Chapter 1 The Solar Neighborhood: Still Under Development

1.1 INTRODUCTION

Within human experience, knowing our neighbors provides a sense of community. Similarly, knowing more about the stars in the solar neighborhood gives us a sense of place within both our Milky Way Galaxy and the larger Universe. The stars within a limited distance of the Sun make up the one sample that we can hope to know thoroughly. Although a growing volume of observations and improved technology allows us to consider a current outer limit of 25 parsecs (pc) for the solar neighborhood, the 5-pc volume around the Sun first cataloged by Hertzsprung (1922) is still incomplete.

We can obtain more information observing nearby stars than observing similar stars that are more distant. For any intrinsic luminosity, the nearby stars are the brightest and easiest to examine from the Earth, so we can study their characteristics in detail and detect more subtle differences among similar stars. Using trigonometric parallax, we measure their distances directly; this measurement establishes whether they are truly nearby stars and improves our determinations of their luminosity and space velocity. Better knowledge of stars for which parallactic distances can be determined also enhances our techniques for estimating the distances and related properties for stars even farther away. Catalogs of stars within the solar neighborhood provide local examples of interesting categories for further study.

This dissertation is based on a study of historic photographic plates from Leander McCormick Observatory from 1969 through 1998, recent charge-coupled device (CCD) observations from Siding Spring Observatory from 1991 through 2002, on-going CCD observations at Cerro Tololo Inter-American Observatory that began in 2003, and astrometric calibration regions observed at Fan Mountain Observatory in 2005. It expands our knowledge of fifty-eight nearby, or possibly nearby, stars:

- Barnard's Star: Parallax, Proper Motion, and Possible Planetary Perturbation—The second closest star to our Sun is Barnard's Star, which may be an old disk or halo star passing through the solar neighborhood. Analysis of its distance, proper motion, and secular acceleration fails to confirm earlier detections that planets orbit this star (van de Kamp 1963b, 1982).
- Planets in the South: Astrometric Search for Companions to Stars on the Southern Parallax Program—Using techniques similar to those used to evaluate the motion of Barnard's Star, preliminary parallaxes and proper motions of thirteen nearby stars in the southern hemisphere are investigated to detect possible planets. Although one star, LHS 288, exhibits signs of additional periodic motion, no star is clearly accompanied by a companion.
- Solar Neighborhood Census: Identifying and Characterizing New Nearby Stars—Preliminary parallaxes confirm that twenty-eight out of forty-three possible nearby stars do lie within 25 pc of the Sun. New photometry and spectroscopy is available for several of these helping to quantify their fundamental properties.

- Continuing the Solar Neighbor Census: Infrared Parallax Program at Fan Mountain Observatory—Preliminary study of the astrometric quality of the 31-inch (0.8-meter) reflector at Fan Mountain indicates an infrared parallax program would be feasible. Such a program would increase the number of parallactic distances available for very low mass stars and brown dwarfs, many of which should be members of the solar neighborhood.

1.2 ROLE OF NEARBY STAR SAMPLES

A well-understood, volume-limited sample of nearby stars is an essential input for the stellar luminosity function, the mass-luminosity relationship, stellar velocity distribution, and the stellar multiplicity fraction, including substellar companions. Such samples help us define stellar populations and estimate how much of the local mass is contributed by stars. In addition, the stars in this volume provide insight into stellar evolution and the history of star formation in the disk. These physical relationships and subsamples allow us to understand the make-up of our Milky Way Galaxy and by extension more distant galaxies (Kuiper 1942; Reid & Cruz 2002).

Stars definitely known to lie within the solar neighborhood have accurate distances measured with trigonometric parallaxes, which is the only direct method of measuring stellar distances. Stellar luminosity is determined from the apparent brightness of the star combined with its distance. Therefore, luminosities are also better determined when trigonometric parallaxes are used for distance determination.

The stellar luminosity function relates the number of stars with a given luminosity in a particular region, such as the solar neighborhood or a cluster, and the mass-luminosity relationship estimates the mass of a star based on its luminosity. Together, these expressions reveal the initial mass function used to describe star formation. Structure and gradients in the stellar luminosity function can indicate historical star formation trends. The luminosity function provides a test of stellar evolutionary theories. An adequate luminosity function requires an accurate catalog of stars with well-determined luminosities (Bessell & Stringfellow 1993).

The mass of a star determines its development throughout its life. This defining quantity can only be measured directly for stars with companions, stellar or otherwise. The mass-luminosity relationship provides a mass estimate for single stars based on their luminosity, a more easily measured quantity and one that depends on distance. However, the relationship between mass and luminosity also depends on age and metallicity. Through the mass-luminosity relationship, the stellar luminosity function becomes a stellar mass function used in estimating the contribution of stars to the mass of the Galaxy. Small changes in the mass-luminosity relationship for the lowest mass stars, which are so populous, can have a significant effect on calculations of the Galactic mass (Henry 2004). Currently, the mass-luminosity relationship appears most likely to flatten for the lowest mass stars (Reid, Gizis, & Hawley 2002). The structure of this relationship could constrain theories about the formation of these cool objects. The mass-luminosity relationship used in this work to estimate the masses was determined by Delfosse *et al*. (2000), which expands on the work of Henry *et al*. (1999) though the inclusion of additional binary systems and consideration of infrared luminosities.

