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TRIGONOMETRIC PARALLAXES FROM THE SOUTHERN HEMISPHERE

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RESUMEN

Presentamos las principales motivaciones, objetivos, métodos y primeros resultados de un programa astrométrico que tiene por finalidad la determinación de paralajes trigonométricas de estrellas cercanas ($D <$ 25 pc) del Hemisferio Sur. Las observaciones se están llevando a cabo en el Observatorio Inter-Americano de Cerro Tololo (CTIO), Chile.

ABSTRACT

We present an outline of the main motivations, goals, procedures, and first scientifiic results of a dedicated astrometric program aimed at determining trigonometric parallaxes for new nearby ($D < 25$ pc) stars in the Southern sky. This program is being carried out at the Cerro Tololo Inter-American Observatory (CTIO), Chile.

Key Words: **ASTROMETRY — STARS: DISTANCES — STARS: FUNDAMENTAL PARAMETERS — STARS: LOW-MASS, BROWN DWARFS — SURVEYS**

1. INTRODUCTION

We give an overview of a Southern Sky trigonometric parallax survey known as the Cerro Tololo Inter-American Observatory Parallax Investigation (CTIOPI), which is carried out in collaboration with the Research Consortium On Nearby Stars (RECONS, see Sect. 2). The primary goals of CTIOPI are to discover and characterize nearby red, brown, and white dwarfs that remain unidentified in the solar neighborhood. This program was selected as a NOAO Survey Program and observations started in late 1999. CTIOPI used both the 0.9-m and 1.5-m telescopes at CTIO under the umbrella of the NOAO Surveys Program. In the first term of 2003, this program continued on the 0.9-m telescope as part of the SMARTS (Small and Moderate Aperture Research Telescope System Consortium (see `http://www.astro.yale.edu/smarts/`). Supplementary time at the CTIO 1.5-m was provided by Chilean time. The RECONS team at Georgia State University is responsible for data reduction for the 0.9-m program, while data from the 1.5-m program is being analyzed by Costa and Méndez at the Universidad de Chile in Santiago. The extended 0.9-m program has recently surpassed 400 systems on the observing list, whereas the final 1.5-m program included ~ 50 systems that were fainter. Most of the target stars were selected for CTIOPI because available astrometric (e.g, high proper motion), optical (& near-IR) photometric, or (low & medium-resolution) spectroscopic data indicated that they might be closer than 25 pc. In the 0.9-m program, roughly 95% of the parallax stars are red dwarfs and the remainder are white dwarfs (of the overall sample, about 30% are members of what we call the MOTION sample, i.e., stellar systems having $\mu \geq 1.0$ arcsec/yr). The fainter very low-mass & brown dwarf candidates were included in the 1.5-m program. The preliminary results from the 0.9-m effort were published in Jao et al. (2005), while the first final trigonometric parallaxes and proper motions resulting from observations carried out with the 1.5-m telescope were presented by Costa et al. (2005).

2. MOTIVATION

The first stellar trigonometric parallax was reported by F. Bessel in 1838 for 61 Cygni, narrowly defeating F. G. Wilhelm Struve and T. Henderson, who published the parallaxes for Vega and α Centauri, respectively, the following year. Since then, trigonometric parallax measurements have provided one of the most important parameters for understanding stellar astronomy (distance) and have provided one of the most solid steps on the cosmic distance ladder. Trigonometric parallaxes are used to derive intrinsic luminosities of stars, calculate accurate masses for binary system components and answer questions about stellar populations and Galactic structure. In addition, the solar neighborhood can be mapped via trigonometric parallaxes: These nearby objects provide the brightest examples of their stellar types and supply benchmarks to which

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more distant stars are compared. Two of the most important parallax references are the Yale Parallax Catalog (van Altena et al. 1995) and Hipparcos Catalog (ESA 1997). When combined, they offer $\sim 120,000$ parallaxes both from space and the ground. Nearly 92% of these trigonometric parallaxes are from the Hipparcos mission. However, because of the relatively bright magnitude limit of Hipparcos, many nearby & intrinsically faint stars were excluded. Consequently, the faint members of the solar neighborhood are badly represented. These faint red, brown, and white dwarfs are precisely the objects targeted by recent dedicated trigonometric parallax efforts, including the one discussed in this paper. Recent results for nearby red and brown dwarfs include those of Ianna et al. (1996), Tinney et al. (1995, 2003), Dahn et al. (2002), and Vrba et al. (2004), which together have published 130 ground-based parallaxes since 1995.

Indeed, the nearest stars provide astronomers with much of our understanding of stellar astronomy. For most types of stars, the fundamental framework of stellar astronomy is built upon direct measurements of luminosities, colors, temperatures, and masses of stars in the solar neighborhood. By investigating the luminosity function, mass function, kinematics, and multiplicity of stars in the solar vicinity, we can probe the stellar populations of the Galaxy, determine their contributions to its total mass, and estimate the age of the Galactic disk. Furthermore, a more complete census of the solar neighborhood (including precise distance determinations) is highly desirable for upcoming space-based planetary searches that will require well constrained target lists.

