OB ASSOCIATIONS AND THE FOSSIL RECORD OF STAR FORMATION

ADRIAAN BLAAUW
Kapteyn Laboratory
P.O.Box 800
9700 AV Groningen
The Netherlands

Abstract. Properties of OB Associations within 1.5 kpc are reviewed as "fossils" of local star formation, and as a reference frame for the more detailed discussions, elsewhere in this volume, of star formation occurring within the sample. Special attention is paid to the process of sequential star formation. For the nearest associations this can be traced back to the formation of the Gould Belt between 30 and 50 million years ago. A few remarks on future research conclude the review.

1. Introduction, Definition, Nomenclature

The present chapter deals with "fossil" properties such as structures, motions and stellar content of the OB Associations in the domain within about 1.5 kpc from the sun, and in some more detail with those within 1 kpc. Ages range from a few to about 30 million years, and dimensions from a few parsec upward. Emphasis will be on morphology more than on interpretation.

Increasing observational resolution and sensitivity allows modern research on star formation to focus more and more on the detailed phenomena, approaching the sub-parsec scale, and aiming at revealing the formation of the individual star or compact cluster. However, virtually all of these local birthplaces have a physical history as parts of larger structures, and perhaps there might be a tendency for investigators to not see the wood for the trees. For example, the star forming ISM in the Ophiuchus clouds has a history over the past 30 or 40 million years within which during the last 5 million years or so it has been exposed to supernova explosions and stellar winds from the rapidly evolving massive stars in the neighbouring, youngest subgroup of the Ophiuchus-Scorpius-Centaurus Association, whereas this latter subgroup was formed at an earlier stage under the influence of its neighbouring still older subgroup on the opposite side. The formation of this oldest subgroup, in turn, probably was the result of star formation processes that have to be linked to the origin of the Gould Belt system. Similarly, the current active star formation in Orion, including that in and around the Trapezium Cluster, must be linked genetically to the earlier generations of massive stars in adjacent subgroups of Ori OB1.

C. J. Lada and N. D. Kylafis (eds.), The Physics of Star Formation and Early Stellar Evolution, 125–154.

We distinguish three main themes:

Section 2 describes the Ophiuchus-Scorpius-Centaurus Association, henceforth referred to as OSCA. This will serve a double purpose: because of its proximity to the sun (distance about 150pc) it allows more complete analysis than most of the other associations, and as it exhibits many of the features characteristic for OB Associations in general, it is a good example to illustrate the model of sequential star formation. The equally close, and evolutionary more advanced association Cas-Tau is next dealt with in this section, and we also deal briefly with some features of the three times more remote, but intensively studied association Ori-OB1.

Section 3 describes the pattern of space distribution, ages, association with molecular clouds, and some statistics of intrinsic properties of the ensemble of associations surrounding the sun up to distances of 1500 pc.

Section 4 pays attention to the Gould Belt System. This subsystem in the local ensemble shows features pointing to a common, very early, formation process that may be related to the Cas-Tau Association, and of which the formation of the (younger) associations within the Gould Belt may be a consequence.

The study of stellar associations is somewhat complicated by the lack of precise definition of their stellar content. Whereas in most cases it is not difficult to point to the group of stars that form the association's main body, in its outer parts the gradual transition to the field star population renders the assignment of "membership" uncertain, unless precise data are available on the motion of the star which allows tracing back its location of origin.

As to nomenclature, for most objects the IAU system applies, like for instance for Mon OB1 and Mon OB2, i.e. reference to the constellation in which the (main body of the) object is located followed by running numbers which are not necessarily in order of right ascension because of the inclusion of recent discoveries. However, for such nearby groups as Cas-Tau and Oph-Sco-Cen this system did not work to begin with, because they did not stand out clearly as clusterings against the general background population; in fact, as a consequence they did not even occur in the earliest listings of associations. On the other hand, we now list as OB Associations some objects, like Collinder 121, that were classified originally as open clusters.

2. The Nearest Associations OSCA and CAS-TAU; ORI-OB1

2.1. THE OPHIUCHUS-SCORPIUS-CENTAURUS ASSOCIATION (OSCA)

Properties of the Ophiuchus-Scorpius-Centaurus Association (henceforth called OSCA) are shown in Figure 1 and Table 1. The association spans an angle of about 70° in galactic longitude, from 290° to 360°. At the low longitudes it is centred slightly above the galactic circle, but between 310° and 360° around latitude +17°, well detached from the plane. The largest linear dimension is about 200 pc, and the lateral size about 40 pc.

The association can be subdivided into subgroups of different ages. The principal ones are denoted OPH (Ophiuchus), US (Upper Scorpius), UC-L (Upper Centaurus - Lupus), and LC-C (Lower Centaurus - Crux), the existence of which was recognized long ago (Blaauw 1960). Recent investigation (de Geus et al. 1990, de

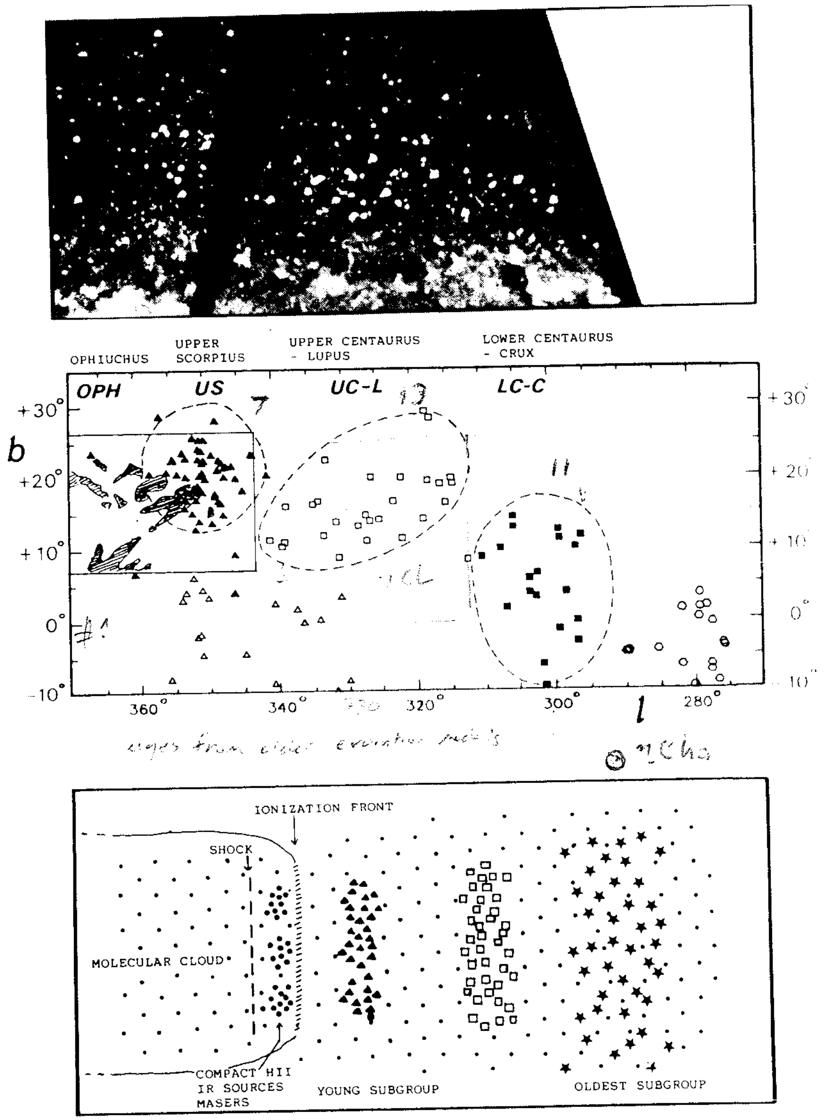


Fig. 1. Top: Section of a wide-angle blue photograph of the southern Milky Way sh the Oph-Sco-Cen Association (OSCA), published by Code and Houck (1955). M Plot of the bright B-type stars in the region of the photograph, based on de Geus (1986), with outline of the subgroups and sketch of the Ophiuchus dark clouds. B Schematic model of sequential star formation, as it may apply to OSCA, adapte certain modifications (see text) from Thaddeus (1977).

Geus 1988) of the Ophiuchus molecular cloud complex with its imbedded star forming regions has confirmed that OPH must be considered as the youngest, but integral part of the whole complex OSCA. Loosely connected, but probably genetically related with these four main subgroups, and at about the same distance from the sun, are two groupings of B stars: at negative latitudes between longitudes 325° and 5°, and around zero latitude between longitudes 270° and 290°. These two groupings have not been the subject of recent investigation.

2.2. AGES IN OSCA AND PROGRESSION OF STAR FORMATION

Nuclear ages of the subgroups US, UC-L and LC-C: 7, 13 and 11 million years, respectively, were most recently determined by de Geus et al (1989) from Walraven photometry and by de Zeeuw and Brand (1985) from Strömgren photometry, in combination with isochrones derived from evolution models of Maeder (1981). Earliest main sequence spectral types of the stars used in these determinations are B0V (Tau Sco) in US (not counting Zeta Oph, O9.5V, see § 3.8); B1.5V (Eta Cen) in UC-L, and B1.5V (Xi-2 Cen) in LC-C. The zero-age in Table 1 for OPH is indicative for the properties of the extremely young imbedded infrared cluster (Vrba et al 1975, Wilking and Lada 1983).

