The Large-Scale Distribution and Motions of Older Stars in Orion

Anthony G. A. Brown
Sterrewacht Leiden
P.O. Box 9513, 2300 RA Leiden, The Netherlands
brown@strw.leidenuniv.nl

Frederick M. Walter
Department of Physics and Astronomy
SUNY Stony Brook, NY 11794-3800, USA
fwalter@astro.sunysb.edu

Adriaan Blaauw
Kapteyn Astronomical Institute
P.O. Box 800, 9700 AV Groningen, The Netherlands
A.Blaauw@astro.rug.nl

Abstract.
We review the current knowledge of the population of ‘older’ stars in the Orion OB1 association, specifically those in subgroups 1a and 1b. We briefly outline the history of the subject and then continue with a summary of the present state of knowledge of the early-type stars in Orion OB1. New results from the Hipparcos parallaxes and proper motions will be presented. The main result is that subgroup 1a is located at about 330 pc from the Sun, much closer than the previously determined distance, and about 100 pc distant from the other subgroups of the association and the Orion molecular clouds. Unfortunately, due to the unfavorable kinematics of the association with respect to the Galactic background, Hipparcos proper motions do not allow a clear kinematic separation of the association from the field. For this purpose accurate and homogeneous radial velocities are needed. Traditionally, the massive O and B stars have received most of the attention in the studies of OB associations. However, we will present results showing that significant numbers of low-mass stars are associated with Orion OB1. Unbiased, optically complete, spectroscopic and photometric surveys of areas within subgroups 1a and 1b have the potential to determine the complete low-mass stellar population, down to the brown dwarf limit. This will provide much insight into the overall initial mass function and studies of the kinematics of the low-mass stars will yield insights into the dispersal of the association.

1Present address: Instituto de Astronomía, U.N.A.M., P.O. Box 877, Ensenada, 22800 Baja California, Mexico; brown@bufadora.astrosen.unam.mx
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 thus motivated primarily by the fact that they form the fossil record of star formation processes in giant molecular clouds, but is also important in the context of the evolution of the Galaxy. The kinematics of the nearest OB associations provides detailed insight into the properties and origin of the Gould Belt system (e.g., Blaauw 1991; Elmegreen 1992), which is an example of the star complexes discussed in the chapter by Elmegreen & Efremov in this volume.

In this context, the Orion complex has received a lot of attention. It is the nearest giant molecular cloud complex and a site of active star formation, including the formation of high-mass (O and B) stars. All stages of the star formation process can be found here, from deeply embedded protoclusters to fully exposed OB associations. The different modes of star formation occurring in these clouds (clustered, distributed, isolated) allow us to learn more about the influence of the environment on the star formation process. Furthermore, the Orion region forms an excellent nearby example of the effects of early-type stars on the interstellar medium. The Orion/Eridanus Bubble, surrounding the association and visible in H$_\alpha$ and soft X-rays is being blown by the supernovae and stellar winds from the evolved O and B stars in the Orion OB1 association (see chapters by Bally, Theil, & Sutherland, and Heiles in this volume). And last but not least, the Orion molecular cloud complex is a prime site for studies of interstellar chemistry.

In this contribution the emphasis will be on the older stellar population of the Orion complex, namely the already exposed subgroups of the Orion OB1 association. We shall concentrate mostly on the subgroups 1a and 1b; the other subgroups (1c, around Orion’s Sword, and 1d, containing the Orion Nebula Cluster) are discussed in the chapters by Allen & Hillenbrand and McCaughrean et al. in this volume.

We start with a short historical outline of the studies of the Orion OB1 association, discussing the division into subgroups and summarizing the work done on the stellar content up to the extensive photometric study by Warren & Hesser (1977a, 1977b, 1978). We then summarize recent work on the massive O and B stars (mass $\gtrsim 4 \ M_\odot$) of the OB association. This includes a discussion of the Hipparcos proper motions and parallaxes and their implications for the distance to the Orion complex.
Much work on nearby OB associations has gone into study of the high-mass O and B stars. For these stars, proper motions from large scale surveys were available for membership studies, and the contamination from the Galactic background is minimized in this spectral type range. However, recent work by, e.g., Walter et al. (1994) on the Upper Scorpius association (part of Sco OB2; see, e.g., de Geus, de Zeeuw, & Lub 1989) showed that it contains a field star mass function extending down to at least 0.3 $M_\odot$, with about 2000 members less massive than about 1 $M_\odot$. We shall also discuss recent work on the region surrounding the star $\sigma$ Orionis, which shows that there is a clustering of low-mass stars around this star. It may possibly be an older analog of the Orion Nebula Cluster (ONC). The implications for the initial mass function in Orion will be discussed.

2. Short Historical Overview

Much of the material in this section is derived from the review by Blaauw (1964) and the work by Warren & Hesser (1977a, 1978). We refer to these papers for many more details on the early investigations into the stellar content of the Orion OB1 association. We note that the overview that follows is not complete and certainly biased towards the studies of the O and B stars in Orion.

The earliest large-scale investigations into the stellar content of the Orion OB association were those by Shahovskoj (1957), Parenago (1953, 1954) and Sharpless (1952, 1954, 1962). These studies concentrated mainly on the stars in the Belt and Sword regions of the Orion constellation and all concerned spectroscopic and photometric data. A clear division of the association in subgroups was not yet established. It was Blaauw (1964) who suggested the division of the Orion association into four subgroups: 1a, which contains the stars to the northwest of the Belt stars; 1b, containing the group of stars located around the Belt (including the Belt stars themselves); 1c, in which the stars around the Sword are included; and 1d, which contains the stars in and close to the Orion Nebula (including the Trapezium stars). The figure of the subgroups shown by Blaauw (1964) shows an increasing concentration of the subgroup members going from 1a to 1c. Assuming that the subgroups are unbound and expanding, this suggests a sequence of decreasing ages, which was confirmed by the studies of the HR diagrams at that time.

The studies above were followed by the massive photometric investigation by Warren & Hesser (1977a, 1977b, 1978). They presented $uvby$$\beta$ and $UBV$ photometry for 526 stars in the Orion region. They analyzed the data in terms of reddening and $M_V$ determinations, possible correlations with stellar axial rotation, and effects on the photometry caused by anomalous extinction, possibly due to circumstellar material associated with pre-main sequence stars. They subsequently determined membership for each subgroup based on the photometric parallax of the stars. The spatial distribution and the ages of the subgroups were then studied based on the membership determinations.

