RECENT RESULTS ON ASSOCIATIONS: ANATOMY OF CMa OB1 AND Mon OB1

William Herbst
Van Vleck Observatory, Wesleyan University

1. INTRODUCTION

Three types of associations are presently recognized. These are OB, R, and T, and represent, respectively, concentrations of O and B-type stars, reflection nebulae, and T Tauri stars, in certain regions of the sky. OB and T associations are identified on objective prism plates; R associations may be found using direct plates such as those of the Palomar Sky Survey. All associations are intimately connected with what appear optically as dark clouds and are now detected as sources of molecular line emission and known as molecular clouds. Often, all three types of associations are found within the same cloud complex (eg. Mon OB1). However, there are also examples of T associations (Taurus) and R associations (Mon R2) which are not connected with recognized OB associations.

The most massive stars in OB associations have lifetimes of 10^7 years or less. The T Tauri stars, being pre-main sequence stars of around $1M_\odot$ also exhibit their distinguishing spectral properties for times of the same order. Hence, OB and T associations are regions where star formation has occurred within the last $\sim 10^7$ years or less. R associations are of two varieties. Some such as that which the Pleiades comprises, occur as a result of the encounter between a dust cloud and a cluster. More interesting and probably more common, are those that result when an episode of star formation occurs in a cloud, producing B-type stars (3 to $10M_\odot$) but not O stars. The young B stars are sufficiently luminous and closely connected with their placental cloud that they produce detectable nebulosity. The presence of O stars in the group inhibits the detection of R associations by (1) producing an emission nebula against which the fainter reflection nebulae are not detectable and/or (2) disrupting the placental clouds.

We have reached a critical time in the study of associations, because it is now possible to routinely obtain data on the distribution and kinematics of every major component of an association - stellar, interstellar and protostellar. The prospect is to fully illuminate the

James E. Hesser (ed.), Star Clusters, 33–49.

structure of all nearby associations and, hopefully, to deduce their evolution. Since most stars form in associations (eg. Miller and Scalo, 1978) this will tell us much of what we want to know about star formation. A proper understanding of the evolution of associations is relevant to a wide range of astrophysical problems, including the structure of spiral galaxies, and the formation of the solar system. While important progress has been made in recent years (see, for example, Elmegreen and Lada, 1977, and Woodward, 1978a, b), we are, in my opinion, still considerably shy of our goal.

Rather than describe the various models and speculations concerning the evolution of associations which have been proposed, let us look, in some detail, at the structure of two associations, Canis Major OB1 and Monoceros OB1. These were selected for discussion mainly because the author happened to be most familiar with them, but they may rightly be called "representative" associations in so far as that word can be applied to any member of such a diverse set of objects. An apology must be made for not discussing Orion OB1, which is undoubtedly the association for which the most data is available, especially since the work of Warren and Hesser (1977a, b, 1978). There is, however, some advantage in looking at the relatively sparse associations described here. In particular, O stars inject a large amount of energy into the interstellar medium via ultraviolet photons and stellar winds. They can significantly alter their surroundings on a short time scale. In effect, they erase any memory in the neighboring gas of the conditions under which they formed. In this respect, it is preferable to study the sparse OB associations, R associations and T associations if one would like to ascertain the conditions under which stars form.

2. CANIS MAJOR OB1

2.1 The Gas

On the red print of the Palomar Sky Survey, the most prominent feature of CMa OB1 is a partial ring of emission nebulosity (see, for example, Figure 2 of Herbst and Assousa, 1977). It is quite circular, with a diameter of about 3° corresponding to 60pc. This main emission ring is shown by the shading in Figure 1, a drawing of the association. Some faint, filamentary extensions of the emission nebulosity are also shown. The ones to the north are just detectable on the Palomar prints. Gull (private communication) has obtained deep, wide field, Hα photographs of the region on which the very faint extension to the south of the main ring, indicated by the lightest shading in Figure 1, may be seen. The faint northern filaments appear roughly symmetrical about HD 54662, an O6.5V star, which is the earliest type member of CMa OB1. There is also structure in some of the brighter nebulosity within a degree or so of HD 54662 which belies its influence on the emission ring.

The molecular hydrogen, as traced by CO emission, is concentrated in two large clouds and several fragments (Blitz 1978). These are