Whereas an uncertainty of, say, 20% may well have to be assigned to these ages in absolute sense, the age ratios between the different subgroups must be considered sufficiently well established that we may conclude that star formation has progressed over the body of the association, beginning at UC-L or/and LC-C, to US to OPH (where it still is manifest), with steps of the order of 2 to 6 million years.

The relative number contents, the "richness" given in Table 1 for the three oldest subgroups as judged from the numbers of unevolved stars of types B5 and earlier, is not widely different, nor is this the case for their global linear sizes.

2.3. OSCA AND THE MODEL OF SEQUENTIAL STAR FORMATION

Whereas the general occurrence of a sequential age order among association subgroups was noticed in the early 1960s (Blaauw 1960,1964), understanding of its physical origin grew only after the discovery of the intimate relation between OB Associations and molecular clouds. This soon led to a model for the mechanism involved, due to Elmegreen and Lada (1977) of which we reproduce the schematic presentation in the lower section of Figure 1. This has been taken from Thaddeus (1977), but was adapted to include the more uniformly distributed low mass stars, supposedly formed prior to the formation of the massive stars (Lada 1987). It also has been modified in an other respect: we assume that the subgroups in their initial stage are cigar shaped chains of clusterings, rather than spherical or disklike units, for reasons given in § 3.6.

2.4. STELLAR CONTENT OF OSCA

For the subgroups UC-L and LC-C our knowledge of the stellar content does not reach beyond about spectral type B5, i.e. about 5 solar masses, notwithstanding the proximity of the association to the sun. Principal clue to membership would be the proper motions; however, for the stars fainter than about visual magnit
available proper motions (derived from meridian observations) do not have
quired accuracy of ".003 per year. Considerable gain in our knowledge of m
ship of low massive stars may be expected from the extensive programme of
motions in OB Associations that forms part of the Hipparcos project now i
ation (de Geus et al 1986).

The situation is more favourable for subgroup US for which a special e
determining proper motions of faint stars by means of the meridian positio
lected over the years was made by Bertiau (1958), and photometric and sp
scopic follow-up by Garrison (1967) and Glaspey (1972). As a result, we know
for this subgroup membership extends to at least spectral type A7 (2 solar ma
For the OPH subgroup, we know of the occurrence of intermediate and low
stars in the infrared imbedded cluster (Wilking and Lada 1983).

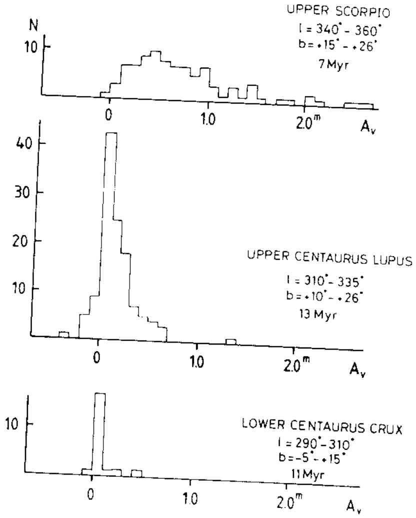


Fig. 2. Statistics of visual absorption, Av, in the regions of the three subgroups
Oph-Sco-Cen Association.

2.5. RELATION OF OSCA TO THE INTERSTELLAR MEDIUM

In dealing with the relation of OSCA with the interstellar medium (ISM) w
tinguish between a) the primordial ISM, i.e. the remnants of the molecular
from which the association was formed, and b) the envelopes or loops in the
of which the structure has been determined by the stellar winds and superno
the association. First, however, a general remark on the degree of associatio
the ISM is useful.

In Figure 2 we present statistics of the visual absorption, Av, for the three groups US, UC-L and LC-C, based on photometric data for B-type stars in de Geus et al (1989). The striking difference between US on the one hand, and UC-L and LC-C on the other hand is apparent: in the two latter subgroups values of Av peak around 0.2 and 0.1 mag., respectively, whereas in US Av ranges more or less uniformly between 0 and 1 mag. and in some cases reaches values up to 2 mag. and more. Clearly, UC-L and LC-C, with ages around 12 million years have been efficiently "cleaned", whereas this is by no means the case for US at the age of 7 million years. These statistics suggests that the time scale for cleaning of an OB-Association subgroup is about 10 million years.

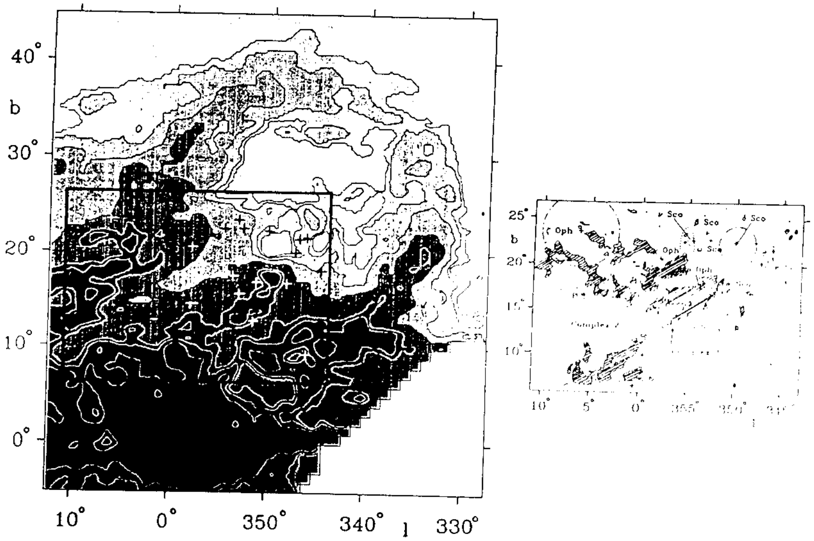
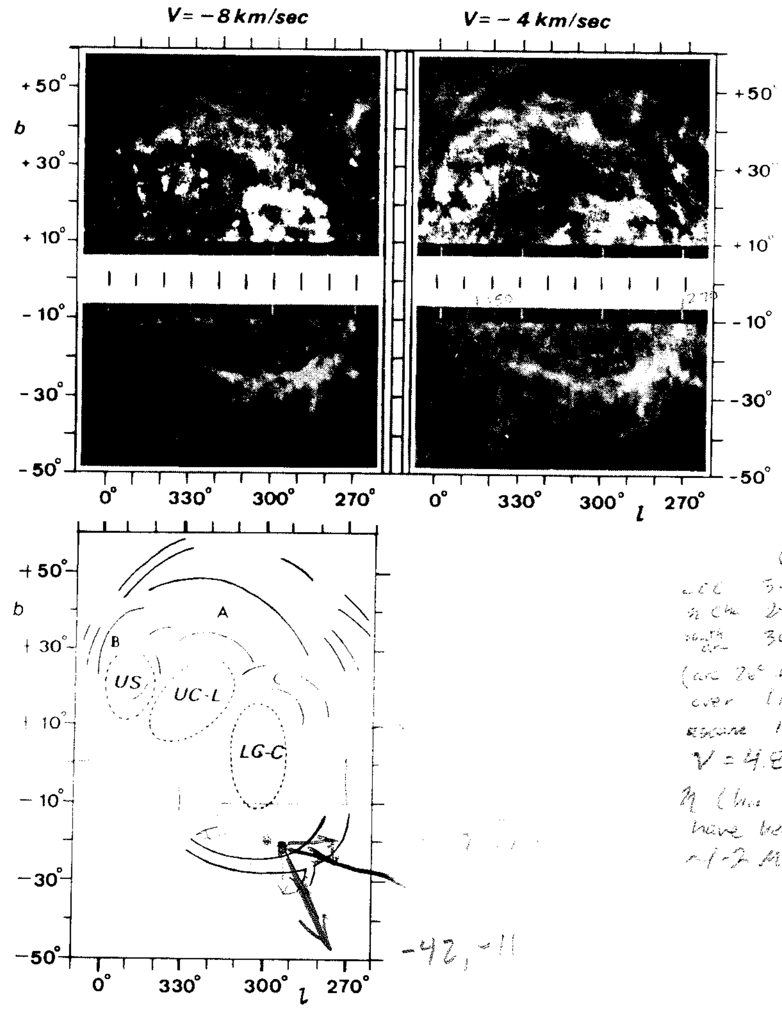


Fig. 3. Left: Shell structure in HI related to the young subgroup Upper Sco, with indication of the area of the Ophiuchus dark cloud star-forming complex, the latter shown separately in the figure at right (based on de Geus, 1988).

The process of breaking up the ambient ISM in subgroup US is nicely demonstrated in Figure 3, taken from a recent discussion by de Geus (1988). HI is still present in a nearly complete shell structure with diameter of about 50 pc, inside of which HII is present, whereas the molecular cloud remnant with its elongated "streamer" structures, now the site of current star formation, extends from the US OB stars toward higher galactic longitudes.

