Mem. S.A.It. Vol. 85, 710

Memorie della

Kinematics and luminosities of brown dwarfs with the BDNYC group

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Abstract. Due to magnitude limits, the Gaia survey will not delve as deeply into the local population of brown dwarfs as it will other stellar populations. While hundreds or thousands of brown dwarfs will be measured by Gaia, we propose a different, indirect method wherein studies using Gaia data will help teach us about brown dwarfs: Identifying moving groups that contain brown dwarfs. This use of Gaia data will directly help attempts to disentangle the effects of age and mass on brown dwarf spectra, which opens the possibilities for determining empirical constraints on brown dwarf evolution.

Key words. Stars: low-mass – Stars: atmospheres – Stars: – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

Brown dwarfs are by definition starlike objects that never attain core temperatures sufficient to sustain fusion of hydrogen into helium due to their low masses. Because they do not sustain hydrogen fusion, they are not stars. Due to the continuum of surface temperatures, brown dwarfs nevertheless resemble stars in many ways, and form a bridge between stars and gas giant planets. Without a fusion power source, they continuously shrink and cool, rather than falling onto a main sequence. Thus, we are left with a situation where it is difficult to tell if a brown dwarf of a given temperature is young and low-mass, or old and high-mass. The degeneracy in apparent gravity and age makes it difficult to make evolutionary tracks without assumptions about the internal physics of the brown dwarfs. To solve this problem, we must break the age-mass degeneracy. This can be done by measuring the brown dwarf masses – preferably dynamical masses, although brown dwarfs in binaries are notoriously rare – or by measuring the ages of the brown dwarfs. This can be done by connecting them to a group of stars with a known age. The nearby young moving groups are expected to be coeval groups of a few hundred stars, the products of single small bursts of star formation, in the process of dissipating into the galactic disk. They are young enough to exhibit a wide range of brown dwarf evolutionary states, and are close enough that particularly low-mass objects are bright enough for serious study.

2. Moving group kinematics

Historically, finding young stars was a tricky business. The closest star-forming regions (i.e. Taurus-Auriga, Scorpius-Centaurus, Orion) are not very near, and the nearest groups (The Hyades, Ursa Major) were not particularly young. In recent decades, “Isolated T Tauri stars” have been found, and there are now at least 20 proposed groupings of young (less than 150 Myr old) stars near the Sun, many of which are now believed to contain brown dwarfs. At present, the memberships of the various groups are not settled, though many authors (most recently Malo et al., 2013; Gagné et al., 2014) have attempted to derive lists of true consistent members.

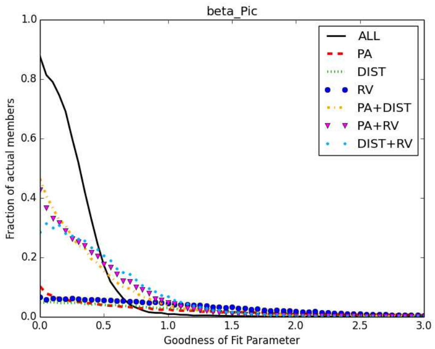

Fig. 1. Plot of the fraction of members of β Pictoris as a function of the goodness-of-fit parameter, for all combinations of available data.

2.1. Moving group kinematics codes

The workhorse technique for identifying memberships is kinematics. Other methods – spectroscopic, astrometric, and photometric – can provide precise estimates of the ages of systems, but only kinematics can identify a particular moving group.

The method analyzed here is a semi-convergence method. It considers up to three metrics (proper motion, parallax, and radial velocity as available; spatial positions are not considered) to determine memberships. The methodology is much like a classical convergence code (as in Rodriguez et al. 2013) in that it operates by comparing a predicted proper motion vector (for a given moving group, at the RA and DEC of the target star) to the measured proper motion vector of the target object. The difference is that the semi-convergence method uses the UVW matricies from Johnson & Soderblom (1987) to convert UVW space velocities to $\mu_{RA,pred}$, $\mu_{DEC,pred}$ and RV_{pred} rather than calculating the vector from the convergent point of the group.

From that point onward, the methods are similar: in both cases, the observed motion of the system μ_{RA}, μ_{DEC} is split up into $\mu_{parallel}$ and $\mu_{perpendicular}$ components for analysis, where the perpendicular component should be zero if the system is a perfect match to the group. The magnitude of the proper motion vector can be used to derive a kinematic distance; in the same way, the expected RV_{pred} can be compared to a measured RV for a third goodness-of-fit estimate.