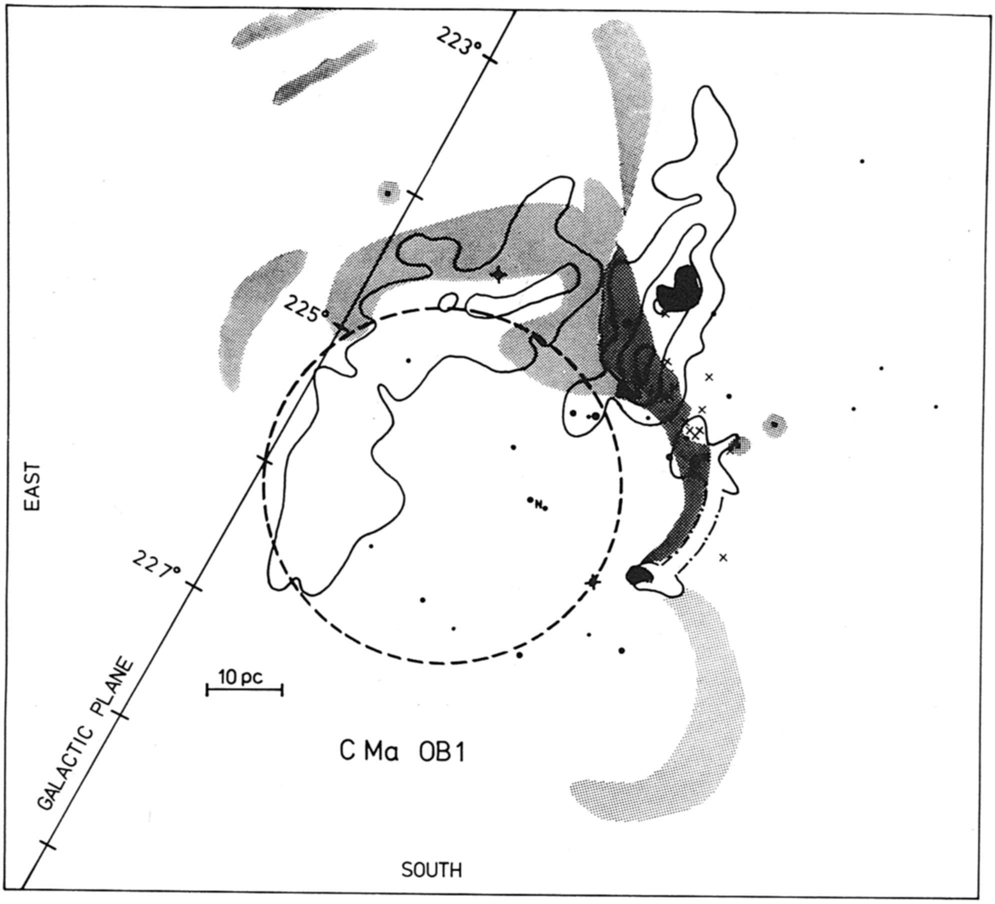

Figure 1. A drawing of CMa OB1. Symbols are described in the text.

shown in Figure 1 by the solid lines. The most massive cloud lies between galactic longitudes 223° and 225° and contains about 2 x 10^5 $M_\odot$ of gas according to Blitz. The other large one extends between 224° and 227° and contains about 10^5 $M_\odot$. The masses and dimensions of these clouds are typical of those which have been discovered around virtually every nearby OB association (Blitz 1978). It is clear that these large molecular clouds are the most massive components of typical associations.

South of the more massive molecular cloud and running along the western edge of the main emission ring is a thin, dark cloud, seen clearly on optical photographs. Blitz's (1978) survey showed a curious lack of CO emission associated with this feature, but a more recent, higher resolution study (Blitz, private communication) shows that it is indeed, a CO source, as one would expect from its high opacity at optical wavelengths. While no CO map is yet available, I have indicated the position of the dust lane in Figure 1, by a dashed-dotted line. This fragment of the main cloud contains several stars in reflection nebulae, including the Herbig Ae/Be star Z CMa.

It will be difficult to study the neutral hydrogen distribution in this association because of confusion with foreground and background material. To the author's knowledge no one has yet undertaken such a study. Examination of the Weaver and Williams (1974) 21-cm survey maps of this region, however, does provide some information, as summarized by Herbst and Assousa (1977). There is evidence for negative velocity (~30 km/sec with respect to the association) neutral hydrogen towards the center of the emission ring, and for an HI concentration along the western edge of the association. This is supported by the presence of two stars in Stromgren spheres in that direction, indicating a hydrogen density of ~ 2 cm^{-3}.

The distribution of ionized hydrogen, as detected from Hα photographs has already been discussed. The kinematics of the gas has been studied by Reynolds and Ogden (1978) who observed CMa OB1 with a Fabry-Perot spectrometer. They found that the ionized gas was contained in an expanding shell with a spatial distribution similar to that inferred for the HI by Herbst and Assousa (1977). They sampled three regions within the dashed circle in Figure 1 and found in all cases two components to the [NII] line split by a maximum of 26 km/sec. Outside the dashed circle (i.e. in the optical emission ring) they found single lines. From the extent and expansion velocity of the shell they estimate its age to be ~10^6 years and the energy required to form it ~2 x 10^{50} ergs. These numbers are roughly consistent with those inferred for the HI shell by Herbst and Assousa (1977). Blitz (1978) claims, however, that there are inconsistencies in the data, which cast doubt on the reality of the HI shell. The issue should be settled by a detailed 21-cm study of CMa OB1.

Expanding shells, both of ionized and neutral gas, are probably a common feature of OB associations. Sancisi (1974) has discussed the existence of HI shells in Per OB2, and Sco OB2, and was the first to suggest that they may be important for star formation. Assousa _et al._ (1977) made a similar suggestion for the HI shell in Cep OB3. Reynolds and Ogden (1979) have recently shown that a very large shell of ionized gas, requiring energies in excess of 10^{52} ergs for its formation, exists around Orion OB1. Its brighter portion forms Barnard's Loop. A similar feature may be seen on the Palomar Sky Survey photograph of Cep OB4. Both of these shells also appear to have neutral H components (Reynolds and Ogden, 1979; Grayzcek, private communication).

2.2 The Stars

Candidate members of CMa OB1 have been identified on objective prism plates by Claria (1974a) and in a follow-up study (Claria 1974b) he lists probable members, based on their inferred distance. The distribution of stars which Claria calls members is shown in Figure 1 by the dots. The size of each dot is proportional to the luminosity of the star. The earliest type O star is HD 54662 (O6.5V) and is the circle with a plus sign through it at $\ell \sim 224°$. The other O star (HD 53975, O8V) near $\ell \sim 226°$ is similarly marked. HD 54662 is a runaway star, having a radial velocity relative to the association mean of ~30 km/sec (Herbst and Assousa, 1977).

