJ | CoD | Cordoba Durchmusterung identifier |
| BK | CPD | Cape Durchmusterung identifier |
| BI | SAO | Smithsonian Astrophysical Observatory identifier |
| BM | PPM | Position and Proper Motion Catalog identifier |
| Col | Header | Description (with HIP Col) |


| BN | HR | HR - Bright | Star Catalog identifier |
| :---: | :---: | :---: | :---: |
| BO | F/A/S | Other ident | fiers, FOR EXAMPLE: |
|  |  | A: | AGK3 Catalog |
|  |  | BPM : | Bruce Proper Motion Survey |
|  |  | F: | FK5 Catalog |
|  |  | $G$ : | Lowell Proper Motion Survey (Giclas) |
|  |  | GC: | General Catalog |
|  |  | GJ: | Gliese Extension Catalog |
|  |  | GL: | Gliese Catalog |
|  |  | IC: | Index Catalog |
|  |  | IRC: | Caltech 2-micron Survey |
|  |  | K: | FK4 Supplement |
|  |  | L: | Luyten Catalog |
|  |  | LP: | Luyten Proper Motion Survey |
|  |  | LTT: | Luyten Two-Tenths Catalog |
|  |  | LHS: | Luyten Half-Second Catalog |
|  |  | McC: | McCormick Observatory Catalog |
|  |  | Mel: | Melotte Cluster |
|  |  | NGC: | New General Catalog |
|  |  | S: | Southern Reference System Catalog |
|  |  | WD: | Catalog of White Dwarfs |
| BP | GL/GJ | More identi | fiers, as in BO |
| BQ | GL/LTT | More identi | fiers, as in BO |
| BR | MC/etc | More identi | fiers, as in BO |

## DATA EXTRACTED EROM CATALOGS OTHER THAN HIPPARCOS

| BS | HIP | HIP Identifier |
| :--- | :--- | :--- |
| BT | VNEW | Newly Converted V-magnitude, based on conversion data |


|  |  | given in Bessell (2000), who found improved relations between the standard UBVRI system and the |
| :---: | :---: | :---: |
|  |  | HIPPARCOS/TYCHO bandpasses |
| BU | VNEWSRC |  |
|  |  | Source of V-magnitude given in column BT: <br> G: Photometry listed in HIP Cat from ground-based |
|  |  | measurements, kept when std error in ground-based |
|  |  | measurements was smaller than std errors for Tycho photometry (1121 stars) |
|  |  |  |
|  |  | G-Hp-BVT: Hp magnitude was converted to Johnson V |
|  |  | using the Tycho BT-VT color index and Tables from |
|  |  | Bessell (2000). The HIP Catalogue listed ground-based photometry for these entries but the BT-VT standard |
|  |  |  |
|  |  | errors were smaller than the ground-basedmeasurements. 209 stars) |
|  |  |  |
|  |  | measurements. (209 stars) <br> H-cat: Taken from the HIP Catalogue, since no BT-VT |
|  |  | or V-I data were available for transformation usingthe Bessell (2000) Tables. (83 stars) |
|  |  |  |
|  |  | Hp-BVT: Hp converted to Johnson $V$ using BT-VT index (which was preferred over $V-I$ conversion) using the |
|  |  |  |
|  |  | Tables in Bessell (2000). (896 stars) <br> Hp-VI: Hp converted to Johnson $V$ using $V-I$ index |
|  |  |  |
|  |  | given in the HIP Catalogue (where no BT-VT wasavailable). (39 stars) |
|  |  |  |
|  |  | VT: VT converted to Johnson $V$ using BT-VT index and |
|  |  | Tables in Bessell (2000), for stars where Hp standard |
|  |  | errors were greater than Tycho standard errors. (2 |
|  |  | stars) |
| COL | Header | Description (with HIP Col) |
| BV | BVNEW | Newly converted $B-V$ Johnson magnitudes, based on |
|  |  | Tables in Bessell (2000) |
| BW | BVNEWSRC | Source of $B-V$ index given in Column $B V$ : <br> __ No data available (51 stars) <br> G: Ground-based Johnson $B-V$, as listed in HIP Cat (1599 stars) |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  | GTN: New Johnson B-V converted from Tycho BT-VT using Tables in Bessell (2000). HIP Cat lists ground-based |
|  |  |  |
|  |  | data, but BT-VT standard errors were smaller. (384 stars) |
|  |  |  |
|  |  | TN: New Johnson B-V converted from Tycho BT-VT using Tables in Bessell (2000). (316 stars) |
|  |  |  |
| BX | SIGBVNEW | Standard Error in the converted Johnson $B-V$ index given in Column BV. Taken either from the Hipparcos Catalogue (where ground-based data was used) or |
|  |  |  |
|  |  |  |
|  |  | calculated from the standard errors in Tychophotometry. Residuals in the fit to Bessell's data |
|  |  |  |
|  |  | were less than 0.01 mag. |
| BY | SIGPX/PX | The fractional uncertainty in the parallax (Column $P$ divided by Column K). |
|  |  |  |
| BZ | DIST | The distance in parsecs, calculated as looo/parallax |
|  |  | with the parallax in milliarcseconds, as in Column K. |
| CA | MV | The absolute $V$ magnitude, calculated as: |