Shell structures in HI on a much larger scale, enveloping large parts or all of



-42, -11

Fig. 4. Top: Large-scale shell structures in HI for the velocity intervals around -8 an km/sec according to Colomb et al (1980). Bottom: schematic outline of principal structures with respect to the OSCA subgroups. Note that in these presentations the in galactic longitude has been contracted with respect to the latitude scale!

(
ucc 5-5
[illegible] 2/2
[illegible] 3c5
(arc 20° [illegible]
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[illegible] 12
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have been
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OSCA are apparent from plots of HI integrated over narrow velocity intervals as shown in Figure 4, derived from Colomb et al (1980). These structures and their kinetic energies can be reasonably well understood as the consequence of the energy input into the ISM over the time span of the age of the subgroups, taking into account what we know of their (initial) stellar content (de Geus 1988; see also the discussion of the Evaporation Function in § 3.4.) According to de Geus, the main source of energy input to the ISM, causing shell A, has been subgroup UC-L, with about 80% of this energy due to supernovae and 20% due to stellar winds. The total energy input compares reasonbly well with the kinetic energy estimated from the mass and expansion velocity of the shell, taking into account that a fraction only (20%?) of the input energy contributes to the kinetic energy. The input energy of subgroups US and LC-C (with about 50% and 75%, respectively, due to supernovae) accounts satisfactorily for the energies observed in shells B and C.

2.6. KINEMATIC PROPERTIES OF OSCA

We distinguish two aspects of the kinematics: the motion of OSCA with respect to the local standard of rest, and internal velocities. We shall return to the former in the context of the discussion of the Gould Belt in Section 4. Reasonably accurate knowledge of the internal velocities we have so far only for the subgroup US. It is based on proper motions determined especially for this object by means of available fundamental and meridian catalogues, with an accuracy of about ".0015 per year which corresponds to about 1.2 km/sec (Blaauw 1978). The resulting pattern of (projected) internal motions after elimination of common motion is shown in Figure 5. From it, we find:

a) the average relative velocity in one component is about 2.2 km/sec, corresponding to an average relative space velocity of 4.4 km/sec if an isotropic velocity distribution is assumed. Evidently, the accuracy of the proper motions just sufficed for establishing the internal velocity spread. Radial velocities of the required accuracy, 1.5 km/sec or better are not available yet for these B stars as a consequence of the high incidence of spectroscopic duplicity and fast stellar rotations.

b) tracing back the individual proper motions, as shown in Figure 5, leads to a "minimum-size configuration" at epoch about 4.5 million years ago, with dimensions of about 45 x 15 pc. We return to the latter aspect in § 3.6. The time scale mentioned here, 4.5 million years, is called the kinematic age of the subgroup. We note that it is close to, but somewhat shorter than, the nuclear age of 6-8 million years mentioned before.

2.7. DOUBLE STAR PROPERTIES AND RUN-AWAY STAR IN OSCA

We shall return to these two subjects in the context of the more general discussion of § 3.7 and § 3.8.

2.8. THE CASSIOPEIA-TAURUS ASSOCIATION (CAS-TAU)

The most fossil in character, and the nearest to full disintegration and dispersion into the general field population, is the Cas-Tau Association. It is located at the

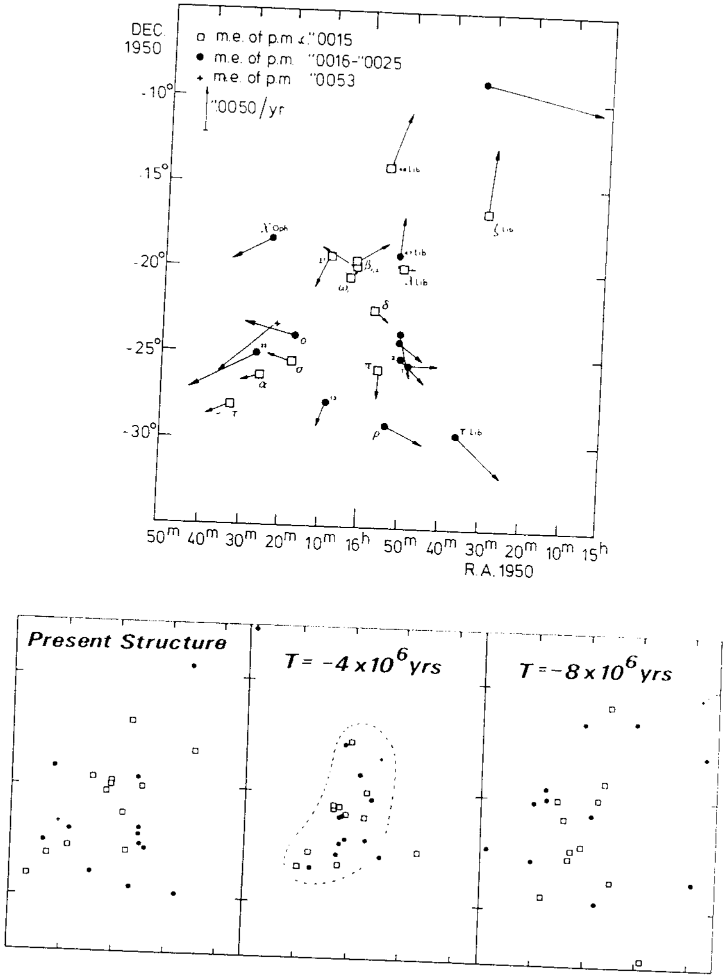

Fig. 5. Top: Internal motions in subgroup US of OSCA (relative to mean motion) as sh by the proper motions. Bottom: The present positions of these stars and those traced for 4 and 8 million years, respectively, suggesting minimum-size configuration arou million years.

same distance from the sun as OSCA, about 140 pc, but on the opposite side, between galactic longitudes 110° and 200°. As shown in Figure 6, it is recognized only by the parallelism of the motions of its members with respect to the sun, and since the projected solar motion reflex amounts to about 20 km/sec, this implies that the internal velocities are much lower: the average velocity in one component was found to be 2.0 km/sec (Blaauw 1956), about the same as that in OSCA. The dimension of Cas-Tau also is close to that of OSCA.

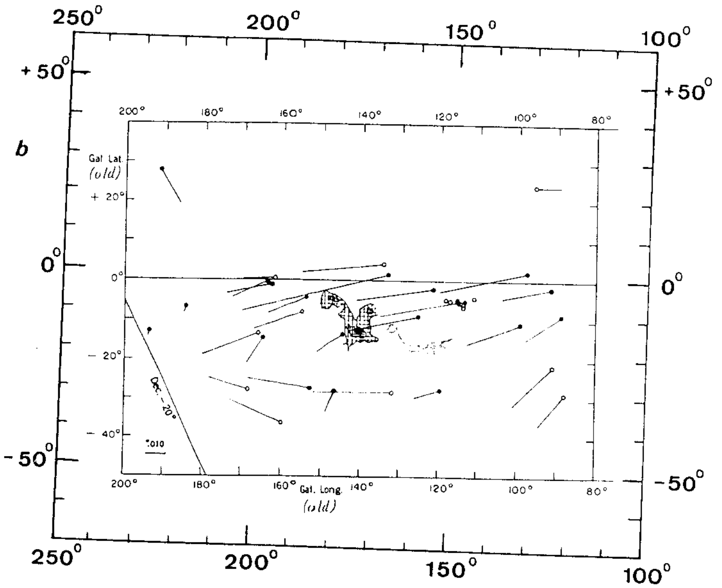

Fig. 6. Proper motions of early B-type stars in the region of Cassiopeia and Taurus, the parallelism of which reveals the existence of the old association Cas-Tau. In the centre, the Taurus dark clouds are marked schematically. (Adapted from an almost fossil paper, Blaauw 1956, still in "old" galactic coordinates.)

With two exceptions, earliest spectral types in Cas-Tau are B2V, and in accordance with this the photometric age estimate of de Zeeuw and Brand (1985) turned out to be about 25 million years. Nothing is known about membership later than B5, although this may be remedied once accurate proper motions will be available from Hipparcos. An interesting aspect is the probably close association of the - probably unbound - Alpha Persei Cluster with Cas-Tau. In agreement with the "cleaning time scale" of 10 million years for subgroups found from OSCA, there is no obvious association with interstellar matter. An interesting, and perhaps puzzling feature is the location of the Taurus molecular cloud complex near the c
of the association (see also Section 4).

