A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Spying on your neighbors with ultra-high precision

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Abstract. We are entering the era of microarcsecond astrometric accuracy. Breaking the milliarcsecond barrier will lead to consequent leaps in astronomical understanding of diverse topics. Here we review some current ground-based trigonometric parallax efforts and their recent scientific results. We highlight the current status of nearby star research, including the RECONS census of stars within a 10 pc horizon, white dwarfs and cool subdwarfs, and the push to detect substellar objects via astrometry. We also provide details about recent improvements in the methodology that have permitted the determination of parallaxes with ∼1 milliarcsecond accuracy, and what might be done to push routinely into the sub-millarcsecond regime.

Keywords. astrometry, stars: kinematics, white dwarfs, subdwarfs

1. Introduction

The nearest stars provide astronomers with much of our understanding of stellar astronomy. For most types of stars, the fundamental efforts of stellar astronomy are built upon direct measurements of luminosities, colors, temperatures, radii, and masses for nearby stars. With a robust sample of nearby stars, we can also determine the total contribution of stellar mass to the Galaxy.

Only ∼480 total trigonometric parallaxes have been published since the Yale Parallax Catalog (van Altena *et al.* 1995, hereafter YPC) and the *Hipparcos* astrometry mission (ESA 1997). Since 1995, parallax contributions have been made by Dahn *et al.* (2002), Ianna *et al.* (1996), Smart *et al.* (2007), Tinney *et al.* (1995), Vrba *et al.* (2004) and Weis *et al.* (1999), among others. RECONS (Research Consortium on Nearby Stars) initiated its Cerro Tololo Inter-american Observatory Parallax Investigation (CTIOPI) in August 1999 under the NOAO Surveys program to search for missing nearby stars in the southern sky. As of February 2003, CTIOPI has continued as part of the Small and Moderate Aperture Research Telescope System (SMARTS) Consortium. Both the CTIO 0.9m and 1.5m telescopes were used during NOAO time, and the program continued on the 0.9m during SMARTS time. To date, we have published 136 parallaxes (28% of all parallaxes, and the most of any group since 1995) in four different papers (Jao *et al.* 2005, Costa *et al.* 2005, Costa *et al.* 2006 and Henry *et al.* 2006).

A total of 440 targets are being or have been observed for parallaxes during CTIOPI. Here we present the current census status for red dwarfs, white dwarfs (WDs) and cool subdwarfs, and some of the astrometric perturbations we have detected. In the final

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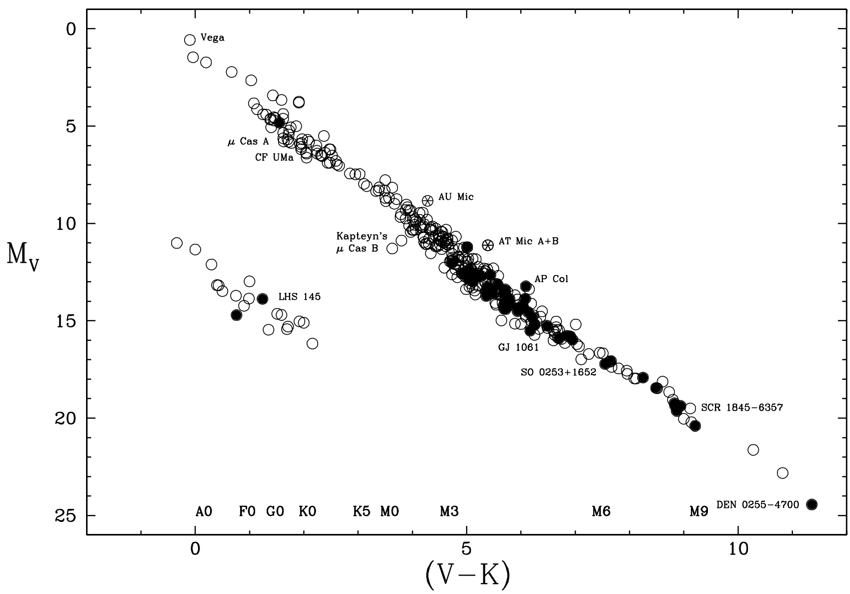

Figure 1. Members of the current RECONS 10 pc sample are shown on the HR diagram, $M_V\, vs. (V-K)$. Filled circles indicate stars and brown dwarfs for which RECONS has determined the first accurate parallaxes placing them within 10 pc. The two asterisk points are for the three components of the AU/AT Mic system that is only $\sim 8--20$ Myr old. Other labeled stars are discussed in the text.

section, we discuss a few techniques that have recently been employed to reduce trigonometric parallax errors, and offer a few additional techniques that may improve the errors to sub-milliarcsecond accuracy.

