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PARSEC'S ASTROMETRY - THE RISKY APPROACH

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RESUMEN

Paralajes - y por tanto la determinación fundamental de distancias estelares - se ubica entre las mediciones astronómicas más viejas, directas y difíciles. Podría decirse que es de las más esenciales. La manera directa de obtener paralajes, usando un conjunto restringido de ecuaciones para derivar posiciones, movimientos propios y paralajes, ha sido catalogado como riesgoso. Efectivamente lo es, porque el eje de la elipse paraláctica aparente es menor a un segundo de arco para las estrellas más cercanas, y solo una fracción de su perímetro puede ser trazado. Usualmente se ha aplicado el procedimiento clásico de linealizar el problema, resolviendo un conjunto de observaciones realizadas en posiciones y momentos concretos y precisos de la Tierra, ignorando la dinámica de su órbita y realizando un examen cuidadoso de las pocas observaciones disponibles. En el programa PARSEC se planeó medir las paralajes de 143 enanas marrones. Cinco años de observaciones de los campos fueron realizadas con la cámara WFI en el telescopio ESO de 2.2m en Chile. El objetivo es obtener un número estadísticamente significativo de paralajes trigonométricas para enanas marrones de subclases L0 a L7. Haciendo uso de la gran cantidad de observaciones disponibles, regularmente espaciadas, nosotros tomamos el camino riesgoso de ajustar un elipse a las coordenadas eclípticas observadas para obtener la paralaje. Nosotros también combinamos soluciones que emplean diferentes métodos de centrado, ampliamente probadas en investigaciones astrométricas previas. Como cada uno de estos métodos evalúa diversas propiedades de la PSF, estos son considerados como mediciones independientes y combinadas en una solución general de mínimos cuadrados pesados. Los resultados obtenidos se comparan bien con la literatura y el método clásico.

ABSTRACT

Parallaxes - and hence the fundamental establishment of stellar distances - rank among the oldest, most direct, and hardest of astronomical determinations. Arguably amongst the most essential too. The direct approach to obtain trigonometric parallaxes, using a constrained set of equations to derive positions, proper motions, and parallaxes, has been labelled as risky. Properly so, because the axis of the parallactic apparent ellipse is smaller than one arcsec even for the nearest stars, and just a fraction of its perimeter can be followed. Thus the classical approach is of linearizing the description by locking the solution to a set of precise positions of the Earth at the instants of observation, rather than to the dynamics of its orbit, and of adopting a close examination of the few observations available. In the PARSEC program the parallaxes of 143 brown dwarfs were planned. Five years of observation of the fields were taken with the WFI camera at the ESO 2.2m telescope in Chile. The goal is to provide a statistically significant number of trigonometric parallaxes for BD sub-classes from L0 to T7. Taking advantage of the large, regularly spaced, quantity of observations, here we take the risky approach to fit an ellipse to the observed ecliptic coordinates and derive the parallaxes. We also combine the solutions from different centroiding methods, widely proven in prior astrometric investigations. As each of those methods assess diverse properties of the PSFs, they are taken as independent measurements, and combined into a weighted least-squares general solution. The results obtained compare well with the literature and with the classical approach.

Key Words: astrometry — brown dwarfs — parallaxes

1. INTRODUCTION

Brown dwarfs are very low-mass stars whose masses (M $<$ 0.075 Msol) are insufficient to sustain the core hydrogen fusion reactions that balance radiative energy losses. Supported from further gravitational contraction by electron degeneracy pressure, evolved brown dwarfs continually cool and dim over time as they radiate away their ini-

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tial contraction energy, ultimately achieving photospheric conditions that can be similar to those of giant planets. The first examples of brown dwarfs were identified as recently as 1995. Today, there are hundreds known in nearly all Galactic environments, identified largely in wide-field, red and near-infrared imaging surveys such as 2MASS, DENIS, SDSS and UKIDSS. The known population of brown dwarfs encompasses the late-type M ($T_{eff} \approx$ 2500-3500 K), L ($T_{eff} \approx 1400-2500$ K) and T spectral classes ($T_{eff} \approx 600-1400$ K), while efforts are currently underway to find even cooler members of the putative Y dwarf class.

