STAR FORMATION IN THE ORION ARM

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ABSTRACT

We assemble principal constituents of the morphology of the Orion Arm within 1500 pc as a starting point for the study of progression of star formation.

STRUCTURE FROM OB-ASSOCIATIONS

Although the Orion Arm (also referred to as the Local Feature or the Local Spur) is less prominent than major constituents of galactic spiral structure like the Perseus and Sagittarius Arms, it is of considerable interest for the study of the process of star formation. It is only here that, with current means, three-dimensional structure can be investigated in the relation between different star-forming regions and in the kinematic pattern of the young stellar components. Lack of photometric distance resolution is a major stumbling block for investigating such problems in the other galactic arms, let alone in extragalactic systems.

As a comparison with star-forming activity elsewhere, it is of some interest to note that the surface density (projected on the galactic plane) of luminous early-type stars in the Orion Arm is similar to the features of secondary importance in the Large Magellanic Cloud. For instance, the surface density of stars with M_V brighter than -4 in the string of subgroups numbered 1, 2, 5, 8, - - - - 66, 69, 107, 110 by Lucke and Hodge (1970) in their Fig. 1 is about the same as that of the Orion Arm. For further comparison, see also Fig. 4a to 4c of Schmidt-Kaler (1977).

The Orion Arm is a distinct feature in plots of the projection on the galactic plane of objects younger than 30 million years or selected by main-sequence spectral type B2 or earlier. Fig. 1 is such a plot, reproduced from Becker and Fenkart (1970). As observational information rapidly diminishes with increasing distance, we limit the present

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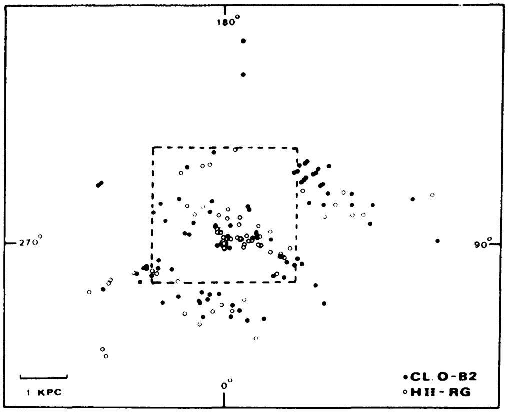

Figure 1. Positions of recently formed objects projected on the galactic plane according to Becker and Fenkart (1970). Dotted lines outline the region discussed in the present paper.

description to the section represented by the dotted square in Fig. 1, i.e. effectively to objects within 1500 pc. We shall see that even within this volume more data within reach of current observational means are required for a comprehensive analysis.

In Fig. 2a to 2c we present the spatial arrangement of the OB-associations, however with the omission of dubious cases like, for instance, Cas OB 14, Cyg OB7 and Vul OB4. We also omit, pending a more complete discussion, presentation of young clusters and of most of the loose groups of very young stars and of high-luminosity field stars; together these form a small fraction of the entire population of recently formed stars. We introduce a co-ordinate system s, t, z, adapted to the orientation of the Orion Arm, to be referred to as the OA system. The z co-ordinate has the conventional meaning; co-ordinate t is in the plane in the direction longitudes 60° - 240°, which is the rounded-off value for the direction of the ridge line of the Orion Arm in Fig. 1; hence the third co-ordinate, s, is roughly perpendicular to the OA. Accordingly, 30° is the chosen pitch angle for the OA. As this is considerably lower than the pitch angles found for spurs in extra-galactic spiral structure (see, for instance, Elmegreen 1980), we shall refrain from using the expression "spur" for the feature under study. Fig. 2a to 2c show the projections of the positions of the associations on the planes s,t, t,z, and z,s respectively.

Two of the main properties of the OB associations are represented in these diagrams. The size of the central dot is a measure of the star-forming activity. It is based on the number N, which is the sum of the number of OB stars brighter than M_V = -5 and the number of O-type stars; the latter ones are thus counted double if more luminous than -5. See the key at the bottom of Fig. 2a. In these counts we included the associated clusters. The circles around the central dots are roughly equal in diameter to the projected size of the association in the direction of galactic longitude.