The results of the studies above can be summarized briefly as follows. The ages of the Orion OB1 subgroups from studies of colour-magnitude diagrams were listed by Blaauw (1964) as 12, 8, 6, and about 4 Myr, going from 1a to 1d. Warren & Hesser (1978) found the ages to be 7.9, 5.1, 3.7, and < 0.5 Myr. Various methods for determining the ages have been brought to bear and an extensive listing up to 1978 is provided by Warren & Hesser (1978). The distance to the Orion OB1 association is listed by Blaauw (1964) as 460 pc. Warren & Hesser (1978) determined distances to the sub-
groups separately and found distances of 400, 430, 430, and 480 pc, going from 1a to 1d. These authors also list various other distance determinations.

Proper motion studies have focused mainly on the ONC. The earliest of these studies (Parenago 1954; Strand 1958) showed the Trapezium Cluster to be unstable and its expansion age to be about 0.3 Myr. Investigations of the motions in the more dispersed subgroups were carried out by Lesh (1968), who derived an expansion age for subgroup 1a of 4.5 Myr, and Blaauw (1961), who derived kinematic ages of 2.2–4.9 Myr for the three runaway stars, AE Aur, µ Col, and 53 Ari, probably originating from subgroup 1b. Adding the ages of the progenitors of the supernovae responsible for the runaways, led to an age of subgroup 1b in rough agreement with the photometric age (at that time) of 5–8 Myr. Proper motion studies are difficult to carry out in the Orion region due to the crowding of the stars. Moreover, the interpretation of the proper motions in the more dispersed subgroups is not straightforward, because the motion of the association is directed mostly radially away from the Sun, making it difficult to detect a common space motion for the members of Orion OB1.

Finally, we comment on the division of Orion OB1 into subgroups. In several studies, subgroups 1b, 1c and 1d were subdivided further. Warren & Hesser (1978) split subgroup 1b into three parts because Hardie, Heiser, & Tolbert (1964) and Crawford & Barnes (1966) found that the distance of the Belt stars increases from west to east. However, Brown, de Geus, & de Zeeuw (1994) found no significant differences in their mean distances, and no trend with right ascension for the 1b stars as claimed by Warren & Hesser. Morgan & Lodén (1966) and Walker (1969) had divided 1c into several smaller subgroupings located close to the Orion Nebula, but Warren & Hesser found no evolutionary differences between these groups. Therefore, most recently, Brown et al. (1994) decided to treat subgroups 1b and 1c as a whole. However, as we shall discuss further on, the issue of the exact division into subgroups is not yet settled.

3. Recent Work on the Massive Stars of Orion OB1

The interstellar medium near Orion OB1 contains several large scale features, including Hα emission extending to Eridanus, partly observable as Barnard’s Loop, and a hole in the H I distribution, which is surrounded by expanding shells (Goudis 1982). Reynolds & Ogden (1979) and Cowie, Songaila, & York (1979) argued that the coherent gas motions in Orion are the result of a series of supernova events which took place up to 4 Myr ago, but they ignored the effects of stellar winds. In the past twenty years a wealth of new data has been gathered on the large scale interstellar medium in Orion, through surveys in 12CO (Maddalena et al. 1986), 13CO (Bally et al. 1987), CS (Lada, Bally, & Stark 1991), the far-infrared (IRAS sky survey), and H I (Chromey, Elmegreen, & Elmegreen 1989; Green 1991; Green & Padman 1993; Hartmann & Burton 1997). Much of the work on the ISM around Orion was reviewed by Genzel & Stutzki (1989). During the same period, the theory of stellar winds has been developed to the extent that their impact on the surrounding medium can be readily estimated (Kudritzki et al. 1989; McCray & Kafatos 1987; de Geus 1991, 1992).

As a consequence of these extensive studies, Brown et al. (1994) decided to carry out a new investigation of the stellar content of the Orion OB1 association in conjunction with a study of the impact of the early-type stars on the surrounding ISM. These authors studied a sample of stars in Orion OB1 that were included in a 1982 Hipparcos proposal to observe all OB associations within 800 pc from the Sun. The stars were
studied with the VBLUW Walraven photometric system (Lub & Pel 1977). Physical parameters of the stars were derived and membership (based on photometric distances) of the subgroups was determined. The distances to the subgroups of Orion OB1 as determined by Brown et al. (1994) are smaller than distances derived previously. A distance of 380 pc was derived for subgroup 1a; 360 pc for 1b; and 400 pc for 1c. The distance to 1d (including the Trapezium) could not be determined reliably by Brown et al. (1994) due to the nebulosity in that region and insufficient stars. The smaller distances to the subgroups of Orion OB1 were also found by Anthony-Twarog (1982), who reanalyzed the data of Warren & Hesser with a revised calibration of the uvbyβ system.

Brown et al. (1994) also derived ages for the subgroups in Orion OB1 by isochrone fitting in the log $g$–log $T_{\text{eff}}$ plane. The ages found were 11.4 ± 1.9 Myr for 1a, 1.7 ± 1.1 Myr for 1b, and 4.6 ± 2 Myr for 1c, and less than 1 Myr for subgroup 1d. These results imply that there is not a sequence of decreasing ages going from 1a to 1d, but that 1b is a young subgroup in between the older subgroups 1a and 1c. This result was found previously by de Zeeuw & Brand (1985), and Brown et al. (1994) discussed other supporting evidence for 1b being younger than 1c. One of the arguments in favor of a sequence of ages has been the increasing degree of concentration in the early-type stars from 1a to 1c. However, as we shall discuss below, the structure of 1b may be more complicated. The concentration of low-mass stars around $\sigma$ Ori suggests that that system is an older analog of the Trapezium (Section 6). This implies that one cannot treat what is considered to be subgroup 1b as a whole. Doing so may lead to wrong inferences about the degree of concentration of the group of early-type stars.

Brown et al. (1994) also derived the initial mass function (IMF) for subgroups 1a, 1b, and 1c. They determined the masses from the surface gravity, luminosity, and effective temperatures of the stars, and carefully corrected for the presence of binaries. It was assumed that the present-day mass function for the interval of masses where the stars are on the main-sequence is a good approximation of the IMF. The IMF was found to be a single power law: $\xi(\log M)d\log M = AM^{-B}d\log M$, where $B = 1.7 ± 0.2$ for all three subgroups. The mass-ranges over which the IMF was determined were 4–15 $M_\odot$, 4–120 $M_\odot$, and 7–36 $M_\odot$ for subgroups 1a, 1b, and 1c respectively, the limits being set by the age of the subgroup and the completeness of the observations. Previously, Claudius & Grosbøl (1980) had found a value for $B$ of 1.9 ± 0.2.

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 by Brown et al. (1994). The total energy output of the association over its lifetime is of the order of $10^{52}$ ergs. This energy is enough to explain the observed Orion/Eridanus H I shell surrounding the Orion OB1 association. More details on the Orion/Eridanus Bubble can be found in the chapter by Bally et al. and Heiles in this volume, and in Burrows et al. (1993) and Brown, Hartmann, & Burton (1995).