Because brown dwarfs cool over time, their spectral properties are inherently time dependent. However, the primary observables of a brown dwarf - temperature, luminosity and spectral type - depend on both mass and age (and weakly on metallicity). This degeneracy complicates characterizations of individual sources and mixed populations. For instance, the Malmquist bias comes from the intrinsic dispersion in the absolute magnitude-colour relationship and a limited sample in the absolute magnitude direction. A given colour (or spectral type) does not correspond to a unique luminosity, but rather to a distribution due to intrinsic scatter in metallicity and age (and non detected binaries that appear brighter for their colour).

Low-mass dwarfs compose some 70% of all stars, nearly half of the stellar mass of the Galaxy and perhaps 80% of the Solar neighborhood, which preferentially consists of relatively old objects. Therefore, the majority of low-mass BDs near the Sun should be T-type (older than 1Gy) - whereas young M-type BDs can probably only be found in young open clusters and associations, which are beyond the local neighborhood. BDs hold key evolutionary information about cosmology and the Milky Way, since their long lives make them primordial objects. For the dynamics of galaxies, including our own, they offer clues on the baryonic content and on the evolution of the galactic mass. For field star formation, their space and age distribution contribute to answer basic questions about the variation of the initial mass function or indeed if there is a lower limit mass of the formation region below which the birth of normal stars is inhibited. BDs bridge the gap between formation of dwarf stars and giant planets; their photosphere ultimately decaying into hot Jupiter-like atmospheres. Their relatively undisturbed convection zone and thin chromosphere enable the study of these zones, that are quite complex in normal stars.

TABLE 1

BROWN DWARFS AT A GLANCE

BD science drivers
• Very low-mass (nearly) stars.
• Main stellar component of the galaxy.
• Galactic chronometers.
• Sub-stellar IMF and low-mass cutoff for star formation.
• Sub-stellar and hot-Jupiters atmosphere models.
BD critical problems
• Degeneracy in the age-temperature relation – from the mass-luminosity one.
• Complex dependencies of spectral type on T_{eff}, log(g), [Fe/H].
• Derivation of BDs absolute luminosities through the measurement of trigonometric parallaxes is essential to disentangle their physical properties.

Table 1 summarizes the many science topics addressed in brown dwarf research. Ultimately, because of their large numbers, ubiquity and long-lasting evolution, brown dwarfs represent an especially interesting class of objects for a variety of Galactic studies. Astrometric observations are a must to take advantage of such studies. With these objectives in mind, the PARSEC program (followed by its successors NPARSEC and IPERCOOL) was established.

2. THE PARSEC PROGRAM

The PARSEC (Parallaxes of Southern Extremely Cool Objects) program started in April 2007 using the Wide Field Imager on the ESO 2.2m telescope (WFI/2p2) at La Silla, and lasted for 5 years (plus a current 2 year extension sought to refine the proper motion determinations). Its main goal was to even the number of targets with precise trigonometric parallaxes for every sub-class type of brown dwarf. The WFI is a mosaic of 8 CCDs with sizes of 2k x 4k 15μm pixels, providing a scale of 0.2"/pixel and a total field of view of 0.3deg^2. All images were taken in the z filter (central wavelength 964.8nm), a suitable compromise between the optimal QE of the system in the I band and the expected brightness of the targets, whose (I−z) is typically larger than 1.5. Exposure times were 150s and 300s for bright (z<18) and faint (z≥18) objects respectively; during nights with par-

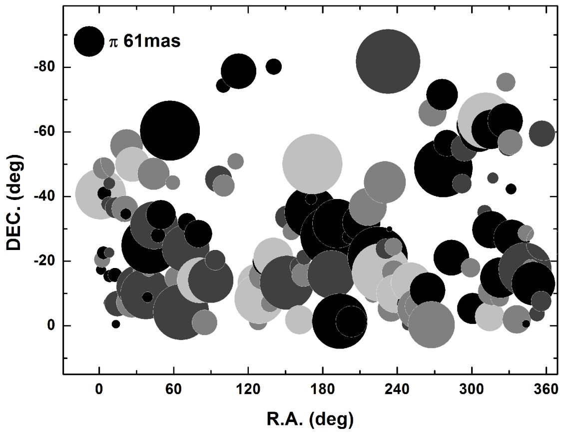

Fig. 1. Equatorial coordinates map of the 143 targets in the PARSEC program. The size of the symbols is proportional to the parallax (model on the upper-left corner). The gray tone symbols reflect the z-magnitudes according to the template on the right.

ticularly poor seeing (> 1.5"), times were adjusted to obtain a highest-pixel signal of >100 counts above the background.

