STRUCTURE AND EVOLUTION OF NEARBY OB ASSOCIATIONS

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ABSTRACT

We present the first results of a comprehensive census of the stellar content of the nearby OB associations based on Hipparcos positions, proper motions and parallaxes for 12842 candidate member stars distributed over 21 fields on the sky. We use a new method to identify moving groups in these fields (see de Bruijne et al., these proceedings). Previously, astrometric membership in nearly all the nearby OB associations was known only for stars with spectral types earlier than B5. The Hipparcos measurements now allow us to identify members down to late F. This census provides a firm basis for studies of galactic and extragalactic star forming regions.

Key words: OB associations; HR diagram; luminosity calibration; stars: early-type

1. INTRODUCTION

Ever since spectral classifications for the bright stars became available it was evident that O and B stars are not distributed randomly on the sky, but instead are concentrated in loose groups (Blaauw 1964 and references therein). Ambartsumian (1947) found that the stellar mass density in these groups, which were subsequently called OB associations, is usually less than $0.1 M_\odot$ pc^{-3}. Bok (1934) had already shown that such low-density stellar groups are unstable against Galactic tidal forces, so that the observed OB associations must be young, a conclusion supported by the ages derived from Hertzsprung–Russell diagrams. These groups are prime sites for the study of star formation processes and of the interaction of early-type stars with the interstellar medium (see, e.g., Blaauw 1964, 1991 for reviews). Detailed knowledge of the stellar content and structure of OB associations allows us to address fundamental questions on the formation of stars in giant molecular clouds. What is the initial mass function? What are the characteristics of the initial binary population? What is the star formation efficiency? Do all stars in a group form at the same time? What process causes the distinction between the formation of bound open clusters and unbound associations? How is angular momentum redistributed during star formation?

The study of OB associations is also important in the context of the evolution of the Galaxy. The kinematics of the nearest OB associations provides insight into the properties and origin of the Gould Belt system. Furthermore, OB associations are responsible for large bubbles in the interstellar medium filled with hot gas (e.g., Mac Low & McCray 1988). More detailed knowledge of their stellar content is important for understanding the energetics and dynamical evolution of the bubbles. Ultimately, establishing the properties of the nearby associations is a prerequisite for the interpretation of observations of extragalactic star forming regions and starburst galaxies.

The Solar neighbourhood contains a number of OB associations, so that detailed studies are possible. The most reliable membership determinations for OB associations are based on proper motion studies. Although these groups are unbound, their expansion velocities are only a few km s^{-1} (e.g., Mathieu 1986), so that the common space motion is perceived as a motion of the members towards a convergent point on the sky (e.g., Blaauw 1946; Bertiau 1958). Membership determinations have been carried out by various investigators (see Blaauw 1964, 1991 and references therein). Due to their large extent on the sky, OB associations are not amenable to proper motion studies with photographic plates. Instead, one had to rely on proper motions from large scale surveys with meridian circles. This resulted in much uncertainty on membership of stars of spectral type later than B5. As a result, our knowledge of these young stellar groups remained rather limited.

In order to remedy this problem the `SPECTER` consortium was formed in Leiden in 1982. It successfully proposed the observation by Hipparcos of candidate members of nearby OB associations. An extensive program of ground-based observations was carried out in anticipation of the release of the Hipparcos data (see de Zeeuw et al. 1994). This included Walraven (*VBLUW*) photometry (de Geus et al. 1989; Brown et al. 1994), mm and radio observations of the interstellar medium surrounding the associations (de Geus 1992; Brown et al. 1995), and spectroscopy aimed at obtaining precise radial and rotational velocities (Verschueren et al. 1997; Brown & Verschueren 1997). Theoretical work included the distinguishing features of the formation of bound and unbound groups (Verschueren & David 1989), and the reliability of the so-called kinematic ages of OB associations (Brown et al. 1997a).