Full comprehension of the overall significance of nearby star studies to astronomy led first to the creation of the Research Consortium on Nearby Stars in 1994 (RECONS; see: `http://www.chara.gsu.edu/RECONS/`), a widely scoped program aimed at completing the census and understanding the nature, both individually and as a group, of the stellar sample within 10 pc. In 1998, the Nearby Stars Research Project (NStars) was started, whose its primary goals were to foster research on nearby stars and produce a master database of stars in the solar neighborhood to a distance horizon of 25 pc.

Potential applications of the nearest stars are, however, hampered by the fact that the faint members of the solar neighborhood are significantly underrepresented. Assuming that the density of stellar systems within 5 pc carried out to 10 pc, the RECONS list of stars closer than 10 pc indicated that 130 systems ($\sim 35\%$) were missing from the 10 pc

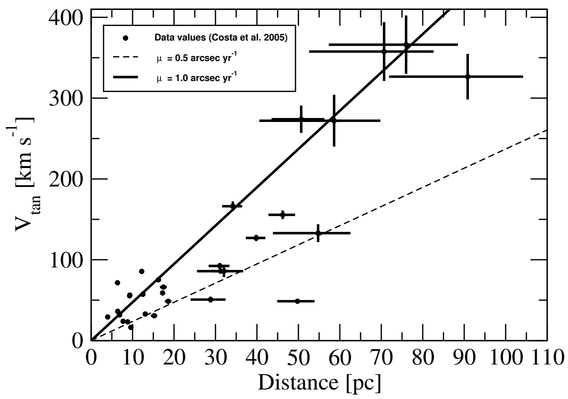

Fig. 1. Derived tangential velocities *vs.* distance for the sample objects in Costa et al. (2005). Distance error bars have been computed from the derived parallax errors. It is clear that our 2-4 mas error budget limits the usefulness of these parallaxes to objects closer than about 30 pc. We can also clearly see the kinematic bias introduced in the input sample by the high proper motion selection criteria: The solid and dashed line indicate a fixed proper motion of 1.0 and 0.5 arcsec yr^{-1}, respectively.

census (Henry et al. 1997). The problem is worse to 25 pc, a distance at which the incompleteness is anticipated to be $\sim 60\%$ for the entire sky, and nearly 70% for the southern sky (Henry et al. 2002).

Only large trigonometric parallax programs can help remedy this problem, therefore, RECONS started CTIOPI in 1999: a 3-year trigonometric parallax program aimed at discovering some 150 new southern star systems within 25 pc, thereby increases the population of stars known within that distance by $\sim$20%. This survey was carried out at the CTIO, under support of the NOAO Surveys Program (see: `http://www.noao.edu/gateway/surveys/`), supplemented with Chilean time.

3. THE SAMPLE

A trigonometric parallax effort requires a substantial investment of telescope time. Therefore, to make our survey efficient at discovering truly close stars, our input target list was refined as much as possible by selecting candidate nearby stars on the basis of "closeness" indicators, such as large proper motions and/or a photometric or spectroscopic estimate of their distances (see Fig. 1). For example, six of the 21 systems reported by Costa et al. (2005) have $\mu > 1.0''$/yr (part of the so-called MOTION sample described by Jao et al. 2005), an important sample for the discovery of very nearby stars and high velocity local subdwarfs.

Our targets were then discriminated essentially on the basis of their apparent brightness, and two working lists were produced; a bright sample ($V\sim$10-15) to be observed with the CTIO 0.9-m telescope, and a fainter ($V\sim$15-20) sample to be observed with the CTIO 1.5-m telescope (see Jao et al. 2005, and Costa et al. 2005).

Follow-up photometric and spectroscopic observations, which are necessary to determine accurate optical luminosities and fully characterize the nearby stars discovered, were started more or less simultaneously at CTIO, La Silla (ESO) and Las Campanas Observatory (LCO).

4. OBSERVATIONS & REDUCTION STEPS

The 0.9-m telescope is equipped with a 2048x2048 Tektronix CCD camera with 0.4 $''$/pixel plate scale. However, from all the observations made the central quarter of the chip was used, yielding a 6'.8 square FOV. At the 1.5-m, the astrometric observations were *all* carried out with the same Tektronix 2048$\times$2048 detector (24μ pixels) attached to the Cassegrain focus in its f/13.5 configuration. This combination gives a nominal scale and field of 0.24 $''$/pixel and $8.19'\times 8.19'$, respectively.

To minimize the effects of differential color refraction (DCR), a great deal of effort was made to take all parallax frames as close as possible to the meridian. For the brightest targets, the observations were restricted to $\pm$30 minutes from transit, and within that timespan four or more frames were acquired. For the faintest program objects (some requiring exposure times as long as 1,200 sec), they had to be observed within $\pm$60 minutes from the meridian, and each time the target was visited, only two or three frames could be taken. Exposure times were kept between a minimum of 30 sec (to average out transient seeing effects) and a maximum of 1,200 sec (to minimize DCR effects and image distortions caused by an imperfect guiding). In some cases, the exposure times were determined according to the brightness of the parallax star; in others, by reference stars brighter than the parallax star. In both cases, we always aimed at the highest possible number of counts, restricted by the saturation level and by the maximum acceptable exposure time.