There is no obvious (positional) sub-group structure to this association as, for example, exists in Orion OB1 and some other associations (Blaauw, 1964). The two O stars are separated by a projected distance of greater than 40pc. There are no clusters or even vague concentrations of association members, except possibly around W CMa, an N-type carbon star (marked by an N in Figure 1). If this is really a member of the association it is very luminous ($M_{bol} = -7.2$; Herbst et al., 1977) and is presumably descended from an O star. There are a few likely association members in its vicinity.

In addition to W CMa, there are two luminous members of CMa OB1 which are not on the main sequence, HD 53367 (BO IVe) and HD 53974 (BO IIIn). Both illuminate reflection nebulae, and HD 53367 is a Herbig Ae/Be star (Herbig, 1960). Note that their being above the main sequence does not imply that they are post-main sequence stars. They could also be pre-main sequence, or, what is more likely, they could be rapid rotators. Main sequence stars rotating near critical velocity can mimic evolved stars (Collins and Sonneborn, 1977).

It is often the case that OB associations contain stars embedded in reflection nebulae, now known as R associations. Blaauw (1964) showed that such stars make up the youngest subgroup in some associations; Cep OB3 is an example. CMa OB1 contains an R association known as CMa R1, whose thirty members have been identified and studied by Herbst et al. (1978). They are marked on Figure 1 as crosses. Their spectral types range between BO and A1 and several had already been identified by Claria as OB association members. The color-magnitude diagram of CMa R1 has been discussed by Herbst et al. (1978). It contains many likely pre-main sequence B-type stars including the Herbig Ae/Be star Z CMa (Herbig, 1960). As with other associations, the reflection nebulae of CMa R1 evidently locate the portions of CMa OB1 where star formation has been recently active.

The question of ages of the OB and R associations has been a matter of some discussion and controversy. Claria (1974b) assigns an age of 3×10^6 years to CMa OB1 assuming that the O6.5V star is at the turnoff point. This is certainly the best estimate one can make, but it is really an upper limit to the age of the association. As pointed out previously, the BOIII and BOIV stars in CMa OB1 may not be post-main sequence stars, so there is no basis for determining a definitive age from the turn-off point. Herbst et al. (1978) suggested an age of 3 x 10^5 years for the R association. This was based on their identification of B5 ($6.5M_{\odot}$) as the turn-up point (latest spectral type on the ZAMS), and Iben's (1965) contraction time for a $6.5M_{\odot}$ star. Blitz (1978) has pointed out one uncertainty in this age determination - namely that the free-fall time required to get to the starting point of Iben's models may (depending on initial conditions) be of the same order as the quasi-static contraction time itself. A better estimate of the age of CMa R1 might then be 6 x 10^5 years. However, there are additional uncertainties arising from the use of highly simplified (eg. non-rotating, non-magnetic) models to describe complex objects, and from difficulties of interpretation of data. In particular, three A-type stars exist in CMa R1 which are very close to the ZAMS. This may indicate: (1) an age spread of ~3 x 10^6 years for star formation in CMa R1, (2) the importance of physical processes not included in the models, such as rapid rotation, disk formation, and/or magnetic field effects, and/or (3) the presence of interlopers in CMa R1; that is, field stars, which by chance have come close enough to the dark clouds to illuminate detectable reflection nebulae. Given the cloud volume, it would not be unlikely to find three early A interlopers in CMa R1.

A related issue is whether the OB and R associations in CMa have distinctly different ages. This is to be expected on general principles, namely: (1) Blaauw's (1964) discussion of reflection nebulae in other associations, (2) the intimate connection between the star and dense interstellar matter required of an R association member, (3) the more extended distribution on the sky of OB association members compared with R association members, and (4) the presence of emission-line and otherwise peculiar stars among the R association members and their absence throughout the rest of the association. Eggen (1978) and Blitz (1978) have attempted to test this by comparing the color-magnitude diagrams of the R association and OB association members. Each finds no significant age difference. Unfortunately, however, the result is unreliable, since it depends critically on identifying OB association members with spectral types later than B5. Claria (1974b) lists only what he calls "probable" members among these later-type stars and the field contamination problem discussed below with regard to B3 and B5 stars becomes virtually insurmountable for these stars.

There are no definite T Tauri stars yet known to be associated with CMa R1. Herbig (1960) remarked on the peculiar paucity of such stars in the vicinity of Z CMa. It would be a worthwhile project to search the entire association for such stars, which should appear at V~ 15 mag if they have absolute magnitudes around +4.

