1. INTRODUCTORY REPORT

S. B. Pikelner

The Orion Nebula has been the frequent object of investigations not only because it is the brightest nebula in the northern sky, but also because this fact permits detailed spectrophotometric studies. This stage of investigations is completed in the main. At present the central problem is the cosmogonical significance of the Nebula and the Orion Complex as a whole. The principal part of the Complex is the thick H I envelope, whose outer part is the bright Barnard Loop, with a radius of 70 pc. The envelope is expanding with a velocity of 10 km/sec. An H II zone is located inside the envelope. According to Menon, the total mass of the Complex exceeds $10^5 \odot$. The age of the Complex is several million years. This age follows from the time of expansion of the envelope, the motion of runaway (escaping) O-type stars, and the fact that some A stars and an enormous number of later spectral type stars (including RW Aur-type stars) belonging to the Complex are in the stage of gravitational contraction. In the region there are about 10 Herbig-Haro objects, five of which form a chain. The T-association occupies the central part of the Complex, i.e. if it is expanding, then it must do so considerably more slowly than the envelope. The study of the Complex allows one to determine the properties of young stars, the interaction of stars, neutral and ionized gas, and dust, and compare them with conditions of gravitational contraction of the interstellar medium. For contraction of a gas cloud at normal conditions, the mass must exceed $10^3 \odot$. Therefore stars must form in groups. Large dense complexes of gas and dust (similar for example to the dark clouds in Taurus, Cepheus and Ophiuchus) provide such conditions for condensation. After contracting to some degree, such complexes can divide and give birth to clusters and associations. The character of the division depends on the rate of cooling: the more rapid the rate, the smaller are the parts into which the system divides.

The age of the Orion Nebula, or more precisely of its most dense part located in the centre of the Complex, is not greater than 3×10^4 years, i.e. considerably less than that of the Complex as a whole. Although RW Aur type stars show a concentration towards the Nebula, they are all much older than the Nebula. Only the bright Trapezium stars are of an age which is comparable to that of the Nebula, so this is evidence that the process of star formation in the Complex is not as yet completed, and that a new stage is underway. A detailed investigation of the Trapezium stars is necessary to establish whether there are spectroscopic indications of contraction. If the O6 star became hot 3×10^4 years ago, the B stars cannot have completed their contraction stage if simultaneous formation is assumed. On the other hand, there may be objects in the Nebula with masses equal to those of A-type stars but which have not as yet become stars. It is true that the search for such objects may not be successful if they are as yet located deep in the Nebula where absorption is large. It should be noted that besides the dense part of the Orion Nebula, there is a much more extended and rarefied part which should be older if it has expanded from the centre. However, it is possible that it originated from scattered cold gas which was ionized after the ionization of the central part of the Nebula. In any case, it is desirable to exclude, if possible, that there may have been a still earlier stage of star formation in the Nebula. The reason for a renewal of star formation in the centre of the Complex (from which the expanding hot gas must have swept out the supply of cold gas) is of interest. It can be assumed that massive stars of the Complex lost gas after evolution, and that this gas condensed towards the centre where at the time there were no hot stars, and a new process of condensation then commenced. However, this fact can be considered from another point of view, proposed by Ambartsumian. He assumes that the stars and the emission nebula were formed not during the contraction process of cold gas but were ejected at the disintegration of super-dense bodies, possibly of the hyperon star type. Developing this hypothesis, Academician Ambartsumian concluded that such a process acts during the formation of galaxies, the matter of which is ejected from dense bodies in their nuclei. The assumption of dense body-ejecting material could explain why star formation commenced anew at the same place after several million years. However, it seems to me that the whole concept meets with insurmountable difficulties. Dense bodies cannot be held by magnetic fields. Therefore it is not understandable why star formation takes place in spiral arms if the dense stars were scattered over the galactic plane. The concentration of newly-formed stars to the galactic plane can be explained only by the loss of energy of the gas already at the first phase of existence of the galaxy. Dense bodies should have kept the same space distribution as stars of the spherical sub-system. Upon expansion from a super-dense state, an enormous amount of energy must be transmitted to matter so that its dispersion is much more probable than transformation into stars. Finally, expansion cannot explain the rapid rotation of hot stars and of close binaries.