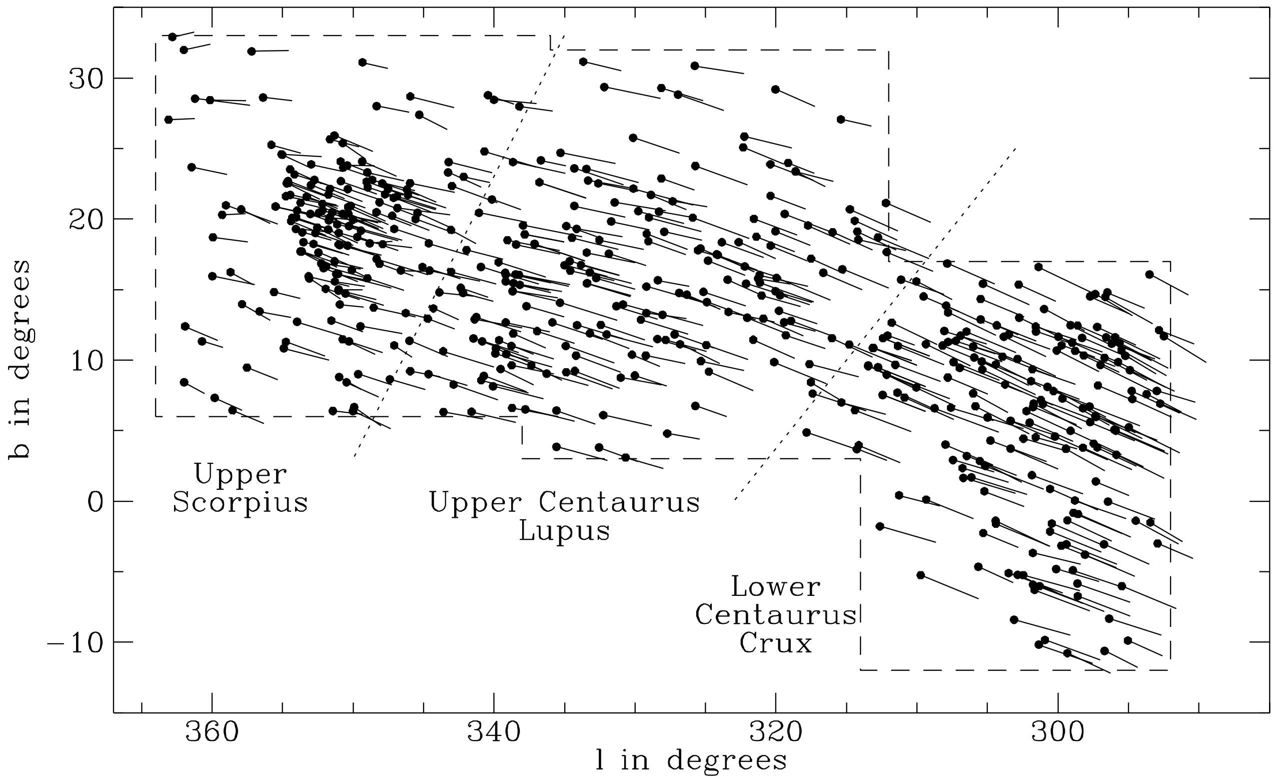

Figure 1. Proper motions for 532 members of the Sco OB2 association selected from 4156 candidate stars in our Hipparcos sample for the area bounded by the dashed lines. The dotted lines are the schematic boundaries between the three classical subgroups Upper Scorpius, Upper Centaurus Lupus, and Lower Centaurus Crux.

Here we present the preliminary results of the `SPECTER` census of the nearby associations based on the Hipparcos proper motions and trigonometric parallaxes. We have developed a new procedure to identify moving groups in the Hipparcos Catalog (de Bruijne et al. 1997), and have applied it to 21 fields for which we have Hipparcos data. The fields are centered on 18 known associations and 3 suspected groups, all within 800 pc from the Sun. A list of the fields and their boundaries, with the number of objects, can be found in de Zeeuw et al. (1994). The dataset also includes 153 candidate runaway OB stars as well as 49 stars from the dispersed Cas–Tau association. Below we discuss a few examples of the results obtained so far. Other examples are given in de Bruijne et al. (1997) and Hoogerwerf et al. (1997).