Modern proper motion studies of the ONC include those by Jones & Walker (1988), van Altena et al. (1988) and McNamara et al. (1989). The results of these studies are summarized by Hillenbrand (1997) and Hillenbrand & Hartmann (1998). Most recently, the proper motions in the ONC were studied by Tian et al. (1996). Their results generally agree with those of the three studies above. Assuming a distance of 470 pc to the ONC, Tian et al. (1996) derive an upper limit on the velocity dispersion of the ONC of $\sim 2$ km s$^{-1}$, and they conclude that the ONC is an unbound system. The
most recent large-scale study of proper motions in Orion is that by Smart (1993), who used photographic plates to study the area of Orion OB1b and 1a.

Abundance patterns in stars of Orion OB1 have recently been studied in a series of papers by Cunha & Lambert (1992, 1994), Cunha, Smith, & Lambert (1995), and Cunha et al. (1997). The abundance analysis of these authors shows that the stars in Orion 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 abundances that are up to 40% higher than those in subgroups 1a and 1b (although still subsolar). Cunha & Lambert (1992) suggest 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. This enrichment scenario is confirmed by the fact that Cunha & Lambert (1994) observe no abundance variations for C, N, and Fe, but do observe the same abundance variations for Si as for oxygen, as one would predict for cloud material enriched by Type II supernova ejecta. Supernovae must have occurred in Orion OB1 in the past as evidenced by the presence of the Orion/Eridanus Bubble. Brown et al. (1994) estimated that 1 to 2 supernovae have occurred in subgroup 1c.

These results suggest a sequence of star formation from the older 1a, 1b, and 1c subgroups to the young ONC. However, this does not imply that star formation throughout the Orion molecular clouds followed the formation of the older subgroups of Orion OB1. As discussed by Hillenbrand (1997), there is a wide range of ages of young stars in the molecular cloud complex, with most of the low-mass stars in the L 1641 cloud being older than the stars in 1c and 1d. We shall return to this point after discussion of the Hipparcos parallaxes of the stars in Orion OB1.

4. Hipparcos Results on Orion OB1

As mentioned above, the stars in the Orion OB1 association were included in a 1982 proposal to observe all OB associations within 800 pc from the Sun with the Hipparcos satellite. The aim of this project, called SPECTER, is to carry out a comprehensive census of the stellar content of nearby OB associations. Detailed knowledge of the stellar content of nearby associations allows one to address fundamental questions on the formation of stars in giant molecular clouds, and comparisons between the different associations may lead to further insight into the question of whether the outcome of the star formation process is universal or depends on local conditions. Project SPECTER was described most recently by de Zeeuw, Brown, & Verschueren (1994).

The original proposal asked for observation of all O and B stars and later-type stars within certain magnitude ranges, in the region around Orion OB1 defined by the Galactic coordinate limits $196^\circ \leq \ell \leq 217^\circ$ and $-27^\circ \leq b \leq -12^\circ$. Within this region there are 1142 stars in the Hipparcos Catalogue (ESA 1997; see Perryman et al. 1997 for a summary of the catalogue contents) of which 294 are O and B stars, 391 are A stars, 208 are F stars, and the rest are of type G or later. Part of the effort for project SPECTER involved the development of new methods for identifying OB associations in the Hipparcos data. Although these groups are unbound, their expansion velocities are only a few $\text{km s}^{-1}$ (e.g., Mathieu 1986; Blaauw 1991), 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). Two methods that make use of the common space motion of stars in association were developed. One is an improved version of the
Figure 1. Proper motions of the O and B stars in the region of the sky around Orion OB1. The proper motions are indicated as vectors normalized to 3 mas/yr. The contours are the IRAS 100μm skyflux and they outline the location of the molecular clouds. Note the absence of a clear pattern of common proper motions near the Orion OB1 subgroups and the larger proper motions towards the edges of the field.

convergent point method employed by Jones (1971), and the other a newly developed method which uses both the parallaxes and the proper motions from Hipparcos. These methods are described in more detail by de Bruijne et al. (1997) and preliminary results on the nearby associations are presented by de Zeeuw et al. (1997) and Hoogerwerf et al. (1997). We note that these methods of membership determination are also strictly applicable in the case of associations in a state of expansion.

Unfortunately in the case of Orion OB1 the motion of the association is mostly directed radially away from the Sun. This makes it very hard to detect the association with proper motion studies. This is illustrated in Figure 1. The figure shows the Hipparcos proper motions for all the O and B stars in the region of Orion. No clear pattern of motions emerges in the region of the Orion OB1 subgroups. However it is clear that most of the large proper motions occur towards the edges of the field. A rough selection
Figure 2. Same as Figure 1 but after selection of the stars according to their proper motions. Note that now there is a clear concentration of stars towards the known locations of the Orion OB1 subgroups. This indicates that the rough selection process indeed filters out non-members of the association.

The list of stars obtained largely overlaps with the photometrically determined list of members from Brown et al. (1994). The resulting distribution of stars is shown in Figure 2. There is a clear concentration of stars towards the well known subgroups of Orion OB1. Among the OB stars along the edges of the field that remain after proper motion selection are a number which have parallaxes larger than 7 mas, corresponding to distances smaller than 140 pc. These are clearly not members of the association. The rest of the discussion will be focused on the stars located near the Orion molecular clouds, in the region of the association subgroups.

Figure 3 shows the distribution of Hipparcos parallaxes for the stars located in the Orion OB1 subgroups and selected by proper motion according to the criteria above. The stars were divided among the subgroups following the division given by Warren &
The parallaxes in subgroup 1a are larger on average than those in 1b and 1c. This difference is statistically significant and implies that 1a lies closer to the Sun than 1b and 1c.

From the parallaxes one can infer the distances to the subgroups of the association. However, the distance depends non-linearly on the parallax, namely \( d = 1/\pi_H \), where \( \pi_H \) is the measured parallax, which is distributed as a Gaussian around the true parallax \( \pi \). In this case the expectation value for \( d, E[1/\pi_H] \) is in general different from \( 1/\pi \), even if the measured parallax is unbiased \( (E[\pi_H] \approx \pi) \). In other words, \( 1/\pi_H \) is a biased estimate of the star’s true distance. For individual stars the magnitude of the bias depends on the ratio of the measurement error to the true parallax. The bias can be calculated analytically as shown by Smith & Eichhorn (1996). Another bias in the distance estimate for a sample of stars enters because of selection effects and completeness limits. An example of this is the Lutz-Kelker bias (Lutz & Kelker 1973). The bias due to selection effects and the completeness of the sample depends very much on the
details of the sample selection. Blindly applying a Lutz-Kelker correction will lead to erroneous estimates of the bias involved. For more details and references on how to treat parallaxes correctly see Brown et al. (1997).