| CB | MVCUT1 | $M \mathrm{~V}=-5 * \log (1000 / \text { parallax })+5-\mathrm{V}$ <br> where the parallax is in milliarcseconds (Column $K$ ) and the $V$ magnitude is from Column BT. <br> The minimum absolute magnitude for main sequence stars of this star's B-V color, agreed upon at the 25 November 2003 TPF Target List Subgroup meeting. Stars with absolute magnitude less than this have evolved beyond the main sequence. |
| :---: | :---: | :---: |
| CC | MVCUT2 | The maximum absolute magnitude for main sequence stars of this star's B-V color. |
| $C D$ | BC | The bolometric correction, interpolated from the Tables in Flower (1996) based on the $B-V$ index in Column BV. |
| CE | L | The stellar luminosity in Solar luminosities, from Mv and bolometric correction. |
| CE | T | The stellar effective temperature, based on $B-V$ color. |
| CG | R | Approximate stellar radius in Solar radii. |
| CH | R (mas) | Approximate stellar radius in milliarcseconds. |
| CI. | HZin | The inner "runaway greenhouse" habitable zone location, interpolated/extrapolated from Kasting et al. (1993), this includes the effects of stellar effective temperature. |
| CJ | HZout | The outer "maximum greenhouse" habitable zone location, also from Kasting et al. (1993). |
| CK | EARTH | The approximate equivalent Earth insolation distance in AU, i.e., lAU times the square-root of the stellar luminosity. |
| CL | Hzin(mas) | The inner HZ as in Column CI, given in milliarcsec. |
| Col | Header | Description (with HIP Col) |
| CM | Hzout (mas) | The outer Hz as in Column CJ, given in milliarcsec. |
| CN | EARTH (mas) | The approximate equivalent Earth insolation distance in arcseconds. |
| CO | SPEC | The stellar spectral type, taken preferentially from Houk's catalogs of spectral types for HD stars, and from the HIPPARCOS catalog where unavailable from Houk. |
| CP | RHK-S | The Calcium II $H$ and $K$ variability indicator, log R'HK, taken from data provided by Todd Henry and David Soderblom in private communication. |
| CQ | RHK-W | The Calcium II $H$ and $K$ variability indicator, log $R^{\prime} H K$, taken from data provided by Jason Wright in private communication. |
| CR | PROT | Rotation period derived from spectral data by Jason Wright, private communication. |
| CS | VSINI | Projected rotational velocity, $v$ sin (i), as listed in Glebocki \& Stawikowski (2000). This data was only listed where three times the quoted uncertainty was less than the quoted $v$ sin (i). |
| CT | NPLANETS | Number of planets reported as of 25 November 2003. |
| CU | [ $\mathrm{Fe} / \mathrm{H}$ ] | Iron abundance [Ee/H], taken either from Cayrel de Strobel et al. (2001) spectroscopic measurements or |