2.9. THE ASSOCIATION ORI-OB1

Star formation in Ori-OB1 covers the whole range, from incipiency in a wide r
of locations and particularly in the high density rims of Clouds A and B, tot the
vanced stage of the Trapezium Cluster and its immediate neighbourhood. The
forming regions in the Orion molecular clouds are currently probably the ones n
intensively studied. Moreover, there is the fortunate circumstance that the asso
tion is situated at the celestial equator, and hence accessible to both northern
southern observatories. For a recent review we refer to Genzel and Stutzki (19
Features of the large-scale envelope of atomic hydrogen were most recently st
ied by Chromey et al. (1989); for an early study of "Orion's Cloak", the expand
shell centered on the association, see Cowie et al. (1979). A broad programm
photometry and analysis of the subgroups in Ori OB1 was carried out by Wa
and Hesser (1977, 1978), to which we refer for more detailed study. The presen
view only describes some large-scale properties as they resulted from the cons
tive stages of star formation, and to their relation to current star formation.

These past stages of star formation can be recognized in a series of subgrou
sequential age order. They are listed in Table 1, and shown in Figure 7 together w
the main structures in the molecular clouds, taken from the study of Madda
et al. (1986). Not included in Figure 7 is the star forming region around lam
Orionis at Decl. +10° that is loosely connected with the main body of Ori
(Murdin and Penston 1977, Duerr et al. 1982, Maddalena and Morris 1987),
that may have a more isolated history of formation.

There is interesting similarity to the association OSCA: in both, earliest
formation occurred about 12 and 7 million years ago and continues into the pre
in OSCA in subgroup OPH, and in Orion most strongly in the region ar
the Trapezium Cluster in Cloud A, and less conspicuously in Cloud B. Age
in between the Trapezium Cluster and subgroup 1b is subgroup 1c which w
projected on the region around the Trapezium Cluster, but the degree of detach
is not clear. (Its age estimate seems uncertain: de Zeeuw and Brand mentioned
million years, but the estimate of Warren and Hesser, several million years
more likely.) Subgroup 1c probably is the one most responsible for the induc
of star formation in the upper part of Cloud A.

There is conspicuous interaction between the oldest subgroup, Ori-OB1a,
molecular Cloud B. According to Table 1, over the past 12 million years ar
six or seven massive stars must have evolved away from this subgroup which
particularly rich one. As its age is about the same as that of subgroup U
OSCA and its stellar content about twice larger, the energy output over the
must have been about twice that of UC-L. Subgroup 1a probably is the main
of the sharp "molecular ridge" on the western side of Cloud B that was po
out by Baud and Wouterloot (1980) on the basis of OH observations, and
also conspicuous in CO (Maddalena et al. 1986) and in CS (E.A.Lada 1990
influence of subgroup 1a can, in fact, be traced all along the western edge of

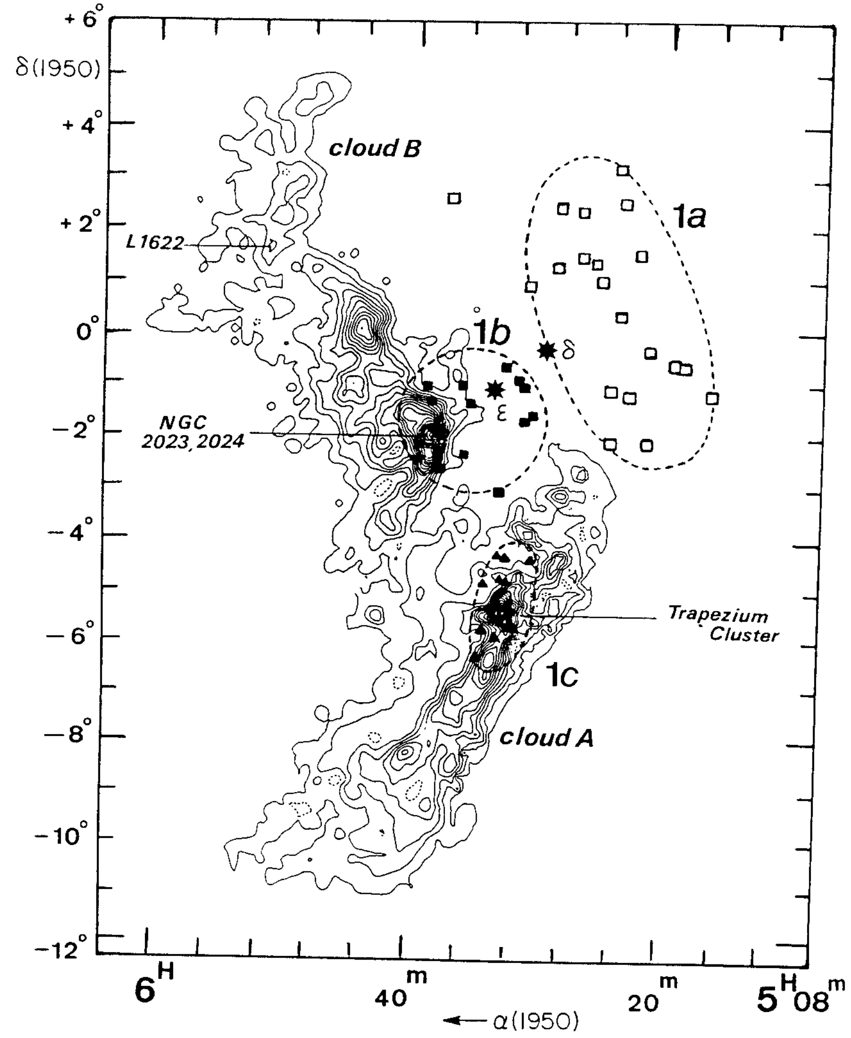

Fig. 7. The association Ori OB1 with the subgroups a, b and c outlined, in relation to the molecular clouds A and B, the latter according to Maddalena et al (1986). Note that this map does not show the other clouds occurring in this region - partly also related to Ori OB1 - as revealed by these authors and by, for instance, Kutner et al (1977).

TABLE 1. OB ASSOCIATIONS WITHIN 1 KPC

	Projected dimensions pc	Age Myr	Relative richness (U Sco =1)	Number evaporate
Within Gould Belt				
OPHIUCHUS	-	0	-	-
UPPER SCORPIUS	40 x 40	7	1.0	0.8
UPPER CEN - LUPUS	70 x 35	13	1.2	3.5
LOWER CEN - CRUX	50 x 40	11	0.6	1.3
CAS - TAU	200 x 50	25	1.6	15.0
PER OB2	60 x 40	7	0.3	0.2
ORI OB1a	45 x 25	12	2.6	6.5
ORI OB1b	25 x 20	7	1.0	0.8
ORI OB1c	20 x 10	3?	1.1	0.1?
ORI OB1d	-	0	-	-
Lambda ORI ASSOC.	12 x 8	4		
Outside Gould Belt				
CYG OB7	80 x 80	?	?	?
LAC OB1a	110 x 90	25	0.7	6.6
LAC OB1b	35 x 35	16	0.8	3.4
CEP OB2a	120 x 100	7	1.6:	1.3:
CEP OB2b		3	1.6:	0.2:
CEP OB3a	25 x 15	10	0.7	1.1
CEP OB3b	15 x 7	7	0.8	0.6
CEP OB4	60 x 60	2:	1.4	0.1
MON OB1	60 x 45	15	0.8	3.0
COLL 121	130 x 65	25	1.3	12.2

B and its extensions northward, for instance in the CO maps of the region ar L1622 at declination +1°50' described by Reipurth in this Volume.

The centre of subgroup 1a lies approximately in the extension of the main of Cloud A, and subgroup 1c perhaps in between these two. Relation betwee supernovae and stellar winds of subgroup 1a and Cloud A is not as clear as with Cloud B.

The energy output of subgroup 1b has been only 10-15% of that of subgrou However, due to its probably closer proximity to Cloud B this subgroup may be the one mostly responsible for the star formation in the region around NGC and 2024. Its role seems comparable to that of subgroup US of OSCA in rel to the Ophiuchus clouds.

3. The Sample within 1500 pc

We review properties of the ensemble of OB Associations within 1500 pc, with attention to both features of the sample as a whole and, for the individual associations, properties we encountered in the description of the nearest associations.

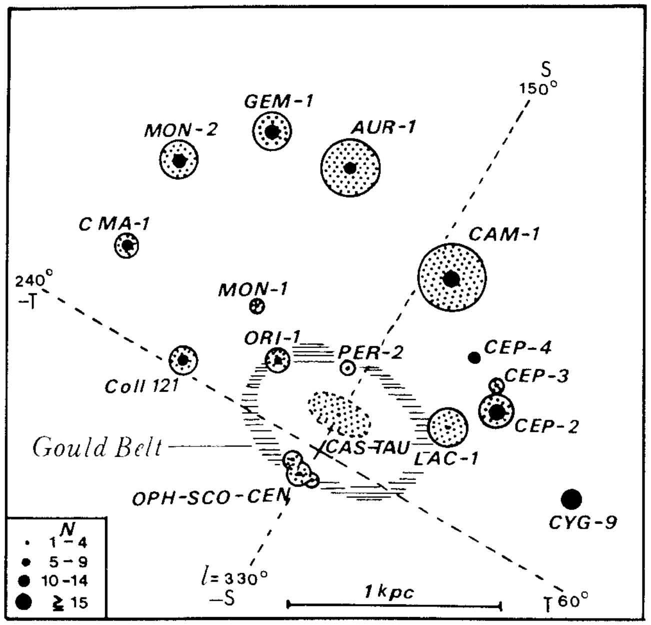

Fig. 8. Schematic presentation of the positions of the OB Associations within 1.5 kpc, projected on the galactic plane. The Sun is located at the origin of the coordinate system S,T of which the T axis was chosen in the direction of the ridge line of the "Orion Arm" (galactic longitude 60°,240°). The sizes of the central dots mark the current or recent star formation activity (N being the number of the O-type stars plus those more luminous than visual absolute magnitude -5.0). The diameters of the sorrounding circles correspond to the projected dimensions of the associations. (Adapted from Blaauw 1985a.)