In order to elucidate the course of development of the Orion Complex, a detailed investigation of the clusters and associations belonging to it is necessary. Their composition and age need to be compared and their motions and degree of dissipation studied. It is also necessary to study the gas to dust ratio in the Nebula. Theoretical considerations are not sufficient to conclude whether the dust particles in the emission nebula are increasing in size or are disintegrating. (This last possibility of disintegration arises since a fraction of the dust particle evaporates at formation on its surface of an H_2 molecule.) The study of the relative abundance of dust in different nebulae of the Complex can help in the solution of this problem.

An investigation of the structure and motions in the Nebula is of great importance. The gas pressure gradient leads to the expansion of a nebula, and separate density fluctuations also expand. Internal motions in expanding nebulae should gradually be damped. The disintegration of motions with velocity gradients into turbulent pulsations should facilitate this process. Observations, however, show the presence of rapid motions, and the shock waves from these should rapidly transform the kinetic energy of the gas into heat. It is difficult to understand the presence of such motions from the point of view of a purely hydrodynamic expanding nebula even if the presence of a magnetic field is assumed.

The Orion Nebula is one of the youngest nebulae. However, the Omega Nebula (NGC 6618) is apparently still younger. On the contrary the Lagoon Nebula (NGC 6523) and others are somewhat older. It is very essential that a comparative study of these objects be made in the future. Such a study could reveal the variations of the properties of dust and the character of internal motions during the process of development. For example, R. Gershberg and P. Scheglov have detected internal motions in the Omega Nebula with velocities up to 50 km/sec, i.e. considerably larger than in the Orion Nebula. Gershberg explains these velocities by a supernova outburst in the Nebula, where massive stars could have been located. The filamentary structure of a part of the Nebula supports this hypothesis. I hope that the Discussion, which we open here, will provide incentive for more detailed studies of young complexes.

2. THE STAR CLUSTER IN THE NEBULA

H. M. Johnson

The stars in the Orion Nebula to a radius $r = 24'$ will be called 'the cluster' in this discussion. To visual magnitude 18 on the charts of Strand and Teska (1), Johnson (2) showed that the areal and spatial densities of the cluster steadily fall in radial steps of $\Delta r = 2\overset{'}{.}4$ from a center at the Trapezium to $r = 24'$, and he derived a spatial model within this limit. There are provisional clusters farther from the center but within one degree of it (3).

Field stars account for about 90 per cent of the areal density in the annulus from $r = 21'.6$ to $r = 24'$. Most of these field stars are probably outer parts of the complete cluster (as distinct from the model) because stars brighter than magnitude 18 in the distance to the cluster at the density of the solar neighborhood provide only 10 per cent of the areal density in this annulus.

Wesselink (**4**) has analyzed the relation between the absorption and the function $\Delta \log N/\Delta m$ in a stellar system, where N is the number of stars between magnitudes $m - 1/2$ and $m + 1/2$. For cluster stars brighter than $V = 10^{m}$, $\overline{\Delta \log N/\Delta m} \cong 0{\cdot}18$. This predicts median absorption $\overline{A} = 1^{m}.7$ in the optically thick case. For comparison the median color excess of all cluster B stars brighter than $V = 10^{m}$ is $\overline{E}_{B-V} = 0^{m}.16$ (**5**) so that $\overline{A} = 7{\cdot}37 \times 0^{m}.16 = 1^{m}.2$ if we use the ratio $\overline{A}/\overline{E}_{B-V} = 7{\cdot}37$ for the cluster (**6**). This suggests that the dust in the cluster may not be optically thick, especially if $\overline{A}/\overline{E}_{B-V}$ has been overestimated. The distribution of the r.m.s. electron density is concentric and fairly coextensive with the distribution of the stars (**7**). Unless this is a mere coincidence, a major part of the cluster is observable despite the dust in the Nebula, for the 3·75-cm observations of electron density are unaffected by the dust.

