OB ASSOCIATIONS

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1. Introduction

Starting with the earliest studies of the distribution of the bright stars by Kapteyn, Rasmuson, and Pannekoek ([80], [81], [110], [118], and [119]), it was evident that O and B stars are not distributed randomly on the sky, but instead are concentrated in loose groups, which were subsequently called 'OB associations'. This inspired research on their individual properties, and on their motions and space distribution. From dynamical considerations it followed that OB associations must be young [4], a conclusion supported later by the ages derived from color-magnitude diagrams. Blaauw's 1964 review [9] already discussed the relation between OB associations and interstellar matter. Subsequent observations of molecular clouds (e.g., [151], [16]) indicated that these groups are usually located in or near star-forming regions, and hence are prime sites for the study of star formation processes and of the interaction of early-type stars with the interstellar medium.

An important aspect of the study of OB associations is the identification of their 'members'. Associations have small internal velocity dispersions (e.g., [99], [130]), so that the streaming motion of the association as a whole, as well as the Solar motion, is reflected as a motion of the members towards a convergent point on the sky (e.g., [6]). This can be used to establish membership of these 'moving groups' based on measurements of proper motions. At the time of the previous NATO-ASI on star formation [85] few astrometric membership studies existed for nearby OB associations because these generally cover tens to hundreds of square degrees on the sky. Ground-based proper motion studies therefore almost invariably had been confined to modest samples of bright stars ($V \lesssim 6$) in fundamental or meridian circle catalogues, or to small areas covered by a single photographic plate. Photometric studies can extend membership to later spectral types (e.g., [143]–[145]), but are less reliable due to, e.g., undetected duplicity, or the distance spread within an association. As a result, membership for many associations had been determined unambiguously only for spectral types earlier than B5 (e.g., [9], [13]).

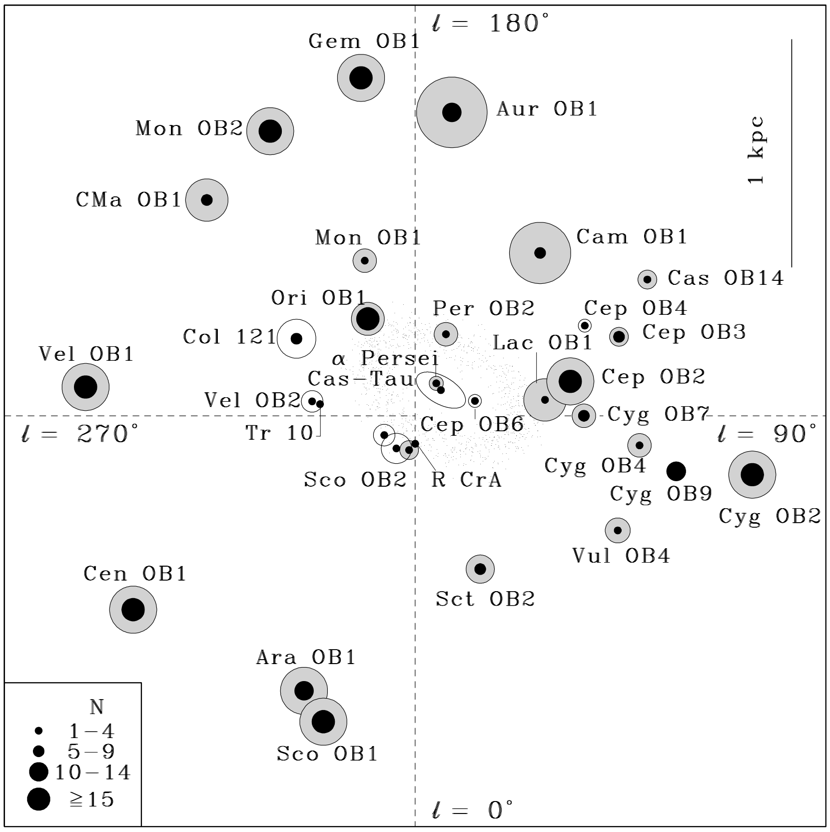

Figure 1. Locations of the OB associations within ∼1.5 kpc, projected onto the Galactic plane. This figure is an update of Figure 8 in [13] and is based on a list by Ruprecht [122] (see de Zeeuw et al. [150] for more details). The Sun is at the center of the dashed lines which give the principal directions in Galactic longitude, ℓ. The sizes of the circles represent the projected dimensions of the associations, enlarged by a factor 2 with respect to the distance scale. The sizes of the central dots indicate the degree of current or recent star formation activity, as given by the number N of stars more luminous than absolute magnitude $M_V \sim -5$ [76]. Associations which are absent from Ruprecht's list are represented as open circles. The distribution of small dots indicates the Gould Belt [115]. Figure 9 presents the post-Hipparcos map of the nearby OB associations.

This review is concentrated on OB associations located within ~ 1.5 kpc from the Sun, and updates and extends the chapter by Blaauw in the previous edition of this NATO-ASI [13]. The material discussed in Blaauw's chapter is still relevant but we chose to emphasize the developments in the field since 1991. The X-ray surveys by the EINSTEIN and ROSAT satellites enabled the identification of large numbers of low-mass stars in OB associations. Major progress in the identification of high-mass members of OB associations has been made possible through the use of precise astrometric data from the Hipparcos Catalogue [50]. Also, Blaauw's 1964 review [9] still is essential reading. Reviews concerning OB associations throughout the Local Group include [60], [97], and [103]. In addition there are conference proceedings that contain material on OB associations: [20], [33], [79], [100], and [132]. For more background on the historical development of OB association research we refer to [9], [30], [49], and [150].

This chapter proceeds as follows. §2 discusses the reasons for studying OB associations. §3 describes the problem of accurately defining what is meant by an OB association. §4 contains an overview of recent ground-based studies of OB associations, and §5 describes the Hipparcos census of the nearby OB associations [150]. §6 contains a discussion of Gould's Belt and the origins of OB associations. §7 points out directions for future research.

Most of the OB associations discussed here appear in a list compiled by Ruprecht [122], which contains field boundaries, some bright members, distances, and uses a consistent nomenclature, which was subsequently approved by the IAU. Figure 1 shows the distribution of the nearby OB associations, based on Ruprecht's list and including additional associations discussed by De Zeeuw et al. [150], projected onto the Galactic plane.

2. The Importance of Studying OB Associations

In the context of star formation a detailed examination of the stellar content, structure, and kinematics of OB associations allows us to address the following fundamental questions:

- What is the initial mass function? Young stellar groups are prime sites for the study of the initial mass function (IMF) because the corrections for stellar evolution and star formation history are minimal or at least straightforward [125]. Moreover, OB associations contain the entire range of stellar masses (cf. §§4.1 and 4.2).
- What are the characteristics of the binary population? A detailed answer to this question will furnish a better understanding of the processes through which binaries form, but also of the formation of massive stars and star clusters. Recent theories ([21], [22], and the chapter by Bonnell in this volume) predict the occurrence of few widely separated binaries among systems with

massive primaries. A characterization of the binary population in OB associations is a direct test of these theories.

- OB associations have traditionally been characterized as unbound groups of stars [9]. However, the youngest subgroup of Ori OB1, the Orion Nebula Cluster, may eventually evolve into a bound cluster [71]. What causes the distinction between the formation of bound open clusters and unbound associations? Various studies show that the fate of a particular young group of stars depends on the gas fraction, the time scale on which this gas is removed and the stellar velocity dispersion (e.g., [84], [135]). However, the processes that set the values of the above parameters during the formation of a star cluster are not well understood.
- Observations show that molecular clouds and cloud cores contain much more angular momentum than the stars that form from them (e.g., [18], [105]). How is angular momentum redistributed during star formation? What is the resulting distribution of rotational velocities of stars? Important clues to the answers of these questions may be obtained from studies of the distribution of rotational velocities of the members of OB associations in conjunction with studies of their binary population.
- O- and B-type runaway stars are a subset of the O and B stars characterized by their high space velocities, up to 200 km s^{-1}, and almost complete absence of multiplicity. For a number of these stars, the motion through space, when traced backwards in time, leads to the identification of a parent OB association. Possible mechanisms for the origin of the OB runaways are: release of the secondary following the supernova explosion of the primary member of a binary [8], and purely dynamical interactions amongst members of a protocluster [58]. The precise characterization of OB runaways as well as more identifications of parent associations can provide more insight into massive binary evolution [120] and massive star formation [34]. OB runaways were most recently reviewed by Blaauw [14].