The stellar multiplicity fraction places constraints on theories of stellar formation, evolution of stellar systems, and history of the Galaxy. It also plays a significant role in the search for very low mass companions, including brown dwarfs and planets, and in the development of the mass-luminosity relationship. Approximately 67 percent (%) of systems with solar-type stars appear to contain multiple stellar members (Duquennoy & Mayor 1991). Worley (1977) found that 58% of nearby systems have at least two stellar members. However, the fraction appears smaller for lower mass stars. About 32–42% of M dwarfs are the primary star in a multiple configuration (Worley 1977; Henry & McCarthy 1990; Fischer & Marcy 1992). Furthermore, about 12% of solar-type stars appear to host planets (Marcy *et al*. 2005). Fewer planets have been detected orbiting M dwarfs than anticipated (Butler *et al* 2004), but radial-velocity planet searches have studied only a handful of these cool stars because they are so faint. To increase the numbers of M dwarfs evaluated as planet hosts, Endl *et al*. (2003) have begun a radial velocity search program focused on these late types. These multiplicity estimates are lower limits of the incidence of such companions because the possibility of detecting additional companions always remains.

Baade (1944) first identified the bluer and more luminous stars of the Galactic disk as a separate stellar population from the redder and fainter stars found in globular clusters and elliptical galaxies, populations I and II respectively. Population I stars, which make up the bulk of the solar neighborhood, are younger and more metal-rich than population II stars, a small number of which may be found among the nearby stars. Population II stars may also be found in the Galactic bulge and halo indicating that these regions formed before the disk where star formation is still continuing. The existence of an even older metal-free generation of stars, population III, has also been theorized but not detected; the most metal-poor star known, HE1327−2326, has about 250,000 times less iron than the Sun, or $[\mathrm{Fe/H}]_{\mathrm{non\text{-}LTE}} = -5.4 \pm 0.2$ (Frebel *et al*. 2005).

The Milky Way is not comprised of stars alone; it also contains gas, dust, and other dark matter. From its rotation curve, the mass contained within a particular radius can be measured. The dynamic mass is greater than the mass implied by the luminous matter. In order to determine the amount of missing mass, or dark matter, present, the stellar contribution to the local mass must be well-understood. The distribution of stellar types varies vertically through the disk. Counts of nearby stars along with models of the Galactic potential are used to estimate the stellar mass present.

The stellar velocity distribution is a measure of the gravitational potential of our Milky Way Galaxy. It also indicates the overall structure of our Galaxy and identifies subpopulations within it. Ideally, studies of stellar velocities should include both the radial and tangential velocities, which are obtained through spectroscopy and astrometry respectively. To obtain a tangential velocity, both a distance to the object and its angular motion across the sky must be measured. Although measuring tangential velocities is time-consuming, the resulting full three-dimensional space velocities map the Galactic potential in detail.

The traditional plotting of luminosities versus spectral types as was done by Hertzsprung (1911) and Russell (1913), the HR-diagram, or the more practical plotting of luminosities versus colors, the color-magnitude diagrams (CMD’s), delineates the stages through which stars evolve. With appropriate photometry, such diagrams can be prepared for nearby stars with known distances or for clusters with member stars all at the same age and distance. The illustrated relationships among luminosity, temperature, mass, and radius guided development of theories of stellar structure and atmospheres. Detailed observations of oscillations, spots, and other physical features of nearby stars continue to contribute to the development of these theories. In addition, comparisons of theoretical HR-diagrams or CMD's with observational ones test the plausibility of proposed star formation histories and Galactic evolution theories.

1.3 DEFINING NEARBY STARS

Astrometry is the precise measurement of the positions and motions of celestial bodies. It provides several fundamental measurements essential to the census of nearby stars: position on the sky, distance from Earth, and proper motion along the celestial sphere. Combining distance with proper motion produces tangential velocity. Of these measurements, distance from the Earth determined by trigonometric parallax is crucial because it determines whether a star lies within the solar neighborhood.

In addition to determining membership in the solar neighborhood, trigonometric parallaxes provide the second rung of the cosmic distance ladder, a highly stable rung. Trigonometric parallaxes depend on our knowledge of the distance between the Earth and Sun, the astronomical unit, which is established by radar ranging among Solar System bodies. In turn, trigonometric parallaxes are used to measure the distances to stars within 100 pc using ground-based telescopes, or farther with space-borne instruments. Nearby stars with parallaxes are plotted on HR-diagrams or CMD's to produce the spectral type-absolute magnitude or color-absolute magnitude relationships used for spectroscopic and photometric distance estimates and for lower main-sequence fitting, which along with the moving cluster method, is used to estimate distances to stellar clusters. Trigonometric parallaxes measured by the Hubble Space Telescope (HST) Fine Guidance Sensors (FGS) appear to have established a distance to the Pleiades open cluster that is consistent with those by other techniques (Soderblom *et al*. 2005). Fewer discrepancies occurred among efforts to establish a trigonometric parallax for the Hyades open cluster (van Altena *et al*. 1997; Perryman *et al*. 1998; Narayanan & Gould 1999).

Classical astronomers and philosophers understood the significance of stellar parallaxes. In the fourth century BC, Aristotle argued that the lack of parallactic shift in the positions of stars was evidence of a stationary Earth. Brahe, arguably the greatest naked-eye astronomer, was unable to measure any stellar parallaxes leading him to develop a hybrid geocentric-heliocentric model of the Solar System in 1588. However, parallax angles are too small to be measured without the aid of a telescope. Bessel published the first trigonometric parallax of 61 Cygni in 1838. Parallaxes immediately followed for α Centauri by Henderson (1839), whose actual measurement was earlier but unpublished, and Vega by von Struve (1840). The first stars to be definitively identified as nearby were known.

At the beginning of the twentieth-century AD, parallaxes had been measured for fewer than one hundred stars (Newcomb 1904). Although the introduction of photography for measuring stellar parallaxes was initially controversial (Pritchard 1887, 1888; Ranyard 1887), it eventually improved the quality and quantity of parallax measurements (Hunter & Martin 1956). By 1924, Schlesinger, Palmer, and Pond listed 1,682 stars with parallaxes thought to be reliable. Progress continued steadily with measurements for stars within the solar neighborhood as well as many outside of it. The 1995 edition of *The General Catalogue of Trigonometric Stellar Parallaxes* contained parallaxes for 8,112 stars (Van Altena, Lee, & Hoffleit 1995; hereafter YPC). Shortly thereafter, the Hipparcos Space Astrometry Mission (ESA 1997, Hipparcos) made a tremendous contribution to the number of stars with parallaxes; and the associated Hipparcos catalog contains parallaxes for nearly 50,000 stars. However, Hipparcos observed for less than 3.5 years, which is a very short baseline for the measurement of proper motions (Perryman *et al*. 1997). For accurate proper motions, longer-lived ground-based programs or historical collections remain important.