On average a frequency of 3-4 observing runs per year was obtained, thus the parallax ellipse was optimally sampled for almost all targets. Nevertheless, since the program had entire nights allocated, half of the observations were made far from the appropriate evening/morning twilights, when stars crossing the meridian are approximately perpendicular to the direction of the setting/rising sun. Targets were picked from the nightly schedule according to a priority flag to best equalize the observing history of each object. After an initial acquisition, the pointing was refined to always move the target to the same (x,y) position, which falls on the top third of CCD#7. For the subsequent parallax reductions only the data from this portion of the detector is used: it is sufficiently large that we have enough reference objects for a transformation to a common system and sufficiently small to assume that a variation in astrometric distortion over the observational campaign would be smaller than the errors of a linear transformation.

The initial image treatment uses standard IRAF routines for bias and flat subtraction. However, fringing removal required a tailored approach. The interference fringes in the infrared images of the WFI camera are severe: an examination of the counts shows they can vary by up to 10% over the distance of a few pixels. The ideal case would be to make a fringe map for each image: since this was not feasible, our compromise was to make a nightly fringe map whenever possible. The details of our method

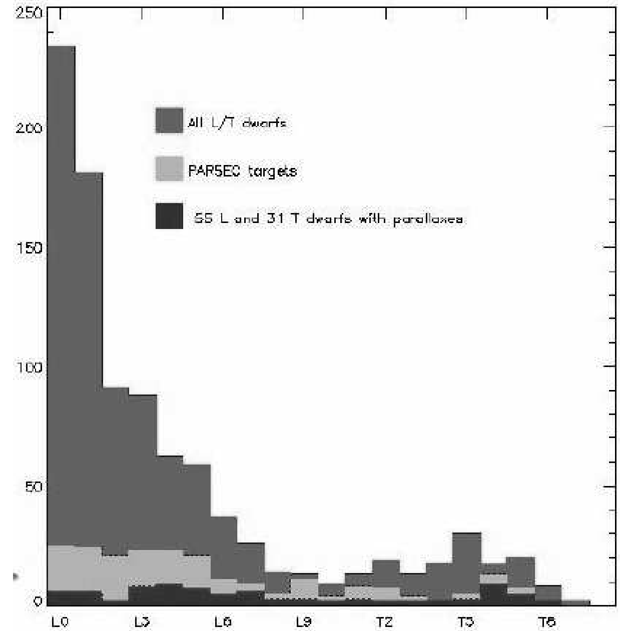

Fig. 2. Comparative histogram of counts for the PARSEC program (darker gray, bottom); brown dwarfs for which currently there are trigonometric parallaxes determined (light gray in the middle); and the total knowm brown dwarfs (gray, on top).

are given in Andrei et al. (2011). We emphasize here that a suitable subset of images scaled by their exposure time was selected to make an initial fringe map, removing in such a way most of the fringe patterns; thereafter, the same subset of pre-cleaned images was combined into a final fringe map by adopting the image mean counts as a scale factor to take into account the sky-dependent intensity of the fringe pattern as well. Figure 3 illustrates a comparison between object centroiding errors using a standard fringe map (as provided by ESO) and ours showing a sensible improvement. All the objects identified on each CCD frame were initially measured using ROBIN, a CCD software package developed at OATo (Smart 2003), which estimates the centroids (x,y); then, positions from different frames/epochs were cross-matched by means of a low-order polynomial fit, before feeding them to the astrometric model. There are presently several sky surveys that could be combined with our data to provide longer time coverage, and this was done with the 2MASS in an earlier determination of proper motions (Andrei et al. 2013) and reduced proper motions for the search of candidates for the NPARSEC program. Here, instead, in order to match observations spanning a long time interval, where usual cone search