Further questions related to star formation that can be addressed through studies of OB associations include the star formation rate and efficiency, the issue of the star formation history in clusters and associations (i.e., do all stars in a group form at the same time?), and the propagation of star formation throughout molecular cloud complexes (i.e., sequential star formation [45]). In a broader context the investigation of OB associations is important for numerous areas of Galactic and extragalactic research. A few examples follow:

- The calibration of the absolute luminosity of the upper main sequence is based largely on the bright members of the nearest OB associations (e.g., [7]).
- Massive stars influence the interstellar medium through their ionizing radiation, stellar winds, and supernovae. They may be responsible for determining the pressure of the gas and the velocity dispersion of atomic clouds [101],

and for the destruction of the molecular clouds in which they are born. Acting collectively, massive stars in OB associations have an even larger impact on the evolution of the interstellar medium and create H I supershells and superbubbles (e.g., [131]).

- The recent discovery of unexpectedly large amounts of gamma-ray emission in the direction of the Orion molecular cloud complex [15] have been linked to the presence of the nearby O and B stars in Ori OB1 (e.g., [111]).

The nearby associations contain few massive stars: even in Ori OB1 the upper mass limit is only about 50 $M_\odot$. More distant associations enable the determination of the IMF for the most massive stars. A well-known example of an OB association beyond 1.5 kpc is NGC 3603, which contains 50 O stars and ionizes the second most luminous H II region in the Galaxy [44]. The Carina H II region/molecular cloud complex contains numerous star clusters, the most famous of which are Trumpler 14 and 16 [24]. The latter are among the most massive clusters in the Galaxy and contain many O stars, including some of type O3 ($\gtrsim$ 80 $M_\odot$).

A better characterization of the IMF at the high-mass end, the luminosities and spectral characteristics of massive stars, and the fraction of Wolf–Rayet stars in OB associations are essential items to consider when interpreting observations of extragalactic starforming regions and starburst galaxies.

3. Defining Characteristics of OB Associations

In 1947 Ambartsumian [3] introduced the term 'association' for groups of OB stars; he pointed out that their stellar mass density is usually less than 0.1 $M_\odot$ pc^{-3}. Bok [19] had already shown that such low-density stellar groups are unstable against Galactic tidal forces, which led Ambartsumian to conclude that OB associations must be young ($\sim$10 Myr) [4]. Because of these low stellar densities associations will quickly disperse. This makes them hard to recognize once they are older than about 25 Myr due to their large spatial extent ($\sim$10–50 pc). These properties were used in the earliest definitions of OB associations given by Ambartsumian and Blaauw [3], [9]. However, such definitions do not necessarily encompass all associations. For example, the Orion Nebula Cluster is considered a subgroup of the Ori OB1 association, but is likely to remain bound and thus compact [71]. If the cluster in reality is unbound a velocity dispersion of a few km s^{-1} will be enough to disperse it from its present 1 pc size to a size of a typical OB association within 5–10 Myr.

Another definition of an OB association was proposed by Lada & Lada [86]; a group of at least 10 members whose stellar density is less than 1 $M_\odot$ pc^{-3}. However, as the authors themselves pointed out, this would mean that the Hyades would be classified as an OB association and the association NGC 2264 as an open cluster. This led Brown et al. [27] to define OB associations as those stellar groups that are left unbound after the process of gas removal from the protocluster has been concluded. This is not a very practical definition as it is not easy to determine whether a particular stellar group is bound or not.

Recently, the problem of accurately defining the term ‘OB association’ has been discussed by Elmegreen & Efremov [49]. Numerous observational selection effects that occur when looking for OB associations are considered. For instance, how stellar groups are selected depends on distance, because a particular group of luminous stars can resemble a dense cluster if it is at a large distance, or a rarefied association if it is nearby. Observations of patches of Cepheid variables in the LMC and in local star formation regions [48] reveal a correlation between the duration of star formation in a region and its size. This means that if an OB association is defined as a grouping of OB and other young stars of, for example, less than 10 Myr, the association will be observed to have a maximum size of about 50 pc because larger regions will generally contain older stars. Elmegreen & Efremov argue that these difficulties arise because there is no physical scale associated with star formation. Rather, there is a whole hierarchy of scales varying from single/binary stars to star clusters, star complexes, and even up to small pieces of a spiral arm. In combination with the size-age correlation mentioned above this will lead to stellar groupings with particular dimensions being selected according to the age limits imposed. Hence, if one allows for enough range in age it could be argued that all of Gould’s Belt, consisting of several associations and a wider distribution of early-type stars in the Solar neighbourhood, is actually one association. It is further argued [49] that the hierarchical and scale-free nature of star formation results from the fractal structure of interstellar gas. However, McKee & Williams ([102], [147]) showed that there is a physical upper limit to the size of OB associations and giant molecular clouds. This finding supports the idea that the characteristic sizes observed for OB associations ($\sim$10–50 pc) are a reflection of the sizes of giant molecular clouds from which they form. Moreover, it was recently inferred that the nearest molecular cloud complex, in Taurus, has a characteristic size scale and hence does not have a fractal structure [17].

Based on studies of Hertzsprung–Russell diagrams for OB associations it was realized early on [9] that several associations could be divided further into subgroups. These can primarily be distinguished on the basis of the ages of their members and their degree of association with interstellar matter ([9], [61], [143], [145]). Defining the boundaries of these subgroups is a thorny question. To date, one cannot distinguish subgroups kinematically, not even with proper motions of Hipparcos accuracy (see §5). A good example is Ori OB1. Originally this association was divided into four subgroups 1a–1d [9]. Subgroup 1b consists of the stars around Orion’s Belt and was further subdivided in some studies, but was recently treated as a whole [25]. The latest finding on the Belt stars is that the star σ Ori is surrounded by a cluster of young stars, which may represent an older analogue of the Trapezium cluster [140], [141]. This suggests that more such clusters of pre-main sequence stars surrounding bright OB stars may be found and a further subdivision of subgroup 1b may thus be warranted. This serves as a warning that established subgroup boundaries in associations are not 'cast in stone' and that future work may lead to different subdivisions.

In summary, it is not entirely trivial to accurately define what is meant by the term 'OB association'. Nevertheless, for the purpose of this review we define OB associations to be young ($\lesssim$50 Myr) stellar groupings of low density—such that they are likely to be unbound—containing a significant population of B stars. Their projected dimensions range from $\sim$10 to $\sim$100 pc.

4. Recent Research

We now turn to work on OB associations carried out since 1991 but before the availability of Hipparcos data, and grouped by subject. We first concentrate on the high-mass stars and then discuss low-mass stars. This overview is not intended to be complete but serves as an introduction to recent literature on OB associations.

4.1. HIGH-MASS STARS

Stellar Content. Extensive studies of the stellar content of OB associations were carried out using photometric data. As explained in §1 this allowed an extension of membership lists to later spectral types, for which no accurate large-scale proper motion surveys were available yet. The work on Sco OB2 was summarized in [13] and the details can be found in [61].

The Ori OB1 association consists of four subgroups: 1a, located to the northwest of Orion's Belt, 1b, located around the Belt, 1c, located around the Sword of Orion, and 1d, which is the Trapezium cluster (see figure 7 in [13]). Brown et al. [25] analyzed available Walraven photometry [94] for Ori OB1. Model atmospheres and empirical calibrations were used to determine effective temperatures, surface gravities, and absolute bolometric magnitudes of the stars, and to derive ages for the association subgroups by isochrone fitting in the Hertzsprung–Russell diagram. It was found that the distances to subgroups 1a–1c are 380, 360, and 400 pc, respectively. The distance to 1d could not be determined reliably due to the nebulosity in that region and insufficient stars. These distances were smaller than the distances derived previously, a result which also followed from a reanalysis of the data of Warren & Hesser [143] using a revised calibration of the $uvby\beta$ system [5]. The ages of the Ori OB1 subgroups were found to be 11.4 ± 1.9 Myr for 1a, 1.7 ± 1.1 Myr for 1b, 4.6 ± 2 Myr for 1c, and less than 1 Myr for subgroup 1d. The IMF was found to be a single power law with $\mathrm{d}\log(\xi(\log m))/\mathrm{d}\log m = -1.7 \pm 0.2$ for all three subgroups (see also [30]).

