IMPROVED METHODS FOR IDENTIFYING MOVING GROUPS

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ABSTRACT

We present a new procedure for the identification of moving groups. It is a combination of two independent member selection methods. One is a modern implementation of a classical convergent point method for proper motion data. The other objectively identifies moving groups in velocity space using proper motions and parallaxes. We briefly describe both methods, and illustrate their power by applying them to Hipparcos measurements of a field containing the Upper Scorpius subgroup of the Scorpio–Centaurus association (Sco OB2). We show how our membership selection procedure not only improves the list of previously known B and A-type members, but also identifies many new members, including a significant number of F stars. We apply our procedure to other nearby OB associations elsewhere in these proceedings (Hoogerwerf et al. 1997, de Zeeuw et al. 1997).

Key words: OB associations; moving groups; stars: early-type, kinematics.

1. INTRODUCTION

Stars in moving groups with small internal velocity dispersions share a common space motion, which can be used to establish membership based on measurements of radial velocities or proper motions, or both. Whereas many such kinematic membership studies have been carried out for open clusters (e.g. van Leeuwen 1985, van Altena et al. 1993), there are few such studies for nearby OB associations. These loose stellar groups have internal velocity dispersions of at most a few km s^{-1} (see Mathieu 1986), so the stars share a common space motion, but they generally cover tens to hundreds of square degrees on the sky. Ground-based proper motion studies therefore almost invariably have been confined to modest samples of bright stars ($V \lesssim 6$) in fundamental catalogues, or to small areas covered by a single photographic plate. Photometric studies can extend membership to later spectral types, but are less reliable. As a result, membership for many associations has previously been determined unambiguously only for spectral types earlier than B5 (e.g. Blaauw 1991).

The advent of Hipparcos allows a major step forward in our understanding of the nearby associations. We are carrying out a census of OB associations within 800 pc from the Sun based on the Hipparcos measurements (see Hoogerwerf et al. 1997, de Zeeuw et al. 1997). The parallaxes and proper motions allow kinematic membership determination in the nearby associations to unprecedented accuracy, and for stars significantly fainter than accessible previously. This requires an objective and reliable way to identify moving groups in the Hipparcos Catalogue. Here we present a new procedure to do just this, and illustrate its application by considering the well-studied Upper Scorpius subgroup of the Scorpio–Centaurus association (e.g. Blaauw 1978).

2. SELECTION METHODS

The common space motion of stars in a nearby moving group results in converging proper motions. We developed a modern implementation of a classical convergent point method (Brown 1950, Jones 1971). This method searches for the maximum likelihood coordinates $(\alpha, \delta)_{\rm cp}$ of the convergent point by minimizing the sum over all N stars in the data sam-

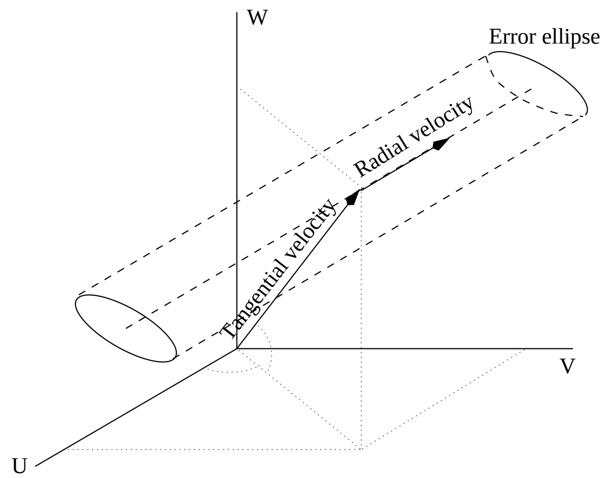

Figure 1. The five astrometric parameters of a star measured by Hipparcos define an elliptic cylinder in velocity space. All cylinders of stars in a moving group intersect.