DCR corrections are required because the parallax star and reference stars do not have the same spectral energy distributions; therefore, their positions as seen through Earth's atmosphere shift relative to one another because of different, but calibrateable amounts of refraction. Although most of our parallax observations suffer minimal DCR because they are made close to the meridian, sometimes frames are taken far enough from the meridian that it is advantageous to make DCR corrections, e.g., for important targets observed in non-ideal observing seasons, and when the total number of available frames can be boosted by utilizing photometry frames taken in the parallax filter. Different observing and reduction strategies to deal with DCR have been discussed by Monet et al. (1992), Tinney (1993), Stone (1996), and Stone (2002). A fully empirical method, even it provides optimum results, is very time consuming for a large survey like ours. Therefore, we adopted a combination of both the theoretical methods proposed by Stone (1996) and the empirical methodology proposed by Monet et al. (1992) to measure DCR for the CTIOPI program, and to make final corrections during the astrometric reductions (readers are referred to Jao et al. 2005, and Costa et al. 2005 for details on this point).

All CCD frames were first calibrated by using standard `IRAF` tasks. For this purpose, zero exposures and dome flats were taken every night. After that, using `SExtractor` (Bertin & Arnouts 1996), we determined (X,Y) centroids, peak flux above background, ellipticity, and FWHM of the parallax star and reference stars in all images. Due to the varied conditions in which the parallax frames were acquired, it was a tricky and time consuming task to select the appropriate `SExtractor` search parameters in order to detect the parallax star while keeping all reference stars in all images. The resulting output by `SExtractor` was then used by a customized program (see Sect. 5) which calculates the parallax factors and takes into account DCR effects to select the frames to be kept for the first iteration in the (relative) parallax calculation.

5. RELATIVE & ABSOLUTE PARALLAXES

The least squares astrometric solution of the multi-epoch frames taken for each parallax star leads to the determination of its (relative) parallax and proper motion. This solution was achieved using a modified version of the University of Texas program `GaussFit` (Jefferys et al. 1987). The procedure requires the selection of one of the frames as "master plate", which defines a fundamental reference system with respect to which all other frames are registered. The true orientation of the trail plate with respect to the International Celestial Reference Frame (ICRF, Arias et al. 1995) was determined by comparison with the Guide Star Catalog, v 2.2. (GSC2.2, 2001).

Because the measured parallax is affected by the distance of the reference star system, to obtain a better estimation of the true parallax (the "absolute parallax") the results were corrected for this effect. From the various possible ways to determine this correction (see Jao et al. 2005), we adopted the photometric parallax method. This method requires the availability of *VRI* photometry for all the parallax reference stars, and uses previously established relationships between absolute magnitude and color to estimate the distance of the reference stars in each parallax star field. The specific relationships between absolute magnitude and color we used were those established between M_v and the colors $(V-R)$, $(V-I)$ and $(R-I)$ by Henry et al. (2004) for dwarfs on the main sequence (using the RECONS database for main sequence stars). In this approach, the weighted mean photometric parallax of the reference star system represents the correction from relative to absolute parallax. For example, for the Costa et al. (2005) sample, the mean of the corrections to absolute is 1.31 mas, while the mean error of these corrections is 0.16 mas. The typical absolute final parallax uncertainty is between 2 and 4 mas.

6. (SOME) RESULTS

From the 0.9-m sample (Jao et al. 2005), four of the MOTION systems (GJ 1068, GJ 1123, GJ 1128 and DENIS J1048-3956) are new members of the RECONS 10 pc sample (Henry et al. 1997). An additional 22 systems are new members of the 25 pc sample. In addition, valuable new nearby subdwarfs have been identified, and two rare sdK/M+WD pairs have been discovered. Both samples are useful probes of the history of our Galaxy.

Among the 21 systems with first parallaxes reported by Costa et al. (2005), one is within 10 pc (LP 647-013) and six additional systems are between 10 and 25 pc, the classical distance limit of the Catalog of Nearby Stars and the NStars Project. Three of the objects, namely, DEN 1048-3956, GJ 2005 and LP 647-013, lie at distances less than 10 pc, which is the horizon of the Research Consortium on Nearby Stars. Today, this consortium has promising objects for upcoming extra solar planetary searches from space, such as the Space Interferometry mission and the Terrestial Planet Finder mission. Color-magnitude and color-color diagrams, in combination with theoretical isochrones, have also aided to identify the nature of most of the targets. In this way, we have discovered five new subdwarfs (APMPM J2204-3348, LHS 148, LHS 162, LHS 367 and WT 233) and several very low mass (possibly brown dwarf)stars.

This research program shows how a well-focused astrometric program can greatly benefit from small-aperture telescopes + solid-state detectors in a good site. Moreover, researchers can produce very valuable information concerning fundamental stellar parameters when they use public astronomical facilities.

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