2. Census status

2.1. *The RECONS 10 parsec sample*

One of the main science goals of the CTIOPI project is to develop a complete census of stars within the RECONS horizon of 10 pc. In order for a stellar system to be included in the RECONS sample, it must have trigonometric parallax larger than 100 mas with an error less than 10 mas. As of January 1, 2000, there were 215 stellar systems containing 295 objects known within 10 pc.

Efforts by RECONS and other groups continue to fill in the census. The 2000 census list is based almost entirely on the combination of ground-based parallaxes included in the YPC and the results from the *Hipparcos* mission. New candidate members are selected from proper motion and photometric studies, from which the best candidates are usually revealed using a suite of photometric distance estimate relations (Henry *et al.* 2004). Including our own parallax results as well as the updates by other groups, there are now 260 systems containing 365 objects, constituting a 21% increase in systems (24% in objects) since 2000. Of the 45 new systems, 40 have entered the 10 pc sample via RECONS efforts.

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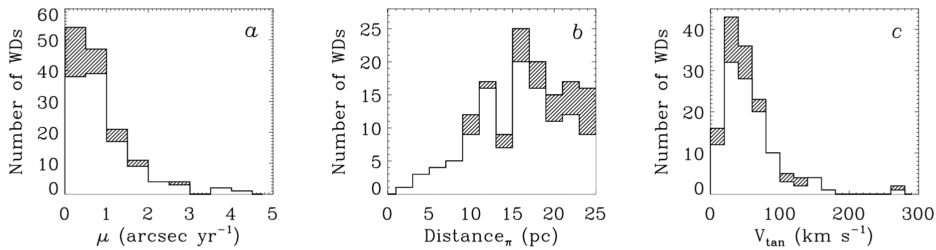

Figure 2. Histograms of astrometric properties of the new and known 25 pc WD samples. Plot (a) shows the proper motion distribution, binned by 0.5″ yr^{-1}. Plot (b) shows the distance distribution, binned by 2 pc. Plot (c) shows the tangential velocity distribution, binned by 20 km s^{-1}. Shaded regions indicate the new WDs already with reliable parallaxes from CTIOPI placing them within 25 pc. White regions indicate the 110 known WD systems within 25 pc prior to this effort.

Figure 1 shows the current HR diagram for stars in the RECONS 10 pc sample. The main sequence stretches from Vega at the blue end to stars with $M_V \sim 20$, $(V-K) \sim 9$ at the red end. The three points in the lower right are L dwarfs that are likely brown dwarfs. Precise distances of the three subdwarf systems, μ Cas AB, CF UMa, Kapteyn's Star, and the ∼8–20 Myr old system AU/AT Mic allow us to map accurately the location of these relatively rare objects in the HR diagram. Also highlighted are several of the more compelling red and brown dwarfs belonging to the 10 pc sample because of the RECONS efforts that include: AP Col (an X-ray active, likely young star), GJ 1061 (the 20th nearest system), SCR 1845-6397 (the 24th nearest system, which has a T dwarf companion that promises an accurate mass determination), and DEN 0255-4700 (to our knowledge, the faintest object for which M_V has been determined outside our Solar System). SO 0235+1652 (Teegarden *et al.* 2003) at 3.8 pc with μ=5.″1 yr^{-1} is the 23rd nearest stellar system and the highest proper motion star to be found in the past several decades, ranking as the eighth fastest system overall. Also noteworthy is LHS 145, a DA8 white dwarf for which we have determined its first trigonometric parallax, which places it at 9.6 pc.

2.2. *White dwarfs*

The end product of stellar evolution for stars with masses less than ∼8 $M_\odot$ are WDs. The study of nearby WD population provides insight into their space density, formation rate, and evolution. A volume-limited sample provides unbiased statistics that can be applied in broader context to the Galaxy as a whole. In addition, the WD contribution to halo dark matter can be probed by identifying candidate halo WDs that happen to be passing through the solar neighborhood.

We can make an estimate of the number of WDs missing from current compendia by extrapolating the space density from the 18 WDs known within 10 pc, to 25 pc. Within this sphere we anticipate that there should be 281 WDs, yet only 110 are known. Thus, a staggering 61% of the nearby WD population may be undetected. Some will be unseen companions, while others will be free floating in the field, and yet unidentified.