In the case of the subgroups of Orion OB1, we proceed as follows. If one assumes the stars in the subgroup to be distributed in a spherically symmetric way, and if one assumes that one has sampled the stellar distribution representatively, then one can show that the average parallax of that group of stars is an unbiased estimator of the distance to the centre of that group. Both assumptions have to be substantiated in the case of Orion OB1. For the more dispersed subgroups of nearby associations there is no evidence that the distribution of stars is not spherically symmetric. However, recent work by Hillenbrand & Hartmann (1998) on the ONC has shown that cluster to be elongated. The selection effects that enter into the Orion OB1 sample are rather complicated. They include both the selection effects of the 1982 SPECTER proposal as well as the overall Hipparcos Catalogue selection effects. A specific effort was made, however, to include as many O and B stars in the Orion region as possible. Nevertheless, the sample is at least magnitude-limited and the bias in the calculated distance due to selection effects should be studied in detail.

Hence, proceeding from the assumptions above, we can calculate the distances to the subgroups from the average parallax of the members. For subgroup 1a the average parallax is 3.07 ± 0.15 mas (61 stars), for 1b it is 2.28 ± 0.17 mas (42 stars), and for 1c it is 2.16 ± 0.17 mas (34 stars). The quoted errors are the errors in the mean. The median error on the individual stellar parallaxes is ~ 1 mas for all subgroups and the spread in the parallaxes (as measured by the standard deviation) is of the same order. Hence the depth of the association is not resolved by the Hipparcos parallaxes. The mean parallaxes above correspond to distances of 330 pc for 1a, 440 pc for 1b and 460 pc for 1c.

Thus, subgroup 1a is roughly 100 pc closer to the Sun than subgroups 1b and 1c. The distance to 1a is much smaller than the photometrically determined distance. This result is also found for many other nearby OB associations (de Zeeuw et al. 1997). The smaller distance has several implications. Subgroup 1a is now located far enough away from the Orion molecular clouds that it may have triggered star formation simultaneously throughout the cloud complex, as opposed to triggering only one part of the cloud. The latter scenario would more likely lead to a sequence of ages among the subgroups. However, as discussed in the previous section, such a sequence does not appear to exist, and as discussed by Hillenbrand (1997), there is a wide distribution of ages of young stars throughout the molecular cloud complex (outside the Orion OB1 subgroups). A second consequence of the smaller distance to 1a is that the size, mass, and energy of the Orion/Eridanus bubble should be lowered by 13%, 25%, and 25% respectively, if one assumes that 1a is at the centre of the bubble. As a consequence the energy requirements for the creation of the bubble are less stringent. Thirdly, Cunha & Lambert (1992) noted that no self enrichment has occurred in subgroup 1b of the association, whereas it was expected because of supernovae from subgroup 1a. However, with subgroup 1a located at a large distance from the gas out of which 1b formed it is very well possible that most of the supernovae ejecta were lost in the low-density ISM surrounding the molecular clouds. Hence no self-enrichment of the association occurred at the location of 1b.

Finally, we would like to stress again that the distance estimates above are probably biased. A preliminary investigation into this bias (de Zeeuw et al., in preparation)
shows that it is probably small (around 5%) and that the distances are underestimated as derived from the parallaxes. However, examining the parallax distribution directly (avoiding the bias in the distances) clearly shows subgroup 1a to be much closer to the Sun than 1b and 1c.

5. Evidence for Low Mass Stars in OB Associations

Up to now we have focused on the massive (O and B) stars in Orion OB1. However, if one extrapolates the IMF for Orion OB1 the bulk of the stars should be low-mass stars (of mass \( \lesssim 2 M_\odot \)). For many years, the conventional wisdom had been that low-mass stars simply did not form in regions of high-mass star formation. Regions forming low mass stars, the T associations, were dominated by the classical T Tauri stars (cTTS), noteworthy for their strong H\(\alpha\) emission, their UV and IR continuum excesses, and their erratic variability. It was obvious that there were no high-mass stars in T associations. For a field star mass function, the highest mass \( m_0 \) occurs where the expectation of \( N(m > m_0) \) is less than unity. Using the Miller-Scalo (1979) mass function, there will be about one star of \( > 5 M_\odot \) for every 100 lower-mass stars. The Taurus-Auriga T association, with about 100 cTTS, was not expected to have a significant population of high-mass stars, and it didn’t.

However, this tidy picture began to unravel in the early 1980s. X-ray observations with EINSTEIN (and later with ROSAT) revealed a large number of X-ray sources in these T associations. Optical follow-ups (e.g., Walter et al. 1988) showed that these were indeed low-mass PMS stars, with, in many cases, ages comparable to the cTTS. Walter et al. (1988) concluded that the population of the Tau-Aur association had been underestimated by nearly a factor of ten. If this were indeed correct, and the mass function of the association mirrors the field, then there should be a few tens of B stars associated with Tau-Aur.

Blaauw (1956, 1984) had identified a loose group of OB stars, the Cas-Tau group, in this general region of the sky. In fact, subgroups 6 and 7 of this OB group lie at about the distance of the Tau-Aur clouds and are kinematically indistinguishable from the Tau-Aur T association. These stars are all B5 or earlier. Walter & Boyd (1991) searched the Bright Star Catalog (Hoffleit & Jaschek 1982) for evidence of late B stars which might be associated with this association, and identified 29 B stars (\( V < 6^\text{m}.5 \)) which are cospatial with the Tau-Aur T association, and which share the space velocity of the T Tauri stars. Walter & Boyd concluded that the population of the Tau-Aur association was indeed larger than had been thought, that the mass function extended up to the early B stars, and was consistent with the field star mass function.

If T associations can contain high-mass stars, can OB associations contain low-mass stars in the numbers predicted by the field star mass function? Theory suggested that star formation was bimodal, and that high- and low-mass stars formed by different processes (e.g., Larson 1986; Shu & Lizano 1988). There was no reason to expect a universal mass function. Indeed, while there was a decided lack of evidence for low-mass stars in OB associations, much of this was due to observational selection.

The B stars, as well as many of the low-mass stars, have ages of up to a few tens of Myr. They may be ZAMS, rather than PMS stars. Nonetheless, they are kinematic members of the association. As the mass function is integrated over time, it is not relevant to argue that the B stars and some of the low-mass stars may represent an earlier episode of star formation.
Low-mass stars are many magnitudes fainter than high-mass stars, and there were few searches for low-mass stars in OB associations. However, objective prism Hα surveys of the Orion association had revealed what presumably were T Tauri stars in the vicinity of λ Ori (Duerr, Imhoff, & Lada 1982). The Kiso survey has also found a number of Hα-emitting stars throughout the Orion OB1 association, with many concentrated towards the belt of Orion (Kogure et al. 1989; Nakano et al. 1995). Furthermore, the concentration of low-mass stars near the Orion Trapezium has long been known (e.g., Walker 1969).