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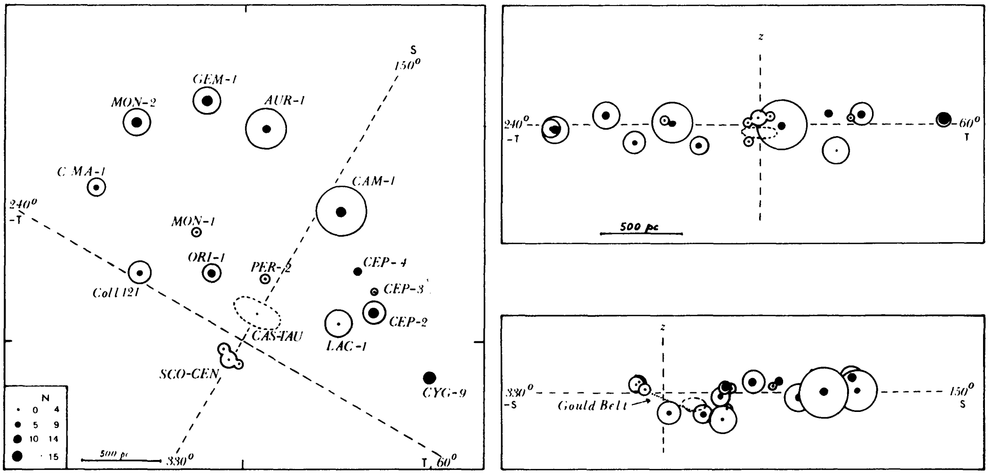

Figure 2. a (left): Position of OB-associations projected on the galactic plane. For meaning of the numbers N and for the Orion-Arm coordinate system s,t see the text; b (upper right): projected positions in the z,t plane; c (lower right): projected positions in the z,s plane.

From Fig. 2a to 2c we note some overall properties. The OA is very thin in the z-direction. The average distance of the associations from the plane (weighted according to the numbers N) is +3 pc and in absolute sense it is 50 pc. The thickness of the OA for the section under consideration here is less than 1/10 of its width measured along the co-ordinate s. At low s-values, the OA is mostly below the plane. We recognize the tilted feature known as the Gould Belt with Ori OB1, one of its constituents, farthest down below the plane; however note that at these s-co-ordinates also Coll 121 and Lac OB1 are well below the plane. Apart from this feature, no wavy or other systematic deviation from a plane structure is discernible in Fig. 2b and 2c. The largest central dots seem to show a preference for large s values, but it would be premature to suggest a systematic trend without more detailed data for Cam OB1, Aur OB1 and Gem OB1. Some of these may, with better data, be resolved into two or more associations and this is also the reason why caution should be exercised before concluding that large dimensions occur at largest s-co-ordinates.

Even within the limited distance range considered here, strong selection effects have to be kept in mind. Included in Fig. 2 is the Cas - Tau Association, a group in advanced state of desintegration containing no stars brighter than M_V = -5 and only 15 between luminosity -5 and -3 which moreover are spread over a relatively large volume; a group like this will not have been recognized at distances

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beyond a kiloparsec or even less. Associations with small membership at large distances are recognized only if concentrated in small volumes, like for instance Cep OB3 and Cep OB4.

MOLECULAR CLOUDS

Masses of the molecular clouds connected with the OB associations are presented in Fig. 3; there is strong evidence that they form the medium from which the associations originate according to the mechanism of sequential star formation. The numbers next to the positions of the associations give the estimated total mass of the cloud (unit 10000 solar masses), which sometimes includes several components. These masses lie in the range from several thousand to several hundred thousand solar masses, and as a rule far exceed the total mass represented by the association stars. There are no great differences between the linear sizes of the clouds, most of them have dimensions between 50 and 100 pc when measured in the direction of galactic longitude. For a summary of principal cloud properties, see Blitz (1980).

Surveys of molecular clouds (by means of CO or OH) have not yet covered the entire sky to such a degree of completeness that masses and sizes of the clouds of our sample are sufficiently known for statistical discussion. Intermediate and high galactic latitudes are only partly covered, and in some directions of small differential galactic rotation, particularly aorund 90°, it is very hard to separate clouds at different distances. One interesting question to explore will be, which OB associations notwithstanding their recent formation are free of associated clouds. A candidate seems to be Lac OB1, for which the high galactic latitude eliminates background complications. The reverse question, whether there are in this volume of space large molecular clouds free of an early stage of a stellar association, also deserves to be pursued further; positive evidence was found by Wouterloot (1981). A particularly intriguing problem is, to what extent the "hole" in the distribution of the associations at about one kiloparsec in the direction of 200° longitude is filled with still unignited clouds. An other intriguing problem concerns the thin filamentary links between the major cloud complexes, like for instance the one between Orion and Monoceros described by Thaddeus (1982).