2.3 Comparison of Star and Gas Distribution

It is interesting to compare the distributions of the OB association members, R association members, and molecular clouds. The OB association members are most widely distributed, with many of the fainter members being at projected distances of 10 to 20pc or more from the molecular clouds in various directions. The brighter members occupy a smaller area of the sky, lying predominately to the high galactic longitude side of the more massive molecular cloud. One should keep in mind the method by which OB association members are selected when attempting to infer properties of the association from their distribution on the sky and/or location on the color-magnitude diagram. Claria (1974b), for example, follows the standard procedure of admitting as members, stars which are 0.5 mag fainter or 0.75 mag brighter than would be expected of a ZAMS star at the adopted association distance. He discusses the reasons for doing this. While this is the best one can do, the procedure can still result in the inclusion of field stars as association members, particularly for B2 stars and later. As an example of the seriousness of the problem, consider CMa OB1. It occupies an area of 4 square degrees, corresponding to 6400 pc^2. The distance spread of stars which might be admitted as members by the magnitude criteria given above is about 700pc; that is, field OB stars lying within $\sim$350pc of the association and projected within its 4° x 4° area might be called members. The number of B3 to B5 field stars expected in such a volume is quite large, (55 if we use the luminosity function given by Allen, 1963). It is not inconceivable, therefore, that many of Claria's B3 and B5 type members are, in fact, field stars. It is interesting that these fainter stars appear much more widely distributed across the association, as one would expect if field star contamination were important.

The R association members occupy a much more restricted region of the association. They congregate at one edge of the more massive molecular cloud, and in the small cloud fragment outside the southern portion of the emission ring. They totally avoid the other large molecular cloud. Evidently recent star formation in CMa OB1 has been confined to a rather small portion of the available molecular gas. Furthermore, the recently active portions of the association are located along one edge of the expanding shell, especially where it intersects the more massive molecular cloud, and along the cloud fragment to the south of this. For these reasons, Herbst and Assousa (1977) argued that the energetic event responsible for the expanding shell was also the cause of an episode of star formation, which we now perceive as the CMa R1 stars.

3. MONOCEROS OB1

3.1 The Gas

Figure 2 shows a drawing of the Mon OB1 association, which includes the cluster NGC 2264. The molecular clouds have been mapped by Blitz (1978), with detailed studies of the NGC 2264 and Mon R1 regions having been made by Crutcher et al. (1978) and Kutner et al. (1979) respectively. As in CMa R1, one finds two large clouds, in this case of about equal mass ($\sim 10^5$ $M_\odot$), and at least one kinematically (but not spatially) distinct fragment located between ℓ = 201° and 202° where the molecular

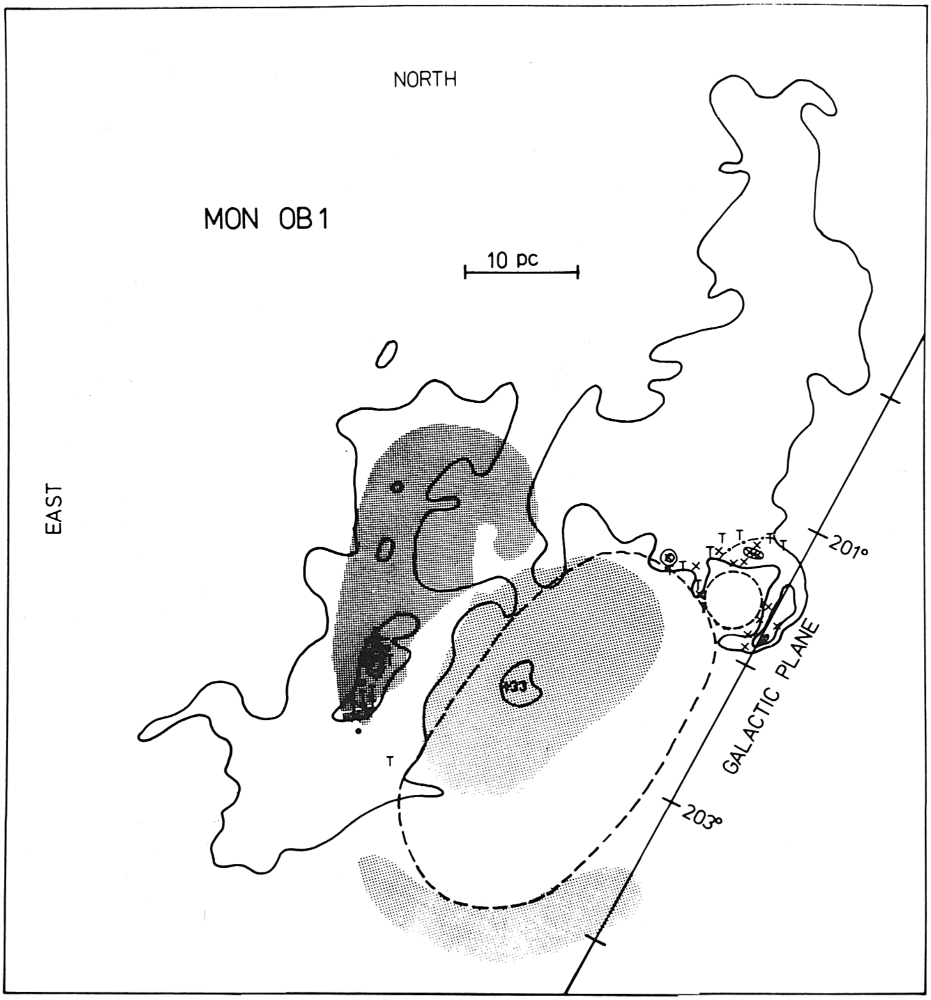

Figure 2. A drawing of Mon OB1. Symbols are described in the text.

emission crosses the galactic plane). There is also a small cloud fragment at much higher velocity (33 km/sec) than the range of -2 to +13 km/sec found for the rest of the association. While it may be a background cloud, it is interesting that it is located in the same direction as a possible HI expanding shell discussed by Blitz (1978). An independent distance estimate to the cloud might be obtained by determining the distance vs. reddening diagram for stars in its direction.