3.1. GLOBAL PROPERTIES

Overall properties of the sample are exhibited in Figures 8 and 9 showing, respectively: the projection on the galactic plane, and on the two planes perpendicular to this and to the axes S and T marked in Figure 8 (from Blaauw 1985a). The axis T has been chosen roughly coinciding with the ridge line of the Orion Arm as it appears in plots on still larger scale of associations and clusters (See, f.i. Becker and Fenkart 1970). In the present context, the precise choice of the axes S and T is not important. As explained in the legend of the Figure 8, the size of the central dot for each association is a measure of the rate of ongoing or very recent star formation. The diameter of the circle surrounding the dot equals the estimated projected dimension of the association.

It must be realized that these presentations are somewhat biassed by selection effects, in spite of the fact that we are dealing with relatively nearby objects. An association like Cas-Tau would not be identified as such at distances beyond, say, five hundred pc, because of the absence of very luminous stars, its lack of spatial concentration, and the present lack of accurate proper motions for stars fainter than 6th magnitude. To a lesser degree this also holds for an association like OSCA. Accordingly, at large distances there is a bias in favour of the youngest associations containing very luminous stars. Also, note that for the more distant associations it is difficult to discriminate subgroups of different ages and their differing degree of association with the ISM.

The most striking feature of the overall distribution is perhaps its flatness, apparent from Figure 9. The average distance of the associations from the galactic plane is only 3 pc, and the average without regard to sign only 50 pc. Within this extreme flatness, there is a disturbance; the Gould Belt System marked in Figures 8 and 9, comprising the OB Associations within 500pc from the centre of Cas-Tau. We return to this in Section 4.

Except for deviating kinematics in the Gould Belt System, the ensemble is kinematically very quiet: the average residual velocity in one component as derived from radial velocities amounts to only 4.5 km/sec, a value corroberated by the residual velocities of the molecular clouds with which the associations are connected (Blaauw 1985a).

3.2. FORMATION OF MASSIVE STARS IN ASSOCIATIONS AS COMPARED TO CLUSTERS

For the fraction of massive stars formed in open clusters as compared to associations, a canonical figure encountered often in the literature is 10%, due to Roberts (1957). This percentage is confirmed if we count the B stars within 1.5 kpc occurring in clusters and in OB Associations. However, a more relevant question would seem to be, what percentage is formed in bound clusters, i.e. systems with negative total energy. This probably is much lower, for the former statistics includes among the clusters objects (like, for instance, NGC 1502) which probably are in a state of disintegration and eventually will disperse into the general field, just like the association stars.

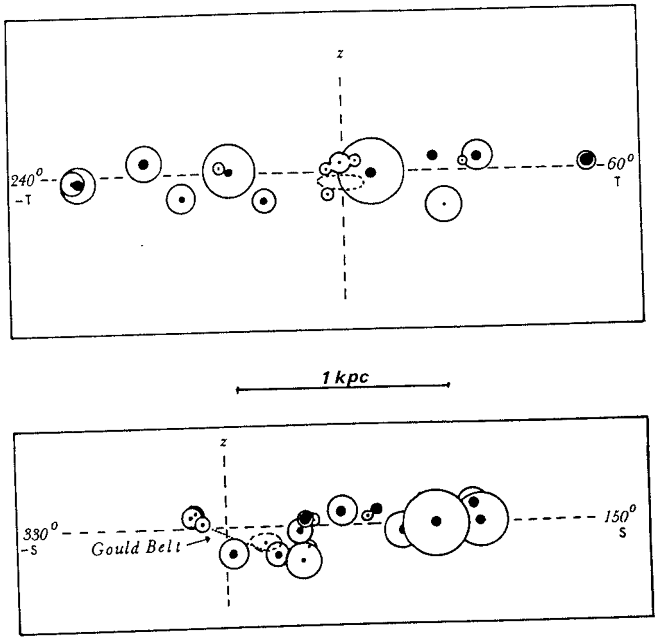

Fig. 9. The same as Figure 8, but now projected on planes perpendicular to the axes S (top) and T (bottom).

3.3. AGES AND SUBGROUPS; STELLAR CONTENT

Data on ages for the subgroups in the associations of Figure 8 are shown in Figure 10 and, for those within 1 kpc, in Table 1. Asterisks in the Figure indicate those associations - the majority - where star formation is still going on. In spite of the selection effects mentioned before, it seems justified to state that there is little evidence of systematic progression of star formation over the volume of space considered here.

Ages listed range from zero to about 25 million years, this upper limit being determined by detectability and stellar evolution: at that age the most luminous stars have evolved into anonymity, and the remaining association stars gradually disperse into the general field population: the average internal space velocity of 4 km/sec, mentioned before, corresponds to a path length of 100 pc after 25 million years, so that no spatial concentration is left except for the stars with lowest relative velocities.

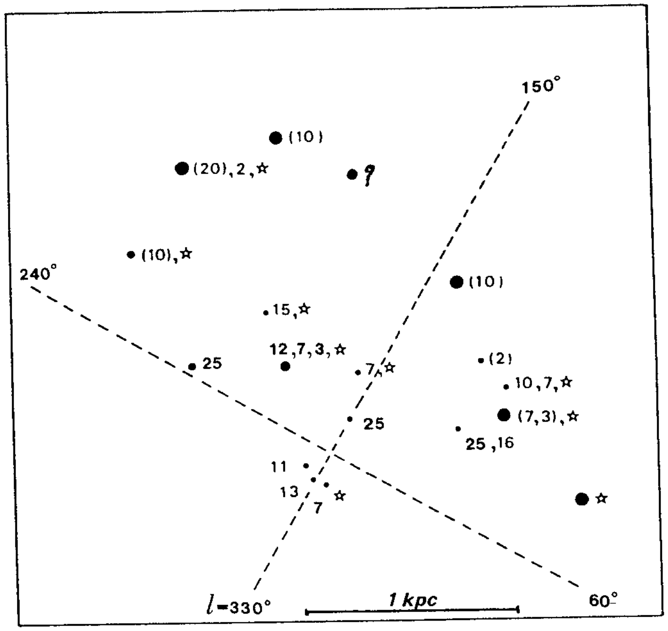

Fig. 10. Ages, in million years, of the (subgroups of) associations plotted in Figure 8. Asterisks mark objects with ongoing star formation. (Adapted from Blaauw 1985a).

A not yet satisfactorily answered question concerns the "membership" of stars of spectral types later than B. Useful objective prism classification surveys have been made in the regions of several associations; examples are the work on Lac-OB1, Ori-OB1, and Per-OB2 by Guetter (1976,1977). These have established excesses of stars down to middle A-types and evidence for a pre-main sequence population, in global agreement with what would be expected at the age of the association. An interesting problem remains, however: were these stars formed at the same location and at the same epoch as the more massive ones? Probably the question of mass dependent location and/or epoch of formation can be taken up only when accurate proper motions will allow back tracing of the past path of these stars.

3.4. EVAPORATION FUNCTION AND EVOLVED STARS

The generally accepted theory that massive stars evolve away from the associations via the supernova phase allows an estimate of the rate at which the subgroups "evaporate" their most massive members. The resulting Evaporation Function E(t) is shown in Figure 11 (Blaauw 1985b). It applies to a "standard subgroup" which is assumed to contain 24 stars of masses exceeding 6 solar masses, that initially follow the standard Initial Mass Function (IMF), and it gives the number of stars that evaporate per million years as a function of age. The shape of E(t) is rather sensitive to the assumed IMF and to the evolution tracks adopted; a somewhat different shape was arrived at by de Geus (1988).

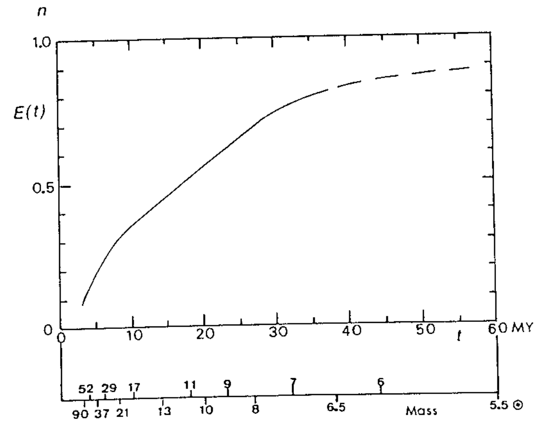

Fig. 11. Evaporation Function E(t), expressed in number of stars evolving away per million years, for a standard association subgroup starting out with 24 stars of masses exceeding 6 solar masses.

