ORION AND THEORIES OF STAR FORMATION

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INTRODUCTION

Star formation and its various effects are evidently responsible for many of the complex phenomena observed in the Orion Nebula region, and one would therefore like to be able to explain the observations of this region on the basis of theories of star formation. At present, however, any theoretical understanding of star formation is still too rudimentary to bear any detailed comparison with the real world, so one can only discuss some possible processes that may play a role in star formation and then appeal to the observations to try to clarify their importance. In this paper, I shall mention some of the small-scale processes that may be important in the formation of stars in molecular clouds and then describe some data on young stars in Orion and other regions that provide information about star formation in these regions.

As a caution against overly simplified theories of star formation, some large-scale properties of the Orion region are worth keeping in mind. One is that the entire Orion complex of molecular clouds and young stars, whose total mass probably exceeds $2 \times 10^5 M_{\odot}$, is located more than 100 pc below the Galactic plane; thus, whatever process formed the Orion clouds must have assembled them well out of the Galactic plane or, equivalently, must have accelerated the material to a substantial velocity away from the Galactic plane. Moreover, the CO maps that Thaddeus presents in this volume reveal that the Orion clouds are very extensive and complex in structure, with several major concentrations and filamentary extensions, and that they also have a complex velocity field. These observations suggest that the Orion clouds were formed in a more or less violent way by processes that left them in a turbulent state; if so, turbulent motions may play a major role in the subsequent evolution of the clouds and the processes that occur may be much more complex than either a simple contraction process or a regular propagation of star formation through each cloud. In fact, the available data show star formation proceeding simultaneously at several sites in several different molecular concentrations in Orion and do not, when examined closely, clearly follow the widely discussed picture of sequential star formation, but suggest a more complex situation in which star formation can be initiated at many sites.

Ultimately, it is necessary to understand how, on small scales, the molecular cloud material actually becomes condensed into stars and groups of stars. Related problems of long-standing interest are understanding the mass spectrum with which stars form, the time dependence of star formation, and the efficiency of the conversion of gas into stars. While complete theoretical answers cannot yet be given to these questions, it is at least possible to discuss some of the processes that may be involved and some observational constraints on their importance.

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Possible Processes of Star Formation

Gravity must clearly play a major role in compressing interstellar matter into stars, and the classical picture of star formation is based on the concept of successive gravitational fragmentation elaborated by Jeans, Hoyle, and others. If a cloud begins to contract under gravity, regions of enhanced density containing more than the Jeans mass can collapse separately to high densities and may fragment again into smaller and smaller units as the density increases and the Jeans mass decreases. Most numerical calculations of collapse and star formation have been motivated by this picture, but the multidimensional calculations have not, so far, supported the concept of successive fragmentation into objects much smaller than the initial Jeans mass. Accordingly, if gravitational fragmentation is the only process that operates, one might expect characteristic stellar masses to be comparable to the Jeans mass in the cloud from which the stars form, being smallest in the regions of highest density.

On the other hand, purely hydrodynamic processes such as shock compression can also play a role in compressing the gas in molecular clouds; shocks should occur often because supersonic internal motions are observed in all but the smallest clouds. The observed motions generally appear to be complex or turbulent, so the shock-compressed regions will probably have an irregular filamentary or clumpy structure; such supersonic turbulent motions may even be responsible for the formation of protostars.[1] If this is the primary mechanism of star formation, one might expect the stars of lowest mass to form in the regions with the highest turbulent velocities. Another purely hydrodynamic process that may become important after dense protostellar clumps have formed, either by gravity or by turbulence, is collisional coalescence and growth of protostellar objects.[2]

In reality, gravity and hydrodynamics probably act together in the formation of stars. For example, once a small dense core or embryonic star has begun to form in a protostellar condensation, its mass can grow by a large factor by gravitationally accreting the more diffuse surrounding gas. The accretion process may involve infall through an accretion shock at the surface of the stellar core if the infalling material has little angular momentum, or viscous inflow in an accretion disk if the material has a large angular momentum. More complex processes involving accretion of lumps or streams of gas may also occur. Numerical simulations[3] and analytical theories[4] of the accretive growth of embryonic stars suggest that this process can account approximately for the form of the observed stellar mass spectrum. If such accumulation processes are important in the formation of stars, it might be expected that the most massive stars would form in the densest regions, *i.e.*, in the dense cores of contracting molecular clouds or forming star clusters where the gas density and accretion rate are highest. Gravitational accretion is a runaway process, since the accretion rate increases with the mass of the accreting object; therefore, stars of extremely large mass may form, unless other effects, such as stellar winds, intervene to cut off accretion before all the available gas has been consumed.