2. SCORPIO–CENTAURUS

The Sco OB2, or Scorpio–Centaurus, association contains three classical subgroups which differ in age (Blaauw 1946, Blaauw 1964; de Geus et al. 1989): Upper Scorpius, Upper Centaurus Lupus, and Lower Centaurus Crux. Our membership selection for Upper Scorpius is described in detail by de Bruijne et al. (1997). We have similarly analysed the other two fields. For Upper Centaurus Lupus 19 of the 29 classical proper motion members, and 30 of the 101 previously known photometric members were selected. We have discovered another 139 members. For Lower Centaurus Crux we confirm 15 of the classical 22 proper motion members, and 3 of the 10 additional photometric members. We have added another 148 members, including one M giant. Figure 1 illustrates the motions in the three fields, and shows that assigning boundaries to the subgroups is not trivial. The numbers given above are based on the preliminary boundaries used by de Zeeuw et al. (1994). Analysis of the entire Hipparcos Catalog, and inclusion of radial velocity data, is needed to determine the full extent of Sco OB2, and the division in subgroups.

Prior to the Hipparcos mission, we collected precise intermediate band Walraven $VBLUW$ photometry for 2243 of the 4156 Hipparcos stars in the three Sco OB2 fields (de Geus et al. 1989, 1990). We have measurements for 276 of the total of 532 Hipparcos members. Figure 2 shows the Walraven $[B-U]$ versus $[B-L]$ diagram for the previously suspected members (top) and the Hipparcos members (bottom). Figure 2 shows that the Hipparcos measurements allow identification of new members to much later spectral types, all the way to the mid F regime! The removal of interlopers in the pre-Hipparcos membership lists results in a much tighter correlation near the S-turn of the main sequence around $([B-L],[B-U]) \approx (0.2, 0.4)$. Stellar evolution moves stars towards the lower left: this causes the slight downward curve at the top of the main sequence. The remaining spread is caused by (i) peculiar spectra with, e.g., emission features (cf. 48 Lib and χ Oph), (ii) (undetected) duplicity/multiplicity; and (iii) stellar rotation: high values of $v \sin i$ move stars towards the lower left. This effect is strongest for B7 – B9 stars $(0.05 \lesssim [B-L] \lesssim 0.13)$.