Finally, we mention Cep OB3, which is considered to be an example of sequential star formation [45]. The most recent studies of its stellar content are by Jordi et al. [77], [78]. Strömgren photometry was used to refine and extend the

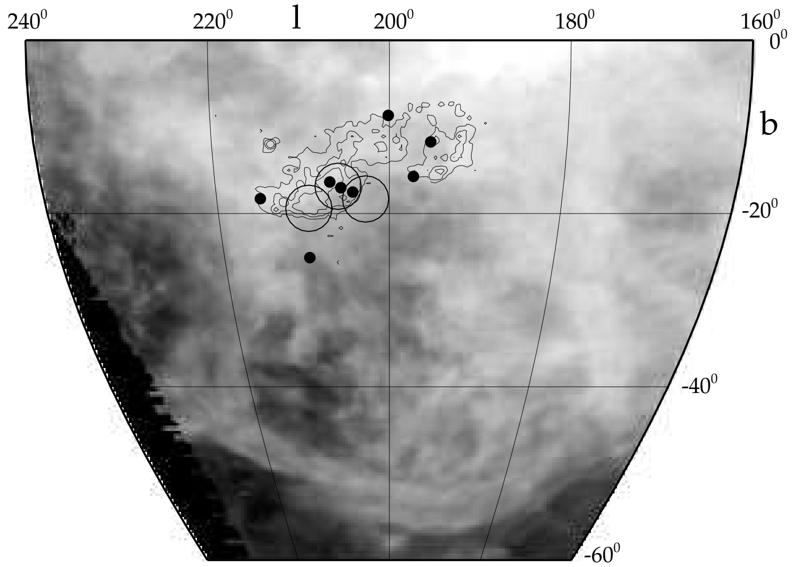

Figure 2. The Orion–Eridanus bubble. The grey-scale image is a logarithmically scaled representation of integrated H I emission from the Leiden–Dwingeloo survey in the velocity interval -1 km s^{-1} $\leq v_{\rm LSR} \leq +8$ km s^{-1}. The contours outline the 100 μm (IRAS) emission from the Orion A and B molecular clouds (the ring around $(\ell, b) = (195°, -12°)$ is the λ-Orionis ring). The dots show the brightest stars in the Orion constellation. The circles show the positions of the three main subgroups of Ori OB1. From right to left are shown 1a, 1b and 1c.

membership lists towards fainter stars. The existence of two subgroups in this association was confirmed and the ages were found to be 5.5 and 7.5 Myr.

Interstellar Medium. The nearby OB associations offer a uniquely detailed view of the relation between early-type stars and the interstellar medium (cf. §2) which helps us understand the impact of associations on the interstellar matter throughout the Galaxy. Much work has been done since 1991, concentrating especially on the interstellar medium around Ori OB1. The characteristics of the interstellar medium related to Sco OB2 were summarized in [13] and [62].

For summaries of studies of the interstellar gas in the vicinity of Ori OB1 we refer to [100]. The impact of the early-type stars in this association has been addressed recently in a series of studies, [26], [32], [67], and [129], taking advantage of the availability of surveys such as IRAS, the ROSAT all sky survey, and the Leiden–Dwingeloo H I survey [69]. Figure 2 shows the distribution of H I around Orion over the velocity range -1 to $+8$ km s^{-1}. One can clearly distinguish a cavity surrounded by a shell of H I, the Orion–Eridanus bubble. The same features can be seen in an image at 100 μm from IRAS [26], and the whole of the cavity is filled with very hot gas, $\sim$10^6 K, emitting in X-rays [32], [26], [129].

The shell has a measured expansion velocity of about 40 km s^{-1} and a mass of $2.3 \pm 0.7 \times 10^5$ $M_\odot$. Taking into account the IMF and the ages of the subgroups, the mechanical energy output in the form of stellar winds and supernovae over the lifetime of the association was estimated to be $\sim 10^{52}$ ergs [25]. Using semi-analytic models of wind-blown bubbles that take the density stratification of the Galactic H I layer into account [83], it was shown that this energy is indeed enough to account for the size as well as for the expansion velocity of the H I shell [26].

Early-type stars also have a large effect on the interstellar medium through their ionizing radiation, producing both localized H II regions and diffuse ionized gas. Based on the distribution of OB associations in the Galaxy, it was shown that their luminosity function can be fit with a truncated power law, and that there probably is a physical limit to the maximum size of H II regions in the Galaxy [102]. A comparison with the distribution of giant molecular clouds [147] showed that a 10^6 $M_\odot$ cloud is expected to survive about 30 Myr, and that on average 10 per cent of its mass is converted into stars by the time it is destroyed (see also the chapters by Blitz and by McKee). The overall distribution of associations is also important for understanding the hot-gas filling factor of the interstellar medium [55]–[57].

Formation of Stellar Clusters. Detailed studies of young clusters and OB associations lead to more insight into the formation of these systems (cf. §2). In an effort to address this question the Orion Nebula Cluster (ONC), with the Trapezium cluster at its core, was studied extensively by Hillenbrand [70]. An optical sample of ~ 1600 stars within 2.5 pc from the Trapezium stars was studied with photometry and spectroscopy. The overall IMF of this core region of the ONC was found not to be grossly inconsistent with 'standard' stellar mass spectra. The observed IMF appears to peak at ~ 0.2 $M_\odot$ and to fall off rapidly towards lower masses. Several substellar objects were identified. The total mass of the stars was found to be ~ 1800 $M_\odot$, and their mean age is less than 1 Myr, with the younger stars being concentrated towards the centre. Mass segregation was shown to be present in the ONC and it is probably not due to dynamical relaxation of the cluster, implying that the massive stars formed near the centre of the cluster. This confirms one of the predictions of cluster formation theories as discussed in the chapter by Bonnell. A study of the wider distribution of stars around the Trapezium shows that the ONC has an elongated structure similar to that of the molecular gas distribution in the region, suggesting that the cluster may still retain a memory of the geometry of the protocluster cloud [71].

Chemical Evolution. The interstellar medium in the Galaxy is continually enriched in chemical elements by stellar winds and by ejecta from supernovae. OB associations are generally still located near molecular clouds and thus are ideal sites for studying ongoing chemical evolution processes in the Milky Way. Abundance patterns of stars in Ori OB1 have been studied by Cunha et al. [38]–[41]. The abundance analysis shows that the stars in Ori OB1, in common with the Orion Nebula H II region, are underabundant in Oxygen with respect to the Sun. The lowest abundances are found in subgroups 1a and 1b. The Trapezium stars and some stars of subgroup 1c seem to have O abundances that are up to 40 per cent higher than those in subgroups 1a and 1b (although still subsolar). It is suggested that this is due to enrichment of the interstellar gas by mixing of supernovae ejecta from subgroup 1c with the gas that subsequently collapsed to form the Trapezium Cluster [38]. This enrichment scenario is confirmed by the fact that Cunha et al. [39] observe no abundance variations for C, N, and Fe, but do observe the same variations for Si as for O, as one would predict for cloud material enriched by Type II supernova ejecta. Supernovae must have occurred in Ori OB1 in the past given the presence of the Orion–Eridanus bubble. It is estimated that 1 to 2 supernovae have occurred in subgroup 1c [25].

Kinematic Ages. Because OB associations are unbound they will expand [4]. In principle one can use this expansion to trace back the motions of the stars in an OB association until some minimum configuration is reached (see e.g., figure 5 in [13]). The time at which this happens would then correspond to the kinematic age of the association, which can be compared to the age derived from the Hertzsprung–Russell diagram. Also, an estimate is obtained of the initial configuration of the association just after it was formed. Kinematic ages have in fact been determined for a number of associations [11], [12], [59], [87], and [89]. However, it was demonstrated that tracing back proper motions in OB associations always leads to underestimated ages and overestimated initial sizes [27]. The main reason is that the space motions of the stars are not rectilinear but are influenced by the N-body interactions in the initially more compact association, by the effects of the remnant molecular cloud, and by the Galactic tidal field.

Binaries. Among the most important clues to understanding the process of star formation are the characteristics of the binary population. Recently, a number of searches for spectroscopic binaries in Sco OB2 and Ori OB1 were carried out [90], [104], and [136], and the statistics of close binaries among early-type stars were summarized by Blaauw [13]. The problem in studying the binary population among early-type stars in OB associations is to obtain precise radial velocities for these stars, which is very difficult due to stellar rotation and the small number of spectral lines [137]. Nevertheless, we can expect progress to be made in the near future when Hipparcos data on binaries is analyzed.

With the advent of speckle and adaptive optics techniques, both in the optical and infrared, much attention has been devoted recently to studying the population of binaries among the stars in the Trapezium cluster and the pre-main sequence stars in Sco OB2 [113], [23]. Both studies conclude that the characteristics of the binary population depend on the star forming environment. In particular, Brandner & Köhler [23] suggest that the conditions which favor the formation of high-mass stars apparently lead to the formation of close binaries among low-mass stars, whereas conditions unfavorable to the formation of high-mass stars lead to the formation of wider binaries among low-mass stars. This bears directly on the issues discussed in the chapter by Bonnell in this volume.

4.2. LOW-MASS STARS

Extrapolating the mass function for OB stars, such as derived in Sco OB2 and Ori OB1 [62], [25], reveals that the bulk of the stars should be of low mass ($\lesssim 2\ M_\odot$). Indeed, evidence was found early on for the presence of low-mass stars in the vicinity of the Orion Nebula [68], [138]. A search of the IRAS Point Source Catalogue for young stellar objects [117] shows how the distribution of these stars clearly outlines some of the OB associations, such as Ori OB1 and the Upper Scorpius (US) subgroup of Sco OB2. Large-scale proper motion searches for these fainter members of OB associations suffer from a much larger contamination by field stars, making it hard to identify the members without additional information. Hence, other techniques are employed in the search for low-mass members of OB associations. The two most widely used are objective prism Hα surveys, which are sensitive to classical T-Tauri stars, and X-ray surveys, also sensitive to weak-line T-Tauri stars (see the chapter by Ménard & Bertout).