Blitz(1978) has discussed the neutral hydrogen distribution in the direction of Mon OB1; the observations come from Raimond (1966) and Weaver and Williams (1974). He finds evidence for an HI shell with an expansion velocity of ~15 km/sec, coincident with a faint, elliptical emission nebula adjacent to the molecular clouds. A rough indication of the location of this feature is given by the large, dashed ellipse in Figure 2. It is reminiscent of the HI shell in CMa OB1. Evidence for a second expanding HI shell in this association has been discussed by Kutner et al. (1979), also using the Weaver and Williams (1974) survey. This is a smaller structure located in the direction of Mon R1 and indicated by the small dashed circle in Figure 2. There is no emission nebulosity connected with this feature. On optical photographs the area within the dashed circle appears relatively transparent as judged by the large number of background stars visible. Kutner et al. (1979) also did not detect any CO emission from that region.

The distribution of ionized H in Mon OB1 as seen on the POSS red print is indicated by the shading in Figure 2. Three patches may be distinguished. The brightest surrounds the only O star in the association, S Mon, extending particularly to the north of it. Fainter patches are seen defining the center and southern edge of the elliptical structure discussed in connection with Blitz's HI shell. Reynolds (private communication) has obtained Fabry-Perot scans of the [NII] line towards the center of the elliptical structure. He finds that there is no evidence for line splitting by more than 12 km/sec; this means that there is no observed HII shell counterpart to the suggested HI shell. Possible explanations for this circumstance include: (1) the feature in the Weaver and Williams (1974) data described by Blitz has some other interpretation than the one he gives it, and in fact, there is no HI shell; (2) the expansion velocity of the ionized shell is much smaller than that inferred for the HI shell, and below the 6 km/sec figure detectable by Reynolds, (note that in CMa OB1, the HI expansion velocity inferred by Herbst and Assousa, 1977, was a factor of 2.5 larger than that obtained by Reynolds and Ogden, 1978, for the HII shell); (3) only one side of the expanding shell is ionized.

3.2 The Stars

Turner (1976) has summarized observations of OB stars in the vicinity of Mon OB1, which are now complete for the Luminous Stars Catalogue to B = 10.4. The OB stars are concentrated in two groups - the cluster NGC 2264 and the R association Mon R1. There are a few stars outside of these groups which Turner assigns to Mon OB1. These range in spectral type from B1 to A0 and cover a 4° x 8° segment of the sky to the west of NGC 2264. Only three lie within the boundaries of Figure 2. The possibility that these are really field stars which happen to have the same distance as the association, as discussed previously with regard to CMa OB1, should be kept in mind. It is interesting that there is no evidence for a subgroup of OB stars within the dashed ellipse or circle. The most luminous star in Mon OB1, by far is S Mon (O7V). The next most luminous stars are W83 and W212 (Walker, 1956), B2IV members of NGC 2264. Walker (1956) showed that stars later than A0 in NGC 2264 lie above the main sequence. Identifying A0 as the "turn-up point" of the cluster suggests an age of ~3 x 10^6 years, although it is possible that an age spread of ~10^7 years exists among members (Warner *et al.*, 1977).

The R association Mon R1 has been studied by Herbst and Warner (1979). Its earliest type member is apparently a highly obscured variable star (V~15 mag), VY Mon which Cohen and Kuhi (1979) classify as O9 using spectral scans with a resolution of ~7Å. There are four stars of spectral class B2.5 to B5 which lie on the ZAMS. The rest of the stars are of later spectral type and lie well above the ZAMS. They include two Herbig Ae/Be stars, HDE 259431 and LKHα 215. Late-type members of the R association include an A3III star, an F star, and a K4e star (LKHα 274). Two rocket-infrared sources lie within the association; one is associated with HDE 259431 and one with VY Mon. The "turn-up point" of ~B5 apparently places Mon R1 among the youngest associations known.

Two groups of T Tauri stars are also associated with Mon OB1, again being concentrated to NGC 2264 and Mon R1. Many more exist within NGC 2264 than have been indicated in Figure 2, but all of those in Mon R1 which Herbig and Rao (1972) list are shown. The extensive study by Cohen and Kuhi (1979) includes many stars in NGC 2264 and Mon R1 (which they call the IC 446 and VY Mon groups).

3.3 Comparison of Stars and Gas

As with CMa OB1, there are vast portions of the Mon OB1 molecular clouds which give no evidence of having participated in recent star formation. It is particularly interesting to survey the large cloud extending to the north of Mon R1, which can easily be seen as a dust cloud on the POSS blue print, and find no stars in reflection nebulae associated with it. Again one finds that the portions of the cloud which are actively producing stars are also the portions associated with the expanding shells. This is particularly evident in Mon R1, where we see star formation on one edge of a large molecular cloud and along a cloud fragment, which has been broken off or newly formed adjacent to the main cloud. For NGC 2264, the connection with an expanding shell is more tenuous, perhaps because it is older. Mon OB1 is also an example of an association which has two subgroups of different age, but no evidence of a sequential triggering relation.

It is interesting that in Mon OB1, star formation has occurred in two distinct clumps, one of which is a *bona fide* cluster. This is in contrast to CMa OB1 where recent star formation has occurred over a more widely spread region, with no distinct clusterings of more than four or five stars. Perhaps if we knew why this was so, we would also know why the galaxy IC 1613 is deficient in young clusters by comparison with the SMC, in spite of similar star formation rates, as van den Bergh discussed during the opening session of this meeting.