The distance of the cluster has never been satisfactorily measured. According to color-magnitude diagrams it depends on absolute magnitudes and intrinsic colors. Sharpless (**8**), following Morgan (**9**), has shown quantitatively that the equivalent width of Hγ in Sword stars, including some cluster stars, exceeds the equivalent width of Hγ in Belt stars. A zero-point in the scale of absolute magnitudes has been established through Hγ measurements of members of the Scorpio-Centaurus moving cluster at a well-known distance. Applying his own corrections for extinction, Sharpless obtained a distance modulus of $8^{m}.2$ for both parts of Orion I, Sword and Belt. The result is complicated by the old question of an abnormality in the ratio $\overline{A}/\overline{E}_{B-V}$ of the stars in the cluster. According to Johnson and Borgman (**6**), Johnson's earlier distance modulus should be corrected $1^{m}.0$ because $\overline{A}/\overline{E}_{B-V} = 7{\cdot}37 \pm 0{\cdot}25$ and $\overline{E}_{B-V} = 0^{m}.3$ for seven Orion Nebula stars. This (questionable (**10**)) result would revise the distance to 260 pc. It is a distance that separates the cluster from the bulk of Orion I, to which the revision does not apply. Strand (**11**) compared the radial velocities of eight stars with the proper motions of 135 stars in the cluster (three in common) and obtained an astrometric distance of 520 pc on the assumption of an isotropic field of velocities. The application of this method to the 21 stars for which there are now good radial velocities and proper motions in common results in a distance of 380 pc. We shall use 300 pc for computations involving the distance.

Trumpler's (**12**) H-R diagram of the cluster included only main-sequence stars from type O9 to type A2. Greenstein and Struve (**13**) recognized K-type 'sub-giants' in the cluster, and Parenago (**14**) produced the first color-magnitude diagram that clearly revealed a sequence of stars 'above the main sequence'. Salpeter (**15**) theoretically explained such stars as stars contracting to the main sequence. Accordingly, massive stars form the upper main sequence, for they have contracted more rapidly during the same time. The time scale for contraction showed that the cluster must be relatively young. How young, however, has been difficult to determine, at first because of the indefinite place of the juncture of the sequence of contracting stars with the main sequence. For example, Johnson (**16**) derived an age of 3×10^{6} yr but Strand (**11**) derived 3×10^{5} yr from similar data and the same theory (**17**), and this represents the uncertainty in the upper limit on the age of the cluster. The theory of contraction should also describe the paths of contraction on the M_{bol}, $\log T_{e}$ diagram and the configuration of stars of given equal age on it. The observed data may be converted to an M_{bol}, $\log T_{e}$ diagram with some difficulty. Differences between the predicted configuration and the observed data have suggested a 'spread in ages' of the cluster stars (**18**). Consider the cluster stars θ^{1} Ori E of composite type B5−8 + G III, and IU Ori of type K2 III. On the theory of 1955, giants would contract at nearly constant M_{bol} and arrive on the main sequence after stars farther down the main sequence had already arrived on it, or they would have evolved off the main sequence earlier than more massive stars. However, the theory is being revised, cf. (**19, 20**), and we cannot yet evaluate discrepancies between it and the observed H-R diagram or color-magnitude diagram, with or without a spread in ages.

