Proper Motions as an Underutilized Tool for Estimating Distances and Ages for Nearby, Young Stars

Eric E. Mamajek

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS-42, Cambridge, MA, 02138 USA

Abstract. The recent availability of accurate proper motion catalogs for millions of stars on the sky (e.g. Tycho-2, UCAC) can benefit projects for which age estimates are needed for stars that are plausibly young (<100 Myr) and within a few hundred pc of the Sun. Here I summarize how accurate proper motions have been useful in (1) identifying new, nearby, post-T Tauri star populations, and (2) estimating distances to young field stars which are lacking trigonometric parallax measurements. The later enables the calculation of stellar luminosities and isochronal ages – two critical quantities for investigations of the evolution of star/planet/disk systems.

1. Motivation

One of the broad aims of modern astrophysical research is to understand how stars and planetary systems form and evolve. This topic is one of the major research themes driving the construction of the next generation of ground-based telescopes (e.g. GMT, GSMT), as well as future space observatories (e.g. SIM, JWST, TPF-C). To study the evolution of star/planet/disk systems, we require accurate stellar ages. As remarkable as the astronomical discoveries of circumstellar phenomena have been over the past decade (e.g. exoplanets, brown dwarfs, debris disks), all too often the age of the host star under study is constrained to an accuracy of tens of percent (at best!). Improved means of robustly estimating stellar ages are sorely needed. Stauffer (2004) said it best: “It would be a waste of all the wonderful IR data if the age estimates from [Spitzer] stellar targets were left as an after-thought.”

Ages estimates for late-type stars (cooler than mid-F) are usually determined through comparing stellar properties like activity, rotation, and Li abundance, to stars with calibrated ages (usually stars in well-studied clusters). Independently, one can estimate an isochronal age through placing the star’s HR diagram position on theoretical evolutionary tracks. Trigonometric parallaxes enable the calculation of luminosity, and hence, isochronal ages. Proper motions, which are much easier to measure than trigonometric parallaxes, have been largely underutilized in the quest for estimating stellar ages. In the instance where we have an empirical velocity model for a sample of objects (say, proposed members of a star cluster), we can statistically test whether a star is consistent with co-moving with that group, and use the star’s proper motion to calculate a secular parallax.

Here I briefly summarize how proper motions have been useful in finding new, nearby young stars, and in estimating ages for previously known specimens that lack trigonometric parallaxes. The results stem from ancillary science done
for the Spitzer Legacy program “Formation and Evolution of Planetary Systems” (FEPS\(^1\); Meyer et al. 2004). These results are presented in more detail in Mamajek, Meyer, & Liebert (2002); Mamajek (2003); Mamajek et al. (2004); Mamajek (2004), Mamajek (in prep.) and Hillenbrand et al. (in prep.).

2. Using Proper Motions to Find Post-T Tauri Stars

Proper motions can aid in discovering low-mass members of nearby stellar associations (i.e. “post-T Tauri stars”). Mamajek, Meyer, & Liebert (2002) conducted a survey for such stars over hundreds of square degrees in the two nearest OB subgroups to the Sun (Lower Centaurus-Crux (LCC) and Upper Centaurus-Lupus (UCL); ages \(\simeq 15\) Myr) using both proper motion and X-ray selection. The memberships of these groups among early-type stars is excellent thanks to Hipparcos satellite astrometry (de Zeeuw et al. 1999). Assuming that the groups had a normal initial mass function, it was very plausible that a large, untapped reservoir of post-T Tauri stars could be found co-moving with the high-mass membership. Using both proper motion and X-ray selection, Mamajek, Meyer, & Liebert (2002) identified \(\sim 100\) G/K-type pre-MS members of UCL and LCC. Proper motion selection yielded \(\sim 3 \times 10^3\) Tycho stars with motions consistent with membership (Hoogerwerf 2000, and priv. comm.), and \(\sim 10^4\) ROSAT All-Sky Survey Bright Source Catalog (RASS-BSC) sources blanket the region. Selection by X-ray emission and proper motions yielded a 93% hit-rate in identifying Li-rich pre-MS G/K-type stars, whereas using proper motions and parallaxes (de Zeeuw et al. 1999, where available), yielded a hit rate of 73%. Selecting by proper motions alone has proved to be rather inefficient at selecting faint members of OB associations (Preibisch et al. 1998), however when used in conjunction with other datasets (i.e. X-rays, color-magnitude diagrams), proper motions are excellent at rejecting interlopers.

3. Using Proper Motions to Estimate Distances and Ages

Proper motions are useful for assessing membership of stars to clusters and associations, as well as estimating secular parallax distances for those stars selected as members. The selection of cluster members, and calculation of improved distances to the individual members using proper motions, has been successfully attempted for several nearby clusters and associations (e.g. de Bruijne 1999; Madsen, Dravins, & Lindegren 2002; Mamajek, Meyer, & Liebert 2002). These individual distances are useful for reducing the scatter in HRD positions, and searching for substructure in associations (Mamajek, Meyer, & Liebert 2002).

Outside of clusters and associations, secular parallaxes can be used for any kinematic group where the velocity dispersion is much smaller than the mean heliocentric space motion. This is the situation for young (<100 Myr-old) field stars in the solar neighborhood, which are moving with respect to the Sun at \(\sim 20\) km/s, but have a 1D velocity dispersion of \(\sim 5\) km/s. Theoretically one should

\(^1\)http://feps.as.arizona.edu/
be able to calculate distances to tens of percent accuracy to any star whose tangential velocity is \(>\text{few} \times \) the 1D velocity dispersion of the group to which it belongs. Numerous active, Li-rich, late-type stars (presumably young) have been discovered in recent years, but have either no trigonometric parallax measurements, or rather uncertain values (e.g. Jeffries 1995). Previous attempts to calculate secular parallaxes for young field stars have either applied the method inconsistently, not propagated uncertainties, or both (e.g. Eggen 1995). Can we estimate distances to young field stars and quote believable error bars?