An EINSTEIN observatory X-ray search was used to look for the low-mass population of US [139]. After correcting for the incompleteness of the X-ray sampling, it was concluded that the association has a field star mass function between about 0.2 and 10 $M_\odot$. The total number of low-mass stars ($< 2\ M_\odot$) is about 2000, which is in good agreement with the number of low-mass stars inferred by de Geus [62]. Recent X-ray studies, based on the ROSAT all-sky survey [116], [126] reveal the presence of many more X-ray selected pre-main sequence (PMS) candidates throughout Sco OB2. Preibisch et al. [116] performed spectroscopic follow-up observations to confirm the PMS character of the X-ray selected sources and also looked for PMS stars among objects without X-ray detections but with proper motions suggesting that they might be members of Sco OB2. No PMS stars were found among these proper motion selected candidates and these authors conclude that the X-ray selected sample of PMS stars is at least 75 per cent complete. However, Sciortino et al. [126], using ROSAT HRI, PSPC and all-sky survey observations, showed that the observations by Walter et al. [139] were much more incomplete than reported. They concluded that EINSTEIN and ROSAT data are far from giving a complete characterization of the X-ray population of US, implying the presence of even more PMS stars in Sco OB2.

To confirm the PMS nature of the objects detected in X-ray surveys the so-called Lithium test is used. Essentially one measures the strength of the Li line which is correlated with stellar age for PMS stars. Main sequence stars should have depleted all their Li in nuclear burning processes, and thus the presence of Li indicates the PMS character of the object under study. However, it has recently been pointed out that the Li test is not completely reliable [51]–[53]. Especially, when using low-resolution spectra to study the Li line one may confuse young and active main sequence stars with bona fide PMS stars, thus further complicating studies of the IMF down to the lowest masses.

In Ori OB1 the Kiso Hα survey [106], and the EINSTEIN [140], [141] and ROSAT [1] X-ray surveys have uncovered hundreds of emission-line and X-ray sources of which many are likely to be PMS or T-Tauri stars. Spectroscopic follow-up observations indeed confirmed the PMS nature of many of these stars [1], [82], [107]. However, it was shown [2] that the population of X-ray sources towards Orion consists of a mixture of true Orion PMS stars and young foreground stars. The latter may be related to Gould's Belt or may be $\sim 10^8$ yr old stars.

Recent studies have revealed a significant population of low-mass PMS stars in the region of subgroup 1b of Ori OB1 [140], [141]. The stars appear to cluster spatially around σ Ori and the narrowness of their PMS locus suggests coevality, at the 2 Myr age of Ori OB1b. The total inferred mass of this group of stars is comparable to that of the Orion Nebula Cluster. In fact the σ Orionis cluster may be an older analogue of the Trapezium cluster. This result illustrates the difficulty in defining subgroup boundaries in associations (cf. §3). It may be that subgroup 1b actually consists of a 'merger' of several Trapezium-like clusters. Most recently, the detection of brown dwarf candidates around σ Ori has been reported. We refer to [142] for the details and more material on low-mass stars in OB associations.

Enormous progress has been made towards characterizing the low-mass population in OB associations. The challenge now is to bring the studies of the high- and low-mass stars together into a comprehensive picture.

5. Results from Hipparcos

We now review the results on the stellar content of the nearby OB associations derived from analysis of Hipparcos data. The material in this section is essentially a summary of [150], [31], and [75] and we refer to those papers for all the details and further references.

The most important data contained in the Hipparcos Catalogue [50] are positions, proper motions, and trigonometric parallaxes for $\sim 120\,000$ stars. The median precision of the astrometric data for stars brighter than $V \sim 9$ is 0.88 and 0.74 milli-arcsecond yr^{-1} for the proper motions in right ascension and declination, respectively, and 0.97 milli-arcsecond (mas) for the parallaxes. Note that at the distance of the nearest associations (~ 150 pc) these numbers translate into individual stellar distances accurate to 15 per cent and transverse velocities accurate to 0.6 km s^{-1}. The astrometric data are supplemented with magnitudes and colors, variability information obtained from the photometry, and detailed data on the properties of binaries observed or discovered by Hipparcos. Simultaneously with the main mission the Tycho experiment was carried out. This resulted in a catalogue of over 1 million stars to $V \approx 11.5$ containing astrometric data with less precision (median ~7 mas for $V \lesssim 9$) as well as accurate photometry.

The Hipparcos Catalogue has a limiting magnitude of $V\sim12$, and is complete to $V\sim7.3$ in the Galactic plane, and to $V\sim9$ in the polar regions. Furthermore, for reasons having to do with the way the observations were carried out, the Catalogue suffers from severe selection effects in some regions of the sky. For OB associations the relevant selection biases are described in §3 of de Zeeuw et al. [150]. For more details on the Hipparcos Catalogue please refer to the extensive documentation provided with the Catalogue itself [50].

5.1. ASTROMETRIC MEMBERSHIP SELECTION

Two methods, based on the assumption of common space motions for stars, were used to select astrometric members of the nearby OB associations [150]. The first is a modification of the classical convergent point method [31], and the second is a new selection method which makes use of the parallaxes as well as the proper motions, and searches for members in velocity space [75]. Both methods were combined to find the members of the nearby associations. This leads to a very powerful membership selection tool in which many spurious interlopers that occur when either method is used alone are automatically removed. Even so, one should still expect that a fraction of the selected stars actually belong to the field but by coincidence have the right motion to be included as members. The fraction of expected interlopers was estimated for each association through extensive Monte Carlo simulations.

To illustrate the dramatic advances provided by the Hipparcos data, Figure 3 shows in detail the membership selection results for the Upper Centaurus Lupus (UCL) subgroup of Sco OB2. The first row displays the Hipparcos measurements for all stars in the UCL field. The panels show no clear sign of a physical group, except for the vector point diagram (panel two), which contains a concentration around $(\mu_\ell \cos b, \mu_b) \sim (-25, -10)$ mas yr^{-1} superimposed upon the broader Galactic disk distribution. The second row of Figure 3 shows 136 stars that were proposed as members of UCL, based on pre-Hipparcos kinematic and photometric studies. They are mostly B- and A-type stars, with fairly little concentration in the vector point diagram. Their parallax distribution is narrower than the one in the first row, and peaks around 9 mas. The characteristics of the set of astrometrically selected members are presented in the third row of Figure 3. The vector point diagram of these secure members is much more concentrated than that of the pre-Hipparcos members, and the parallax distribution is narrower. This is due to a reduced contamination by field stars. The spread and the elongated shape in the

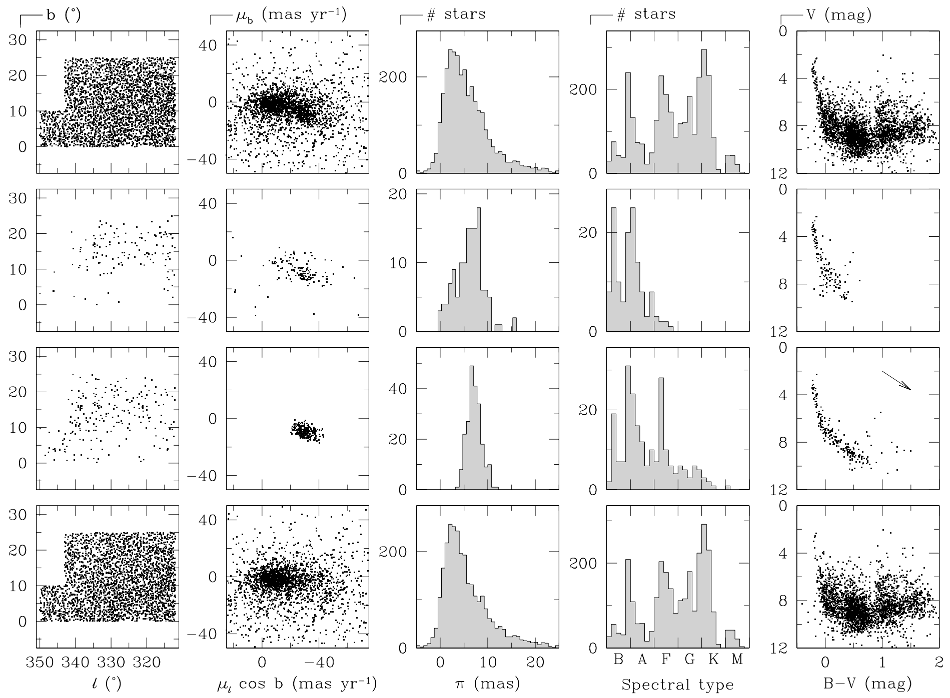

Figure 3. Hipparcos measurements for the subgroup Upper Centaurus Lupus of Sco OB2 (from the top row down): (1) all 3132 Hipparcos stars in the region; (2) the 136 pre-Hipparcos members; (3) the 221 Hipparcos members; (4) the remaining stars after member selection. The columns show (from left to right): (1) positions in Galactic coordinates; (2) Galactic vector point diagram; (3) trigonometric parallax distribution; (4) spectral type distribution; (5) color-magnitude diagram, not corrected for reddening. The arrow indicates the direction of reddening for the standard value $R = 3.2$ of the ratio of total to selective extinction.

vector point diagram are consistent with the combined effects of observational errors, the estimated internal velocity dispersion, and projection on the sky [150]. Note how much more extended the HR-diagram, not corrected for reddening, of the association is after Hipparcos membership selection. The data now extend to beyond spectral type F and in fact some PMS objects are included (see §7.1). Finally, the panels in the bottom row of Figure 3 show the not-selected stars, and demonstrate that the membership selection procedure does not leave 'holes' in the distributions of positions, proper motions, and parallaxes. This indicates that UCL was separated cleanly from the field stars.