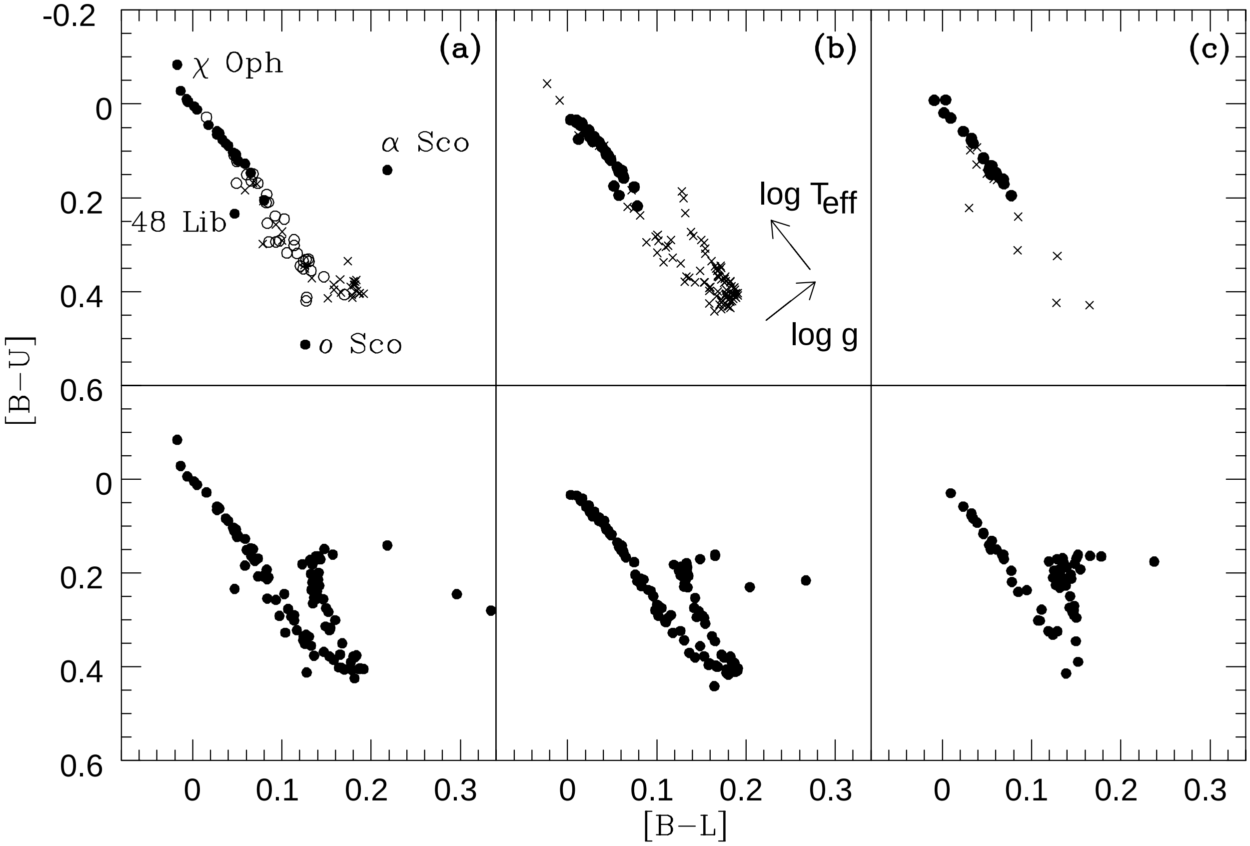

Figure 2. De-reddened Walraven colour-colour diagrams for the three classical subgroups of Sco OB2. a) 84/91 pre-Hipparcos 'members' of Upper Scorpius (top) and 106/178 new members (bottom) for which we have Walraven photometry. Specific stars are indicated. b) Idem for Upper Centaurus Lupus for 124/130 pre-Hipparcos 'members' and 106/188 new members, and c) for Lower Centaurus Crux for 34/42 pre-Hipparcos 'members' and 64/166 new members. The symbols in the top panels have the following meaning: solid dots are the classical proper motion members, the open circles are pre-Hipparcos probable proper motion members and the crosses indicate previously suggested photometric members. The arrows in (b) indicate the approximate directions of increasing $\log T_{\rm eff}$ *and* $\log g$.

The new membership lists can be used to derive reliable mass functions to much smaller masses than possible previously. This requires multi-colour photometry for all members, as well as a careful correction for incompleteness in the Hipparcos Catalog at faint magnitudes. Application of our membership selection procedure to simulated moving groups superimposed on the Galactic field population shows that the expected number of interlopers is insignificant for spectral types earlier than $\sim$ F5. De Geus et al. (1989) derived ages of $\sim$ 5 Myr for Upper Scorpius, $\sim$ 10 Myr for Lower Centaurus Crux and $\sim$ 13 Myr for Upper Centaurus Lupus. These values are not expected to change much, as most of the previously known bright members have been confirmed by our selection procedure. The stars beyond spectral type F may not yet have had time to reach the main sequence, and hence a detailed analysis of membership for these late-type stars will be very interesting.

3. VELA OB2

Brandt et al. (1971) noted the presence of 17 bright early-type stars within a few degrees of the Wolf–Rayet binary system γ^2 Velorum. They took the similar distance moduli for 10 of these stars (including the γ^2 Vel system) as evidence for an OB association at $\sim$ 460 pc: Vela OB2. Straka (1973) investigated SAO proper motions and Bright Star Catalog radial velocities for these 10 stars. Only 5 of them, including the visible multiple system γ^1 and γ^2 Vel, turned out to share a common space motion. Photometric evidence for the existence of an association at a distance of about 450 pc was provided by several large-scale studies (e.g., Upton 1971; Straka 1973; Eggen 1986).