Converting the magnitude of the perpendicular component of the proper motion vector to a probability of membership required calibration. This calibration stage was made by drawing five million points from the 6-dimensional distributions of the various known nearby moving groups, populated according to the size of each group. As an example, field stars are roughly 15 times more common (137 young stars among 2167 star systems within 25 pc, Henry et al. in prep) than young stars, and they accounted for 15 times as many draws as all young stars put together. The probabilities of membership were determined by the fraction of draws that were “actual” members, as a function of the combined goodness-of-fit parameter (Figure 1).

2.2. Lessons learned from moving group kinematics codes

In many cases it is impossible to be 100% certain that an object is a member by kinematics alone. Figure 1 shows the ability of the code to identify members of β Pictoris. If we have only the proper motion (red line) as a parameter, even a perfect match to β Pictoris has only a 10% chance of actually being a member of β Pictoris. Adding in a trigonometric parallax or radial velocity boosts the maximum certainty to just over 40%, but even when using the μ, π,

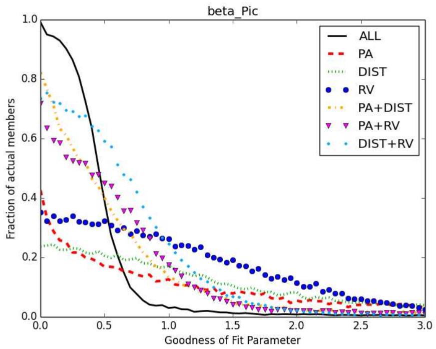

Fig. 2. Same as Figure 1 except that field stars have been removed from consideration, and the probability of an object being a β Pictoris member has increased.

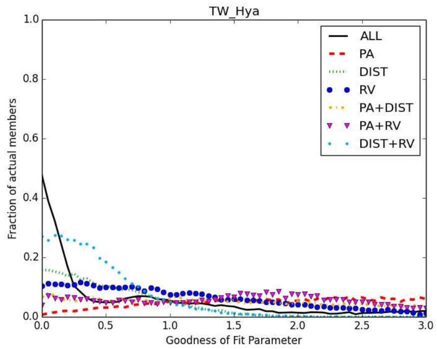

Fig. 3. Same as Figure 2 except showing the plot for TW Hydra. Even without considering field stars, perfect matches to the TW Hydra moving group are still not likely to be TW Hydra members.

and RV predictors together, the maximum certainty only reaches 88%.

If field stars are removed from consideration (a reasonable assumption if it is known that the star is young), the statistics improve significantly (Figure 2). The result is still not perfect in many cases (Figure 3), as several of these distributions overlap, and it is therefore impossible to distinguish between them based on kinematics alone. In these cases, the code will most often suggest a higher probability of membership in the group that has more members. It is readily apparent from these conclusions that other information is needed, and kinematics alone are not sufficient to determine membership.

3. Moving group tracebacks

There is one other kinematic technique that can be used to judge the quality of memberships: kinematic traceback (Makarov et al., 2004; Mamajek et al., 2013). The conceptual underpinning of this technique is that if we assume these groups are the product of a single burst of star formation, they must have been close to each other at the time of formation, where "close" is some function of the size of the initial gas cloud. In practice, this requires all pieces of kinematic information (RA, DEC, π, $\mu_{RA\cos DEC}$, μ_{DEC}, RV) for the star and moving group, and some means of approximating galactic orbital motion, whether it's a simple straight-line motion, an epicyclic approximation to galactic motion (Makarov et al., 2004), or a simulation of the galactic gravitational potential into which particles can be placed (Dehnen & Binney, 1998). All of these methods make simplified assumptions about the actual galactic potential field, neglecting local effects like molecular clouds.

3.1. Traceback methods

The particular implementation considered here is an epicyclic approximation of the galactic potential following Makarov et al. (2004), with updated Oort constants from Bobylev & Bajkova (2010). To calculate the position of the cluster as a function of time, 1000 Monte Carlo points were taken distributed for each of the N bona-fide members of the nearby moving groups. These points were run back in time from the present to 600 Myr in the past. At each timestep of 0.1 Myr, freely-oriented ellipsoids were fit to each set of N bona-fide members at each timestep. The mean and standard deviation on the positions and dispersions of the distributions were recorded in a file.

For each potential young star with full kinematic information, its potential membership was run by computing its own traceback back in time using 20000 Monte carlo points

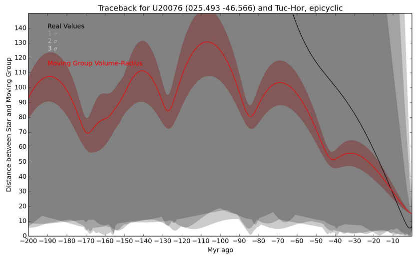

Fig. 4. A kinematic traceback to the Tucana-Horologium moving group. Now is on the right-hand side. the position (1σ, 2σ, 3σ) of the brown dwarf is shown in black (dark gray, medium gray, light gray). The effective radius of the moving group (1σ) is shown in red (pink). Because the 1σ uncertainty envelope is within the pink region 45 Myr ago (the time of formation of Tucana-Horologium), this brown dwarf is potentially a member.