The National Aeronautics and Space Administration (NASA) and Jet Propulsion Laboratory (JPL) expect the planned Space Interferometry Mission (SIM) to measure parallaxes with precisions better than 4 microseconds of arc (μas) and proper motions with precisions better than 3 μas year^{-1} for selected targets during an initial five-year mission (NASA & JPL 2005). As of 2006 November, SIM remains in the preliminary design stage with a target launch date to be determined by NASA.

The Leander McCormick Observatory (McCormick) published approximately a third of the trigonometric parallaxes measured before the Hipparcos mission. McCormick astrometrists measured proper motions and parallaxes from photographic plates taken between 1914 (Mitchell *et al*. 1921) and 1998 (Bartlett & Ianna 2001) producing a collection of over 145,000 plates. McCormick holds over a thousand exposures of Barnard's Star starting in 1916. Chapter 2 describes the final measurement of its parallax and proper motion and an investigation of possible planetary perturbations. The results are comparable to those made with technology that is more modern (Benedict *et al*. 1999; YPC; Hipparcos).

In addition to the important and productive parallax program at McCormick Observatory, the University of Virginia (UVa) also operated programs at Fan Mountain Observatory outside of Charlottesville, Virginia, and at Mount Stromlo and Siding Spring Observatories in Australia. Chapter 3 presents preliminary parallaxes and proper motions for thirteen nearby stars from the CCD program at Siding Spring Observatory in order to search for companions. The deviations between measured and observed positions, or residuals, of those stars are investigated for possible perturbations that might be caused by planetary companions.

Spectroscopic and photometric distance estimates may provide strong indications that a star lies within the solar neighborhood. The possible nearby stars discussed in Chapter 4 were selected based on such estimates. However, without a direct distance measurement, provided by trigonometric parallax, such membership cannot be confirmed. By contrast, photometric and spectroscopic estimates of distance are indirect ones, the precision of which can be enhanced through additional trigonometric parallaxes. A spectroscopic distance is obtained by estimating absolute magnitude from spectral type. Because the mean relationships used to estimate absolute magnitudes do not address the actual scatter in the HR-diagram, an error of one magnitude in estimating the absolute magnitude may produce distance errors of about 50%. Mean relationships may also fail to address the complications presented by possible multiplicity, various stellar populations, and different evolutionary stages. The HR-diagram and mean relationships, on which photometric and spectroscopic distances depend, will improve with better characterization of the solar neighborhood that in turn requires an increase in the number of stars with trigonometric parallaxes. Such improvements would be especially helpful for the cool, faint objects in the late M, L, and T classes because so few of these objects have trigonometric parallaxes.

Lutz and Kelker (1973) discuss a bias in individual absolute magnitudes calculated from parallaxes as a result of the observed parallaxes being too large on average. Because the volume represented by the upper limit of the error on the parallax measurement is larger than that represented by the lower limit, Lutz and Kelker argued that more stars will be scattered into the distance than out of it. The resulting distances and luminosities would, then, be systematically underestimated. However, individual parallaxes are not inherently or universally biased independent of the sample from which they are drawn (Smith 2003). The errors associated with the measurement of an individual parallax are those of position—for the star and its reference frame—and of modeling—plate constants and stellar motions—from which the parallax angle is determined; distance (d) is then calculated from the parallax angle (π)

$$d = \frac{1}{\pi} \tag{1.1}$$

where distance is in parsecs if the parallax is in seconds of arc. When absolute magnitudes are calibrated based on parallaxes, the appropriate truncation, modeling, and transformation biases should be carefully considered and applicable modifications made (Smith 2003). This work deals with individual measurements of nearby stars; therefore, the Lutz-Kelker bias is not a concern. When additional stellar characteristics are calculated from the observed parallaxes as part of this work, no further refinements to those values are made.

For a star with a parallax that places it within the solar neighborhood, knowing its position, motion, spectral type including luminosity class, luminosity and variability, metallicity, and age are desirable. We also want to know whether it is truly a single star or if it has companions. For stars with companions, we want to identify whether these are stars, brown dwarfs, or planets. Completely characterizing nearby stars is a complex task, even for those known to lie within the solar neighborhood. This work concentrates on the distances (parallaxes), tangential velocities (proper motion plus distance), and the presence of astrometric companions (perturbation of proper motion) of stars in the solar neighborhood.

1.4 DEVELOPMENT OF THE NEARBY STAR SAMPLES

Historically, astronomers have defined the solar neighborhood to lie within volumes of radius 5–25 pc. The defining radius lengthens with time and as our understanding of the stars enclosed within grows. In 1907, Hertzsprung published a catalog of ninety-five stars within 10 pc, which he later refined to twenty-nine stars within 5 pc (Hertzsprung 1922). Van Maanen (1933) used his updated count of stars within 5 pc to estimate the expected number of stars within 10 and 20 pc; he noted that a substantial number of faint stars were not yet cataloged in these regions. In 1944, Kuiper listed the data available for 254 stars within 10.5 pc in order to encourage other astronomers to make the observations necessary to complete the census. The Gliese catalogs attempted to describe even larger volumes, starting with a 20-pc sample in the 1957 edition and expanding to 25.6 pc in the 1991 edition (Gliese 1957; Gliese & Jahreiß 1991). Woolley *et al*. also produced a 25-pc catalog in 1970. For the purposes of this study, the solar neighborhood lies within 25 pc of the Sun, with particular attention to those stars within 10 pc. These distances were adopted in accordance with the arbitrary limits established by the NStars Database Project (Backman *et al*. 2000; Henry *et al*. 2000; hereafter NStars Database[1]) and Research Consortium on Nearby Stars (RECONS), respectively.