Walter et al. (1994) used an X-ray-based search to look for the low-mass population of the Upper Sco OB association (de Geus et al. 1989), and found 28 low-mass PMS stars in 7 deg² of the association. After correcting for the incompleteness of the X-ray sampling, they concluded that the association has a field star mass function between about 0.2–10 M⊙. The total number of low-mass stars (< 2 M⊙) is about 2000. Part of the reason that this enormous population of low-mass stars lay undetected is that few of the stars are cTTS: most have lost their circumstellar disks, perhaps because of the influence of the winds and ionizing flux of the B stars, or because of supernovae in the association.

6. The Low-Mass Population of Orion OB1

From the observation that the Upper Sco OB association has a field star mass function, it is possible to conclude that there might indeed be a universal mass function, and if the Orion OB1 association (Blaauw 1991; Brown et al. 1994) has a similar mass function, there should be literally tens of thousands of low-mass stars in this association. These low-mass stars are important to find and study, for a number of reasons:

- The low-mass stars may give a better picture of the history of star formation. The locations of low-mass stars in the H-R diagram are far more sensitive to age than are the positions of the ZAMS B stars.

- The low-mass stars may give a better picture of the kinematics of the association. If there is mass-segregation, it will be revealed by the low-mass stars. Radial velocities are more easily measured for the (narrow-lined) low-mass stars, which have numerous sharp lines, than they can be for the B stars.

- Most low-mass stars form in OB associations, not T associations. Studies of stars in T associations may be misleading, because of the external influences of the high-mass star’s winds and ionizing radiation (not to mention supernovae). These influences may destroy accretion disks, altering the mass function, and affecting the binary fraction and the formation of planets.

6.1. The Orion Nebula region

Haro (1953) noted the existence of many emission-line objects in the vicinity of the Orion Nebula. Walker (1969) obtained spectra of a number of these stars, and showed

---

3Historically this was due to the large extent of associations on the sky (tens of degrees), which meant that they were not amenable to proper motion studies with photographic plates. One thus had to rely on large scale meridian circle surveys, which generally only included the brighter stars. Consequently, membership in OB associations was rather ill-determined for spectral types later than B5.
that they were members of the ONC and hence were pre-main sequence stars. Andrews (1981) published a photometric atlas of Orion showing the existence of many dM stars what were likely PMS stars. Hillenbrand (1997) has reported on a detailed photometric and spectroscopic analysis of the low-mass population in the inner 2.5 pc of the ONC. There have been spectroscopic studies of the G stars in Orion OB1c, just outside the Orion Nebula (e.g., Smith, Beckers, & Barden 1983). Strom et al. (1990) have discussed the low-mass population of the L 1641 cloud, to the south of the ONC. Further details can be found in the chapter by Allen & Hillenbrand.

6.2. \( H\alpha \) surveys

The Kiso survey (Wiramihardja et al. 1989, 1991, 1993; Kogure et al. 1989; Nakano et al. 1995) is an objective prism survey for \( H\alpha \) emission-line objects in a wide region of Orion (extending roughly from 5 to 6 hours in Right Ascension, \(-10^\circ \) to \(+5^\circ \) degrees
in declination. They identified about 1200 Hα emission-line stars in 300 deg². These stars generally fall in the magnitude range \(13^m < V < 17^m\). Based on similarities to the Hα emitting population near the ONC, the authors of this survey conclude that many of these stars are likely to be T Tauri stars. While most of the emission-line stars are concentrated near the ONC and the L1641 cloud, there are many stars in the region of the belt, with what appear to be significant clumpings near \(\sigma\) and \(\zeta\) Ori (Figure 4). Kogure et al. (1992) followed-up with low-dispersion spectroscopic observations of 34 emission line stars in Orion OB1b, and concluded that they were indeed T Tauri stars based on H-Balmer and Ca II K emission lines. Nakano & McGregor (1995) obtained near-IR photometry for a number of these stars, and concluded that they were indeed mostly T Tauri stars.

As the objective prism surveys are only sensitive to stars with strong Hα emission, they miss the naked or weak T Tauri stars (nTTS; wTTS), which greatly outnumber the cTTS (Walter et al. 1988; Neuhäuser et al. 1995). It is not possible to extrapolate from the emission-line stars to the full number of low-mass PMS stars, but if the ratio of nTTS to cTTS is 5–10:1 as it is in Tau-Aur, or 30:1 as it is in Upper Sco, there may be tens of thousands of low-mass stars associated with Orion OB1.

6.3. X-ray surveys

The EINSTEIN observatory was used to observe many regions within the constellation of Orion. Walter et al. (in preparation) have catalogued over 600 X-ray sources, of which about 200 are low-mass PMS stars. The space distribution of these PMS stars is shown in Figure 4. There are concentrations near \(\lambda\) Ori, near the ONC and L 1641, and along the belt, but there are low-mass PMS stars scattered everywhere within the constellation.

Alcalá et al. (1996) found a similar spatial distribution using the ROSAT all-sky survey (RASS). While the RASS does not go very deep in general, it has the advantage of offering complete and nearly uniform spatial coverage. Alcalá et al. identified 112 new PMS stars in 450 deg² (Figure 4). Sterzik et al. (1995) analyzed the spatial distribution of the RASS X-ray sources. By selecting sources based on spectral hardness ratios (X-ray colors), they could select for PMS stars. They showed that the density of PMS candidate X-ray sources showed significant enhancements at the locations of Orion OB1a, OB1b, OB1c, \(\lambda\) Ori, and NGC 1788. Further details of these X-ray surveys can be found in the chapter by Sterzik et al. in this volume.

6.4. The \(\sigma\) Orionis Cluster

The ROSAT PSPC and HRI observations reveal over 100 X-ray point sources within 1° of \(\sigma\) Ori. As part of an investigation of the low-mass population of Orion, Walter, Wolk, & Sherry (1998) investigated the region around \(\sigma\) Ori, a member of Orion OB1b and a Trapezium-like system, using multi-object spectroscopy and wide-field photometry.

\[\text{The Walter et al. and Alcalá et al. surveys are based on fairly low resolution spectra. They did not determine radial velocities for the stars. Briceno et al. (1997) argued that many of these stars could be older (100 Myr), foreground ZAMS G stars, which have not depleted their lithium. While this cannot be excluded for the G stars, it cannot be the case for the K and M stars. The significant enhancement in the density of stellar X-ray sources in the direction of Orion (Sterzik et al. 1995) indicates that most of these stars must be associated with Orion.}\]
Figure 5. The distribution of radial velocities of the stars near σ Ori. The spectroscopically-identified low-mass PMS stars (solid histogram) are well-fit as a Gaussian distribution of mean 25 km s\(^{-1}\) with \(\sigma=5\) km s\(^{-1}\). The secondary peak at 12 km s\(^{-1}\) is due to a systematic shift of M star velocities, and may be an artifact of using a sky spectrum as a velocity template. The stars in the sample (dotted histogram) have a mean velocity of 31 km s\(^{-1}\) with \(\sigma=37\) km s\(^{-1}\).