Blank: No noted multiplicity.
-1: This star has been searched with high resolution imaging for close companions and at this time none have been found. (See Col DH.)
COMP: HIPPARCOS photometry refers to one or more components in a double/multiple system.
DMS: The system is listed in the Double Multiple Systems Annex of the Hipparcos Catalogue.
DVAR: Duplicity-induced variability flag in Col AO.
NRES: Resolved into >1 components by HIPPARCOS
PROX: There is a HIP or TYC star within 10 arcsec.
SNS: Flagged as "Suspected Non-Single" in Column AX.
WDS: Multiplicity data in DA-DK.

| See | http:// | pac.caltech.edu/2mass/releases/allsky/doc/sec2_2.html |
| :---: | :---: | :---: |
| DN | 2MASS | 2MASS Identifier |
| DO | J | 2MASS J-band magnitude |
| DP | Jsig | Total photometric uncertainty in J-band mag |
| DQ | H | 2MASS H-band magnitude |
| DR | Hsig | Total photometric uncertainty in H-band mag |
| DS | K | 2MASS Ks-band magnitude |
| DT | Ksig | Total photometric uncertainty in Ks-band mag |
| DU | JHKqual | Three character flag, one character per band [JHKs], that summarizes the net quality of the photometry. Flags of $A, B$, and $C$ denote relatively good photometry; flags of $D, E, F, X$ and $U$ should be taken as cautionary. See website above for details. |
| DV | RDELG | Three character flag, one character per band [JHKs], that indicates the origin of the default magnitudes and uncertainties in each band. Flags of 1,2 , and 3 indicate the best quality detections; $0,4,6$ and 9 indicate poor quality and positions. See website. |
| DW | BLELG | Three character "blend" flag indicating number of components fit when estimating source brightness. Greater than 1 indicates another star within $\sim 5$ arcsec. Zero indicates nondetection or other problem. |
| DX | CCELG | Contamination and Confusion flag. Non-zero values indicate that the measurements of that source may be contaminated. |

IRAS DATA EROM THE CATALOG OF POSITIONS OF INFRARED STELLAR SOURCES

| DY | IRAS | IRAS PSC Identifier (Hindsley et al. 1994) |
| :--- | :--- | :--- |
| DZ | F12 | IRAS flux density in Janskys at 12 microns |
| EA | F25 | IRAS flux density in Janskys at 25 microns |
| EB | F60 | IRAS flux density in Janskys at 60 microns |
| EC | F100 | IRAS flux density in Janskys at 100 microns |
| ED | Q12 | IRAS flux quality indicators: |


| EE | Q25 | $1=$ Upper limit |
| :--- | :--- | :--- |
| EF | 060 | $2=$ Moderate quality |
| EG Q100 | $3=$ High quality |  |
|  |  |  |
| EH TYC | TYCHO CATALOGUE IDENTIEIER |  |

## FLAGS POTENTIALIY RELEVANT TO TPF

EI SIGPXCUT Flag on fractional parallax uncertainty, stars with more than 5\% uncertainty are flagged as "cut."
EJ SIGBVCUT Flag on photometry uncertainty, stars with sigma( $B-V$ ) > 0.05 are flagged as "cut."