AGES

Basic information for the study of the progression of star formation are the ages of the associations and, if applicable, the breakdown according to the ages of their subgroups. The ages, indicated in Fig. 4 (unit one million years), are all of essentially photometric or spectroscopic origin; we do not include here kinematic age estimates. In the most favourable cases - and this applies to the nearer, brighter, associations - multi-colour photometry, mostly in the ubvy-beta system, is available so that reddening-free colour-magnitude

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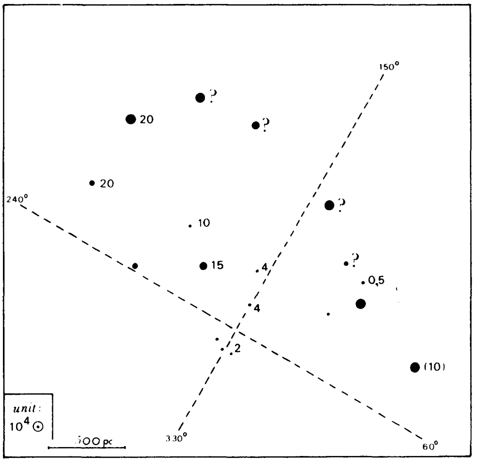

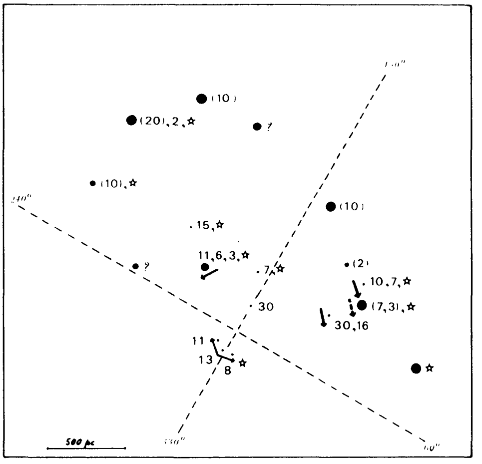

Figure 3 (left). Masses of the identified molecular clouds associated with the OB-associations (unit 10^4 solar masses).
Figure 4 (right). Photometric ages (unit 10^6 years) of the (subgroups of the) OB-associations. Arrows indicate the projected direction of the progression in the formation process within each association. Asterisks mark objects where star formation is still going on.
For identification of the names of the associations see Figure 2.

diagrams could be used. Sequences of numbers in Fig. 4 refer to the ages of subgroups, given in the order of decreasing age. The ages given here were made available to me by J. Brand and T. de Zeeuw of Leiden Observatory and are based on homogenized uvby photometry, carefully transformed into bolometric luminosity - log T_e diagrams. If no such age estimates could be made, less reliable photometric estimates were used, given in parentheses (f.i. based on UBV photometry), and where there is evidence that star formation is still going on this is marked by an asterisk.

The ages in Fig. 4 range from zero to about 30 million years. The oldest groups, Cas-Tau and Lac OB1, are spread very thinly in space and could only be recognized due to their proximity to the Sun or relatively high galactic latitude. Obviously identification of preceding generations of star formation, in the age range 30 to 60 million years, and their location in space will be of great importance for the study of the progression of star formation. One way to identify such groups is by means of space velocities accurate to a few km/sec. Hipparcos will be of basic importance for the nearest domain. For larger distances we will have to rely in addition to Hipparcos on accurate radial velocities in combination with structural features - not yet fully dissolved clustering - in the space distribution. With the data in Fig. 4 no overall gradient in the star formation can be established yet. This

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will require at least good multicolour photometry of the distant associatons.

Progression of star formation is, however, recognized within the individual associations, and we may ask whether the directions along which the sequential process proceeds reveal alignment or randomness. The available data, in Fig. 4, do not suggest the former. The arrows in Fig. 4 are the projected directions (perpendicular to the line of sight) of the progression from older to younger subgroups. Note that Sco-Cen deviates from the usual pattern in that the oldest subgroup seems to be Upper Cen, from which the sequential process proceeded in two nearly opposite directions: to Lower Cen and, via Upper Sco, to the Ophiuchus molecular cloud.

KINEMATICS

The state of motion of the assembly of OB associations and their associated molecular clouds can be described as, on the one hand, remarkable quietness for most parts of the domain surveyed and, on the other hand, the disturbance due to the expanding motions within the region of the Gould Belt. Using the well-observed radial velocities of the molecular clouds connected with the associations Cep OB3, Cep OB4, Mon OB1, Mon OB2, and C Ma OB1, for which moreover the photometric distances are well known, we find after elimination of the effects of differential galactic rotation and (standard) solar motion a residual radial velocity of only 3 km/sec. In the same way, we find for the OB associations themselves from ten objects a residual radial velocity of 4.5 km/sec only. Associations and connected clouds belonging to the Gould Belt system were not included in these figures. Within the Gould Belt we encounter deviations from this quiet pattern up to 10 km/sec (for Per OB2). Evidence for the remarkably quiet state of motion of the youngest stellar population beyond the Gould Belt has also been found from proper motions by Tsioumis and Fricke (1979).