The reduced proper motion (RPM) diagram is a powerful way to find WD candidates (see Figure 5 in Subasavage *et al.* 2005 as an example). The RPM diagram separates high proper motion stars into three different populations – dwarfs, subdwarfs and WDs. Follow-up spectroscopic observations are needed to confirm the luminosity classes of objects in each category. Once the candidates are spectroscopically confirmed, accurate distance estimates are made so that the WDs most likely to be within 25 pc can be

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targeted by CTIOPI. Currently, there are a total of 139 WDs within 25 pc horizon, 110 with parallaxes from YPC and the *Hipparcos* mission, and 29 with parallaxes from CTIOPI, constituting an increase of 26% in the WD population. There are additional 14 WDs on CTIOPI possibly within 25 pc based on their photometric distances, but we do not yet have enough data for these WDs to calculate a definitive trigonometric parallax. Of these, 11 were selected from our SuperCOSMOS-RECONS (SCR) proper motion surveys and three were discovered by other authors (Kawka *et al.* 2004, Kawka *et al.* 2007 and Wegner 1973).

Figure 2 illustrates several important aspects of the WD 25 pc sample as it stands now. Perhaps to be expected, the majority of our new 25 pc members have $\mu < 1''.0$ yr^{-1}(Figure 2*a*) because WD candidates with $\mu \geqslant 1''.0$ yr^{-1} were historically high priority targets for characterization. Figure 2*b* shows that most of the nearby WDs yet to be found are anticipated to be beyond 10 pc (although a few are being revealed within 10 pc). Finally, with precise proper motions and distances, tangential velocities can be determined, as shown in Figure 2*c*. A few possible halo WDs have been identified: WD 1339−340 at ∼22 pc that has $V_{tan} \sim 260$ km s^{-1} (Lépine *et al.* 2005 found that this object's orbit is nearly perpendicular to the Galactic plane so it is likely a halo WD), and WD 1756+827 at 15.6 pc that has $V_{tan} = 266$ km s^{-1}.

2.3. *Cool subdwarfs*

The HR diagram is the most important map of stellar astronomy. It provides a relatively straightforward method for separating different stellar luminosity classes, e.g. supergiants, bright giants, giants, subgiants, main sequence dwarfs, and white dwarfs, using their colors and luminosities. However, the combination of spectroscopic and trigonometric parallax results has revealed a seventh distinct stellar luminosity class — subdwarfs — that lie below the main sequence dwarfs in the HR diagram.

Cool subdwarfs comprise a relatively new species in the HR diagram. Historically, they have been missed during nearby star searches because of their intrinsic faintness and rarity. Consequently, only 97 K and M type subdwarfs are known within 60 pc, compared to tens of thousands of their red dwarf cousins. Revealing nearby cool subdwarfs is one of the goals of CTIOPI. In total, we have made spectroscopic observations for 28 cool subdwarfs within 60 pc, and parallax observations for 16. Reasons for building a census of nearby cool subdwarfs within 60 pc include 1) developing a complete volume-limited sample for population studies, and 2) understanding how their metallicities affect their location in the HR diagram.

Jao *et al.* (2007) discuss different metallicity and gravity effects that lead to differences in the observed spectra of cool subdwarfs (see Figure 3). According to Gaia synthetic spectra, metallicity affects cool subdwarfs' spectra between 6000Å and 8300Å, while gravity affects only the CaHn (n=1–3) bands (Brott & Hauschildt 2005). The traditional spectral classification methods for cool subdwarfs (Gizis 1997, Lépine *et al.* 2007) do not take into account gravity effects, so different spectral sub-types may be assigned to two objects, even though their overall spectra are the same (see the gravity effects in Figure 3). We suggest using the continuum region between 8300Å and 9000Å to yield more consistent spectral sub-types, and to mesh these types with main sequence stars.

Because some of the targets discussed in Jao *et al.* (2007) have trigonometric parallaxes, we can plot these stars in the HR diagram (M1.0VI is shown in Figure 3 as an example). We found that decreasing metallicities generally make subdwarfs bluer (smaller $V-K_s$) and brighter (smaller M_K), while increasing gravities generally make them redder and fainter. These trends are shown at each sub-type we have, but more trigonometric