5.2. SELECTED RESULTS

The outcome of the Hipparcos membership selection is described below with a couple of specifically chosen examples from de Zeeuw et al. [150], meant to illus-

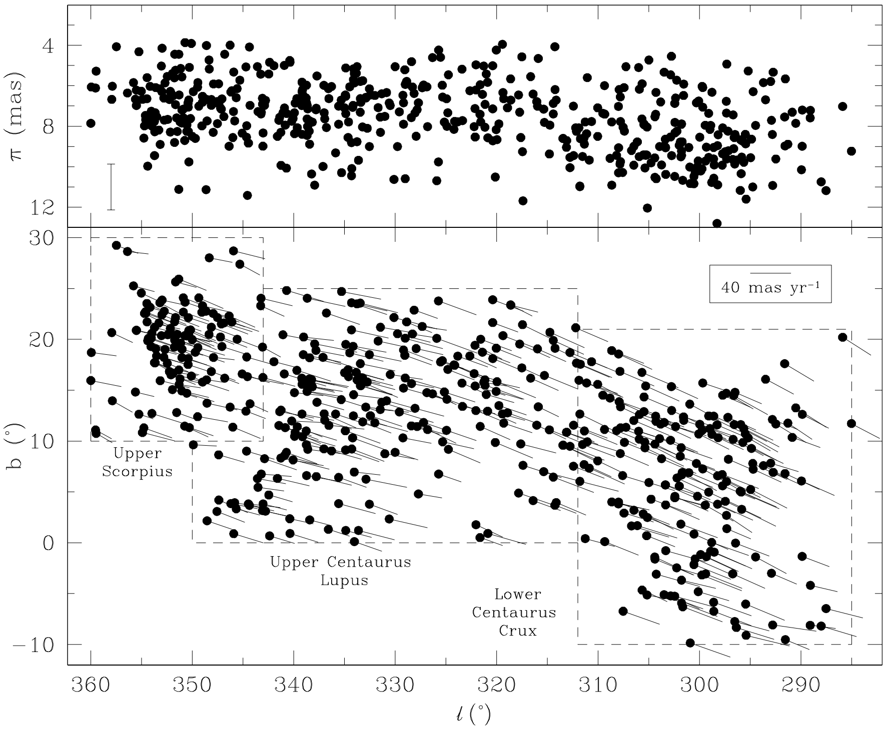

Figure 4. Positions and proper motions (bottom), and parallaxes (top), for 521 members of Sco OB2 selected from 7974 stars in the Hipparcos Catalogue in the area bounded by the dashed lines. The vertical bar in the top panel corresponds to the average $\pm 1\sigma$ parallax range for the stars shown. US is identified as a subgroup based on the concentration of members on the sky, and LCC can be distinguished from US and UCL based on its significantly smaller distance.

trate the various ways in which high-precision proper motion surveys can impact the field of OB associations. The case of Sco OB2 was chosen to show that the membership lists can now be extended into the PMS regime. The findings on Vel OB2 and Tr 10 show the dramatic improvements in the ability to identify OB associations (Vela), and how in some cases what was thought to be an open cluster actually turns out to be an association (Trumpler 10). The results on Col 121 show that we can now detect analogues of Sco OB2 at much larger distances (a factor four in this case). Cep OB6 is an example of a newly discovered association. Finally, we discuss Ori OB1 as an example of some of the difficulties encountered in identifying the members of associations.

Scorpius OB2. Figure 4 illustrates the proper motions of all the Sco OB2 members that have been identified, and also gives the subgroup boundaries. In US a total of 120 members were found located in a volume of $\sim$30 pc diameter at a mean distance of 145 ± 2 pc (see §5.3 for more information on the determination of mean distance). In UCL 221 members at 140 ± 2 pc were found, and in Lower Centaurus Crux (LCC) 180 at 118 ± 2 pc.

Sco OB2 clearly forms one coherent structure, although US stands out in the distribution of Sco OB2 members on the sky, and the parallax distribution clearly distinguishes UCL and LCC. The differences between the Hertzsprung–Russell diagrams of the groups [61] also indicate that a division of Sco OB2 into three separate subgroups is warranted. The field boundary separating UCL from US has, somewhat arbitrarily, been chosen in such a way that US comprises the stellar concentration centered on $(\ell, b) \sim (352°, 20°)$ with radius $\sim 5°$.

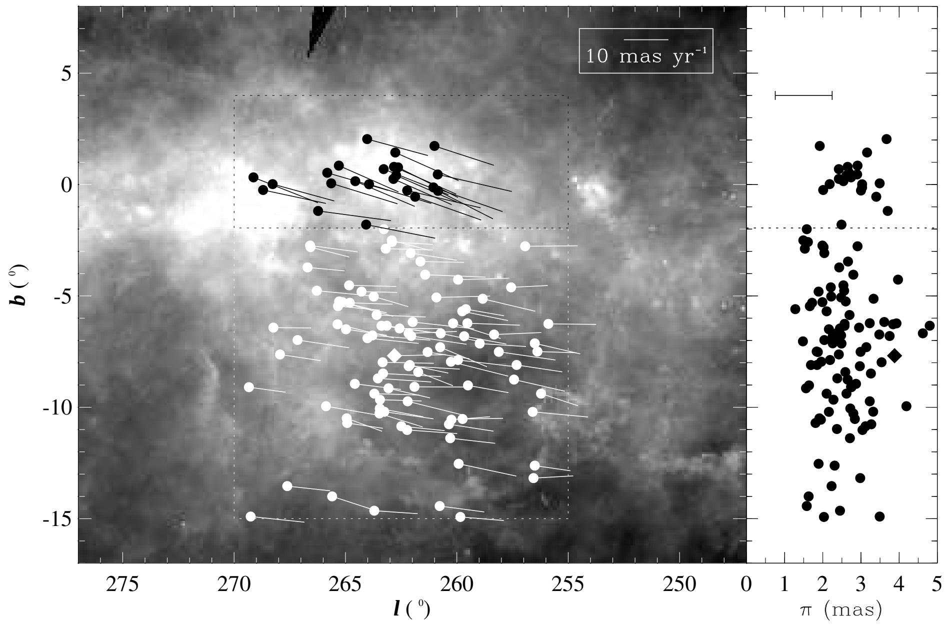

Figure 5. Left: positions and proper motions for the Hipparcos members of Vela OB2 (white) and Trumpler 10 (black). The diamond denotes the Wolf–Rayet star γ^2 Velorum (WR11). The dotted lines indicate the field boundaries. The grey scale represents the IRAS 100 μm skyflux. The IRAS Vela shell is the ring-like structure centered on $(\ell, b) \sim (263°, -7°)$ with a radius of $\sim$6° surrounding Vel OB2. The intense emission in the area $260° \lesssim \ell \lesssim 273°$, $-2° \lesssim b \lesssim 2°$ corresponds to the Vela molecular ridge. Right: parallax distribution for Vel OB2 and Tr 10.

Vela OB2 and Trumpler 10. In his 1914 paper, Kapteyn not only identified Sco OB2, but also discussed a group of bright stars in Vela and, based on proper motions, listed 15 probable members for this so-called Vela Group [80]. Ever since a clear identification of the members of this group has remained difficult

[150]. However, the new Hipparcos results, illustrated in Figure 5, show very clearly the presence of an OB association in the Vela region. In fact 93 members have been identified of which 89 are new! The color-magnitude diagram of this association shows that the earliest spectral type on the main sequence is B1, suggesting an age of $\lesssim$10 Myr. The association is located at a distance of 410 ± 12 pc, and the new members are concentrated on the sky around $(\ell, b) \sim (263°, -7°)$ within a radius of $\sim$5°. Sahu [123] reported the detection of the so-called IRAS Vela shell in the IRAS Sky Survey Atlas maps (cf. [124]). This is an expanding shell, centered on Vel OB2, with a projected radius of $\sim$6° (Figure 5). Sahu showed that the observed kinetic energy of the IRAS Vela shell is of the same order of magnitude as the total amount of energy injected into the interstellar medium through the combined effects of stellar winds and supernovae if the shell were to contain a 'standard' OB association [123]. The subsequent astrometric identification of Vel OB2 as a rich OB association, and the improved distance determination, confirm the relation of the association with the Vela shell.