RUN-AWAY STARS; STOCHASTIC IGNITION OF STAR FORMATION

Fig. 5 shows the position, projected on the galactic plane, of the well-established run-away O and B stars. Criteria were: a space velocity exceeding 40 km/sec and well-determined distance. A few stars were included on the basis of large radial velocity only. Marginal cases reported in the literature based on proper motions only were not included. Different symbols distinguish stars according to mass lower than, or exceeding, 20 solar masses. Dotted connecting lines mark those cases where the parent association is well identified. For the surroundings of the most remote associations, particularly Aur OB1, Gem OB1 and Mon OB2 (see Fig. 2), no well-established run-away stars are marked, reflecting the incompleteness of our data. We estimate that for the whole volume surveyed, only one half of all cases have been identified so far, even less for the low-mass category.

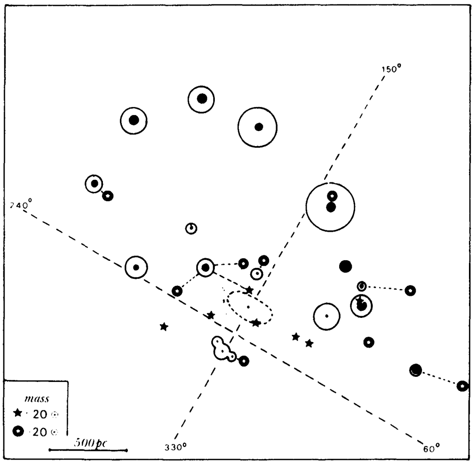

Figure 5. Projected positions of the known OB run-away stars. Dotted lines mark cases where the parent association could be traced back.

Two aspects of the study of run-away stars will deserve further study. One concerns their origin; accurate space velocities to be obtained with Hipparcos may allow identification of the origin for many more than are marked in the diagram, and hence the locations and epochs of past supernova events. An other aspect is their role in remote inducement of star formation. A provisional estimate of the chances of the run-away stars to turn into supernovae in the proximity of molecular clouds away from the parent association - having travelled up to several hundred parsecs - indicates that they may contribute significantly as a stochastic cause of the progression of star formation through the Orion Arm. For this purpose, again, more complete mapping of the molecular clouds, particularly at large distances from the galactic plane, will be essential.

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DISCUSSION

G.D. van Albada: There is one very clear gradient in your pictures, but that may very well be a selection effect. The distant OB associations appear to be larger on average than the nearby ones.

Blaauw: The distant, large circles in the diagram only indicate the presence of fairly large groups of young stars - we do not have sufficient data to discriminate subgroups or, perhaps, superpositions. The resolution at a distance of, say, 1500 pc is already very small for these objects. Hence the apparent size gradient may not be significant.

B.G. Elmegreen: The velocities of the Orion, Perseus and Sco-Cen OB Associations are directed away from the Sun, and are consistent with the idea that these regions are condensations inside the expanding Lindblad Ring. This region is an example of long-range propagating star formation, with the old Cas-Tau Association being the first generation, located in the ring centre, and the Orion, Perseus and Sco-Cen Associations being the second generation, located on the ring itself.

Blaauw: Indeed, in this region the motions are systematic. Analysis of the relative motions in the Gould Belt indicates a time scale of order 40×10^6 years, similar to that found for Lindblad's Feature A. I agree with the suggestion of propagating star formation, and the question is: To what extent does that occur also in other parts of the Local Spur?

B.G. Elmegreen: Regarding your statement that star formation began at about the same time all over the Local Spur, I wonder if this conclusion would change if you included the local galactic clusters, some of which have ages of 60 million years or more. Would OB associations of this large age still be recognized?

Blaauw: Clusters younger than 20 Myr are very scarce in the region. Clusters with ages of 30-60 Myr exist, but are not plotted in Figure 4. Still older clusters give a sytematically deviating pattern, shifted to the left. I have omitted the clusters, because the stellar content of clusters is small compared to that of associations.

A.I. Sargent: In your Figure 4 I should like to reverse one of the arrows indicating the direction in which star formation progresses. I refer to the feature which includes Cep OB2, Cep OB3 and Cep OB4. You have shown star formation proceeding in Cep OB3. In fact, there is a rather larger-scale progression: few stars are now forming and little molecular gas is left in the vicinity of Cep OB2; active star formation is continuing in the relatively small molecular cloud associated with Cep OB3; while around Cep OB4 is a fairly quiescent molecular cloud, $\sim 80 \times 60$ pc in size, in which we may expect future activity. Similar large-scale patterns have been noted by Elmegreen, for example, in the extended M17 complex, and I should expect that further investigation would reveal more such cases and improve our picture of large-scale star formation in the Galaxy.