Figure 1. HRD for a subsample of FEPS targets which are statistically more Li-rich than the Pleiades, and whose proper motions and radial velocities are consistent with Local Association membership [Mamajek 2004]. Isochrones are from [D’Antona & Mazzitelli 1997].

[Mamajek 2004] developed a preliminary iterative method for estimating secular parallaxes that is applicable to field stars younger than the Pleiades (<125 Myr-old; hereafter the “Local Association”). Although the Local Association is not a cluster in the classical “coeval” sense, the kinematics of field stars that are more Li-rich than the Pleiades are remarkably coherent (e.g. Wichmann, Schmitt, & Hubrig 2003), and can be approximated with a simple kinematic model. The input parameters are (a) a star’s position, (b) proper motion, (c) radial velocity, and (d) a velocity model with mean heliocentric velocity at Sun’s position \((U_o, V_o, W_o)\), velocity dispersion \((\sigma_U, \sigma_V, \sigma_W)\), and Oort parameters \((A, B, C, K)\). The star’s parallax is estimated iteratively using the relation \(\pi_{sec} = A\mu/V_{tan}\), where \(\pi_{sec}\) is the secular parallax, \(A\) is the astronomical unit (4.74), \(\mu\) is the proper motion, and \(V_{tan}\) is the tangential velocity predicted by the model. One starts with an initial guess distance to the star (100 pc), calculates the velocity vector \((U, V, W)\) for the velocity field at the guess distance (3D position), calculates a membership probability and secular parallax, and uses the new distance from the secular parallax to revise the estimate of the velocity vector, etc. These steps are repeated until convergence. For stars with high membership probability, that are situated far from the group’s convergent point, typically \(~5\) steps are required for the secular parallax estimates.
to converge to 1 part in $10^6$ precision (not accuracy!). Membership of the star to the kinematic group is tested with a $\chi^2$ statistic which compares how well the proper motion direction and measured radial velocity match that predicted by the velocity field model. The final membership probability is used to assess whether the star’s motion is consistent with that predicted by the model, and whether the distance estimate should be retained.

Using a subsample of two dozen targets in the FEPS Legacy program which are statistically more Li-rich than the Pleiades (and hence plausibly $<125$-Myr-old), Mamajek (2004) calculated secular parallaxes using an empirical “Local Association” velocity model. Three-quarters of the Li-rich FEPS targets had proper motions and radial velocities statistically consistent with being Local Association members. The resultant HRD positions and plotted in Fig. 1 and overlayed with theoretical isochrones. Roughly half of the Li-rich stars are consistent with being pre-MS ($<40$ Myr for $\sim1 M_\odot$). For the few stars with accurate Hipparcos parallaxes, the agreement between the secular parallax distances and Hipparcos trigonometric parallax distances is good (e.g. AO Men: $50 \pm 9$ pc vs. $37 \pm 1$ pc; HD 202917: $53 \pm 7$ pc vs. $46 \pm 2$ pc). A few objects had exceptionally young isochronal ages (e.g. HD 285372, RX J1111.7-7620), however these appear to be associated with the Tau or Cha star-forming regions, so their young ages ($\sim1$ Myr) are not unexpected. A few of the FEPS targets are particularly close. Among those lacking published parallax estimates, Mamajek (2004) found the following stars to be particularly nearby and young: RE J0137+18A ($64 \pm 8$ pc; $\sim9$ Myr old), HD 286264 ($71 \pm 11$ pc; $\sim22$ Myr), and HD 141943 ($67 \pm 7$ pc; $\sim13$ Myr). More results will be forthcoming in Mamajek (in prep.) and a paper on the ages of FEPS targets (Hillenbrand et al., in prep.).

Acknowledgments. EM thanks Michael Meyer and the rest of the FEPS Legacy Science team for useful discussions during the course of the author’s thesis work. EM is supported by a Clay Fellowship through the Smithsonian Astrophysical Observatory (SAO).

References

D’Antona, F. & Mazzitelli, I. 1997, MsdAI, 68, 807
de Bruijne, J. H. J. 1999, MNRAS, 310, 585
de Zeeuw, P. T., et al. 1999, AJ, 117, 354
Eggen, O.J. 1995, AJ, 110, 1749
Hoogerwerf, R. 2000, MNRAS, 313, 43
Jeffries, R. D. 1995, MNRAS, 273, 559
Madsen, S., Dravins, D., & Lindegren, L. 2002, A&A, 381, 446
Mamajek, E. E., 2003, Open Issues in Local Star Formation, eds. J. Lepine & J. Gregorio-Hetem, p.39
Mamajek, E. E., 2004, PhD Thesis, The University of Arizona
Mamajek, E. E., et al. 2004, ApJ, 612, 496
Mamajek, E. E., Meyer, M. R., & Liebert, J. 2002, AJ, 124, 1670
Meyer, M. R., et al. 2004, ApJS, 154, 422
Preibisch, T., et al. 1998, A&A, 333, 619
Stauffer, J.R., 2004, Debris Disks and the Formation of Planets: A Symposium in Memory of Fred Gillett, ASP Vol. 324, in press.
Voges, W., et al. 1999, A&A, 349, 389
Wichmann, R., Schmitt, J. H. M. M., & Hubrig, S. 2003, A&A, 399, 983