Most of the X-ray sources have optical counterparts. Walter \textit{et al.} observed the optical counterparts of the X-ray sources as well as a randomly-selected sample of stars in the HST Guide Star Catalog (GSC), obtaining useful spectra for about 300 stars\(^5\). Among these, they identified 104 likely PMS stars spectroscopically within 30 arcmin of σ Ori. Primary identification was made on the basis of a strong Li\(\text{I}\) \(\lambda6707\)Å absorption line. The H\(\alpha\) strengths ranged from an emission equivalent width of 77Å in a K1 star to apparently normal photospheric absorption. Radial velocities were determined by cross-correlating the spectra with spectra of the dusk or dawn sky. At this fairly low dispersion (1–2Å resolution), uncertainties are about \(\pm5\) km s\(^{-1}\) for spectra with high signal-to-noise. The distribution of radial velocities is strongly peaked at the 25 km s\(^{-1}\) velocity of the OB association (Figure 5).

Of the 104 PMS stars, 28 (27\%) are not X-ray sources. This gives some indication of the completeness of the X-ray sampling. Some 258 of the optical stars observed

\(^5\)Most of the spectra were obtained using the WIYN telescope with the HYDRA multi-object spectrometer, as part of the KPNO queue scheduling program.
were taken from the HST Guide Star Catalog. These stars constitute a magnitude-limited sample unbiased with respect to either activity or color. Of those 258 stars, 57 (22%) are likely PMS. The estimated space density of PMS stars with $10^m < V < 15^m$ within 30 arcmin of $\sigma$ Ori is about 120 stars per deg$^2$.

From $UBVRI$ images at the CTIO 0.9 m telescope in January and February 1996, Walter et al. (1997) sampled stars to $V=19^m$ in 0.15 deg$^2$ surrounding $\sigma$ Ori. The color-magnitude diagram (Figure 6) shows a clear PMS locus, well separated from the background galactic stars. In addition to the 45 PMS stars identified spectroscopically (which have photometry), there are 65 other stars along the isochrone to $V=19^m$, most of which are likely to be PMS stars. These 110 photometric PMS stars imply a space density, in the magnitude range $12^m < V < 19^m$, of about 700 per deg$^2$ (or more, if many stars are multiple).

The GSC PMS sample shows evidence for clustering. The centroid of the PMS star distribution is centered on the position of $\sigma$ Ori. Summation of the stars into radial bins centered on $\sigma$ Ori (Figure 7) shows that the distribution is flat for the non-PMS stars, but that the radial distribution of the PMS stars is peaked at $\sigma$ Ori. The inferred cluster radius (where the density of PMS stars reaches zero) is about 0.5 deg (3.3 pc).
Figure 7. The radial distribution of stars in the GSC sample. PMS stars (solid histogram) show a clustering towards \( \sigma \) Ori, while other stars in the GSC (dashed distribution) do not. The probability that the two samples are drawn from the same parent distribution is 0.0003. The lines are linear least-squares fits to the distribution. The lack of stars within 3 arcmin of \( \sigma \) Ori is an artifact of the glare from the \( V = 3^m 8 \) star.

While the results reported here are still preliminary, with the analysis continuing, the basic conclusion is secure: there is a significant population of low-mass PMS stars in this region. The stars appear to cluster spatially around \( \sigma \) Ori and the narrowness of the PMS locus suggests coevality, at the 2 Myr age of the OB association. The total inferred mass of this group of stars is comparable to that of the ONC. This \( \sigma \) Ori cluster is the second youngest cluster now known after the ONC, and may be an evolved analog of the ONC.

This results implies that there is substructure in subgroup 1b, and that the boundaries of the subgroups are not yet well established. As discussed before, the exact boundaries are important if one wants interpret the concentration of subgroups in terms of their ages. As there is no evidence for evolutionary differences between the early-type stars in subgroup 1b, it may be that this subgroup formed through merging of several Trapezium-like clusters that formed at more or less the same time.
Table 1. Space densities of PMS stars in Orion, $10^m < V < 15^m$

| Field | RA   | Dec | Assn. | PMS/deg$^2$ |
|-------|------|-----|-------|-------------|
| 4     | 5 24 | +1  | OB1a  | 150         |
| 6     | 5 31 | −1  | OB1a/b| 110         |
| 9     | 5 38 | +3  | OB1a  | 70          |
| 15    | 5 31 | −3  | OB1c  | 65          |
| 16    | 5 24 | −2  | OB1a  | 40          |
| σ Ori | 5 42 | −2  | OB1b  | 120         |

6.5. Densities of low-mass stars elsewhere in Orion

Walter et al. (unpublished) have also obtained spectroscopic data on five other regions in Orion OB1. For each of these fields, they determined the spectroscopic PMS population ($10^m < V < 15^m$), based primarily on the Li line strength (photometry exists only for Field 4). The space densities of PMS stars are shown in Table 1. The space density of PMS stars near σ Ori is not extraordinary. Field 4, in a nondescript region in Orion OB1a, has an even higher space density. The PMS stars in Field 4 have an age of about 10 Myr, which is consistent with the age of the OB1a subassociation. This sample of stars includes no slow rotators (Wolk 1996), and only one classical T Tauri star identified to date. Note that, in the absence of photometry and radial velocities, the uncertainties in the densities in Table 1 are about ±30%.

7. Conclusions and Future Work

We have discussed the work done in the past on the early-type stars in Orion OB1 and described the most recent developments. With the Hipparcos parallaxes and proper motions now available, our knowledge of OB associations will be significantly advanced. The most remarkable result concerning Orion OB1 to come out of the Hipparcos data is the much smaller distance to subgroup 1a. The derived distances to the subgroups of Orion OB1 are still preliminary and the biases due to selection effects should be studied. However, the fact that 1a is much closer to the Sun than 1b and 1c is a robust result. The implications are that 1a could have triggered simultaneous star formation throughout the Orion complex, and the mass and energy of the Orion/Eridanus Bubble are probably lower than thought previously.