Our Hipparcos sample for Vela OB2 contains 510 stars of spectral types O (9) and B (501) in the field $255^\circ \leq \ell \leq 270^\circ$ and $-20^\circ \leq b \leq 5^\circ$. The magnitude limits of our sample are $V \leq 9.0$ for the O and B0–B5 stars, and $V \leq 10.0$ for B6–B9 stars. Only 4 of the 10 Brandt et al. stars are confirmed as member. Of the 6 remaining stars, γ^1 Vel was not observed by Hipparcos, and the other 5 are rejected as members. However, our membership selection procedure iden-

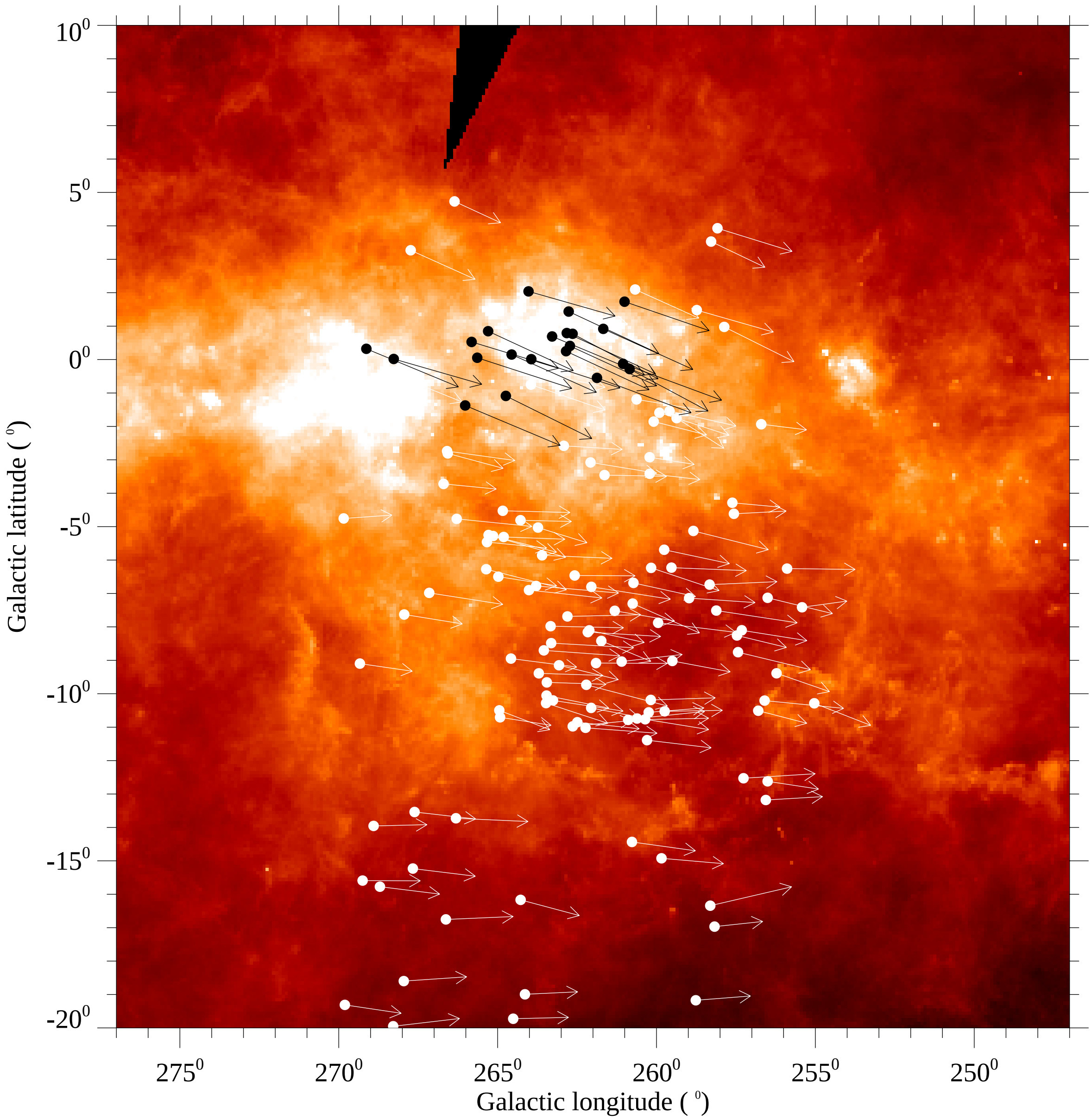

Figure 3. Proper motions in the Vela OB2 association superimposed on a grey-scale representation of the IRAS 100 μm skyflux. The white dots show the Vela OB2 members and the black dots show the members of Trumpler 10 (located at a distance of 362 ± 20 pc). The core of the Vela OB2 association is surrounded by the IRAS Vela shell.

tifies 112 new members for Vela OB2, which brings the total number to 116: 1 O9V star, γ^2 Vel, and 114 B-type stars!