1.4.1 Five-parsec Sample

The first sample of nearby stars included those known to be within 5 pc. It has grown from twenty-nine individual stars in twenty-one systems known in 1922 to sixty-five objects in forty-seven systems in 2001 (Hertzsprung 1922; NStars Database). Table1.1 on the following page tracks its development during the intervening years. This small volume encompasses too few stars to address all the important astrophysical questions that are demanded of the nearby star sample. It also encloses few stars with early types or that have evolved off the main sequence. However, because of its manageable size, its census might be completed eventually. The number of

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[1] The NStars Database may be accessed at http://nstars.arc.nasa.gov/index.cfm

TABLE 1.1
HISTORICAL CATALOGS OF NEARBY STARS

Limit (pc)	Contents			Date	Compiler	Comment
10	95 stars			1907	Hertzsprung	
5	29 stars			1922	Hertzsprung	
5	37 stars			1930	van de Kamp	+8 borderline cases
5	47 stars			1940	van de Kamp	
10.5	255 stars			1942	Kuiper	
5			38 systems	1945	van de Kamp	+70 Ophiuchi AB
5.1	53 stars	in	42 systems	1953	van de Kamp	+5 unseen companions
20	1,094 stars	in	915 systems	1957	Gliese	combines parallaxes with spectroscopic estimates
5.2	59 stars	in	44 systems	1969	van de Kamp	+6 unseen companions
22.2	1,328 stars			1969	Gliese	combines parallaxes with other distance estimates
25	2,150 objects	in	1,744 systems	1970	Woolley *et al.*	includes some spectroscopic distances
25.6	3,803 stars			1991	Gliese & Jahreiß	substitutes other estimates when no or poor parallax
8	151 stars	in	106 systems	1997	Reid & Gizis	only $\delta \geq -30^{\circ}$; includes spectroscopic distance estimates
8	150 objects	in	103 systems	1999	Reid *et al.*	only $\delta \geq -30^{\circ}$; includes spectroscopic distance estimates
25	2,633 objects	in	2,029 systems	2001	NStars Database	
8	151 objects	in	104 systems	2002	Reid[a]	only $\delta \geq -30^{\circ}$; includes spectroscopic distance estimates
5	79 objects	in	49 systems	2006	RECONS	extracted from 100 nearest systems; includes planets
6.7	156 objects	in	100 systems	2006	RECONS	100 nearest systems; includes planets

NOTE— [a]The most recent 8-pc sample updated by I. N. Reid is available at http://www-int.stsci.edu/~inr/8pc.html stars or systems known within 5 pc can be extrapolated to larger volumes and be used to estimate the completeness of larger samples of nearby stars (van Maanen 1933; Henry *et al*. 1997).

A current listing of stars within 5 pc can be extracted from the RECONS list of "The One Hundred Nearest Star Systems,"[2] as shown in Table 1.2 on the following pages. As of 2006 July 1, it included forty-nine stellar systems, including our own, with trigonometric parallaxes greater than 0.2 seconds of arc ("). These systems include sixty-seven individual stars or brown dwarfs plus four extrasolar planets. Three single stars lie on the boundary with errors that could remove two from the volume or bring one into it.

If the 5-pc sample is assumed to be complete, a density of 0.0936 ± 0.0057 systems pc^{-3} is implied. Then, a sphere with a 10-pc radius should enclose about 392 systems while one with a 25-pc radius should include approximately 6,130 systems. However, the NStars Database contains only 233 systems within 10 pc and 2,029 systems within 25-pc as of 2006 October 28. The RECONS census was 249 systems within 10 pc as of 2006 July 1. A substantial number of systems remain undetected or do not have distance measurements considered reliable enough for inclusion in these two tabulations. However, the 5-pc sample, itself, is still incomplete;

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[2] "The One Hundred Nearest Star Systems" is available at http://www.chara.gsu.edu/RECONS/TOP100.htm