Unfortunately, the Hipparcos proper motions do not allow a clear kinematic identification of Orion OB1. However, one may attempt to tackle the problem by using the Hipparcos Intermediate Astrometric Data. These data essentially allow one to reconstruct the original observations from which the astrometric parameters of the stars were derived. One can then try to construct a new solution of the proper motions and parallaxes of the association stars from these data, by solving for a common proper motion and parallax assuming all stars considered are members of the association. For details see Volume 3, Chapter 17 of the Hipparcos Catalogue (ESA 1997) and van Leeuwen & Evans (1998). This procedure may provide better insight into the overall kinematics of the subgroups, as well as into the question of substructure and subgroup boundaries, and will lead to an improved estimate of their parallax and the associated errors. Nev-
ertheless, to really advance our knowledge of the kinematics of the early-type stars in Orion OB1, accurate (∼ 1–2 km s⁻¹) and homogeneous radial velocities are needed.

The Hipparcos parallaxes will also be useful in studying the large scale interstellar medium around Orion OB1. By combining the parallaxes of stars in the Orion region of the sky with studies of interstellar lines along the line of sight to these stars, one may be able to constrain the distances to features in the ISM. This will lead to better insight into the three-dimensional structure of, e.g., the Orion/Eridanus Bubble, which will in turn improve the interpretation of the observations of this interstellar bubble.

We have not addressed the question of the binary population in Orion OB1. A thorough study thereof would require more accurate knowledge of the membership of the association than we have at present. For the early-type stars, a radial velocity survey to search for binaries has been carried out (Morrell & Levato 1991), but was limited to the 100 or so brightest stars in Orion OB1. The Hipparcos observations will provide further information on the binarity of the stars. For the low-mass stars, radial velocity surveys are also needed to sort out the frequency of binaries. Accurate knowledge of the binary population is also needed in order to correctly interpret the kinematics of the association. The presence of undetected binaries may easily lead to an inflated velocity dispersion.

The massive stars in OB associations have traditionally received most of the attention. However, it is now clear that there are significant numbers of low-mass stars associated with the Orion OB1 association. Low-mass stars have indeed formed in great numbers in Orion OB1. The data are still very incomplete, and the interpretations are still immature, but we are confident that further study of this low-mass population will reveal a great deal about the initial mass function in Orion OB1, the distribution of stellar ages, and the kinematics of the association. The best is yet to come.

References

Alcalá, J. M., Terranegra, L., Wichmann, R., Chavarria-K., C., Krautter, J., Schmitt, J. H. M. M., Moreno-Corral, M. A., de Lara, R., & Wagner, R. M. 1996, A&AS, 119, 7
van Altena, W. F., Lee, J. T., Lee, J.-F., Lu, P. K., & Upgren, A. R. 1988, AJ, 95, 1744
Ambartsumian, V. A. 1947, in Stellar Evolution and Astrophysics, Armenian Acad. of Sci. (German transl., Abhandl. Sowjet. Astron., 1, 33 [1951])
Andrews, D. A. 1981, A Photometric Atlas of the Orion Nebula, (Armagh Observatory, Armagh, Northern Ireland)
Anthony-Twarog, B. J. 1982, AJ, 87, 1213
Bally, J., Stark, A. A., Wilson, R. W., & Langer, W. D. 1987, ApJ, 312, L45
Bertieu F. C. 1958, ApJ, 128, 533
Blaauw A. 1946, PhD thesis, University of Groningen
Blaauw, A. 1956, ApJ, 123, 408
Blaauw, A. 1961, Bull. Astr. Inst. Netherlands, 15, 265
Blaauw, A. 1964, ARA&A, 2, 213
Blaauw, A. 1984, in The Milky Way Galaxy, eds. H. van den Woerden, R. J. Allen, & W. B. Burton, (Dordrecht: Reidel), 335
Blaauw, A. 1991, in *The Physics of Star Formation and Early Stellar Evolution*, eds. C. J. Lada & N. D. Kylafis, NATO ASI, vol. 342, p125

Briceño, C. Hartmann, L. W., Stauffer, J. R., Gagné, M., & Stern, R. A. 1997, AJ, 113, 740.

Bok, B. J. 1934, Harvard Coll. Obs., Circular 384, 1

Brown, A. G. A., de Geus, E. J., & de Zeeuw, P. T. 1994, A&A, 289, 101

Brown, A. G. A., Hartmann, D., & Burton, W. B. 1995, A&A, 300, 903

Brown, A. G. A., Arenou, F., Lindegren, L., van Leeuwen, F., & Luri, X. 1997, in *Hipparcos Venice ’97*, ESA SP-402, p63

Briceño, C. Hartmann, L. W., Stauffer, J. R., Gagné, M., & Stern, R. A. 1997, AJ, 113, 740.

Bok, B. J. 1934, Harvard Coll. Obs., Circular 384, 1

Brown, A. G. A., de Geus, E. J., & de Zeeuw, P. T. 1994, A&A, 289, 101

Brown, A. G. A., Hartmann, D., & Burton, W. B. 1995, A&A, 300, 903

Brown, A. G. A., Arenou, F., Lindegren, L., van Leeuwen, F., & Luri, X. 1997, in *Hipparcos Venice ’97*, ESA SP-402, p63

Burrows, D. N., Singh, K. P., Nousek, J. A., Garmire, G. P., & Good, J. 1993, ApJ, 406, 97

Chromey, F. R., Elmegreen, B. G., & Elmegreen, D. M. 1989, AJ, 98, 2203

Claudius, M., & Grosbøl, P. J. 1980, A&A, 87, 339

Cowie, L. L., Songaila, A., & York, D. G. 1979, ApJ, 230, 469

Crawford, D. L., & Barnes, J. V. 1966, AJ, 71, 610

Cunha, K., & Lambert, D. L. 1992, ApJ, 399, 586

Cunha, K., & Lambert, D. L. 1994, ApJ, 426, 170

Cunha, K., Smith, V. V., & Lambert, D. L. 1995, ApJ, 452, 634

Cunha, K., Lambert, D. L., Lemke, M., Gies, D. R., & Roberts, L. R. 1997, ApJ, 478, 211

Duerr, R., Imhoff, C. L., & Lada, C. J. 1982, ApJ, 261, 135

Elmegreen, B. G. 1992, in *Star Formation in Stellar Systems*, eds. G. Tenorio-Tagle, M. Prieto, & F. Sánchez, (Cambridge: Cambridge University Press), p381

ESA 1997, *The Hipparcos and Tycho Catalogues*, ESA SP-1200

Genzel, R., & Stutzki, J. 1989, ARA&A, 27, 41

de Geus, E. J., 1991, in *The Formation and Evolution of Star Clusters*, ed. K. Janes, ASP Conf. Ser. vol. 13, p40

de Geus, E. J. 1992, A&A, 262, 258

de Geus, E. J., de Zeeuw, P. T., & Lub, J. 1989, A&A, 216, 44

Goudis, C. 1982, *The Orion Complex: A Case Study of Interstellar Matter*, Astrophys. Space Sci. Libr. vol. 90, (Dordrecht: Reidel)