EK CMD-CUT Flag on stars failing to fall within the main sequence My range given by Columns $D I$ and $D J$. ( $A$ BASIC CRITERION DECIDED AT THE TARGET LIST MEETING on 11/18/03.)
EI BV-CUT Elag on $B-V$, according to science requirements for the "extended" and "core" target lists:
cut: 0 - and B-type are not appropriate for the "extended" or "core" lists
A: A-type stars not appropriate for the "core" list, ok for the "extended" list
keep: These stars are OK for both list
M: M-type stars are not appropriate for the "core" list, OK for the "extended" list
EM SPEC-CUT Flag on Spectral Type. Stars with "e" or "var" flags
(indicating chromospheric or other stellar activity) in the spectral type given in Column CH are flagged as "cut."
EN RASS-CUT Flag on X-ray emission for stars more distant than 15 pc that were detected by the ROSAT All Sky Survey (RASS). HIP-RASS matches taken from Guillout et al. (1999). A ROSAT detection indicates youth.

EO RHK-CUT Flag indicating youth, based on the chromospheric variability indicator in Columns CJ and CK. The "cut" value for log R'HK was taken to be -4.75, which corresponds to about 2.2 billion years in age and is an observed boundary between generally "active" and generally "inactive" stars.
EP ROT-CUT Cut on rotation period at 10 days (indicates youth).
EQ VSINI-CUT Cut on projected rotational velocity at $5 \mathrm{~km} / \mathrm{sec}$ (indicates youth).
ER AGE-CUT Cut on age indicators - stars failing this cut are likely less than $2-3$ billion years old.
ES FEH-CUT Metallicity cut applied at half solar ([Fe/H] < -0.3)
ET HALO-CUT Cut on stars with non-thin disk kinematics.
EU BINARY-CUT Elag on companions closer than 10 arcsec according to WDS or HIPPARCOS data. See Column DM--stars were NOT cut for duplicity induced variability in HIPPARCOS, as these stars are not likely to be real binaries (S. Urban, private comm).
EV VAR-CUT Cut on HIPPARCOS on variables, see Column AO. includes $A$ and $M$ stars (which ARE candidates for the extended list). This cut leaves 575 stars, 148 of which are brighter than 7 th magnitude.

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Int4 $=$ Fourth Catalog of Interferometric Measurements of Binary Stars, Hartkopf, W.I., Mason, B.D., Wycoff, G.L., \& McAlister, H.A. 2001
(last update: December 2003)
http://ad.usno.navy.mil/wds/int4.html
Orb6 $=$ Sixth Catalog of Visual Binary Star Orbits, Hartkopf, W.I. \& Mason, B.D. 2001 (last update: December 2003) http://ad.usno.navy.mil/wds/orb6.html
SB9 = Ninth Spectroscopic Binary Catalog, Pourbaix, D., editor 2003 http://sb9.astro.ulb.ac.be
WDS = Washington Double Star Catalog, Mason, B.D., Wycoff, G.L., \& Hartkopf, W.I. 2001 (last update: December 2003) http://ad.usno.navy.mil/wds/wos.html

| 57 |  |  |  |  |  | $<0.03$ |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 169 | 00021-6817 | A | 4.2 | 1.3 | $\overline{2}$ |  |  |  |  |
| 171 | 00022+2705 | A | 0.7 | 3.1 | 4 |  | 26.28 | 0.83 | C |
| 400 |  |  |  |  |  |  |  |  |  |
| 428 |  |  |  |  |  |  |  |  |  |
| 436 |  |  |  |  |  |  |  |  |  |
| 439 |  |  |  |  |  |  |  |  |  |
| 473 | $00057+4549$ | A | 6.0 | 0.2 | 7 |  | 509.65 | 6.21 | V |

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[^0]:    ${ }^{1}$ "YES" indicates that the HZ is stable given the orbit of the planet in question.
    2 "YES" indicates that the HZ is stable given the orbits of all planets in the system.
    ${ }^{3}$ Moons in this system may be habitable

[^1]:    ${ }^{4}$ This object was excluded based on erroneous catalog data and has been added back into HabCat.

[^2]:    ${ }^{5}$ This object was excluded based on erroneous catalog data and has been added back into HabCat.