We find a mean distance of $d = 415 \pm 10$ pc for Vela OB2. The intrinsic depth of the association cannot be resolved from the parallax distribution. The new members of Vela OB2 are concentrated on the sky around $(\ell, b) = (263°, -7°)$ within a radius of $\sim 5°$. Sahu (1992) reported the detection of the so-called IRAS Vela shell in the IRAS Sky Survey Atlas maps. This is an expanding shell, centered on Vela OB2, with a projected radius of $\sim 8°$ (Figure 3). Sahu assumed that (i) the center of the IRAS Vela shell has a distance of 460 pc, (ii) Vela OB2 is a 'standard association' with a 'normal' initial mass function, and (iii) Vela OB2 has an age of 20 Myr, and she showed that then the observed kinetic energy of the IRAS Vela shell is of the same order of magnitude as the total amount of energy that the stars have injected into the interstellar medium through the combined effects of stellar winds and supernovae. Now that the present stellar content and the distance of Vela OB2 have been determined, a careful multi-colour photometric study will allow a considerable refinement of Sahu's analysis. The Hipparcos photometry already indicates that many of the Vela OB2 member stars are evolved.

The Vela OB2 field contains a number of other moving groups. One example, Trumpler 10, is illustrated in Figure 3.

4. OTHER GROUPS

We have also detected moving groups in the fields of Per OB2 (Blaauw 1950), Lac OB1 (Blaauw & Morgan 1953), and Cep OB3 (Garmany 1973), and have confirmed the reality of the highly dispersed association Cas–Tau (Blaauw 1956). The associations α Persei (Per OB3) and Collinder 121, as well as a new group discovered in the field of Cep OB2, are discussed by Hoogerwerf et al. (1997). The Orion OB1 association has been studied extensively, mostly by photometric means (e.g., Warren & Hesser 1978; Brown et al. 1994). It lies at a distance of ~ 380 pc, near the direction of the Solar antapex. As a result, it is difficult to distinguish its members from the general Galactic disk population based only on the Hipparcos proper motions and parallaxes. We will report on this interesting association elsewhere.

Our Hipparcos sample also includes 153 candidate OB runaway stars. The study of these stars is of interest for settling the question of their origin; supernova explosions in high mass binaries (Blaauw 1961) or dynamical ejection (e.g., Gies & Bolton 1986). We are in the process of retracing the paths of the runaways and the OB associations in the Galactic potential in order to identify the parent associations, as well as the age of the runaways. This is of considerable interest for studies of high mass binary evolution (e.g., van Rensbergen et al. 1996) and of high mass X-ray binaries (e.g., Kaper et al. 1997).

5. DISTANCES

We have used the Hipparcos parallaxes for the members in the associations to determine their mean distances. This requires some care, as the inverse of the parallax is a biased distance indicator (Brown et al. 1997b). As there is no evidence for a strong central concentration of stars in our associations, we assume that to first order the members are distributed homogeneously in a sphere. In this case the expectation value of the mean of the measured parallaxes is equal to the true parallax, and corresponds to the true distance of the association. The resulting distances to the associations are presented in Table 1. The errors are derived from the errors in the mean parallaxes. Figure 4 shows that the new distances to the associations are systematically smaller than previous estimates which were based mostly on photometry.