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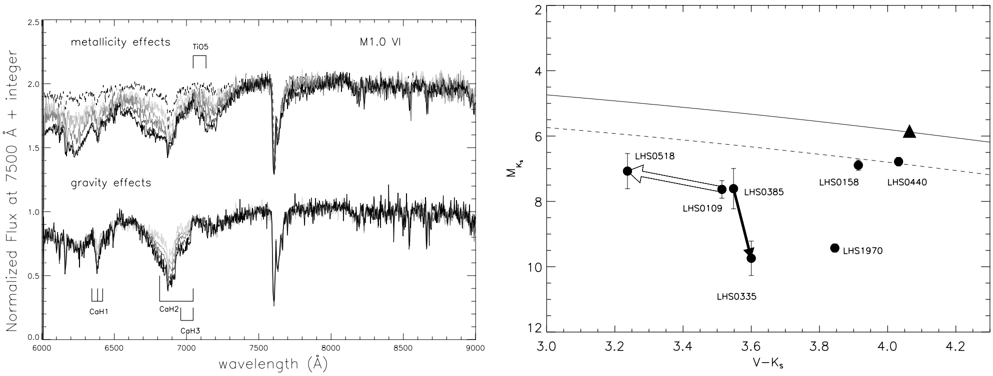

Figure 3. Left: M1.0VI subdwarf spectra are plotted at different metallicities (top spectra) and gravities (bottom spectra). The top spectra show metallicities decreasing from bottom to top (black to gray, where the lowest metallicity is plotted as a dashed line). There are seven different metallicity scales shown (0–6), including a black spectrum (scale 0) that represents our M1.0V dwarf spectral standard. The bottom spectra show the effects of gravity, decreasing from bottom to top (black to gray). All of these spectra have been selected from metallicity scale 4. Right: The HR diagram is shown for the M1.0VI subdwarfs in our sample. Filled circles indicate M1.0VI subdwarfs and a filled triangle represents the M1.0V spectroscopic standard star. The hollow arrow illustrates the shift on the HR diagram caused by decreasing metallicity (bluer stars). The solid arrow illustrates the shift caused by higher gravity (fainter stars). The solid line represents a fit to main sequence stars, while the dashed line is one magnitude fainter than the solid line.

parallaxes of later type subdwarfs (later than M5) are necessary to make a more complete map of their locations in the HR diagram.

3. Perturbation results from CTIOPI

We initiated ASPENS (Astrometric Search for Planets Encircling Nearby Stars) in 1999 with two dozen targets, and have been building the program since 2003, when D. Koerner (Northern Arizona University) joined the effort. The targets are primarily red dwarfs and WDs within 10 pc that are south of δ=0 deg and fainter than VRI=9. We have just reached 100 targets in the ASPENS program, which includes 86 red dwarfs and 14 WDs. The main goal is to have the most comprehensive astrometric search for companions to red dwarfs and WDs in the southern sky.

In Figure 4, we present two of the new definite perturbation detections from ASPENS. These initial results show stars with $\sim$8 years of astrometric coverage. The left plot is for a binary M dwarf system with orbital period 6.8 years and photocentric semimajor axis 28 mas. The right plot is for an M/L dwarf pair. The orbital motion has not yet wrapped in our dataset, but the perturbation is clear.

Since the days of van de Kamp (1982) the discovery and confirmation of a planet orbiting a nearby star via astrometry has been elusive, although using $HST - FGS$, Benedict *et al.* (2002) have detected one of the planets orbiting GJ 876, which was first revealed using radial velocities. As shown in Figure 5, we are on the brink of detecting our first planetary companion. The astrometry indicates a possible companion, although the lack of a clear signature in declination is worrisome. However, we are heartened by the supportive, but not yet conclusive, radial velocity results from four epochs that hint at a confirmation.

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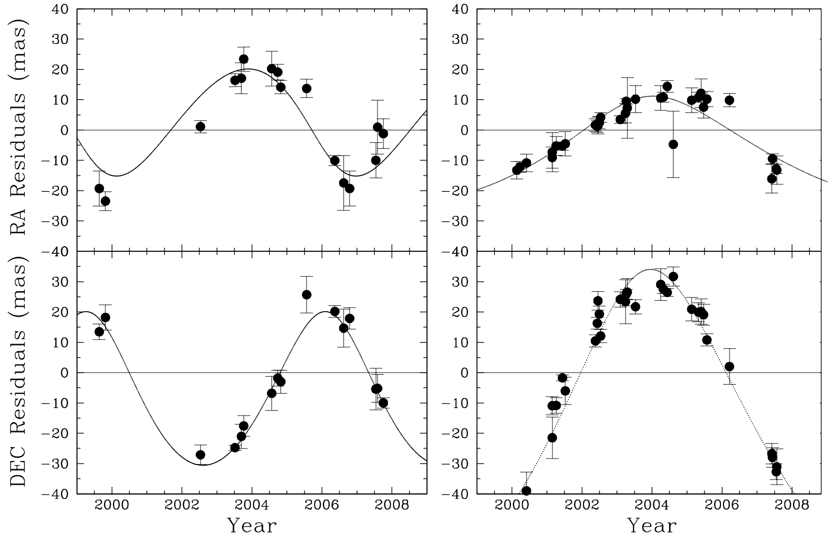

Figure 4. Astrometric residuals in the RA and DEC directions are shown for two definite perturbations, after solving for parallax and proper motion. Each point represents typically 5–10 frames taken on a single night.