Based on relative proper motion data for 29 stars, Lyngå [95], [96] identified 19 probable members of the sparse open cluster Trumpler 10. Analysis of the Hipparcos data showed that Tr 10 is actually a moving group. The Catalogue contains 23 members: 22 B-type stars (earliest spectral type B3V) and 1 A0V star. Figure 5 shows the members of Tr 10 seen in projection in front of the Vela molecular ridge. Tr 10 is located at a distance of 366 $\pm$ 23 pc. Based on its color-magnitude diagram this group is clearly older than Vel OB2, and a provisional age estimate based on the earliest spectral type is $\sim$15 Myr.

Collinder 121. Collinder [35] studied the structural properties and spatial distribution of Galactic open clusters, and discovered a cluster of 20 stars at $\sim$590 pc in an area of $1° \times 1°$ on the sky: Col 121. Schmidt–Kaler [127] noted a large number of evolved early-type stars in a field of $10° \times 10°$ centered on the bright supergiant *o* CMa located in the central part of Col 121. Subsequent studies revealed the possible existence of an OB association in this field [150].

This is indeed confirmed by the Hipparcos results. 103 stars were selected in the Col 121 field with a mean distance of 592$\pm$28 pc. Figure 6 shows both the stars previously considered members of this group as well as the newly selected Hipparcos members. The figure also presents the Hipparcos color-magnitude diagram, not corrected for reddening. It shows that Col 121 contains a number of evolved stars. The abrupt cutoff of the main sequence near V=10 is caused by the completeness limit of the Hipparcos Catalogue. Some of the late-type stars may well be interlopers. The presence of an O star and early-type B stars indicates this is a young group, of age $\sim$5 Myr.

Col 121 has completely changed its appearance compared to the classical membership lists. The middle panel of Figure 6 suggests two subgroups, $(\ell, b) \sim (233°, -9°)$ and $(238°, -9°)$. A possible third subgroup lies at $(\ell, b) \sim (243°, -9°)$.

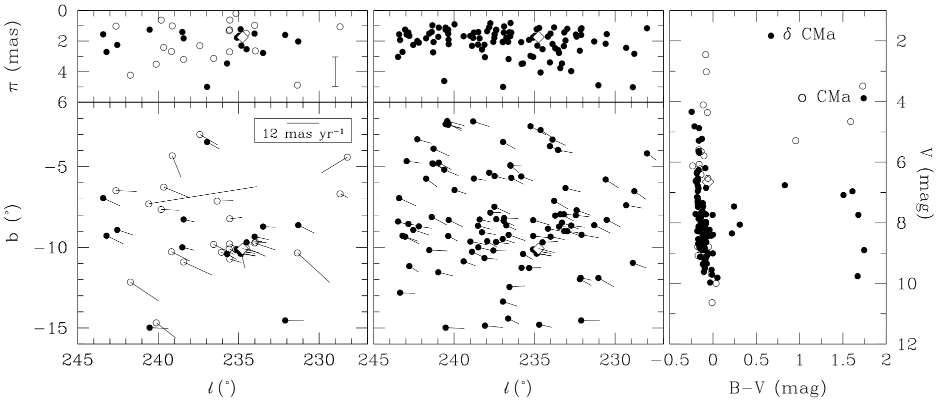

Figure 6. Left: positions and proper motions (bottom) and parallaxes (top) of the pre-Hipparcos members of Collinder 121. Filled circles are confirmed members. Open circles indicate stars not considered members after analysis of Hipparcos data. The confirmed member EZ CMa (WR6, see [150]) is indicated by an open diamond. Middle: same diagram for all stars selected as member of Col 121, illustrating the dramatic change from pre- to post-Hipparcos. Right: color-magnitude diagram, not corrected for reddening, for the Col 121 members (filled circles), and rejected classical members (open circles). The unusual position of EZ CMa (open diamond) may be caused by systematic effects in the Hipparcos photometry of this star [150].

The linear dimensions of this complex are 100×30 pc, similar to that of the Sco OB2 association. The color-magnitude diagram also resembles that of Sco OB2, in the sense that the earliest spectral type and amount of extinction are similar.

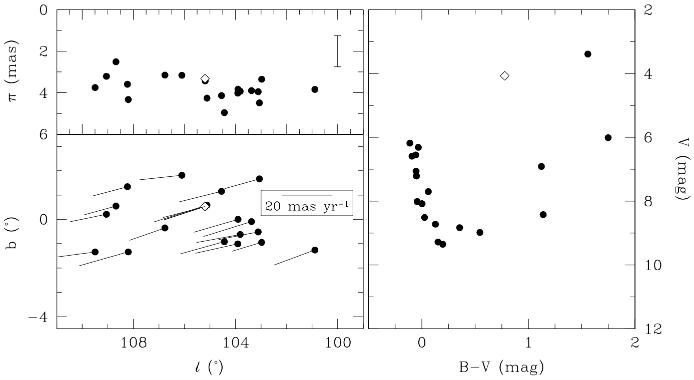

Figure 7. Left: positions and proper motions (bottom) and parallaxes (top) for the new moving group in Cepheus, designated Cepheus OB6. Right: color-magnitude diagram, not corrected for reddening. The open diamond denotes δ Cep.

Cepheus OB6. Following a discovery by Hoogerwerf et al. [74], de Zeeuw et al. [150] examined the field $100° < \ell < 110°$ and $-4° < b < 3°$ in the Cepheus region and found a previously unknown moving group. This group, designated as Cepheus OB6, consists of 20 members. Their positions, proper motions and parallaxes are shown in Figure 7. The color-magnitude diagram is very narrow and strengthens the evidence that these stars form a moving group. It is probably an old OB association: the earliest spectral type is B5III, suggesting an age of ∼50 Myr. A noteworthy member of this group is δ Cep, the prototype classical Cepheid.

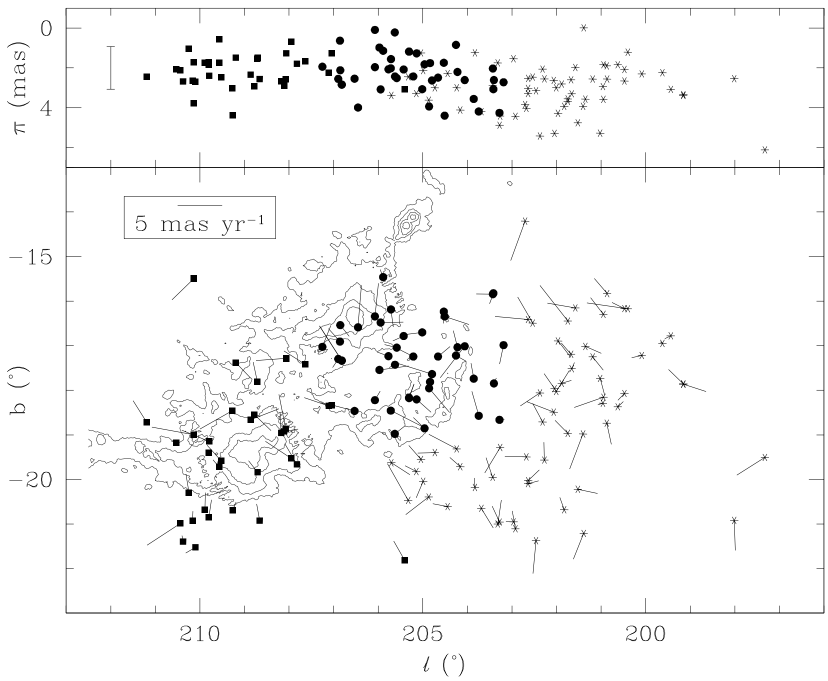

Figure 8. Positions and proper motions (bottom) and parallaxes (top) for the stars of Ori OB1 selected by Brown et al. [30]. The proper motions are small because Ori OB1 lies near the direction of the Solar Antapex. The parallaxes in subgroup 1a (asterisks) are generally larger than those in 1b (filled circles) and 1c (filled squares). The contours indicate the 100 μm IRAS flux map.

Other Associations. Astrometric membership detection for OB associations with Hipparcos data was successful out to $\sim$ 650 pc. The following associations were also detected: Per OB2, α Persei (Per OB3), Cas–Tau, Lac OB1, and Cep OB2. Astrometric evidence for moving groups in the fields of R CrA, CMa OB1, Mon OB1, Ori OB1, Cam OB1, Cep OB3, Cep OB4, Cyg OB4, Cyg OB7, and Sct OB2, is inconclusive. OB associations do exist in many of these regions, but they are either at distances where the Hipparcos parallaxes are of limited use, or they have unfavorable kinematics, so that the group proper motion does not distinguish them from the field stars in the Galactic disk.