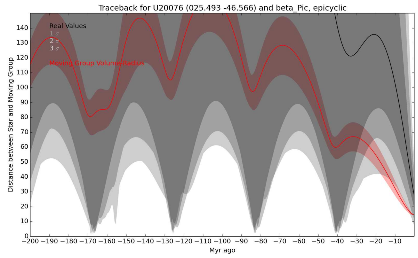

Fig. 5. A kinematic traceback to the β Pictoris moving group, for the same brown dwarf as Figure 4. At the time of formation (25 Myr ago), the brown dwarf position only overlaps with the β Pic radius (unrealistically large as it is) at the 2σ level; it is therefore not as likely to be a member.

within 1σ, 2σ, and 3σ of its values. The separations between the positions of the star and of the moving group are then calculated (Figure 4).

3.2. Lessons learned from tracebacks

At the moment, large uncertainties on (primarily) stellar parallaxes and radial velocities make kinematic tracebacks less useful than they might otherwise be. The current state of the art in proper motions, parallaxes, and radial velocities do not constrain the positions of stars very well, with the result that they can appear to be equally good matches to multiple moving groups (see Figure 5) and therefore have limited discriminative power.

The larger problem inherent in all of this is that the bona-fide members of the young moving groups do not trace back to the same location in space (see Figure 4), leading to enormous apparent sizes at the time of formation, and a generally contracting cluster. Tucana-Horologium, for example, has an effective radius of over 50 parsecs at t=45 Myr ago, which is enormous compared to the tidal radius of the far more massive Pleiades cluster, 13 pc (Adams et al., 2001), which has presumably not significantly enlarged since forming from a molecular cloud 125 Myr ago.

To have a moving group whose members are moving in parallel (as is the case for TW Hydra, Weinberger et al. 2013) makes some physical sense, given that the constituent stars are so far apart they have probably never physically interacted. Some of this discrepancy may be due to the large uncertainties on the data mentioned above, but the more likely conclusion is that some of the stars are physically unrelated, and their current proximity and similar space motions are accidental. Chemical analyses of the members of moving groups (such as AB Dor, Barenfeld et al. 2013) show that current member lists are indeed contaminated with non-members, but the youth of the bona-fide members is well-established by other means. Even if they are not members of a particular group, they are still young stars whose origins need to be explained. If data of improved precision (Figure 6) does not resolve the discrepancies, the remaining possibility is that the currently known groups are not the physical entities we thought they were.

4. The impact of Gaia

Many of the moving groups proposed over the years have not stood up to scrutiny. A large part of this problem is that the definition of a moving group has become increasingly strict, going from a mere group of stars with similar space motions, to the group as the product of a single burst of star formation. A good ex-

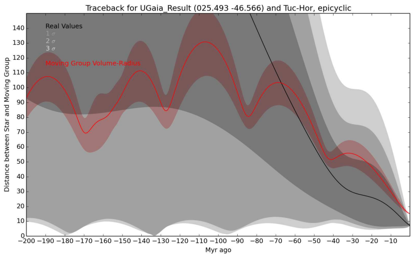

Fig. 6. The kinematic traceback for the brown dwarf in Figure 4, where the astrometry has been replaced by Gaia-quality values that would make it a match, demonstrating the improved constraints possible with Gaia. The remaining mismatch is entirely due to the radial velocity.

ample of this is the IC 2391 Supercluster from Eggen (1991), which was identified on the basis of similar proper motions to the IC 2391 open cluster. Within the paper itself, it is noted that there are multiple subgroups with different ages, but at the time this was not seen as a problem.

The other major change that has happened in the last 20 years is the general availability of milliarcsecond astrometry, largely due to the Hipparcos catalog. The increased precision makes it possible to identify smaller structures in velocity space, which are more likely to be coeval groups. Asiain et al. (1999) was one of the first to apply the new Hipparcos results to the "Local Association" and was among the first to note the newly visible overdensities in the kinematic space. Based only on kinematic overdensities, the paper identified a structure whose properties are very similar to (and may actually be) the AB Doradus young moving group canonically discovered by Torres et al. (2003). Gaia will provide a similarly large leap in quality and quantity of available kinematic information. Gaia's increased precision will allow us to tease out finer, smaller groups that are more likely to be truly co-eval products of a single burst of star formation, and may even completely sweep away the current landscape of nearby young moving groups. In this way, Gaia will prove fundamental to our understanding of brown dwarfs for which it will not obtain any data. We need this leap, and Gaia's new datasets, to provide a firm foundation for our moving groups so that we can confidently derive brown dwarf properties.

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