The numbers of "evaporated" stars for the (sub)groups within 1 kpc are given in the last column of Table 1. They are of considerable interest when it comes to understanding the influence the evolved stars may have exerted on the neighbouring ISM through their supernova explosion and, preceding these, by their stellar winds. We referred to this when dealing with the shell structures around OSCA in § 2.5, and with the rim structures observed in the molecular clouds associated with Ori-OB1 in § 2.9. The evaporation function also plays an essential role in estimates of the rate of generation of pulsars (Blaauw 1985b).

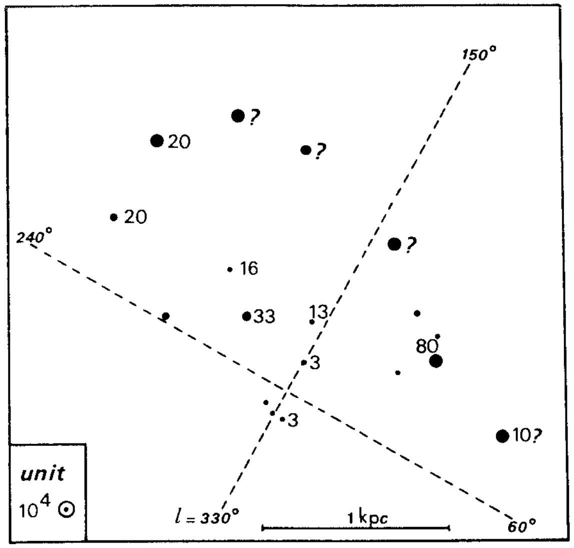

Fig. 12. Masses of the molecular clouds (in units of 10,000 solar masses) connected with the associations of Figure 8.

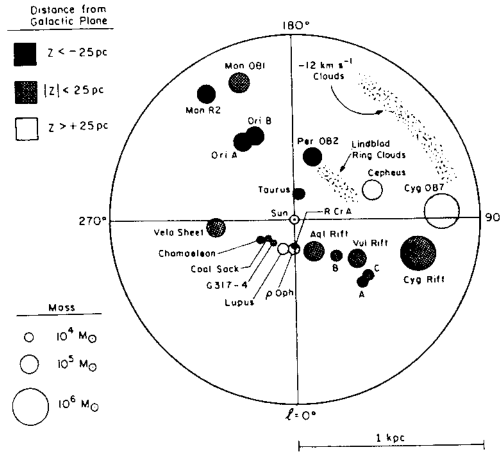

Fig. 13. Map of the molecular clouds as given by Dame et al (1987).

3.5. ASSOCIATED MOLECULAR CLOUDS

With very few exceptions, the OB Associations shown in Figure 8 are associated with molecular clouds detected in CO or OH. The masses of these clouds, expressed in units of 10,000 solar masses, are indicated in Figure 12 (updated from Blaauw 1985a with Dame et al 1987, and Sodroski 1990). The more complete compilation of the local molecular clouds given by Dame et al (1987) is shown in Figure 13, on the same linear scale as Figure 12. An interesting feature is the string of clouds within which is located the association OSCA (including the Ophiuchus clouds) as well as the Chamaeleon star-forming region. It probably forms part of the Gould Belt.

3.6. INTERNAL MOTIONS; INITIAL SHAPES AND SIZES OF SUBGROUPS

In Table 2 we collect data on the internal motions for some of the associations. For most of them, a mean speed in one coordinate of about 2.0 km/sec is found, hence a mean space velocity of about 4.0 km/sec if isotropic velocity distribution is assumed. However, there is at least one exception: the association Per-OB2 with a considerably larger mean speed, 6 km/sec as found from both proper motions and radial velocities. The association is in a state of rapid disintegration. As the time scale for dispersion of their members into the general field population for associations like this is relatively short, such cases tend to soon escape detection.

The velocity of about 2 km/sec found for most of the OB Associations is the same as that found for various categories of objects of very recent formation: 1.5 to 2.3 km/sec in the Orion Trapezium Cluster (Jones and Walker 1988, van Altena et al. 1988); 1.5 km/sec for Taurus Clouds TT stars (Jones and Herbig 1979), and 2.0 km/sec for the Lambda Ori Association (Mathieu 1986, 1987).

In § 2.6 we noted that back tracing of the positions of stars in the subgroup US of OSCA led to the conclusion that its initial, oblong shape probably cannot have had a largest dimension smaller than 45 pc, and excludes initial cluster size of the order of several pc. It is important to note that evidence from other cases, for which a reasonably accurate estimate of the limiting initial size can be derived from proper motions, leads to the same conclusion. Thus, a minimum size of about 50 pc was found for the strongly elongated initial configuration of Per OB2 (Blaauw 1983) and unpublished estimates by the author based on proper motion studies in the Ori OB1a subgroup by Lesh (1968) lead to a minimum largest initial dimension of 35 pc. Preliminary analysis of existing proper motions in subgroup UC-L of OSCA by the author leads to a minimum largest initial dimension of 50 pc.

The interpretation of these findings is guided by what is found from observations of those, most condensed, parts of molecular clouds where a new generation of stars is about to emerge. A striking case is that of the L1630 Orion molecular cloud as it results from CS observations by E.A.Lada (1990); see the chapter by C.J.Lada in this Volume. A linear string of clumps is observed at the western side of this cloud over a total length of about 25 pc, that may give rise to nearly coeval emergence of new stars that after several million years will show the typical features of subgroups observed now in the youngest associations. Somewhat similar evidence occurs in the CO contours observed in the W3-W4-W5 region by Lada et al (1978).

As a preliminary conclusion we infer from these cases, that in the model of sequential star formation elongated initial structures, consisting of a series of small clusterings of pre-main sequence stars, should be assumed to figure, as illustrated in the (revised) model at the bottom of Figure 1.

TABLE 2. INTERNAL VELOCITIES IN ASSOCIATIONS
(Average velocity in one coordinate)

	From proper motions (km/sec)		From radial velocities (km/sec)	
SCO-CEN (all subgroups)	1.7	(1)	$\lesssim 2$	(1)
UPPER SCORPIO	2.2	(2)		
CAS-TAU	2.0	(3)	3.0	(3)
PER OB2	6.5	(4)	6.0	(5)
ORI OB1a	$\lesssim 6$	(6)		
LAC OB1			2.0	(7)

(1) Bertiau (1958). (2) Blaauw (1978). (3) Blaauw (1956). (4) Derived from Lesh, J.R. 1969, Astron.J. 74,891. (5) Blaauw, A. 1952, Bull.Astron. Inst. Netherlands, 11,405. (6) Derived from Lesh (1968). (7) Blaauw, A. and Delhaye, J., unpublished.

3.7. STATISTICS OF CLOSE BINARIES

Duplicity and multiplicity properties of newly born stars are among the most important clues to understanding the process of star formation. We shall deal here only with duplicity and limit ourselves to the statistics of separations in the associations of the local sample. Accordingly, the properties observed are those occurring in the interval between several and, say, 30 million years after star birth, so that by necessity we skip changes in the elements during the first few million years. As we shall see, even during the subsequent 25 million years, evolutionary effects can be recognized in the statistics.

The frequency of spectroscopic, i.e. the closest, binaries among B-type stars has been investigated by many authors; for a summary we refer to van Albada (1985), from whose paper also the data below have been taken. There appears to be a concensus of opinion that the frequency of duplicity is about 30%.

Useful statistics is obtained by plotting the semi-amplitude of the radial velocity variation of the primary component against the (logarithm of the) period; both

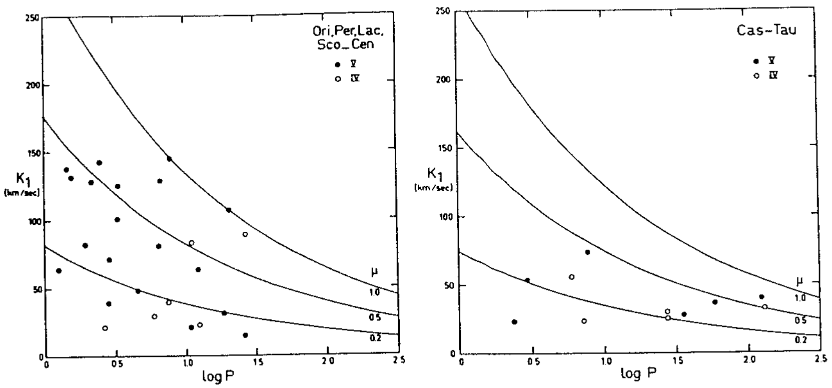

Fig. 14. Semi-amplitude of the radial velocity variation of the primary components of early-type spectroscopic binaries, plotted against Log Period; left: for a number of the young associations or their subgroups; right: for the older Cas-Tau group. From van Albada (1985).