Among the latter group we note especially Ori OB1. It is the best-studied nearby OB association but unfortunately it is located close to the Solar Antapex, and its space motion is almost purely radial with respect to the Sun. This means that it is very difficult to select members in Ori OB1 based on proper motions. A discussion on Ori OB1 is given in [150] based on the preliminary study described in detail in [30]. In that study a very crude selection of Ori OB1 members was done, based on Hipparcos proper motions, and the mean distances to the subgroups were calculated. These distances are: 336$\pm$16 pc for 1a, 473$\pm$33 pc for 1b and 506$\pm$37 pc for 1c, where the quoted errors are the formal errors on the mean distances. The actual uncertainty is larger due to the simplified member selection. All of this is illustrated in Figure 8 which shows the proper motions and parallaxes of the selected members. Note that from the parallaxes alone it is clear that subgroup 1a is located much closer to the Sun than 1b and 1c [30].

5.3. MEAN DISTANCES AND MOTIONS

Use of the Hipparcos trigonometric parallaxes of the secure members to determine mean distances to the associations or their subgroups requires some caution, as the inverse of the parallax is a biased distance indicator [128], [28], and the conversion of mean parallax to mean distance for a group of stars depends on the distribution of stars within the group. It can be shown [150] that for all spherical groups the expectation value of the mean of the measured parallaxes is equal to the true mean parallax, and corresponds to the true distance of the centre of the group. For elongated associations the bias in the mean parallax is small, typically less than 1 per cent. Hipparcos parallaxes measured in regions of high stellar density (in the Catalogue) have to be interpreted with care [93], [114], [121]. This is not a problem for the low-density associations.

Furthermore, the observed distribution of parallaxes may not be representative of the true underlying parallax distribution of an association. Magnitude limits and the characteristics of the Hipparcos Input Catalogue bias the selected members (see [150] for more details), and some stars in the Hipparcos Catalogue have a negative measured parallax. The member selection method described in §5.1 rejects these, which introduces a bias towards a smaller mean distance. De Zeeuw et al. [150] were able to correct the mean distances to the associations for this bias, by carrying out Monte Carlo simulations to estimate its magnitude.

The resulting distances and projected sizes of the kinematically detected nearby OB associations are listed in Table 1. This table also lists the mean proper motions. The means are based on the individual measurements for the association members. The Hipparcos Input Catalogue lists radial velocities from a variety of sources. They are not available for all secure association members, and therefore Table 1 lists the median radial velocity, and no error estimates are given.

The mean distances derived in Table 1 have very small formal errors due to the averaging over large numbers of stars. However, associations have large physical sizes, and the mean distances listed here should not be taken as 'the distance' to all association members, but rather as an indication of the location of their centroid.

The comparison between the new Hipparcos distances and the distances in the literature for OB associations reveals a tight correlation, although the Hipparcos distances are systematically smaller by about 0.2 magnitudes in the distance modulus. This issue is discussed in more detail by de Zeeuw et al. [150].

To conclude we return to the issues discussed in §3. The projected sizes of the associations correlate roughly with their distances. This is obviously not a real physical effect but merely a reflection of how the field boundaries were established prior to membership selection. The case of Col 121 is a good illustration of how an association like Sco OB2, which consists of three subgroups, may resemble a single entity at larger distances (see Figure 6). Moreover, any kinematic distinction between subgroups within an association is difficult to establish (cf. Figure 4), and extra information, such as photometry, is required. Thus, even though OB associations may possibly form with particular characteristic dimensions one should always bear in mind the observational biases that enter when addressing the question of initial configurations of young star clusters.

6. Gould's Belt and the Origin of the Nearby Associations

Mean space motions of the nearby OB associations, in km s^{-1}, were derived from the mean proper motions, mean distances, and the median radial velocities [150]. Figure 9 shows the result, after subtraction of Solar motion [42] (lower panel) and, additionally, differential Galactic rotation [54] (upper panel). When considering the motions with respect to the Local Standard of Rest, some of the associations in Figure 9 (lower panel) seem to fit a coherent pattern of expansion and rotation, which is very similar to that derived from Hipparcos measurements of OB stars with ages less than $\sim$30 Myr [92], [133]. This large-scale feature is known as Gould's Belt, which is the flat system of early-type stars within $\sim$500 pc [64], associated with a large structure of interstellar matter, including reflection nebulae, dark clouds, and H I. Its most striking feature is a tilt of $\sim 18^\circ$ with respect to the Galactic plane. It has also been detected in the distribution of young stars observed in X-rays by ROSAT [66]. Pöppel [115] recently wrote a comprehensive review of this structure, with emphasis on the role and characteristics of the interstellar medium.

Following a suggestion by Blaauw [10], who studied the mean space motions of the nearby OB associations, Lindblad [91] interpreted the observations of the local H I gas associated with Gould's Belt in terms of a ballistically expanding

TABLE 1. Mean distances and mean motions of the nearby OB associations

Name	D	N	Size	$\langle \mu_\ell \cos b \rangle$	$\langle \mu_b \rangle$	$v_{\rm rad}$	Age	$N_{\rm br}$
US	145 ± 2	120	30	-24.5	-8.1	-4.6	5	5
UCL	140 ± 2	221	65	-30.1	-9.1	4.9	13	10
LCC	118 ± 2	180	45	-32.1	-13.1	12.0	10	4
Vel OB2	410 ± 12	93	70	-10.4	-1.3	18.0	10	12
Tr 10	366 ± 23	23	45	-14.3	-4.9	21.0	15	0
Col 121	592 ± 28	103	115	-5.1	-1.5	26.0	5	24
Per OB2	318 ± 27	41	45	8.4	-2.3	20.1	4–8	2
α Persei	177 ± 4	79	15	33.5	-8.7	-1.0	50	2
Lac OB1	368 ± 17	96	65	-2.3	-3.4	-13.3	16	7
Cep OB2	615 ± 35	71	105	-4.1	-0.5	-21.4	5	11
Cep OB6	270 ± 12	20	40	15.9	-4.4	-20.0	50	2
Ori OB1a*	336 ± 16	61	30	0.8	0.1	-23.0	11	6
Ori OB1b*	473 ± 33	42	30	0.8	0.1	-23.0	2	9
Ori OB1c*	506 ± 37	34	30	0.8	0.1	-23.0	5	12

All distances, in pc, include a correction for systematic effects as described in §5.3. The first column lists the association. The second column contains the mean distance and the error on the mean. The third column lists the number of Hipparcos members. Column 4 lists the projected size in pc of the associations derived from their extent on the sky and assuming spherical symmetry. Columns 5 and 6 list the average proper motions in the directions of Galactic longitude and latitude. The formal errors on the mean are typically 0.1–0.2 $\rm mas\,yr^{-1}$. Column 7 contains the median radial velocity in $\rm km\,s^{-1}$ compiled from the Hipparcos Input Catalogue. Column 8 contains the (approximate) age in Myr; see [150] for references. Column 9 contains the number of stars with absolute magnitude brighter than -2. The absolute magnitudes were calculated from the mean distances and values for V as listed in the Hipparcos Catalogue. Due to its large physical size and unknown orientation, the Cas–Tau association cannot be represented adequately by a single mean distance, proper motion, and radial velocity, and has been excluded from this table.
* The distances and numbers of members for Ori OB1 are based on an *ad hoc* selection procedure and should be regarded as *provisional* numbers only.

ring. Subsequent kinematic models combined with new observations confirmed this picture (e.g., [46], [109]). However, these models seem inadequate for a description of the space motions of the clumpy distribution of early-type stars, as no unique expansion center and/or expansion age can be defined for them (e.g., [10], [36], [88], [146]). The lack of homogeneous and accurate radial velocities for all local early-type stars prevents an optimal exploitation of the Hipparcos data, and a full kinematic model is not yet available. Even so, we can use the mean motions of the OB associations to shed light on the systemic motions in Gould's Belt.