No spectral types are known of cluster stars in the range $\overline{m}_{\rm pg} > 16^{m}.6$, where $\overline{m}_{\rm pg}$ means the mid-range of variable-star magnitudes. Spectral types are known of very few cluster members in the range $12^{m}.8 \leqslant \overline{m}_{\rm pg} \leqslant 16^{m}.6$. They are late G's, K's, and M1-M4's, some with emission lines, and some labelled as MK-type IV, V or V. Blanco (**21**) has found 10 M stars in the cluster. About one foreground M star brighter than his limiting magnitudes should be in the area. The observed M stars lie at the red end of the sequence of stars above the main sequence, and Blanco says that there is a real cut-off at type M4. It is around $V = 14^{m} \pm 1^{m}$. Possibly this type marks the transition between freefall collapse and Helmholtz contraction, which sets in around a mass of $0{\cdot}1\odot$ and which requires a much longer time scale (**20**). According to the freefall theory the collapse from interstellar density n atoms cm^{-3} to the observed sequence on the H-R diagram occurs in $t_{\rm ff} = 5 \times 10^{7}\, n^{-\frac{1}{2}}$ yr, excluding magnetic or rotational effects. This is upwards of 4×10^{5} yr for collapse from the present densities of central clouds in the Nebula (**22**) (not to imply that stars form in the H II region or that present H II densities are as great as those of an earlier state of H I). Entry on to the H-R diagram takes place in the last few hundred years of these periods because of the very sudden rise of temperature at the end of the collapse. The existence of a Ptolemaic middle-Sword star establishes a lower limit of 2000 yr on the age of the hot stars and the ionization of the Nebula.

There are 26 stars of spectral type A0 or earlier that are probably all members of the cluster rather than field stars. Several stars in the area of the cluster have been classified in the range A2 V - G7 V. They may be field stars. Converting spectral types to bolometric magnitudes and these in turn to masses, by means of the empirical mass-luminosity law, one finds that the total main-sequence mass of the cluster is about $180\odot$. Hayashi's (**19**) theory and Limber's (**23**) initial-mass spectrum lead to a mass of about $630\odot$ for about 1000 contracting stars brighter than $V = 18$, so the total mass of the visible cluster is about $800\odot$ and the mean density is about $21\odot$ pc^{-3}. The superficial velocity of escape is 1·8 km/sec, computed from the stellar mass, and about 0·1 km/sec larger with the inclusion of about $100\odot$ of nebular mass. The time of relaxation of the cluster is about 10^{8} yr, so that there has been no approach to a steady state.

The observed r.m.s. proper motion of 135 stars brighter than magnitude 15 within $r = 20'$ is $\pm\ 1''.94/1000$ yr in the x or y co-ordinate (**11**). This equals $\pm$ 2·75 km/sec. The cluster apparently rotates in a period of about 8×10^{6} yr; and there is a (questionable (**24**)) component of uniform expansion in the proper motions, amounting to 0·3 km/sec per minute of arc, equivalent to an expansion age of 3×10^{5} yr. Subsystems of the cluster, notably the Trapezium (**14**), also appear to be unstable.

Radial velocities are known for 45 stars in the cluster. The velocity appears to be a function of spectral type, decreasing about 4 km/sec for each whole spectral class from O to G. K stars are too poorly observed to be included here, and a group of six B-F stars appear to have excessive redshifts. The mean of the radial velocities of the remaining 33 O-G stars is + 25 km/sec, or 8 km/sec in excess of the mean radial velocity of the visible gas in the Orion Nebula. The radial-velocity dispersion increases with cluster radius and conforms to uniform expansion of the cluster, but does not establish it.

If the cluster is expanding, it must reflect an initially larger mass within the present arbitrary boundary of the system. Herbig (**18**) has explained the positive energy of the cluster, if it is present, by supposing that, until recently, the mass of the Nebula was much larger, that most of it has now dispersed after the formation of the O stars and the ionization of the gas, but that the stars continue to move as fast as they did under the earlier gravitational field. Would a catastrophic dispersal of mass leave the remaining gas symmetrically concentrated with respect to the cluster? The mass may have entered and left the volume of 2 pc radius rather smoothly. We imagine a transition from a collapsing and fragmenting gas cloud (**25**) to an expanding star cluster near the minimum radius and maximum density. The Orion Nebula that we observe would be the remnant of gas in motion before it was ionized.