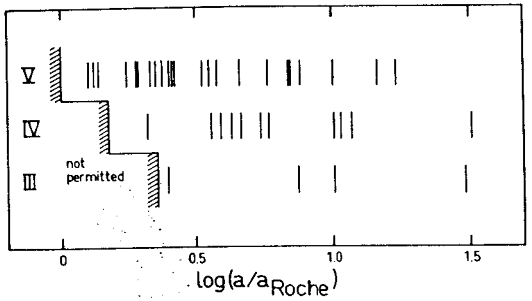

Fig. 15. Distribution of the ratio a/a(Roche) for the binaries of Figure 14, for the luminosity classes V, IV and III.

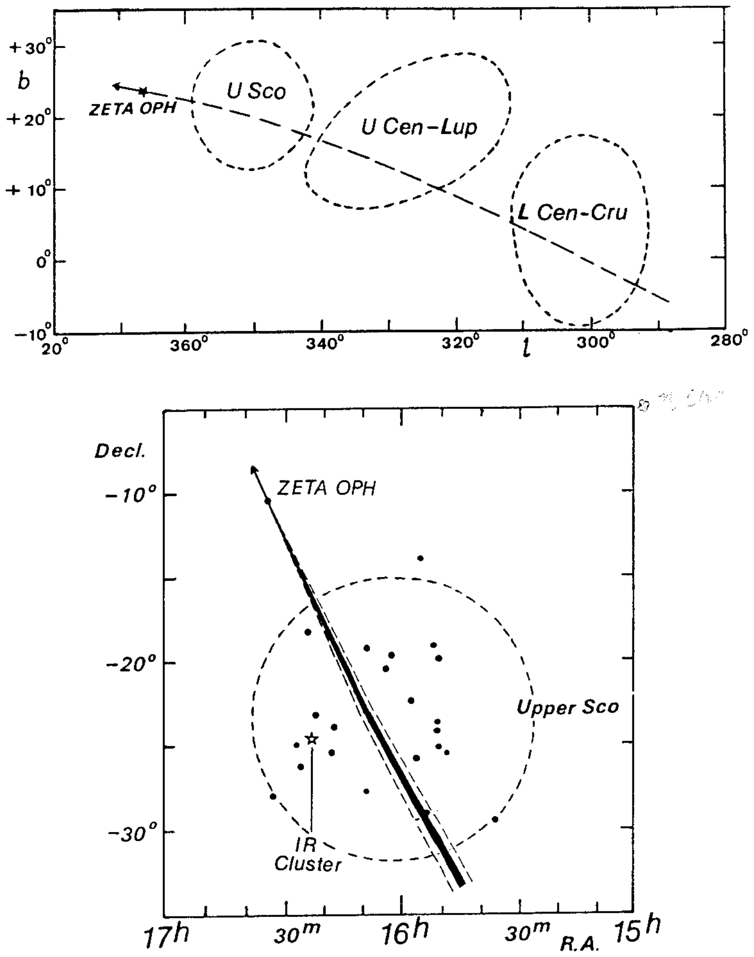

Fig. 16. The Run-Away star Zeta Ophiuchi (O9.5V) in relation to the association OSCA (relative space velocity about 42 km/sec). Top: The projection on the sky of the past path; Zeta Oph originated most likely in subgroup U Sco about 1 Myrs ago, but origin in U Cen-Lup, about 2.5 Myrs ago cannot be excluded. Bottom: Close-up of the situation with respect to U Sco; dashed lines indicate the uncertainty in the direction of the projected motion corresponding to the probable error of the proper motion.

quantities are directly obtained from the observations. [Note that bias favouring systems with large velocity amplitudes was avoided by specially designed observing programmes as referred to by van Albada (1985).] Fig.14 shows such plots for a) stars in the associations, respectively subgroups, with ages in the interval 5 to 15 million years, and b) those in the older association Cas-Tau, with age about 25 million years. We note the lack of binaries with high velocity amplitudes and short periods in the latter, and thus recognize the effect of the evaporation of the most massive stars from the Cas-Tau association as estimated in Table 1. Since for systems with a given mass of the primary component the period is primarily determined by the separation of the two components, it follows from plots like these that evolution effects have to be taken into account in determining the initial frequency distribution of the separations of the components.

The effect is also illustrated in Fig. 15, showing for the same stars statistics of the ratio between the actual separation of the components and the Roche radius of the primary component, separately for the luminosity classes V, IV and III. Clearly, already for classes IV, and even stronger for class III, as a consequence of the evolution of the primary the peak in the distribution of the ratios has shifted, indicating that for the estimate of the initial distribution of the separations only luminosity class V should serve. A median initial value for the separation in terms of the Roche radius appears to be about 3. For a discussion of the effects in the distribution of the eccentricities, reference is also made to van Albada's paper.

3.8. RUN-AWAY OB STARS (RAOBS)

Run-away OB stars, henceforth denoted as RAOBs, are those OB stars that with moderately to high space velocities, i.e. from about 40 to more than 100 km/sec, run away from the young (subgroups of) OB Associations that can be identified as their place of origin. This definition has to be relaxed somewhat for those (older) objects that must be considered to fall in the same physical category, but for which the origin cannot be so well established. The run-away phenomenon seems to be a regular feature, inherent to the evolution of every OB Association.

Typical cases are those illustrated in Figures 16 and 17 (Blaauw 1988): the star Zeta Oph moving away from OSCA and most likely originating from its subgroup US, and the stars AE Aur, Mu Col and 53 Ari moving away from Ori OB1 but for which it is less well possible to identify the subgroup within this association from which they came. For these four examples, the velocities with respect to the generating associations are estimated to be 42, 137, 141, and 55 km/sec, respectively, and the times elapsed since they left their origin 1.0 (or perhaps 2.5), 2.6, 2.8, and 6.0 million years. Principal aspects of current investigations of the run-away phenomenon are: the question, how to explain it, and the implication for the inducement of star formation far outside the parent association of the RAOB.

As to the first, at this moment there are two hypotheses. The one assumes an explosive event in close, massive double stars, most likely a supernova explosion of one of the components, as a consequence of which the other component is released from the original gravitational binding and escapes with a velocity close to its orbital velocity (Blaauw 1961; see also Stone 1985). In this scenario, the run-away

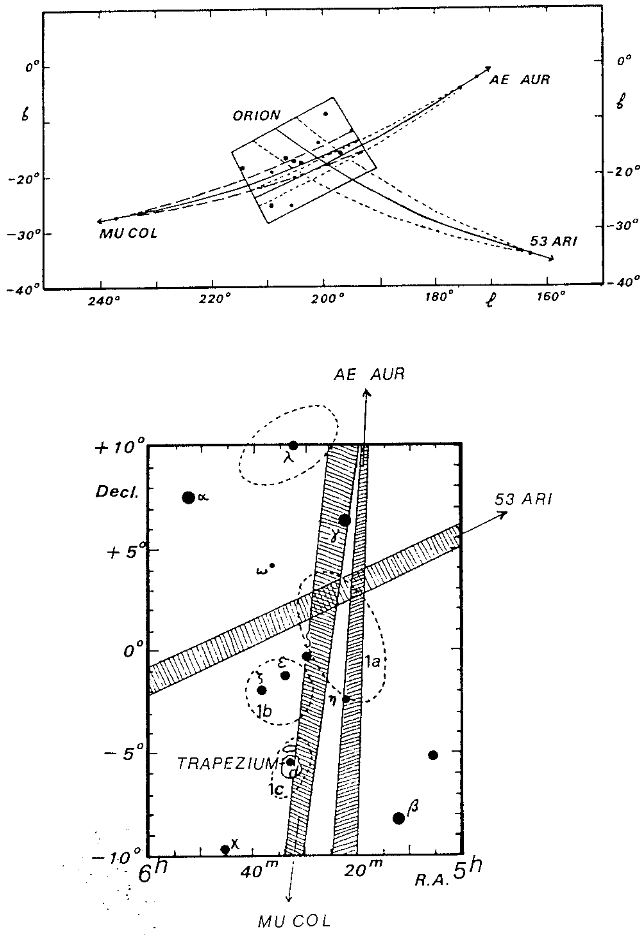

Fig. 17. Top: The Run-Away stars AE Aur (O9.5V), Mu Col (O9.5V) and 53 Ari (B2.5) in relation to the association Ori OB1. Relative space velocities are about 137, 141 and 55 km/sec, respectively and "kinematic ages" about 2.6, 2.8 and 6.0 Myrs. Bottom: close-up indicating that 53 Ari most likely originated in subgroup 1a or 1b, but that for AE Aur and Mu Col the generating subgroup cannot be well established from the projected past path.

phenomenon is not directly related to the circumstances of star formation. An obstacle encountered by this hypothesis is the prediction that, as a consequence of mass transfer from the primary to the secondary component preceding the explosion, a large fraction of the RAOBs would be expected to have retained a companion; yet radial velocity observations show that most of the RAOBs are single (Gies and Bolton 1986).

The alternative hypothesis, which does have direct relevance to the circumstances under which RAOBs are formed, assumes dynamical ejection from a young cluster (Gies and Bolton 1986, Leonard and Duncan 1990, Leonard 1990). A problem with this interpretation is, that we have no convincing evidence yet of the existence of such a parent compact cluster in those cases where the past track of the RAOB is known.