4. CONCLUDING REMARKS

Comparing the distributions of the stars and gas in CMa OB1 and Mon OB1 leads one to the conclusion that some local energetic events (i.e. something which can produce circular symmetry) are responsible for the most recent episodes of star formation in these associations. This is particularly evident in Mon R1 and CMa R1, probably because they are so young, but may also be true for NGC 2264.

Three energetic shells have been discussed. They have roughly similar ages ($\sim 10^6$ years) and require roughly similar inputs of energy into the interstellar medium ($\sim 10^{50}$ to 10^{51} ergs) to have been formed. They do not have luminous stars in their interiors, unless W CMa is a member of CMa OB1 and lies inside the shell. They also do not have concentrations of B-type stars in their interiors which might be indicative of the presence of older subgroups of associations; again CMa OB1 may be an exception, since there is some concentration of association members to the general region of the expanding shell. There is no star earlier than B8 in the HDE catalog within the CO ring in Mon R1.

A plausible mechanism for generating expanding shells with the properties observed in CMa OB1 and Mon OB1 is a supernova explosion. The shells adjacent to CMa R1, and possibly NGC 2264, have dimensions and expansion velocities which are simple extrapolations of those exhibited by old supernova remnants. The Mon R1 ring is smaller than a typical old supernova remnant, and this requires that the explosion occurred in a cloud of density ~ 1000 cm^{-3} (Kutner, et al., 1979).

Other possible energy sources for the shells are the ultraviolet photons and stellar winds from O stars. While these O stars do not exist within the shells at the present time, it is impossible to prove that they were never there. If they were there, where are they now? The conventional view is that O stars end their lives as supernovae. It is, therefore, difficult to avoid having a supernova involved in the generation of these shells, particularly Mon R1.

This is particularly interesting since isotopic studies in meteorites suggest that a supernova occurred in the vicinity of the solar system shortly before its formation (eg. Cameron and Truran, 1977; Schramm, 1978). One requires $\sim 2\%$ of the metals in the solar system to have been supplied by the supernova. This is about the level of contamination expected in the Mon R1 and CMa R1 stars, assuming a typical Type II supernova produced those shells (Herbst and Rajan, 1979a, b).

The morphology of Mon R1 and CMa R1 is also interesting with respect to the means by which the energetic events triggered the star formation. It has been customary, at least in the case of the solar system, to consider a pre-existing cloud brought to the point of collapse by passage of a supernova shock. Hydro-dynamical calculations of this type of event have been done by Woodward (1976, 1978b). A characteristic of these calculations is that density enhancements occur on the edge of the cloud facing the direction the shock came from, and a tail develops behind the cloud pointing in the direction the shock is travelling. This shape is reminiscent of the cometary globules associated with the Gum nebula (Hawarden and Brand, 1976), one of which contains an F-type emission star embedded in its head (Harwarden, private communication). The morphology of Mon R1 and CMa R1 is distinctly different. Here we see thin (but dense) arced clouds, forming either sheet-like or rope-like portions of a shell. These do not appear to be pre-existing, shocked clouds, but newly formed ones, created during the snow-plow phase of the shell's expansion. It is interesting that these sheets or ropes in Mon R1 and CMa R1 lie adjacent to large molecular clouds; that is, in environments where the ambient (pre-shock) density of the interstellar medium is likely to have been high. In each case we also see star formation apparently occurring within the adjacent portions of the large molecular cloud. Herbst and Rajan (1979a, b) discuss this further.

Let me finish this report with a caution and a plea. The caution is against extrapolating the results and inferences obtained for a small number of associations to every association. Blaauw's (1964) article illustrates clearly the diversity which exists among the stellar components of OB associations. Different processes may operate in different associations, and there may well be no unique answer to the question of how OB associations evolve. Discussions of this point should be related to particular associations. The plea is for more data, particularly in the optical and infrared. One requires high quality photoelectric and spectroscopic material if one is to identify rapid rotators and binaries, for example, a chore which must be undertaken before a color-magnitude diagram may properly be interpreted. Radial velocities and proper motions of association members are of particular value in elucidating the immediate past history of an association. Finally, we need continuing and increased communication between astronomers working on the stellar component of association and those working on the interstellar components.

It is a pleasure to thank Dr. G. E. Assousa for his involvement in the formative stages of this work. Drs. L. Blitz, R. Reynolds, M. Cohen, and E. Grayzcek kindly sent me unpublished material which has been included in this report. The Third Annual Santa Cruz Summer Workshop in Astrophysics was a particularly useful forum for developing some of the ideas presented here.

REFERENCES

Assousa, G.E., Herbst, W. and Turner, K.C.: 1977, Astrophys. J. (Letter) 218, L13.
Blaauw, A.: 1964, Ann. Rev. Astron. Astrophys 2, 213.
Blitz, L.: 1978, NASA Technical Memorandum 79708 (Ph.D. Thesis, Columbia University).
Cameron, A.G.W. and Truran, J.W.: 1977, Icarus 30, 447.
Claria, J.J.: 1974a, Astron. J. 79, 1022.