The associations Sco OB2, Ori OB1, Per OB2, and possibly Lac OB1, are thought to be components of the Gould Belt (e.g., [109]). The pattern displayed in the lower panel of Figure 9 seems to be shared by Tr 10, and perhaps also by Vel OB2 and Col 121. Moreover, all these associations are younger than $\sim$

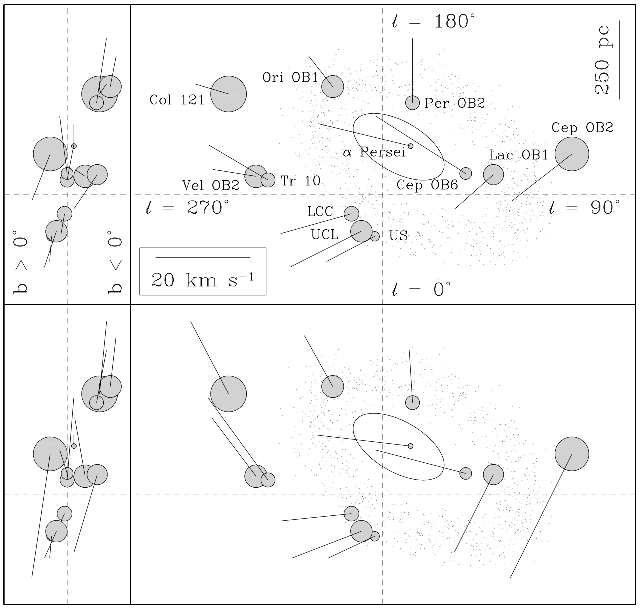

Figure 9. Locations of the kinematically detected OB associations projected onto the Galactic plane (right, cf. Figure 1) and a corresponding cross section (left). The grey circles indicate the physical dimensions as obtained from the angular dimensions and mean distances, on the same scale. The lines represent the streaming motions, derived from the average proper motions, mean distances and median radial velocities of the secure members, corrected for 'standard' Solar motion and Galactic rotation (upper panel) or for Solar motion only (lower panel). The ellipse around the α Persei cluster indicates the Cas–Tau association. The small dots schematically represent a model of the Gould Belt [109].

20 Myr, suggesting that these may all belong to the same coherent structure. If it is part of Gould's Belt, the new distance of Lac OB1 reduces the extent of the Belt in the direction $\ell \sim 90°$. Cep OB2 is not located in the plane of the Belt, and its motion is parallel to the Galactic plane. It does not seem to belong to the Belt. The Cas–Tau complex which surrounds the α Persei cluster and shares its motion, as well as Cep OB6, are located inside the main ring of associations, have a different space motion, and are all significantly older at $\sim$50 Myr.

The following scenario was suggested for the formation of Gould's Belt and its constituent associations [47], [49]. The Carina spiral arm is presently $\sim$4 kpc from the Sun along the Solar circle at $\ell = 282°$ [65]. If the pattern speed of the associated spiral density wave is 13.5 km s^{-1} kpc^{-1} [149], then the physical speed of the local arm is 114 km s^{-1} in the tangential direction. This means that the time since the passage of the Carina spiral arm near the Sun would have been 35 Myr without streaming motions parallel to the arm. With streaming, the time may be twice this value. As the oldest components of Gould's Belt have a similar age, this suggests that the Belt began as a giant gaseous condensation in the Carina spiral arm when the location of the arm and the Sun last coincided. In this gas probably the Cas–Tau, α Persei, Cep OB6, and Pleiades clusters formed, as well as many dispersed B and later-type stars [88], [115]. The combined action of the stellar winds and supernovae from the massive stars in these older stellar groups may have led to the ring-like gaseous structure from which the younger associations formed [13]. An alternative scenario for the origin of Gould's Belt, invoking the oblique impact of a large high-velocity cloud onto the Galactic disk, was put forward to explain the tilt in Gould's Belt [36].

7. Future Perspectives

In his 1991 chapter on associations Blaauw concluded with the promise of major advances in the field through the availability of Hipparcos data as well as much improved radial velocities. Although precise radial velocities for the early-type stars are not yet available, the Hipparcos data have now been analyzed and have put the issue of association membership on much firmer ground. Below we will discuss how this provides an excellent start for future investigations and we briefly discuss what is in store for work on OB associations beyond the Galaxy.

7.1. THE NEARBY OB ASSOCIATIONS

Hipparcos has provided a much improved description of the ensemble of young stellar groups in the Solar neighbourhood, out to a distance of $\sim$650 pc. The list of members in the astrometrically detected associations has in all cases been refined and extended and a much better kinematical description of Gould's Belt is now available. With the number of candidate members greatly reduced, we are now in an excellent position to start gathering additional data such as photometry and radial velocities, which will help in further refining the membership lists and studying the physical properties of the association members.

The discovery of Cep OB6 in the Cep OB2 field [150] suggests that there might be other previously unidentified nearby associations. A systematic search in regions of the strip $-30^\circ \leq b \leq 30^\circ$ not covered by de Zeeuw et al. [150] might reveal such groups. It will also be interesting to investigate whether, as in the Cas–Tau/α Persei pair, more open clusters exist with an extended halo, which appears as an old association.

De Zeeuw et al. [150] presented color-magnitude diagrams based on the V and $B-V$ data in the Hipparcos Catalogue, but the physical parameters of the member stars were not discussed in detail, mostly because the required homogeneous multi-color photometry (and spectral classification) is incomplete. It is now relatively easy to acquire the necessary photometry. This is particularly interesting in Sco OB2, where the faintest astrometric members can be connected directly to the populations of PMS objects discovered through X-ray searches. This will provide accurate ages, initial mass functions [29], and the energy and momentum input into the interstellar medium, thus enabling a detailed investigation of the influence of young stellar groups on the surrounding distribution of gas and dust. The Leiden–Dwingeloo H I survey [69], which has recently been completed for the southern sky, can be used to undertake a comprehensive study of the interstellar medium surrounding the nearby associations. It will also be interesting for the nearest associations to combine the Hipparcos parallax measurements with absorption-line measurements of gas in order to gain insight into the 3D-structure of the interstellar medium.

An important next step is to complement the uniform astrometric measurements provided by Hipparcos with homogeneous radial velocities with accuracies of $\sim$ 3 km s^{-1} or better, which is a considerable challenge for earlier spectral types (cf. §4.1). An unbiased member selection based only on radial velocities is still impractical, but measurement of the radial velocity of the proper motion members identified here is feasible. This will allow removal of a significant number of remaining interlopers [150] and will provide further information on the distribution of spectroscopic binaries in these groups. Combined with the many new astrometric binaries discovered by Hipparcos this will greatly improve our knowledge of the binary population in OB associations.

The Hipparcos parallaxes are not sufficiently accurate to resolve the internal structure of even the nearest associations. This would be interesting, as it might help to delineate substructure, and hence shed light on the details of the star formation process throughout an interstellar cloud. However, it is possible to improve the individual distance estimates by using the proper motions (and radial velocities) of established members to compute so-called secular parallaxes (e.g., [43]).

The lists of astrometrically selected members of OB associations are incomplete beyond $V \sim 7.3$, and a few genuine bright members (including some long-period binaries) may have been excluded (see [150] for details). The lists extend to $V \sim 10.5$, and include a few PMS objects in the nearest groups. Available ground-based studies which can now be put on the Hipparcos reference system can possibly complete the member list for the bright stars, and extend them to fainter magnitudes. Unfortunately, the space motions of the young groups are not large, and as a result the proper motions of the group members do not differ very much from those of the field stars. Reliable extension of the membership lists requires proper motions with accuracies of order 2 mas yr^{-1} or better. These are provided by the ACT Catalog [134] and the TRC Catalogue [73], through a combination of the positions in the Astrographic Catalog with the Tycho positions to $V \sim 11$. The individual stellar positions in these two catalogues have modest accuracy, but the $\sim$ 80 yr epoch difference results in quite accurate proper motions. The first installment of the ACT and TRC catalogues both contain about 1 million measurements. The completion of the second edition of the Tycho Catalogue [72] will provide proper motions of similar quality for about 2.5 million objects to

$V \sim 12$. However, the 1 mas accuracy parallaxes obtained by Hipparcos, which are generally not available for fainter association members, play a crucial role in culling interlopers from the membership lists. A complete study of all OB associations in the Solar neighbourhood (extent, distance, structure, kinematics) has to await the future GAIA space astrometry mission [112], [63], which will gather astrometric data at the 10 micro-arcsecond precision level to 20$^{\rm th}$ magnitude.

7.2. BEYOND THE GALAXY

Armed with a detailed understanding of associations in the Solar vicinity and throughout the Milky Way, we can now venture further and investigate the vast variety of extragalactic star forming regions, ranging from individual associations to complete star bursts.

The nearest extragalactic associations are to be found in the Large Magellanic Cloud. For example, at the heart of the 30 Doradus nebula one finds the spectacular R136 cluster, which has a stellar density ~ 200 times greater than that of a typical OB association and contains 39 identified O3 stars [98]. This cluster is even considered a possible analogue of a young globular cluster. Thus by studying R136 we may gain a much more detailed understanding of the 'super star clusters' observed with the Hubble Space Telescope in other galaxies (e.g., [37], [108], [148]), which are also thought to be progenitors of globular clusters.

One important lesson that has been learned from studying massive stars is that because of their very high effective temperatures ($> 30\,000$ K) it is vital to perform spectroscopy of these stars if one wants to obtain reliable physical parameters, such as masses [97]. High sensitivity combined with high spatial resolution are thus needed to perform detailed studies of the luminous young star clusters observed in galaxies in the Local Group and beyond. This will require the capabilities of the Hubble Space Telescope or the largest ground-based facilities. A good understanding of these extragalactic associations and the role they play will be very important if we want to make sense of the observations of the earliest epochs of star and galaxy formation that will eventually be carried out by future millimeter-arrays and by the Next Generation Space Telescope.

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