TABLE 1.2

Stars Known to be Within 5 Pc

System	Star	Alternate Name	Position (2000.0) α (hh mm ss.s)	Position (2000.0) δ (hh mm ss)	Parallax (mas)	Proper Motion (mas yr^{-1})	Proper Motion (deg)	Spectral Type	References
	Sun[a]							G2V	1
1	GJ 551	Proxima Centauri	14 29 43	-62 40 46	772.0[b] ± 2.3	3853[c]	281.5	M5.5V	2, 3 & 2, 2, 4
	GJ 559A	α Centauri A	14 39 37	-60 50 02	747.2 ± 1.2	3710	277.5	G2V	2, 3 & 5, 2, 1
	GJ 559B	α Centauri B	14 39 35	-60 50 14	747.2 ± 1.2	3724	284.8	K0V	2, 6, 2, 1
2	GJ 699	Barnard's Star	17 57 49	+04 41 36	547.0[d] ± 1.0	10358[e]	355.6	M4.0V	2, 3 & 2, 2, 4
3	GJ 406	Wolf 359	10 56 29	+07 00 53	419.1 ± 2.1	4696	234.6	M6.0V	1, 3, 1, 4
4	GJ 411	Lalande 21185	11 03 20	+35 58 12	393.42 ± 0.70	4802	186.9	M2.0V	2, 3 & 2, 2, 4
5	GJ 244A	Sirius	06 45 08.9	-16 42 58	380.0 ± 1.3	1339	204.1	A1V	2, 3 & 2, 2, 1
	GJ 244B	Sirius B	06 45 08.9	-16 42 58	380.0 ± 1.3	1339	204.1	DA2	6, 6, 6, 1
6	GJ 65A	UV Ceti	01 39 01.3	-17 57 01	373.7 ± 2.7	3368	80.4	M5.5V	1, 3, 1, 4
	GJ 65B	BL Ceti	01 39 01.3	-17 57 01	373.7 ± 2.7	3368	80.4	M6.0V	6, 6, 6, 4
7	GJ 729	Ross 154	18 49 49	-23 50 10	336.9 ± 1.8	666	106.8	M3.5V	2, 3 & 2, 2, 4
8	GJ 905	Ross 248	23 41 55	+44 10 30	316.0 ± 1.1	1617	177.0	M5.5V	1, 3, 1, 4
9	GJ 144	ε Eridani	03 32 56	-09 27 30	309.99 ± 0.79	977	271.1	K2V	2, 3 & 2, 2, 1
	GJ 144b		03 32 56	-09 27 30	309.99 ± 0.79	977	271.1	Planet	6
10	GJ 887	Lacaille 9352	23 05 52.0	-35 51 11	303.64 ± 0.87	6896	78.9	M1.5V	2, 3 & 2, 2, 4
11	GJ 447	Ross 128	11 47 44	+00 48 16	298.7 ± 1.4	1361	153.6	M4.0V	2, 3 & 2, 2, 4
12	GJ 866A	EZ Aquarii A	22 38 33	-15 18 07	289.5 ± 4.4	3254	46.6	M5.0V J	1, 3, 1, 4
	GJ 866B	EZ Aquarii B	22 38 33	-15 18 07	289.5 ± 4.4	3254	46.6	…	6
	GJ 866C	EZ Aquarii C	22 38 33	-15 18 07	289.5 ± 4.4	3254	46.6	…	6
13	GJ 280A	Procyon	07 39 18	+05 13 30	286.05 ± 0.81	1259	214.7	F5IV-V	2, 3 & 2, 2, 1
	GJ 280B	Procyon B	07 39 18	+05 13 30	286.05 ± 0.81	1259	214.7	DA	6, 6, 6, 1
14	GJ 820A	61 Cygni A	21 06 54	+38 44 58	286.04 ± 0.56	5281	51.9	K5.0V	2, 3 & 2, 2, 4
	GJ 820B	61 Cygni B	21 06 55	+38 44 31	286.04 ± 0.56	5172	52.6	K7.0V	2, 6, 2, 4

TABLE 1.2 (CONTINUED)
STARS KNOWN TO BE WITHIN 5 PC

System	Star	Alternate Name	Position (2000.0) α (hh mm ss.s)	Position (2000.0) δ (hh mm ss)	Parallax (mas)	Proper Motion (mas yr^{-1})	Proper Motion (deg)	Spectral Type	References
15	GJ 725A		18 42 47	+59 37 49	283.0 ± 1.7	2238	323.6	M3.0V	2, 3 & 2, 2, 4
	GJ 725B		18 42 47	+59 37 37	283.0 ± 1.7	2313	323.0	M3.5V	2, 6, 2, 4
16	GJ 15A	GX Andromedae	00 18 23	+44 01 23	280.6 ± 1.0	2918	81.9	M1.5V	2, 3 & 2, 2, 4
	GJ 15B	GQ Andromedae	00 18 23	+44 01 23	280.6 ± 1.0	2918	81.9	M3.5V	6, 6, 6, 4
17	GJ 845A	ε Indi A	22 03 22	-56 47 10	275.84 ± 0.69	4704	122.7	K5Ve	2, 3 & 2, 2, 1
	GJ 845B	ε Indi B	22 04 11	-56 46 58	275.84 ± 0.69	4823	121.1	T1.0	7, 6, 7, 8
	GJ 845C	ε Indi C	22 04 11	-56 46 58	275.84 ± 0.69	4823	121.1	T6.0	7, 6, 7, 8
18	GJ 1111	DX Cancri	08 29 50	+26 46 37	275.8 ± 3.0	1290	242.2	M6.5V	1, 3, 1, 4
19	GJ 71	τ Ceti	01 44 04.1	-15 56 15	274.39 ± 0.76	1922	296.4	G8Vp	2, 3 & 2, 2,1
20	GJ 1061		03 35 59.7	-44 30 45	272.0 ± 1.3	826	117.7	M5.5V	4
21	GJ 54.1	YZ Ceti	01 12 31	-16 59 57	268.8 ± 3.0	1372	61.9	M4.5V	2, 3 & 2, 2, 4
22	GJ 273	Luyten's Star	07 27 25	+05 13 33	263.8 ± 1.3	3738	171.2	M3.5V	2, 3 & 2, 2, 4
23	SO 0253-1652		02 53 00.9	+16 52 53	260.6 ± 2.7	5106	138.2	M7.0V	4
24	SCR 1845-6357A		18 45 05.3	-63 57 48	259.5 ± 1.1	2664	76.6	M8.5V	4
	SCR 1845-6357B		18 45 02.6	-63 57 52	259.5 ± 1.1	2664	76.6	T	6
25	GJ 191	Kapteyn's Star	05 11 41	-45 01 06	255.27 ± 0.86	8670	131.4	M1.5V	2, 3 & 2, 2, 4
26	GJ 825	AX Microscopii	21 17 15	-38 52 03	253.4 ± 1.1	3455	250.6	M0.0V	2, 3 & 2, 2, 4
27	GJ 860A	Kruger 60 A	22 27 60	+57 41 45	248.1 ± 1.4	990	241.6	M3.0V	2, 3 & 5, 2, 4
	GJ 860B	Kruger 60 B	22 27 60	+57 41 45	248.1 ± 1.4	990	241.6	M4.0V	6, 6, 6, 4
28	DEN 1048-3956		10 48 15	-39 56 06	247.7 ± 1.6	1530	229.2	M8.5V	9, 4, 4, 4
29	GJ 234A	Ross 614A	06 29 23	-02 48 50	244.3 ± 2.0	930	131.7	M4.5V J	2, 3 & 5, 2, 4
	GJ 234B	Ross 614B	06 29 23	-02 48 50	244.3 ± 2.0	930	131.7	…	2, 6, 6
30	GJ 628	Wolf 1061	16 30 18	-12 39 45	236.0 ± 1.7	1189	184.5	M3.0V	2, 3 & 2, 2, 4
31	GJ 35	WD 0046+051	00 49 09.9	+05 23 19	231.9 ± 1.8	2978	155.5	DZ7	2, 3 & 2, 2, 1