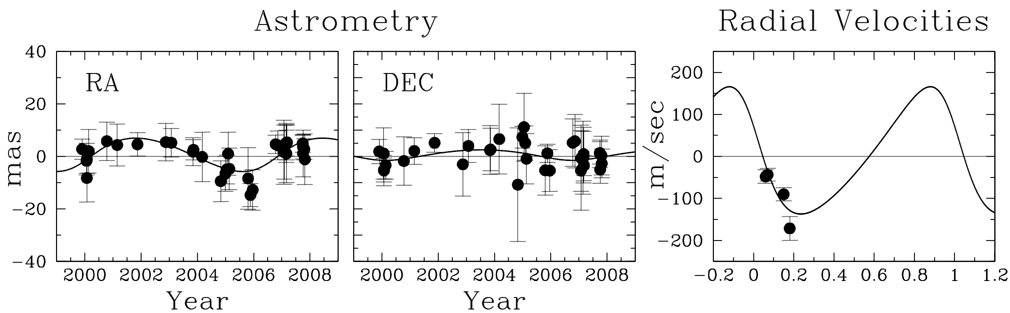

Figure 5. Left and center panels: Astrometric residuals in the RA and DEC directions are shown for a red dwarf in ASPENS, after solving for parallax and proper motion. Each point represents typically 5–10 frames taken on a single night. The orbital fit shown has a period of 6.6 years and photocentric semimajor axis of 6.5 mas. Right panel: Using the orbit derived from the astrometry, we plot the four nights of radial velocity data acquired so far using the HET. Each point represents 2–3 spectra taken on a single night. The shape of the orbit is set entirely by the astrometry, while the curve slides up/down depending on the systemic velocity. Although the confirmation is tentative, there does appear to be a change in velocity consistent with the astrometric predictions.

4. How to reduce parallax errors

Parallax errors have dropped dramatically moving from photographic plates to modern CCD observations. Since the era of CCD observations began, astrometrists have used several modifications to parallax observations and data analysis to reduce errors, including 1) using a finer pixel scale CCD imagers or improved stellar centroiding methods to yield better PSF centers (Pravdo *et al.* 2005), or 2) using improved global iterative

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methods to reduce parallax errors (Ducourant *et al.* 2008). These different attempts have decreased the parallax errors from several milliarcseconds to roughly 1 mas.

Other possible solutions that can be used to decrease errors in ground based trigonometric parallaxes include 1) adding tip/tilt or adaptive optic systems to improve image quality and stability, 2) building telescopes with better optical designs to produce finer images and reduce field distortions, and 3) setting "no-fly" zones over the observing sites to reduce the effects of airplane contrails. Additional error-reducing strategies have focused on reducing the effects of the Earth's atmosphere, arguably one of the greatest remaining causes of parallax errors. Parallax observations made in the near infrared (Vrba *et al.* 2004) have effectively eliminated the need for differential color refraction (DCR) corrections, while strictly observing targets within ±15 minutes of meridian (Dahn *et al.* 2002) reduces the DCR effect even at optical wavelengths. In CTIOPI, we typically acquire data within 30 minutes of the meridian in the VRI filters, and use the method of Monet *et al.* (1992) to correct for DCR effects. As demonstrated in Jao *et al.* (2005), we can also successfully reduce the DCR effect to manageable levels for images taken at high airmass. However, as Monet *et al.* (1992) pointed out, the DCR corrections can be improved further with better models that mimic "real" atmosphere refraction and by using a better choice of colors, e.g. $(V-K)$, to compute the refraction coefficients.

A few large scale observational efforts promise to provide large number of parallaxes in the future. On the ground, Pan-STARRS is likely to be the first sky survey effort to yield parallaxes, while LSST is the future for the southern sky. In space, Gaia and SIM will not likely provide definite parallaxes until 2015–2020. All these projects will provide us with astrometric data of unprecedented precision. Thus, the promise for compelling results on nearby stars, white dwarfs, and cool subdwarfs is high, and we are poised to see a whole new view of our Galaxy. In addition, by breaking through the barrier of milliarcsecond astrometry into the realm of microarcsecond astrometry, new research fields will undoubtedly open up, thereby providing a wealth of scientific opportunities in the decades to come.

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