Claria, J.J.: 1974b, Astron. Astrophys. 37, 229.
Cohen, M. and Kuhi, L.V.: 1979, Astrophys. J. (Suppl.), in press.
Collins, G.W. and Sonneborn, G.H.: 1977, Astrophys. J. (Suppl.) 34, 41.
Crutcher, R.M., Hartkopf, W.I. and Giguere, P.T.: 1978, Astrophys. J. 226, 839.
Eggen, O.J.: 1978, Publ. Astron. Soc. Pacific 90, 436.
Elmegreen, B.G. and Lada, C.J.: 1977, Astrophys. J. 214, 725.
Hawarden, T.G. and Brand, P.W.J.L.: 1976, Monthly Notices Roy. Astron. Soc. 175, 19P.
Herbig, G.H.: 1960, Astrophys. J. (Suppl.) 4, 337.
Herbig, G.H. and Rao, N.K.: 1972, Astrophys. J. 174, 401.
Herbst, W. and Assousa, G.E.: 1977, Astrophys. J. 217, 473.
Herbst, W., Racine, R. and Richer, H.B.: 1977, Publ. Astron. Soc. Pacific 89, 663.
Herbst, W., Racine, R. and Warner, J.W.: 1978, Astrophys. J. 223, 471.
Herbst, W. and Rajan, R.S.: 1979a, Carnegie Yearbook '78, in press.
Herbst, W. and Rajan, R.S.: 1979b, in preparation.
Herbst, W. and Warner, J.W.: 1979, in preparation.
Kutner, M.L., Dickman, R.L., Tucker, K.D. and Machnik, D.E.: 1979, Astrophys. J., in press.
Miller, G.E. and Scalo, J.M.: 1978, Publ. Astron. Soc. Pacific 90, 506.
Raimond, E.: 1966, B.A.N. 18, 191.
Reynolds, R.J. and Ogden, P.M.: 1978, Astrophys. J. 224, 94.
Reynolds, R.J. and Ogden, P.M.: 1979, Astrophys. J. 229, 942.
Sancisi, R.: 1974, in Galactic Radio Astronomy, F.J. Kerr and S.C. Simonson, eds. (Reidel, Dordrecht), p. 115.
Schramm, D.N.: 1978 in Protostars and Planets, ed. T. Gehrels (U. of Arizona Press, Tucson), p. 384.
Warner, J.W., Strom, S.E. and Strom, K.M.: 1977, Astrophys. J. 213, 427.
Warren, W.H. and Hesser, J.E.: 1977a, Astrophys. J. (Suppl.) 34, 115.
Warren, W.H. and Hesser, J.E.: 1977b, Astrophys. J. (Suppl.) 34, 207.
Warren, W.H. and Hesser, J.E.: 1978, Astrophys. J. (Suppl.) 36, 497.
Weaver, H. and Williams, D.R.W.: 1974, Astrophys. J. (Suppl.) 17, 1
Woodward, P.R.: 1976, Astrophys. J. 207, 484.
Woodward, P.R.: 1978a, Ann. Rev. Astron. Astrophys. 16, 555.
Woodward, P.R.: 1978b, Proceedings of the International School of Physics «Enrico Fermi» , Course no. 73, preprint.

DISCUSSION

BOK: This very fine paper is now before you. I hope all of you have read the fine *Scientific American* article on this subject by Drs. Herbst and Assousa.

FEAST: Is there any, or do you see any, inconsistency between the view that star formation is triggered by a supernova explosion and the point of view which Sidney van den Bergh was mentioning earlier, where he, in fact, implied really that his supernova in the Large Cloud is really a part of the star formation. I mean, that's how he gets a mass; if the supernova is outside the star formation, then surely you can't say anything about the mass of the supernova progenitor.

HERBST: I think you can have both cases. Clearly you can have an OB association where, in my opinion, it is very easy to get a number of supernova; and I think Dr. Blaauw presented evidence of this in terms of the runaway stars that you see, for example, in the Orion OB1 association. OB associations are likely to be very good sources of supernova explosions. You may also have field supernovae which can, just by chance, go off close to a cloud and could be involved in forming stars. I think you can have both circumstances.

VAN DEN BERGH: I was wondering if you could say a little bit more about the time scales that are involved? Supernova shells with radii of 10 pc have a time scale of the order of 10^4 y, whereas associations must have time scales like 10^6 y associated with them.

HERBST: Right; the ages of the shells in CMa OB1 and Mon OB1 are of the order of 10^6 y.

BOK: That's one of the biggest worries, basically, with the whole supernova thing. That the supernova effects have disappeared by the time the stars run away, and all you can deduce is that there may have been a supernova there at the center.

HERBST: That is the greatest difficulty in knowing for certain whether these things are supernovae.

BROSCHE: Can you exclude cloud collisions as energy sources?

HERBST: No. (Laughter).

BROSCHE: Since you said you have only supernovae left over is it possible . . .

HERBST: If you could get a cloud collision which produced circular symmetry and a swept out region in the center, no.

BOK: But would you say that that was the only thing left over? We are probably seeing dark cloud complexes and, in globules, stars forming before our eyes. That's something else again than what he's talking about, so don't say cloud collisions are the only way that work. (To Brosche:) Did you say that?

BROSCHE: No.

SCHOMMER: Can you make any comments on the relative efficiency of star formation in the case of . . .

BOK: Could you please speak slower? The Europeans may have a hard time understanding so speak slowly. You must remember that it is a great courtesy of them that they don't stop this whole business and insist that French and English are equivalent in the International Astronomical Union. So please talk slowly, clearly, and loudly or they will start saying, "attention, si'l vous plait".