3.9. RAOBS AND STOCHASTIC STAR FORMATION

An aspect relevant to the problem of star formation, and independent of the mechanism of their origin, is the possible role of RAOBs in the propagation of star formation outside the parent association. We have no reason to assume that RAOBs are different from "ordinary" OB stars; they probably also will end their life in supernova explosions. RAOBs, however, will normaly do this far outside their region of origin. With run-away velocities of 50 to 100 km/sec and life times of 5 to 10 million years, the explosion will happen at distances of the order of 500 pc. We must expect this to give rise to stochastic induced star formation if the explosion occurs inside, or in the neighbourhood of, an other molecular cloud.

The efficiency of this mechanism, to be investigated further, depends on the frequency at which the inducement occurs. It will suffice here to state that obviously, for a plane parallel layer of clouds, the efficiency of the process goes with the square of the projected density of the clouds on the galactic plane, as both the production of RAOBs and the reciprocal of the projected mean free path of RAOBs are proportional to this density.

Figure 18 shows the positions of well established RAOBs projected on the galactic plane, and their projected past paths from the parent association in so far as these are well known (Blaauw 1985a). The fact that the best established RAOBs occur preponderately in the solar neighbourhood is an effect of observational selection. Only with much more accurate proper motion data in a fundamental, absolute system, as may be produced by Hipparcos, may we expect the areas void of RAOBs in the diagram to be reliably filled in.

4. The Gould Belt System

The Gould Belt derives its name from B.A.Gould who was the first to describe in some detail the belt of bright stars along a great circle including the constellations Scorpius, Centaurus, Crux, Orion and Perseus. At closer inspection it turns out to be marked especially by the bright B-type stars, part of which belong to the nearby associations OSCA, Ori-OB1, and Per-OB2. Early research on the Gould Belt System has been reviewed by Lindblad (1974). It comprises young stars and

interstellar matter - dust as well as molecular clouds and neutral Hydrogen - and is characterized not only by its peculiar space distribution but also by its internal kinematics. It is a flat subsystem among the local OB population and the interstellar medium with largest dimension about 700 pc, tilted about 15° with respect to the galactic plane, and with low central density; see the sketch in Figure 8. The system is in a state of expansion, with the spatial centre of the system nearly at rest with respect to the local standard of rest. The motions of the associations participating in this expansion are revealed in their radial velocities by positive excesses, up to 10 km/sec and more, when compared to the velocities expected on the basis of the standard solar motion and regular differential galactic rotation.

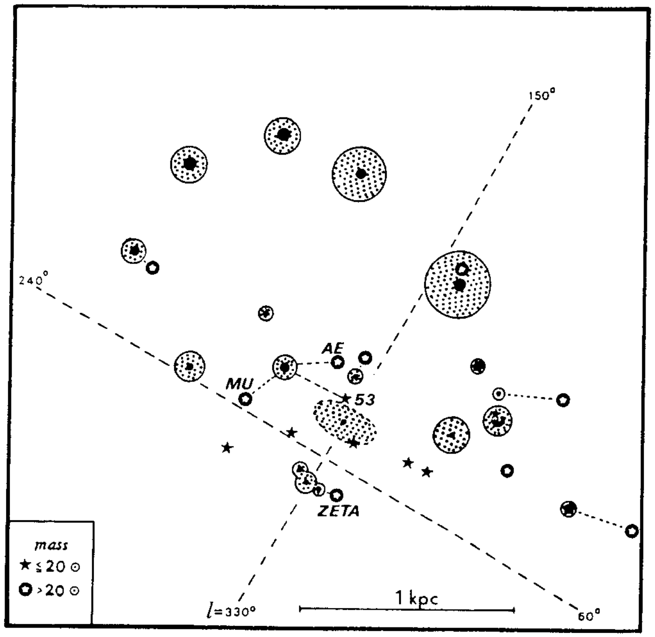

Fig. 18. The sample of best established RAOBs in relation to the OB Associations presented in Figure 8, projected on the galactic plane. Dashed lines connect RAOBs with their parent association in so far as the connection seems well established. The four cases of Figures 16 and 17 are marked individually. The lack of RAOBs at large distances from the sun must be due to observational incompleteness.

A suggestive, but not yet quite satisfactory model of the evolutionary history of the Gould Belt System starts from the assumption that between 25 and 40 million years ago, expansion set in in the ISM in the area where now the Cas-Tau association is situated, and identifies the cause of the expansion with the supernovae and stellar winds inherent to the early stage of this association. The expanding, swept-up ISM, settling at velocities of the order of 20 km/sec, was subsequently subject to the general galactic field of force, leading to a pattern of motions which has certain similarity to the one now observed. Meanwhile, secondary star formation took place in the swept-up ISM, leading to the formation of the OB Associations with ages of 15 million years and lower in the oval shaped configuration marked in Figure 8. The fact that the observed radial velocities of these associations with respect to their local standard of rest are not all in satisfactory agreement with predictions implies that the model is incomplete. Perhaps also elements of the density wave theory of spiral structure have to be included. The model of the expanding system of gas and stars was worked out in detail by Olano (1982). For reviews and further research on the subject, reference is made to papers by Lindblad (1983) and Lindblad and Westin (1985) and a review in preparation by Pö ppel (1991).

A somewhat puzzling feature is the occurrence of the Taurus dark clouds at about the centre of the Cas-Tau Association where we surmise the centre of the explosive forces was located. Contrary to cloud structures like those in Ophiuchus and Orion, the Taurus clouds do not show evidence of one-sided compression as one might perhaps expect on the basis of the scenario just described, and star formation is more or less uniformly distributed over the complex. Could the Taurus clouds have formed after the explosive events mentioned before?

Finally, it is useful to note that the stars of the Gould Belt System are immersed in the general population of older B-type stars that do not show the features (tilt, expansion) of the Belt stars (Lindblad and Westin 1985).

5. Promises for Future Research

In the foregoing we have scanned a variety of prospects, offered by nearby OB Associations, for throwing light on the process of star formation. In view of current interest in this process a broader and considerably more in depth-treatment, far beyond the scope of this review would be in order, in which in particular the interrelations between the various sites of star formation in the domain around the sun would deserve to be pursued. Moreover, the future of research on these fossils looks bright. With accurate proper motions of thousands of stars in the regions of the associations from the satellite Hipparcos in sight, and with the current promise of a considerable improvement of their radial velocities, the identification of the member stars and the early spatial and kinematic history of the associations and their subgroups should bring us a step closer to their formation stage.

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PHYSICAL CONDITIONS AND HEATING/COOLING PROCESSES IN HIGH MASS STAR FORMATION REGIONS

REINHARD GENZEL
Max-Planck-Institut für extraterrestrische Physik
Garching
FRG

1. Introduction

Massive stars have a profound impact on their environment. At a distance of a few pc from a massive O-star ($> 10^6\,L_\odot$) the flux of UV photons is about 1000 times larger than in the average radiation field of the solar neighborhood. Massive stars also have supersonic winds with velocities up to several thousand km s^{-1} carrying between 0.1 and 1% of the star's luminosity in form of kinetic energy. Massive stars affect their environment very soon after a stellar core has formed as their thermal (Kelvin-Helmholtz) time scale is very short compared to all other time scales ($\tau_{KH} \leq 10^4$ y for an O-star). At the end of its lifetime (several 10^6 to 10^7 y) an O star explodes as a supernova, ejecting 10^{51} erg of energy into its surroundings.

Radiation and winds from nearby OB stars dramatically affect the physical conditions, structure and chemistry of dense molecular clouds. Discussion of observations and theoretical models of dense clouds in regions of massive star formation and the physical processes occuring there is the purpose of this review. Dense interstellar clouds primarily consist of molecules, atoms, and dust particles. Analysis of the infrared, submillimeter and radio line, and continuum radiation from these species are our primary tools for studying the physical conditions and processes in these clouds. Chapter III presents an overview of excitation and radiative transport of line and continuum emission in these wavelength bands and shows how physical parameters are derived from them. Chapter IV is a discussion of heating and cooling processes in clouds near newly-formed OB stars.

The most important global application of the effects of massive star formation on the interstellar medium as a whole is in *star burst galaxies*. The average flux of UV photons in the central 700 pc of the infrared luminous galaxy M82 ($3 \times 10^{10}\,L_\odot$) is about the same as that 5 pc from an O-star. The entire interstellar medium of star burst galaxies can thus be expected to resemble a gigantic star forming cloud rather than cold clouds within our Galaxy. There are a number of interesting puzzles that are raised by the recent observations. From those chapter V selects two: the issue of finding "protostars", and the interpretation of warm quiescent molecular gas at the surfaces of clouds.

We begin with a brief overview of the *observational phenomena* in the case of the nearest cloud with massive star formation, the *Orion Molecular Cloud* (for a more detailed review see Genzel and Stutzki 1989).

C. J. Lada and N. D. Kylafis (eds.), The Physics of Star Formation and Early Stellar Evolution, 155–219.