TABLE 1.2 (CONTINUED)
STARS KNOWN TO BE WITHIN 5 PC

System	Star	Alternate Name	Position (2000.0) α (hh mm ss.s)	δ (hh mm ss)	Parallax (mas)	Proper Motion (mas yr^{-1})	(deg)	Spectral Type	References
32	GJ 1		00 05 24	-37 21 27	229.2 ± 1.1	6100	112.5	M3.0V	2, 3 & 2, 2, 4
33	GJ 473A	Wolf 424A	12 33 17	+09 01 15	227.9 ± 4.6	1811	277.4	M5.5V J	1, 3, 1, 4
	GJ 473B	Wolf 424B	12 33 17	+09 01 15	227.9 ± 4.6	1811	277.4	…	6
34	GJ 83.1	TZ Arietis	02 00 13	+13 03 08	224.8 ± 2.9	2097	147.8	M4.5V	1, 3, 1, 4
35	GJ 687		17 36 26	+68 20 21	220.49 ± 0.82	1309	194.2	M3.0V	2, 3 & 2, 2, 4
36	LHS 292		10 48 13	-11 20 14	220.3 ± 3.6	1644	158.5	M6.5V	1, 3, 1, 4
37	GJ 674		17 28 40	-46 53 43	220.3 ± 1.6	1050	146.9	M3.0V	2, 3 & 2, 2, 4
38	GJ 1245A	G 208-44A	19 53 54	+44 24 55	220.2 ± 1.0	731	143.1	M5.5V J	1, 3, 1, 4
	GJ 1245B	G 208-45	19 53 55	+44 24 56	220.2 ± 1.0	731	143.1	M6.0V	1, 6, 6, 4
	GJ 1245C	G 208-44B	19 53 54	+44 24 55	220.2 ± 1.0	731	143.1	…	6
39	GJ 440	WD 1142-645	11 45 43	-64 50 29	216.6 ± 2.0	2688	097.4	DQ6	2, 3 & 2, 2, 1
40	GJ 1002		00 06 44	-07 32 22	213.0 ± 3.6	2041	203.6	M5.5V	1, 3, 1, 4
41	GJ 876A	Ross 780	22 53 17	-14 15 49	212.6[f] ± 2.0	1174[g]	125.1	M3.5V J	2, 3 & 2, 2, 4
	GJ 876d		22 53 17	-14 15 49	212.6 ± 2.0	1174	125.1	Planet	6
	GJ 876c		22 53 17	-14 15 49	212.6 ± 2.0	1174	125.1	Planet	6
	GJ 876b		22 53 17	-14 15 49	212.6 ± 2.0	1174	125.1	Planet	6
42	LHS 288		10 44 21.2	-61 12 36	209.0 ± 2.7	1643	347.7	M5.5V	4
43	GJ 412A		11 05 29	+43 31 36	206.0 ± 1.1	4511	282.1	M1.0V	2, 3 & 2, 2, 4
	GJ 412B	WX Ursae Majoris	11 05 30	+43 31 18	206.0 ± 1.1	4531	281.9	M5.5V	2, 6, 1, 4
44	GJ 380		10 11 22	+49 27 15	205.81 ± 0.67	1452	249.7	K7.0V	2, 3 & 2, 2, 4
45	GJ 388		10 19 36	+19 52 10	204.6 ± 2.8	506	264.0	M3.0V	1, 3, 1, 4
46	GJ 832		21 33 34.0	-49 00 32	202.8 ± 1.3	819	183.2	M3.0V	2, 3 & 2, 2, 4
47	LP 944-20[h]		03 39 35	-35 25 41	201.4 ± 4.2	439	47.6	M9.0V	1, 10, 1, 4
48	DEN 0255-4700[h]		02 55 03.7	-47 00 52	201.4 ± 3.9	1149	119.5	L7.5V	4, 4, 4, 6

TABLE 1.2 (CONTINUED)

STARS KNOWN TO BE WITHIN 5 PC

System	Star	Alternate Name	Position (2000.0) α (hh mm ss.s)	δ (hh mm ss)	Parallax (mas)	Proper Motion (mas yr^{-1})	(deg)	Spectral Type	References
49	GJ 682[i]		17 37 03.7	-44 19 09	199.7 ± 2.3	1176	217.1	M4.5V	2, 3 & 2, 2, 4

NOTES.— [a] Sun has at least eight planets, none of which are listed here.

[b] According to Hubble Space Telescope results, Proxima Centauri has an absolute parallax of 768.7 ± 0.3 mas (11).

[c] According to Hubble Space Telescope results, Proxima Centauri has a proper motion of 3.8517 ± 0.0001” yr^{-1} in 281.52 ± 0.03º (11).

[d] According to Hubble Space Telescope results, Barnard’s Star has an absolute parallax of 545.4 ± 0.3 mas (11). A value of 552 ± 7 mas is measured in Chapter 2.

[e] According to Hubble Space Telescope results, Barnard’s Star has a proper motion of 10.3700 ± 0.0003” yr^{-1} in 355.6 ± 0.1º (11). A value of 10.354 ± 0.006 ” yr^{-1} in 355.85 ±0.06º is measured in Chapter 2.

[f] According to Hubble Space Telescope results, GJ 876 has an absolute parallax of 214.6 ± 0.2 mas (12).