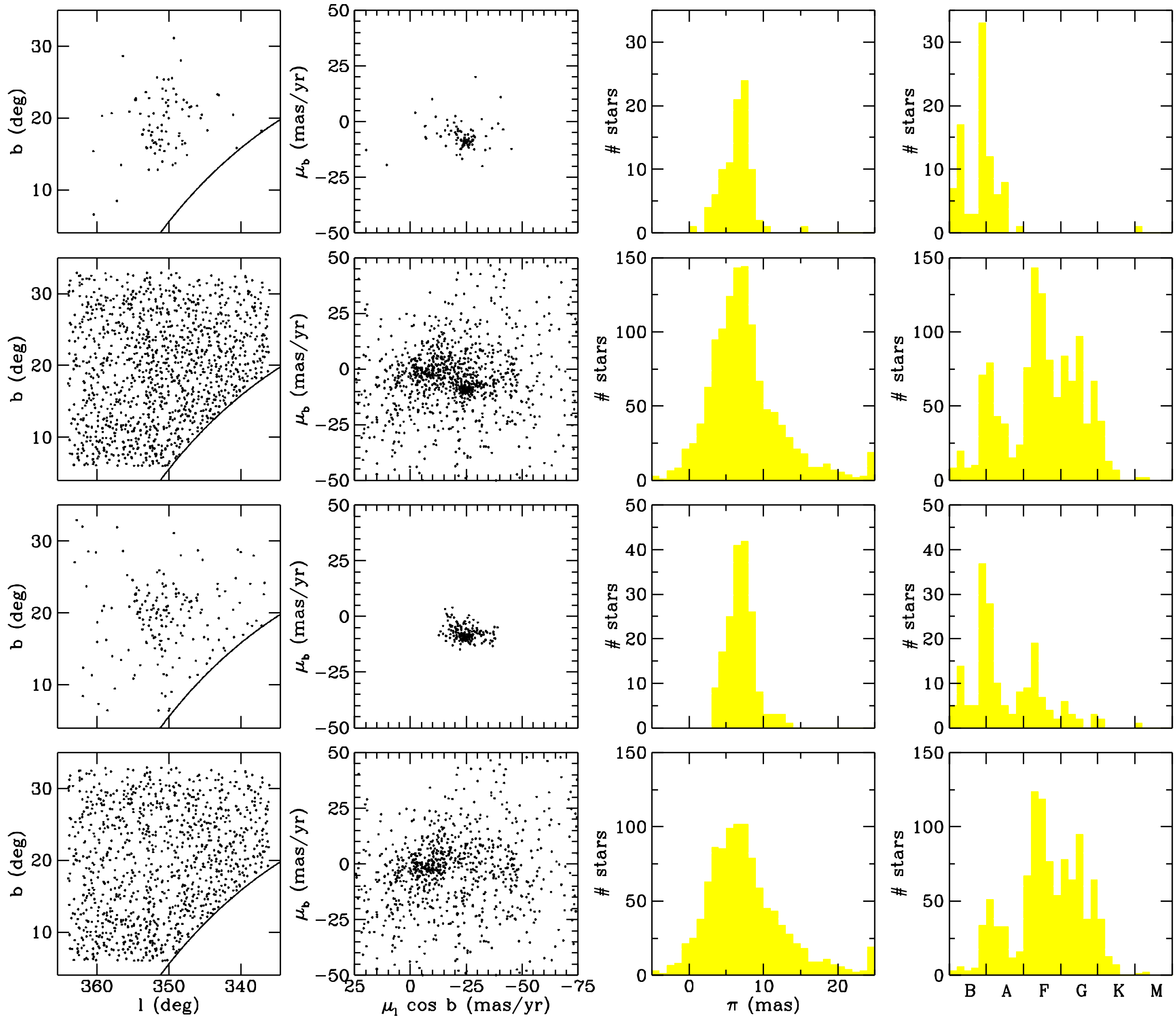

Figure 2. Hipparcos measurements for Upper Scorpius (from the top row down): (1) the 91 pre-Hipparcos members; (2) our data sample; (3) the 178 Hipparcos members; (4) the remaining stars in the sample after membership selection. The columns show (from left to right): (1) positions in Galactic coordinates; (2) Galactic vector point diagram; (3) trigonometric parallax distribution; (4) spectral type distribution. The M-type member is Antares (α Sco, M1Ib). The solid lines in column (1) denote the boundary $\delta = -34^\circ$ with Upper Centaurus Lupus. In the second panel of column (2), the Upper Scorpius clump around $(\mu_l \cos b,\ \mu_b) \approx (-25,\ -10)$ mas/yr is seen superimposed on the Galactic disk distribution. The spread in this clump is caused by a combination of perspective effects and observational errors.

ple of the squared and error-weighted proper motion components $\mu_\perp/\sigma_\perp$ perpendicular to the direction to the corresponding convergent point. This sum is distributed as χ^2 with $N-2$ degrees of freedom. If, after global minimization with respect to $(\alpha,\delta)_{\rm cp}$, the value of χ^2 is unacceptably high, the star with the highest value of $\mu_\perp/\sigma_\perp$ is rejected, after which minimization is repeated until a satisfactory value of χ^2 is obtained. Subsequently, all non-rejected stars are identified as members. This procedure allows for simultaneous convergent point determination and membership selection.