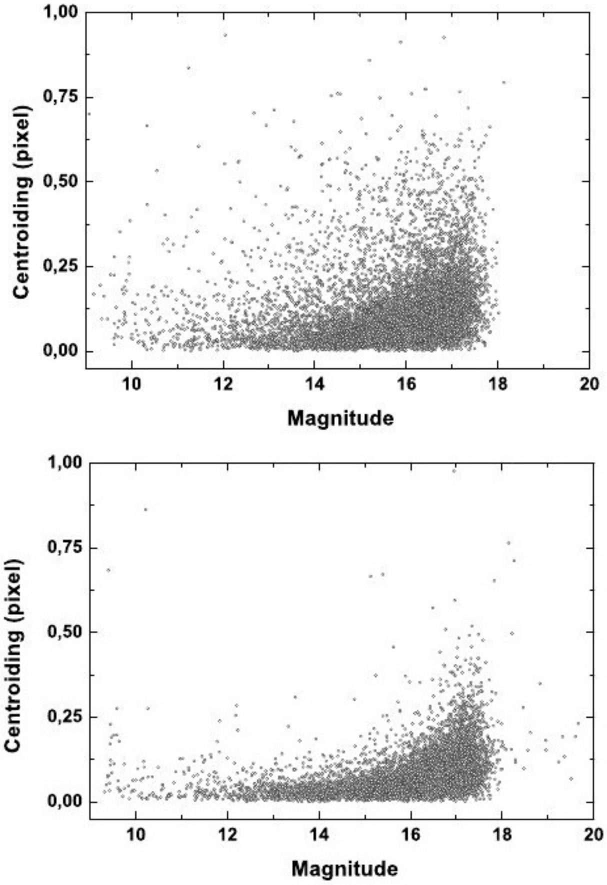

Fig. 3. Image centroiding errors (in pixels) versus object magnitude with a standard fringe removal (top) and with our tailored procedure (bottom).

strategies might fail, we adopted a more sofisticated procedure which assigns higher priority to objects with low proper motion and better positional accuracy, removes matched stars and re-starts the process, also allowing for periodical signatures.

In total, the PARSEC program measured trigonometric parallaxes of 122 L and 28 T dwarfs brighter than z=20 in the southern hemisphere (Fig 1), most of which will not be observed by Gaia. This represented doubling the number of L dwarfs with trigonometric parallaxes (Fig 2). And, in conjunction with the existing results, it left no spectral subclass up to L9 with less than 10 parallax determinations. Out of the 143 targets, only 4 had only 1 year of observation and 2 had 2 years of observation. From L0 to T7 no sub-class had more than 1 star with less than 1 year of observation. Interesting and/or benchmark objects were singled out for extended spectroscopic observations, mostly done at the Spartan/SOAR (Marocco et al. 2013).

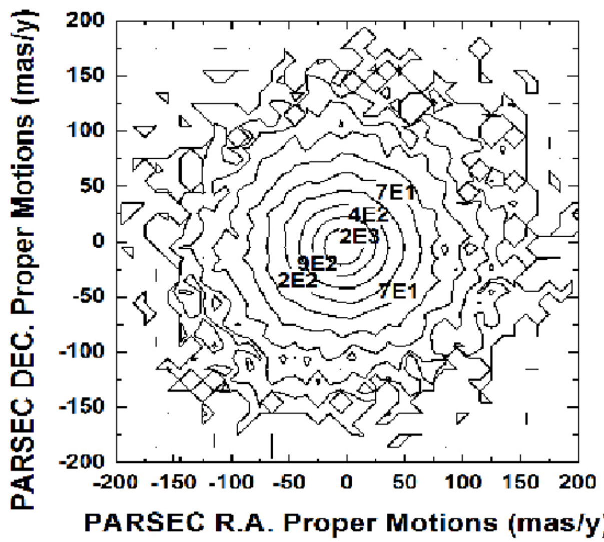

Fig. 4. The right ascension versus declination proper motion contour plot for 197,500 stars in PARSEC fields.

The main outputs of the program were:

• More than 100% increase of L dwarfs with trigonometric parallaxes.

• An increase to at least 10 (in conjunction with published results) of the number of objects per spectral sub-class in the range L0 to T7.

• Study the binarity of brown dwarfs.

• Single out interesting/benchmark objects for extended spectroscopic observation.

Among the additional outputs, it is worth noting the determination of a proper motion catalogue of 197,500 2MASS stars (Fig 4), and ongoing efforts in the search for fast-moving objects, for stellar companions of low-mass objects, and for a catalog of brown dwarf candidates on a field of $143 \times 0.3\mathrm{deg}^2$ that corresponds to the PARSEC's southern sky coverage (Bucciarelli et al. 2012).