[g] According to Hubble Space Telescope results, GJ 876 has a proper motion of 1.168 ± 0.001” yr^{-1} in 125.3 ± 0.1º (12).

[h] Considering the error in its parallax, this borderline star may not actually be within 5 pc although its formal distance places it closer.

[i] Considering the error in its parallax, this borderline star may actually be within 5 pc although its formal distance places it farther away.

REFERENCES.—(1) Gliese & Jahreiß 1991; (2) Hipparcos; (3) YPC; (4) RECONS 2006; (5) Soederhjelm 1999; (6) T. J. Henry 2006, private communication; (7) Scholz *et al*. 2003; (8) McCaughrean *et al*. 2004; (9) Ducurant *et al*. 1998; (10) Tinney 1996; (11) Benedict *et al*. 1999; (12) Benedict *et al*. 2002 the forty-nine systems listed by RECONS include three with their first parallax being published this year (Henry *et al*. 2006; Costa *et al*. 2006).

1.4.2 Ten-parsec Sample

Doubling the radius of the solar neighborhood to 10 pc increases the volume contained within eightfold. This sample should include an increased numbers of stars with greater variety while still being small and close enough that its complete census might be achievable. Reid and Gizis (1997, Reid *et al*. 1999) briefly promoted an 8-pc sample on the grounds it was 90% complete.

In 1997, Henry *et al*. reported the discovery of a star within four parsecs. At that time, they estimated that approximately 130 star systems within 10 pc were not yet discovered based on the stars then known within 5 pc. Since then, RECONS has concentrated on identifying and characterizing stars within 10 pc (Henry *et al*. 1997). In the intervening years, parallaxes have been measured for stars that place them within 5 pc of the Sun and between 5 and 10 pc. Consequently, the estimated number of missing systems actually increased during the intervening years. Chapter 4 describes preliminary results characterizing forty-three possible nearby stars as part of the Cerro Tololo Inter-American Observatory Parallax Investigation (CTIOPI), which is a RECONS endeavor, began in 1999. Of these, two stars, and possibly a third, are new members of the 10-pc sample.

1.4.3 Twenty-parsec Sample

Kuiper (1942) recommended that the nearby star sample be expanded to 20 pc in order to include more stars and improve its utility. This sample is expected to include

3,140 stellar systems or 4,290 individual objects. The Gliese catalogs of nearby stars (1957, 1969) attempted to describe all the stars known at the time within such volume; the second edition listed 1,328 stars including some borderline cases. However, Gliese did not rely solely on trigonometric parallaxes and included spectroscopic and photometric distance estimates to improve the completeness and to make the listings more comprehensive. Consequently, misidentified giants or undetected binaries may be inadvertently included. However, observing programs could select lists of stars without trigonometric parallaxes or photometry for further investigation from these catalogs. Some modern collaborations use a 20-pc limit to the solar neighborhood.

1.4.4 Twenty-five-parsec Sample

Woolley *et al*. (1970) extended the definition of the solar neighborhood another 5 pc with the Royal Observatory catalog of nearby stars and the preliminary version of Gliese's third catalog (Gliese & Jahreiß 1991) likewise moved outward. The NStars Database also uses a 25-pc radius to define the solar neighborhood; its limit was established to meet the requirements of the proposed Terrestrial Planet Finder (TPF). Even with the indefinite postponement of TPF, 25 pc currently remains a good outer limit to the solar neighborhood given the incompleteness of our knowledge of the region within 10 pc of the Sun and the reliability of distances given the precision of parallaxes measured with CCD's. From the list of forty-three possible nearby stars described in Chapter 4, twenty-eight stars are confirmed as new members of the solar neighborhood including two within 10 pc, as mentioned earlier.

1.5 NEW AND COOL MEMBERS OF THE SOLAR NEIGHBORHOOD

Previously unidentified members of the solar neighborhood may be so cool, red, and dim that they were missed in previous studies. Detailed observations, including accurate distances and luminosities, are important for the faint stars and brown dwarfs found at the cool end of the main sequence and least populated part of the mass-luminosity relationship. The search for unseen companions to known nearby stars is another important source of new stars and substellar objects.

1.5.1 M, L, and T Dwarfs

The M dwarfs make up about 70% of the solar neighborhood and about half the stellar mass in our Galaxy. The even-less massive L dwarfs are probably an equally numerous component but may have not been detected in large numbers due to their low luminosity (Henry *et al*. 2002). Many of the missing nearby stars may belong to the faint stars and cool end of the main sequence for which detailed observations are just becoming possible.

The late M and early L dwarfs are probably a mix of true stars and substellar brown dwarfs that will slowly cool to even later spectral types (Burrows *et al*. 2001). Theories about the structure and evolution of these objects are developing based on a relatively small number of examples, few of which have intrinsic luminosities derived from photometry and trigonometric parallaxes.

A significant population of these cool dwarfs was not included in the Hipparcos catalog. Some of the Hipparcos parallaxes are for stars as faint as 12.4 magnitude (Perryman *et al*. 1997) in V-band, which corresponds to an M5 dwarf just beyond 10 pc. Although this mission filled in the bright nearby stars, the Hipparcos catalog is known to be significantly incomplete for stars fainter than 9th magnitude in V (Perryman *et al*. 1997), corresponding to an M5 dwarf just beyond 2 pc. The YPC describes 2,300 stars that are not in the Hipparcos catalog.

Several larger modern surveys, especially the Two Micron All Sky Survey (Skrutskie *et al*. 2006, hereafter 2MASS), the Deep Near Infrared Survey of the Southern Sky (Epchtein *et al*. 1999, hereafter DENIS), and the Sloan Digital Sky Survey (York *et al*. 2000, hereafter SDSS), in combination with existing high-proper-motion studies, are revealing a wealth of candidates for the solar neighborhood. Many of these candidates belong to the faint M, L, and T dwarf classes. While excellent work is being done, the distances to these candidates are primarily estimates from photometry and spectroscopy. Obtaining trigonometric parallax measurements for these objects is highly desirable to reduce the uncertainties in both distances and, more importantly, absolute magnitudes.