To make optimal use of the Hipparcos data, we developed a new kinematic membership selection method which uses, besides proper motions, also parallaxes. Each star is characterized by a line in velocity space: the proper motion and parallax determine the offset from the origin (tangential velocity), while the sky position of the star determines its direction (radial velocity; see Figure 1). The errors and correlations of the astrometric parameters transform the line into an elliptic cylinder. The cylinders of a set of stars with the same space motion all intersect. Thus, we can identify moving groups by searching for maxima in the density of cylinders in velocity space. All stars whose 3σ cylinders contain a maximum are selected as member of the associated group. The membership probability depends on the velocity dispersion of the group, and on the measurement errors.

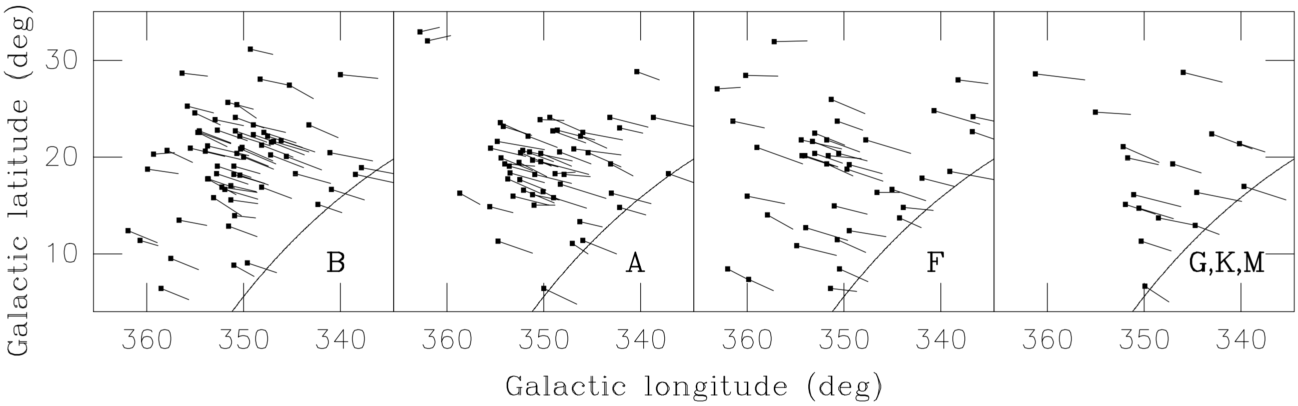

Figure 3. Proper motions for the Hipparcos members of Upper Scorpius, as a function of spectral type: 66 B, 54 A, 41 F, 14 G, 2 K stars, and 1 M star. The F, G, K, and M stars are co-moving with the B and A stars. The F-type stars have a similar distribution as the early-type stars, suggesting that the stellar content of the association has been established down to at least spectral type F. The probability that many of the G-type stars are interloper field stars is significant. Some stars near the field boundary $\delta = -34^\circ$ may be members of Upper Centaurus Lupus.

We have tested both methods on the Hyades cluster. Based on Hipparcos data and radial velocities, Perryman et al. (1997) identified 218 members which have three-dimensional space motions consistent with the cluster motion within 3σ limits. Within 10 pc of the cluster center ($\sim r_t$, the tidal radius), our membership list agrees very well with that of Perryman et al. Furthermore, we have performed extensive tests of both methods based on numerically simulated data sets of moving groups superimposed on a kinematic model of the Galactic disk. We have varied the position of the group on the sky, as well as its distance, streaming motion, internal velocity dispersion, and number of members. The observational errors and covariance matrix for each simulated star were chosen to be consistent with the data in the Hipparcos Catalogue. These tests indicate, in order of decreasing importance, that (i) a clear identification of the moving group requires it to stand out kinematically from the Galactic field distribution; and (ii) an increasing distance of the moving group complicates its identification. When proper motions combined with parallaxes do not allow the separation of the moving group from the Galactic field, accurate radial velocities are an indispensable tool in establishing kinematic membership (see the case of Orion OB1 discussed by de Zeeuw et al. 1997)

Both methods take the full Hipparcos covariance matrix into account. Neither method requires *a priori* knowledge on the (existence or characteristics of the) moving group. We combine the independent results of the two methods to define membership criteria: we consider as secure members all stars that are selected by both methods. Here we restrict our discussion to these stars.

3. UPPER SCORPIUS

Classical kinematic membership studies for Upper Scorpius identified 59 proper motion members with spectral types earlier than B8 (Blaauw 1946, Bertiau 1958, Jones 1971). Several photometric studies suggested membership for another 32 stars down to spectral type A8 (Hardie & Crawford 1961, Garrison 1967, Gutierrez–Moreno & Moreno 1968, Glaspey 1971, Glaspey 1972, de Geus et al. 1989). The upper panels of Figure 2 display the Hipparcos measurements for these 91 pre-Hipparcos members.