SCHOMMER: Excuse me. Can you make any comments on the overall efficiency of star formation between the Canis Major association and the Monoceros OB association, and do we know anything about that in IC 1613 and the SMC?

HERBST: I don't know anything about the second part of the question. Concerning the first part, you might be able to, I haven't done it, and that's probably all I should say.

COHEN: Do you know anything about the slope of the luminosity function for fainter stars and is there any way of finding out?

HERBST: I think the best way to find that out is in the cluster NGC 2264 by doing a very good proper motion study; by studying all the faint stars you can by essentially every technique you can bring to bear to pick out exactly which stars are members and which are not; and then putting it together.

BOK: Another comment I want to make is that I hope that in all your future papers when you plot an association together with the emission nebula you plot all the bloody stars of OB variety over the whole place. For example, in the *Scientific American* article, there you have lovely the stars all lumped. Then any person thinks that there is nothing else elswhere. And I think it is very essential to have them on, because the other point is that in the Vela region I once had a big fight when some of my good friends said that all the OB stars were made from the supernova. Well, what the heck. You have the brightest Wolf-Rayet star, the brightest O star. You can't even by the nebulosity distinguish who comes from one and who comes from the other, for all the nebulosity from the supernova is of the striated variety, whereas the other one is smooth and peaceful and looks very different. So I think it's very important in all these studies that we make it very clear what the whole picture is and that one doesn't just jump too quickly at a conclusion.

BLAAUW: First of all I would like very much to support what Dr. Herbst said, that he would like to have many more CO observations, especially, I would say, in the southern hemisphere. There are very few nebuale, or nothing . . .

BOK: Right.

BLAAUW: . . . while, on the other hand, some of the most interesting OB structures are just there. They are the nearest ones - the whole Scorpius-Centaurus complex. If we would have, say, the mapping of CO in that area, that I think would be one of the most interesting things that we could have in this field. And I wonder whether or not from this meeting something might emerge as a sort of recommendation for getting that kind of observation started someplace?

BOK: I had a resolution at IAU Symposium 85 which I was asked to withdraw, and, being a mouselike person, I withdrew it. I distributed a dozen copies of that resolution to all the people who were at it and are very much aware of it. But I think it would be a good thing if another proposal were in, for I could get a list of the guilty persons (that wouldn't be very nice) . . . . In the Large Magellanic Cloud where star formation takes place without the benefit of dust, we don't know how much CO there is there. We don't know how much molecular hydrogen there is, either, except for a couple of British groups, who have gone to Australia and used the 4-m telescope, which isn't fit for that sort of work. They found that there is very little CO in the Large Magellanic Cloud, and that doesn't seem very cheerful. If you write a resolution, I would be glad to second it.

BLAAUW: Well, I know you are a Magellanic Cloud fan. (Laughter). But there is something much nearer and not at 60 kpc but at 200 pc. I have a few more questions, if I may. One is that you mentioned that there are these CO cloud masses of about 10^5 $M_\odot$; could you also tell us how much neutral hydrogen mass is around there?

HERBST: In the case of Canis Major OB1 it is probably of the order of 10^4 $M_\odot$.

BLAAUW: So it is much less than there is in the form of CO?

HERBST: Yes, but that is not a definite statement, because it is very difficult to pick out the neutral hydrogen that is connected with an association.

BLAAUW: Yep, but all that means is that if you look where the star formation is most violent at the moment then that connects this with what Dr. Lyngå said. It may be that there are areas where there is mostly CO and very little neutral hydrogen.

HERBST: Right.

BLAAUW: On the other hand, if you ask where you would see most of the HII regions, that would be regions where, perhaps, the HI is more abundant, so those differences that were pointed out by Dr. Lyngå may be just differences in the relative proportion of CO and neutral hydrogen. Well, the third thing I would like to say is, you said that there are areas where you have small regions that are kinematically separated from the rest . . .

HERBST: Yes.

BLAAUW: Now, I suppose that means only that the velocities there are different, but that need not mean that these regions are spatially separated from the rest?

HERBST: Oh, no. I think they are spatially connected with the rest of the system. I mean the difference in their velocities with respect to the major clouds is small, like of the order of a few km s^{-1}.

BLAAUW: And that would mean that in 10^5 y only something like 1 pc or so.

RAJAMOHAN: I would like to mention that similar features like you have described are also found in the upper Scorpius region of the Scorpius-Centaurus association. There we have a supernova shell which is seen in the deep H-α sky survey of Shivan. And this has also been found by Sancisi from 21 cm observations; if you take the runaway star, ζ Ophiuchus, and place it back by proper motion it passes close to the center and the age is about 3 x 10^6 y then. The details of this are in poster session 18, a little farther away from the coffee table, and I would suggest that you go and read it.

BAART: On the same subject, we have found - as you will see from the poster session - there is a radio source coinciding with Sco OB2 association. We don't have a spectrum for it, so we don't know whether it is an HII region or a supernova remnant. But it is possible that for these very old supernova remnants, although you might not see any optical evidence of it, there might still be faint radio continuum emission from it.

BOK: Any further comments? If not, we'll continue with the next paper, but first of all may I congratulate the organizers of this Symposium of having done a wonderful thing. We got rid of all these silly ten minute papers that we have been listening to all week long in Montreal. It's nice to be away from them and it's nice to have only the comprehensive papers. I think it works much better. I think we should thank Ken Freeman and company for having made this very sensible decision. (Applause).