The Virginia Astronomical Instrumentation Laboratory (VAIL) led by Skrutskie recently refurbished the 31-inch (0.8-meter) reflector at Fan Mountain Observatory and installed an infrared camera. Chapter 5 discusses the feasibility of using this instrument to measure parallaxes of cool stars and brown dwarfs at infrared wavelengths. Better understanding of the three-dimensional positions and two-dimensional motions of nearby, very low mass objects will improve our understanding of the luminosity function, mass-luminosity relationship, and velocity distribution for the lower end of the main sequence. These physical relationships can then constrain models for the formation, structure, and evolution of the lowest mass stars and the highest mass substellar objects.

1.5.2 Low-mass Companions

Detection of stars in binary and multiple star systems provides measurements of stellar mass and, in eclipsing systems, also stellar radii. The primary star in an astrometric binary, such as Sirius or Procyon, exhibits a characteristic wobble as it orbits the center of mass of its system. Once the parallax and proper motion of a nearby star have been measured, the residuals may reveal an additional perturbation due to an unseen companion.

Van de Kamp (1969) successfully detected six astrometric companions to nearby stars using this method; until recently, astrometric programs were the primary source of very low mass stars. In addition, van de Kamp (1963b, 1969) described a very small amplitude oscillation in the motion of Barnard's Star that he attributed to a planet. Although no other study, including this one, has confirmed his claim, astrometric planet searches could provide valuable information about these smallest of companions.

To date, radial-velocity programs are the primary source of extrasolar planets orbiting main sequence stars with programs looking for transits and gravitational lenses also contributing. Like astrometric companions searches, radial-velocity programs look for the motion of the parent star in response to its planets.

The highly successful radial-velocity searches are most sensitive to massive planets close to their stars that produce high stellar velocities (Nelson 2001). However, this technique is detecting planets of decreasing mass and longer period at improved precision with the least massive now projected to be only about eight times the mass of the Earth (Rivera *et al*. 2005). With time, the orbital axes of detected planets are also increasing; the most distant has a semi-major axis slightly greater than five astronomical units (AU) (Marcy *et al*. 2002). However, radial-velocity searches tend to focus on older main sequence stars later than F8V that are not rapidly rotating (McCarthy *et al*. 2004); these stars have a single-set of well-defined spectral lines that more easily reveal any Doppler shift. Radial-velocity programs cannot determine the inclination of the observed orbit. Therefore, they report estimated lower limits to planetary masses, or projected masses (m sin *i*).

Astrometric planet searches, such as those discussed in Chapters 2 and 3, complement radial-velocity observations in a number of ways. They are sensitive to planets in larger orbits that produce noticeable stellar displacements, a bias opposite of radial-velocity searches. Therefore, they could confirm the presence of more distant planets in systems with short-period planets that are suggested by velocity residuals such as those described by Fischer *et al.* (2001). In addition, they are better suited to detect multiple planets in systems with masses decreasing with distance (Quirrenbach *et al*. 2004). The candidates for astrometric observations are not restricted by age, spectral type, or stellar rotation. Such programs can identify the frequency of planets around the low-mass stars that make up so much of the solar neighborhood and around more massive stars. The identification of planets around pre-main sequence stars could provide insight into planet formation mechanisms and the interactions of among young planets. Astrometric detections allow for the unambiguous determination of the orbital elements, especially inclination. Knowing the orbital inclination of a system allows the determination of actual masses and whether multiple planets have co-planar orbits (Quirrenbach *et al*. 2004).

Despite the detection of at least 176 extrasolar planets since 1995 (IAU WG ESP 2006[3]), our knowledge of them is still rudimentary. Therefore, the non-detections discussed in this dissertation are also significant, if less exciting, and provide information about the frequency, distribution, and masses of extrasolar planets. While brown dwarfs are not as exciting as planets in the popular imagination, they are the transition region between stars and planets. The discovery of new brown dwarfs would improve our knowledge of the faint end of the main sequence and help fill in the census of the solar neighborhood.

1.6 FUTURE OF THE NEARBY STAR SAMPLE

The completion of the nearby star sample is a Sisyphean labor. Progress on the inner regions of the solar neighborhood reveals the incompleteness of the outer regions. Completing an inner volume allows the defining radius to be pushed outward to enclose more territory and additional stars. On the other hand, small improvements in our knowledge of the solar neighborhood ripple outward clarifying our understanding of many branches of astronomy. Despite the progress made in the last century in measuring parallaxes and determining the fundamental properties of nearby stars, the

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[3] The International Astronomical Union (IAU) Working Group (WG) on Extrasolar Planets (ESP) maintains a list of extrasolar planets reported in refereed journals at http://www.dtm.ciw.edu/boss/planets.html

census is still incomplete and observations will continue to be needed well into this century. Each chapter mentions additional projects that grow naturally out of the work described herein and would enhance our knowledge of the nearest stars. Identifying the nearly 4,100 missing stellar systems expected with 25 pc is a daunting undertaking. However, the recently dedicated Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)[4] and planned Large Synoptic Survey Telescope (LSST)[5] promise accurate positions for vast numbers of stars that could be mined in support of the solar neighborhood census along with traditional astrometric programs. The process of detecting and understanding the newest members of the solar neighborhood will also suggest new questions about the solar neighborhood and the Milky Way. How well, after all, can we mortals truly know our neighbors?

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[4] The University of Hawai'i maintains a website describing their new telescope at http://pan-starrs.ifa.hawaii.edu/public/

[5] The LSST Corporation maintains a website detailing their proposed telescope at http://www.lsst.org/lsst_home.shtml