Green, D. A. 1991, MNRAS, 253, 350

Green, D. A., & Padman, R. 1993, MNRAS, 263, 535

Hardie, R. H., Heiser, A. M., & Tolbert, C. R. 1964, ApJ, 140, 1472

Haro, G. 1953, ApJ, 117, 73

Hartmann, D., & Burton, W. B. 1997, *Atlas of Galactic Neutral Hydrogen*, (Cambridge: Cambridge University Press)

Hillenbrand, L. A. 1997, AJ, 113, 1733

Hillenbrand, L. A., & Hartmann, L. W. 1998, ApJ, 492, 540

20
Hoffleit, D., & Jaschek, C. 1982, *The Bright Star Catalogue*, (New Haven: Yale University Observatory)

Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., Lub, J., Blaauw, A., & de Zeeuw, P. T. 1997, in *Hipparcos Venice ’97*, ESA SP-402, p571

Jones, D. H. P. 1970, MNRAS, 152, 231

Jones, B. F., & Walker, M. F. 1988, AJ, 95, 1755

Kogure, T., Ogura, K., Nakano, M., & Yoshida, S. 1992, PASJ, 44, 91

Kogure, T., Yoshida, S., Wiramihardja, S. D., Nakano, M., Iwata, T., Ogura, K. 1989, PASJ, 41, 1195

Kudritzki, R. P., Pauldrach, A., Puls, J., & Abbott, D. C. 1989, A&A, 219, 205

Lada, E. A., Bally, J., & Stark, A. A. 1991, ApJ, 368, 432

Larson, R. B. 1986, MNRAS, 218, 409

Lesh, J. R. 1968, ApJ, 152, 905

van Leeuwen, F., & Evans, D. W. 1998, A&AS, in press

Lub, J., & Pel, J. W. 1977, A&A, 54, 137

Lutz, T. E., & Kelker, D. H. 1973, PASP, 85, 573

Mathieu R. D. 1986, Highlights of Astronomy, 7, 481

Maddalena, R. J., Morris, M., Moscovich, J., & Thaddeus, P. 1986, ApJ, 303, 375

McCray, R., & Kafatos, M. C. 1987, ApJ, 317, 190

McNamara, B. J., Hack, W. J., Olson, R. W., & Mathieu, R. D. 1989, AJ, 97, 1427

Miller, G. E., & Scalo, J. M. 1979, ApJS, 41, 513

Morgan, W. W., & Lodén, K. 1966, Vistas in Astronomy, 8, 83

Morrell, N., & Levato, H. 1991, ApJS, 75, 965

Nakano, M., Wiramihardja, S. D., & Kogure, T. 1995, PASJ, 47, 889

Nakano, M. & McGregor, P. J. 1995, in *Future Utilisation of Schmidt Telescopes*, eds. J Chapman, R. Cannon, S. Harrison, & B. Hidayat, ASP Conf. Ser. vol. 84, p376

Neuhäuser, R., Sterzik, M. F., Schmitt, J. H. M. M., Wichmann, R., & Krautter, J. 1995, A&A, 297, 391

Parenago, P. P. 1953, Astr. Zh., 30, 249; Astron. Newsletter, 74, 20

Parenago, P. P. 1954, Publ. Sternberg Astron. Inst., 25; Astron. Newsletter, 97, 39

Reynolds, R. J., & Ogden, P. M. 1979, ApJ, 229, 942

Perryman, M. A. C., Lindegren, L., Kovalevsky, J., *et al.* 1997, A&A, 323, L49

Shahovskoj, N. M. 1957, Bull. Stalinabad Astrophys. Obs., 20, 3; Astron. Newsletter, 94, 7

Sharpless, S. 1952, ApJ, 116, 251

Sharpless, S. 1954, ApJ, 119, 200

Sharpless, S. 1962, ApJ, 136, 767

Shu, F. H., & Lizano, S. 1988, in *Stellar Matter*, eds. J. M. Moran & P. T. P. Ho, (New York: Gordon & Breach), p65

Smart, R. L. 1993, PhD thesis, University of Florida, Gainesville

Smith, M. A., Beckers, J. M., & Barden, S. C. 1983, ApJ, 271, 237

Smith, H., & Eichhorn, H. 1996, MNRAS, 281, 211
Sterzik, M., Alcalá, J. M., Neuhäuser, R., & Schmitt, J. H. M. M. 1995, A&A, 297, 418
Strom, K. M., Strom, S. E., Wilkin, F. P., et al. 1990, ApJ, 362, 168.
Tian, K. P., van Leeuwen, F., Zhao, J. L., & Su, C. G. 1996, A&AS, 118, 503
Walker, M. F. 1969, ApJ, 155, 447
Walter, F. M., & Boyd, W. T. 1991, ApJ, 370, 318
Walter, F. M., Brown, A., Mathieu, R. D., Myers, P. C., & Vrba, F. J. 1988, AJ, 96, 297
Walter, F. M., Wolk, S. J, & Sherry, W. 1998, in Cool Stars, Stellar Systems, and the Sun, eds. R. Donahue & J. Bookbinder, in press
Walter, F. M., Vrba, F. J., Mathieu, R. D., Brown, A., & Myers, P. C. 1994, AJ, 107, 692
Warren, W. H., & Hesser, J. E. 1977a, ApJS, 34, 115
Warren, W. H., & Hesser, J. E. 1977b, ApJS, 34, 207
Warren, W. H., & Hesser, J. E. 1978, ApJS, 36, 497
Wiramihardja, S. D., Kogure, T., Yoshida, S., Nakano, M., Ogura, K., & Iwata, T. 1991, PASJ, 43, 27
Wiramihardja, S. D., Kogure, T., Yoshida, S., Ogura, K., & Nakano, M. 1993, PASJ, 45, 634
Wolk, S. J. 1996, PhD thesis, SUNY Stony Brook
de Zeeuw, P. T., & Brand, J. 1985, in Birth and evolution of massive stars and stellar groups, eds. W. Boland & H. van Worden, Astrophys. Space Sci. Lib. vol. 120, (Dordrecht: Reidel), p95
de Zeeuw, P. T., Brown, A. G. A., & Verschueren, W. 1994, in Galactic and Solar System Optical Astrometry: Observation and Application, eds. L. V. Morrison & G. F. Gilmore, (Cambridge: Cambridge University Press), p215
de Zeeuw, P. T., Brown, A. G. A., de Bruijne, J. H. J., Hoogerwerf, R., Lub, J., Le Poole, R. S., & Blaauw, A. 1997, in Hipparcos Venice ’97, ESA SP-402, p495

22