Due to the selection effects in the Hipparcos Catalog, the observed distribution of parallaxes may not be representative of the true underlying parallax distribution of an association. For example, magnitude limits will bias the sample towards the stars closest to us, and therefore could be responsible for (part of) the discrepancy evident in Figure 4. For this reason we have carried out Monte Carlo simulations of the distance determination of spherical associations, which take into account the luminosity function, the Hipparcos selection (in a crude approximation) and the error on the parallax as a function of apparent magnitude. We find that the magnitude limit bias is small, and conclude that the results presented in Figure 4 are robust. Part of the difference in distances is no doubt due to the greatly improved membership lists, especially for the more distant associations. However, we suspect that the calibration of the upper main sequence in the Hertzsprung–Russell diagram may need revision.

Table 1. Distances to OB associations. The first column lists the association and the second column the number of members identified from our Hipparcos sample. The third column contains the pre-Hipparcos estimate of the distance to these associations and the last column lists the distance derived from the mean Hipparcos parallax. The errors on the Hipparcos distances correspond to the errors in the mean parallax.

Name	N	$D_{\rm cl}$ (pc)	D (pc)
Upper Scorpius	178	160	145 ± 2
Upper Centaurus Lupus	188	145	140 ± 2
Lower Centaurus Crux	166	120	118 ± 2
α Persei/Perseus OB3	87	170	176 ± 5
Perseus OB2	26	360	305 ± 25
Trumpler 10	21	400	362 ± 20
Vela OB2	116	450	415 ± 10
Lacerta OB1a	45	530	382 ± 25
Lacerta OB1b	24	530	364 ± 25
Collinder 121	105	760	546 ± 30
Cepheus OB2	49	790	559 ± 30

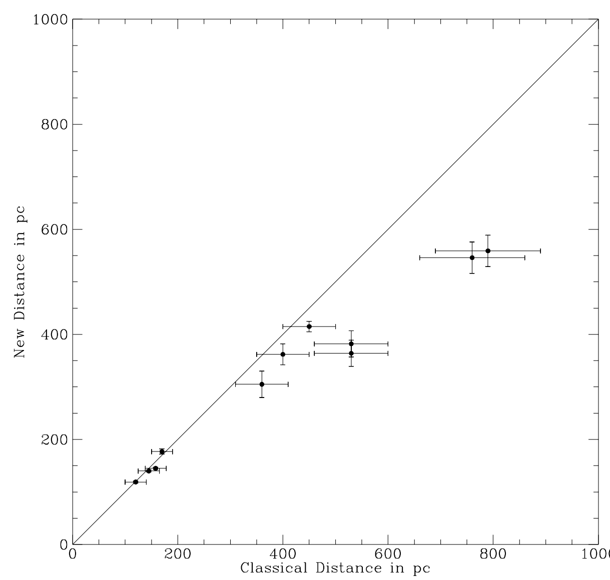

Figure 4. Distances derived from the mean parallax of the Hipparcos members of OB associations versus previous best estimates of the distance to these associations.

6. CONCLUDING REMARKS

Application of our membership selection procedure to Hipparcos parallaxes and proper motions for 12842 candidate stars in 21 fields with previously known or suspected OB associations has significantly improved our knowledge of their stellar content. The number of firmly established kinematic members has increased dramatically. The membership lists for the early spectral types have been refined, and many new members have been found of later spectral type, into and in some cases beyond the regime of the F stars, which is the range where the stars in these young groups are still in their pre-main sequence phase.

The measured distances for the associations are systematically smaller than indicated by previous photometric determinations. Whereas part of this effect must be caused by the much improved membership lists, especially for the more distant groups, we suspect that a recalibration is needed of the upper main sequence in the Hertzsprung–Russell diagram.

The next step is to re-examine our 21 fields, and the adjacent regions, using all data contained in the Hipparcos Catalog. We expect to find additional members that were not included because of our magnitude limits or field boundaries. The resulting astrometric membership lists can then be refined further by radial velocity measurements. This is now feasible, as the astrometric membership selection has reduced the number of candidate association members in a field typically by an order of magnitude. This also applies to the required completion of the multi-colour photometry. In the near future we will obtain radial velocities for the associations Lac OB1, Cep OB2 and Per OB2 from approved observations at the McDonald and Haute-Provence observatories. We will study the binary population in Sco OB2 by means of radial velocity measurements and near-infrared adaptive optics searches for close companions to the B-type stars. Subsequently we will extend these studies to the other associations.

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