3. ASTROMETRY

The determination of parallaxes for the brown dwarf targets is the central goal of the PARSEC program. To reach the precision of 5 mas or better, that translates to a distance uncertaintiy of **10%** or less, are factors of key importance in covering the parallax ellipse, the centroiding method, the astrometric solution, and the solution algorithm. The first and third points have already been described. The centroid algorithm was improved for the parallax determination, by using six independent centroid determinations: the one regularly used from TOPP/OATo parallax programs, IRAF's DAOFIND/PHOT, CASU's barycenter, SEXTRACTORS's barycenter and gaussian settings, and the one from the Gaia GBOT's

TABLE 2

SIMULTANEOUS SOLUTION USING THE THREE PARALLAX METHODS[a].

Method	π (mas)	$\mu_\alpha \cos\delta$(mas/y)	μ_δ(mas/y)
Two Steps Standard Approach	68.7 ± 4.0	458.8 ± 1.2	-391.2 ± 2.0
GAUSSFIT Robust Least-Squares	68.9 ± 0.8	457.5 ± 0.2	-390.4 ± 0.3
Direct Ellipse Fitting	70.0 ± 3.2	467.7 ± 0.7	-392.0 ± 1.7

[a]High proper motion star LHS3482 (2MASS J19462386+3201021), from 6 years of observation, 93 individual frames, and 54 reference stars.

routines. The error based comparison between those methods shows negligible differences for well imaged stars, with averages ranging from **4.9mas** to **7.5mas**. However when all stars are included larger differences appear, the average error ranging from **7.1mas**, for the CASU's centroid (which is optimized for barycentric adjustment), to **27.6mas**, for the TOPP's method.

The unknowns can be grouped forming a linear system of observation equations involving astrometric and instrumental parameters. In the absence of other astronomical knowledge or assumptions, the system linking the measured coordinate (**x**) to the standard coordinate (ξ), at a given time (t), accounting for proper motion (μ_ξ) and parallax (π), and plate constants (**a**,**b**,**c**), is rank deficient:

$$\xi_\mathbf{0} + \mu_\xi \mathbf{\Delta} t + \pi \mathbf{P}_\xi - x - (\mathbf{a}x + \mathbf{b}y + \mathbf{c}) = \mathbf{0} \qquad (1)$$

Three methods were then used to solve for the parallax.

The Two Steps Standard Approach Method has been successfully used in the PARSEC and previous OATo parallax programs (Smart et al., 2003). A base frame is defined, usually the first one well observed, since the number of stars is not a hindrance given the quality of the instrument and site. The other frames are referred to the base frame by using the common stars for solving for the plate constants. The target star and those stars for which the parallax and proper motion are important are excluded from the frames adjustment to avoid biasing the adjustment process.

With all standard coordinates defined on the base frame, the astrometric solution can be solved for: $\xi_t = \xi_{t0}(1 + a) + \mu_\xi \Delta t + \pi P_\xi$. The parallax factors are determined from the best available values for the Earth coordinates. On determining the proper motions and parallaxes, the process can iterate or the degree of the polynomial adjustment to the base frame be elevated - but practice shows that this was usually not necessary in the PARSEC program, due the instrumental, methodological, and observational setups.

The GAUSSFIT least-squares robust estimation software as used for PARSEC (Jefferys et al. 1987; Bucciarelli et al. 2011) takes the approach of building a single system of equations which includes the astrometric parameters of all stars and the instrumental parameters of all frames. The stellar quantities are in equatorial standard coordinates and instrumental parameters are modeled by a first order polynomial. The observation equation for a generic star on a given frame is then:

$$-x = \mathbf{a}x + \mathbf{b}y + \mathbf{c} - \xi_\mathbf{0} - \mu_\xi \mathbf{\Delta} t - \pi \mathbf{P}_\xi \qquad (2)$$

the parameters to be estimated are ξ_0, μ_ξ, and π, i.e., the components of the star position at t_0, its proper motion and parallax, plus the instrumental coefficients (**a**,**b**,**c**) mapping each frame onto the tangential plane. The intrinsic rank deficiency of this problem is tackled by using a direct approach requiring nine additional constraints to fix the solution. The choice corresponds to fixing the astrometric parameters relative to the barycenter assumed at rest. In this way, it orthogonalizes the astrometric parameters of the reference stars with respect to the instrumental parameters.