Our Hipparcos data sample for Upper Scorpius (see second panel row of Figure 2) is limited to the field $336^\circ \leq \ell \leq 4^\circ$, $6^\circ \leq b \leq 33^\circ$, with the extra restriction $\delta \geq -34^\circ$, which provides a boundary with the subgroup Upper Centaurus Lupus of Sco OB2 (see de Zeeuw et al. 1997). The sample contains 1215 stars within broad magnitude ranges, which depend on spectral type (see Table 1).

We first apply our membership selection to the B-type stars. This results in 66 members. The same procedure applied to the A-type stars yields 54 members. Application of our procedure to the *combined* sample of B and A-type stars gives identical results. We also detect the association in the F-type stars, but not as convincing as in the early-type stars. We find no signature of a moving group in the G-type stars. Therefore, we decided to use the 120 B and A-type members to define the space motion of Upper Scorpius. Then, we select the F, G, K, and M-type stars that have a space motion consistent with that of the early-type members. This results in 58 co-moving members. The third panel row of Figure 2 shows the measurements for all 178 Hippar-

Table 1. Visual magnitude limits of the Hipparcos data sample for Upper Scorpius, as function of spectral type.

Spec. type	Range	#	Spec. type	Range	#
O – B5	– 7.0	31	F0 – F4	7.5 –	238
B6 – B9	– 8.0	86	F5 – F9	8.0 –	244
A0 – A4	5.0 – 9.0	130	G	8.5 –	353
A5 – A9	7.0 – 9.5	69	K, M		64

cos members; 63 of them were previously known (43 kinematic, 20 photometric), while 115 of them are new! We confirm Antares (α Sco, M1Ib) as member, but reject the controversial classical proper motion member o Sco (A4II/III; see Blaauw et al. 1955, de Geus et al. 1989, de Zeeuw et al. 1997: Figure 2). The bottom panel row of Figure 2 shows the remaining field star population after membership selection. The small hole in the vector point diagram around $(\mu_l \cos b, \mu_b) \approx (-20, -10)$ mas/yr indicates that a few field stars might erroneously have ended up as members (see discussion below).

Analysis of the parallax distribution results in a mean distance $d = 145 \pm 2$ pc (where the quoted error corresponds to the error in the mean parallax), which can be compared to the value of $d = 160 \pm 40$ pc obtained by de Geus et al. (1989). The intrinsic depth of the association is not resolved by the Hipparcos parallaxes. The observed large spread in the vector point diagram is consistent with zero internal velocity dispersion. It can be fully explained by the combined effects of observational errors and projection on the sky. Unfortunately, this implies that the study of internal motions in associations based on Hipparcos proper motions is beyond our current capabilities.

Figure 3 shows the positions and proper motions for all the Hipparcos members, as a function of spectral type. The figure shows that there is a clear concentration in the early-type stars, surrounded by a group of 'outliers'. However, all stars in Figure 3 have astrometric parameters that are consistent with the space motion of the subgroup. We can remove interlopers (field stars) by using the radial velocity to determine the three-dimensional space motion for each star, and comparing it to that of the subgroup. In the absence of a coherent and homogeneous set of radial velocities for the majority of stars in our list of Hipparcos members, we have estimated the number of expected interlopers by Monte–Carlo simulation. We find that the observed clustering in the F-type star distribution cannot be explained by Galactic disk contamination, whereas the majority of the G-type stars can be explained as such.

The main concentration of F-type stars has spectral types earlier than ~F5. The Hayashi time scale for mid-F type stars is of the order of 5 Myr, which is comparable to the age of Upper Scorpius estimated from the Hertzsprung–Russell diagram (e.g. de Geus et al. 1989). If stars of later spectral types have formed in Upper Scorpius they should lie above the main sequence. As these objects lie near the faint limit of the Hipparcos Catalogue, careful analysis is needed to establish their numbers.

4. CONCLUDING REMARKS

We have developed a new method for identifying moving groups in velocity space, based on all five astrometric parameters obtained by Hipparcos. Combination of this method with a modern version of a classical convergent point method leads to a powerful procedure for identifying moving groups in the Hipparcos Catalogue. We applied this procedure to Hipparcos data for 21 fields related to the nearby OB associations. Results for some of these fields are described by Hoogerwerf et al. 1997 and de Zeeuw et al. 1997, the latter also gives a general overview of the project. Here we present results for Upper Scorpius. We establish a significant improvement of the pre-Hipparcos membership list, and an extension of it to much later spectral types including F-type stars, for a total of 178 kinematic members. Our membership list represents a suitable working set of stars; radial velocities are needed to remove remaining interlopers. The Hipparcos proper motions do not allow an analysis of the internal kinematics of Upper Scorpius.

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