At present the gradients of stellar and interstellar number density toward the center of the cluster are approximately equal (**7**). This must be accidental unless the rate of star formation is independent of interstellar number density n, because about 90 per cent of the total mass of the system has become stellar. If the rate of star formation is proportional to a positive power of n, the gradient of stellar number density towards the center of the cluster has increased during the formation of the cluster, while the corresponding interstellar gradient has decreased. There is no complication if the system is uniformly contracting or expanding. Some of the estimated 1000 T Tau stars in the cluster probably eject mass for an unknown length of time (**26**), but the rate is only $10^{-7}\odot$/yr in the brightest T Tau stars (**27**).

Would fragmentation of contracting masses produce binary stars? Binaries in the cluster are infrequent compared with the normal field frequency of about 50 per cent in all spectral types (**28**). Two or three spectroscopic binaries are known, and others might be suspected from the large dispersion in the radial velocities of a few stars. However, the distribution of radial velocities of T Ori, where more than 20 radial velocities are measured over a large range (**29**), is inconsistent with circular orbital motion and is only possibly consistent with orbital motion of high eccentricity and $\omega \cong 90°$ or 270°. One or two eclipsing binaries and the visual binary AR Ori (**26**) are known.

Stellar rotation is another factor of interest in problems of contracting stars. The $v \sin i$'s of five cluster stars of types B1-3 have been estimated (**30**). They are indistinguishable from other B1-3 stars of Orion I, but the latter are rather slow rotators compared with field stars of the same types. Spectral line-broadening data are not available for the contracting stars of the cluster, and especially for types K and M, in which rotational broadening must be very small if they are to reach the main sequence at types later than F, where no rotation is expected.

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DISCUSSION

A. B. Underhill. In respect to the proper ratio of extinction to reddening for the Orion Nebula, the arguments used by Harold Johnson and Borgman in favor of A_V/E_{B-V} about 7 assume that in the infra-red only the O and B stars of the Trapezium are being measured, and that A/E is to be adjusted to reproduce the conventional energy distribution of such stars. For various reasons, I prefer to consider that $A_V E_{B-V} \cong 3$, but then one must account for the infra-red excess from the immediate region of the Trapezium. There are two interesting possibilities: (*a*) that there is strong infra-red line emission from circumstellar envelopes about these stars, or (*b*) that we are observing the tail of a synchrotron emission distribution generated near the stars. At present, I know of no way of eliminating these possibilities.

H. M. Johnson. I agree that more observations are required to make certain that purely stellar radiation is being observed, and to add to the small amount of data upon which the large values of A_V/E_{B-V} in the Orion Nebula are based.

A. Blaauw. In adopting the distance of 300 pc for the Nebula, Dr Johnson must have attached considerable weight to the results of the comparison between the dispersions in radial velocity and in proper motion. I wonder whether this is justified in view of the small number of stars for which radial velocities are available, and in view of the photometric evidence which, irrespective of whether A_V/E_{B-V} is taken as 3 or 6, gives a distance greater than 300 pc.

H. M. Johnson. I believe that Johnson and Borgman's new photometric distance is 260 pc, after the 1·0 magnitude correction that I mentioned is made. But the real justification for the radial velocity vs. proper motion method is its independence of photometric assumptions.

K. A. Strand. There is now additional evidence that the expansion of the Orion Nebula cluster as determined from astrometric observations is real, rather than caused by instrumental effects. In the initial investigation (**11**), based upon plates taken with the Yerkes 40-inch refractor, plates of the Pleiades were used as control. Since then, plates of h, χ Persei and the cluster NGC 2099 which cover the same years as the Orion series have been measured. None of these other clusters show any net expansion, thus giving evidence that the expansion measured in Orion is real. I would also like to ask Dr Johnson about the accuracy of the new radial velocities of cluster members that he mentioned.

H. M. Johnson. The probable error of a Kitt Peak velocity at this dispersion is about ± 5 km/sec.

I. King. If the expansion of the Orion cluster is real, then any difference in spatial distribution of bright and faint stars must indicate a difference in their initial velocity dispersion. Do you find any such difference?

H. M. Johnson. The bright stars appear to be somewhat more concentrated towards the center but their numbers are small in comparison with the many faint stars.