Finally, in the Direct Ellipse Fitting, as the starting point a mean frame is built by progressively grouping frames close in time; the grouping being made by a polynomial adjustment. By progressively it is meant that from each pair of time neighbor frames a provisional mean frame is formed, which reenters in the time neighbor grouping algorithm with equal footing. At each step crude proper motions are determined which are carried out to the following steps and accordingly improved (cone search). At the end only one mean frame results, to which again all frames are individually adjusted, and new proper motions are calculated.

Next the observed ecliptic standard coordinates of the target star (ξ_i^e, η_i^e) at epoch t_i are derived. They are fit to the target through an elliptical motion for the parallactic effect, superimposed on a linear term for the transverse motion, as:

$$\xi_i^e(x, y) = \bar{\xi}^e + \pi_\xi sin(t_i + \mathbf{\Phi}_\xi) + \mu_\xi \mathbf{\Delta} t \qquad (3)$$

In this formulation, the left hand side is the ecliptic standard coordinate at the observation time, $\bar{\xi}^e$ is the mean ecliptic standard coordinate, π_ξ and μ_ξ are the ecliptic components of the parallactic and transverse motions, and Φ_ξ is a phase free term. There is an analogous equation for the η component.

The effect of the Earth's eccentricity is disregarded, given the typical distances of our targets. However, it can in principle be computed and corrected for, being a purely geometrical effect. Nevertheless a computation of the differences for 3 fictitious stars at **20pc**, and with ecliptic latitude $b = 0°, 45°, 90°$, sampled from **4** to **9** times along **6** months covering the span of the year (or of ecliptic longitudes), and adjusted to a parallactic ellipse, shows no contribution larger than 10^{-8}arcsec to the parallax.

Table 2 compares the three methods to determine the parallaxes. Notice that the errors are internal, and the Two Steps Standard Approach shows larger errors because it takes results from all stars in the field, while the other two methods do not entirely. For the program at large the Direct Ellipse Fitting is being used, as it does not unweight any of the observations. The average parallax error for the first 49 brown dwarf targets is **1.7**mas, which corresponds to a typical error of **2.5%** on the absolute distances. Figure 5 shows an example of the data leading to the determination of parallax for a well observed target, and Figure 6 exemplifies how the parallaxes obtained here contribute to the determination of the mass-temperature relationship.

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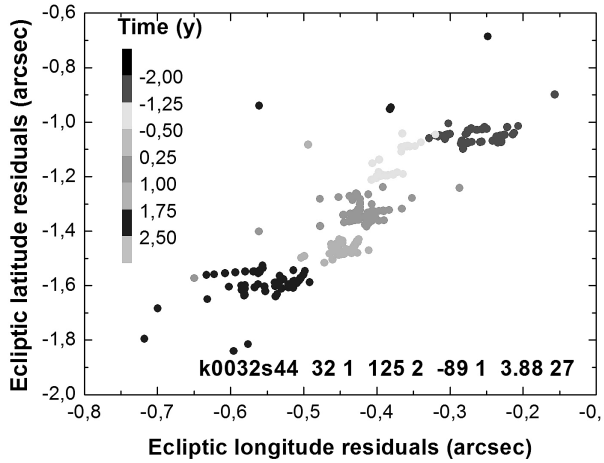

Fig. 5. The data (as residuals from the static solution) leading to the parallax and proper motion of brown dwarf target k0032s44, well sampled throughout the PARSEC program.

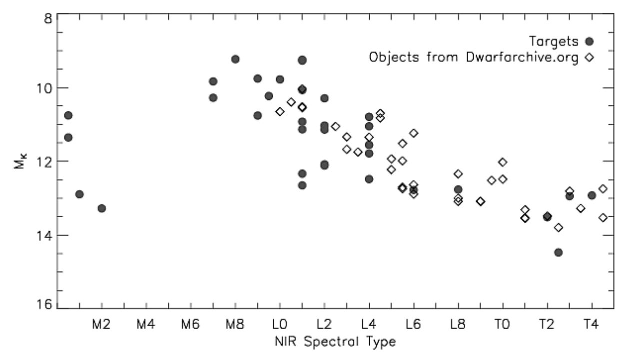

Fig. 6. Absolute 2MASS **K** magnitude versus the spectral type, in which the absolute magnitude is derived from the PARSEC trigonometric parallaxes.

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