Once stars have begun to form in a molecular cloud, they may exert an important influence on subsequent star formation. For example, the stars will begin to contribute to the gravitational field in the cloud and may exert significant tidal forces on the gas. If the cloud contains a dense embedded cluster of stars, such as appears to exist in Orion, the star cluster may produce an approximately symmetrical, centrally condensed gravitational potential well that acts to concentrate the remaining gas to very high densities at the center, possibly favoring the accretive build up of very massive stars there. Since newly formed stars produce stellar winds with mass-loss rates that increase strongly with stellar mass, the accretive build up of a massive star may be cut off when its wind becomes strong enough to blow away the surrounding gas. This would imply an upper mass limit that increases with increasing ambient gas density, as was suggested previously on the basis of radiation pressure and ionization effects.[5]

Given all the possible processes that have been mentioned, and others, such as magnetohydrodynamic effects, that probably also occur, detailed predictions of how stars form cannot yet be made; to understand more about the way in which stars actually form, it is necessary to refer to observations of regions of star formation. Data on the young stars in these regions are particularly useful because they provide a record of the past history of star formation and can be used to study correlations between stellar properties, such as the mass spectrum, and other characteristics of each region, such as the spatial distribution of gas and young stars.

Young Stars in Orion and Other Regions

Cohen and Kuhi have published an extensive study of T Tauri stars in many regions of star formation,[6] providing quantitative data on temperatures and bolometric luminosities from which the ages and masses of the stars can be estimated. These data have been used to study the mass spectra, spatial distributions, and ages of the T Tauri stars in the three most populous regions, namely, Taurus, Orion, and NGC 2264, and to look both for possible differences in the stellar properties and for correlations with other properties of the associated star-forming molecular complexes.[7]

The spatial distributions of the Cohen-Kuhi stars in Taurus, Orion, and NGC 2264 are plotted on similar linear scales in Figures 1–3, coded by stellar mass. In Taurus (Figure 1), the youngest stars are dispersed over a relatively large region about 40 pc across and they are mostly in small groups containing from a few up to about ten stars. These small groups are closely associated with a number of Barnard and Lynds dark clouds whose positions are approximately indicated in Figure 1. Most of the T Tauri stars have masses less than 1 $M_{\odot}$; the most massive star in the region is a highly obscured B2 star, located, as indicated, in the B18 cloud near the center of the region.

The distribution of the T Tauri stars in Orion is strikingly different (Figure 2), being more compact and centrally concentrated than that in Taurus; most of the Orion stars are in a single large cluster about 10 pc across, centered on the Trapezium. A secondary concentration is associated with the reflection nebula NGC 1999, and the remaining T Tauri stars are scattered along the length of the L1640 dark cloud. Most of the known T Tauri stars in Orion have masses greater than 1 $M_{\odot}$, in contrast with those in Taurus whose masses are mostly less than 1 $M_{\odot}$. Another difference is that the Orion stars are somewhat older, having a median age of 1.0×10^6 y, as compared with 6×10^5 y for Taurus. Further evidence that the Orion region is older and more evolved than Taurus is provided by the presence there of large numbers of flare stars, which are generally fainter and older than the T Tauri stars; Orion has 325 known flare stars, whereas Taurus has only 13.[8]

NGC 2264 (Figure 3) differs from Taurus in the same sense and perhaps to an even more extreme degree than Orion; the spatial distribution of the T Tauri stars is more compact and their median age is even greater, about 2×10^6 y. As in Orion, most of the known stars have masses greater than 1 $M_\odot$.

The data therefore suggest that, as a star-forming region evolves, the gas becomes more spatially condensed and the stars form in more massive and concentrated clusters, with larger and larger masses. There is, in fact, direct evidence that, in some young associations or clusters, the more massive stars form later than the less massive

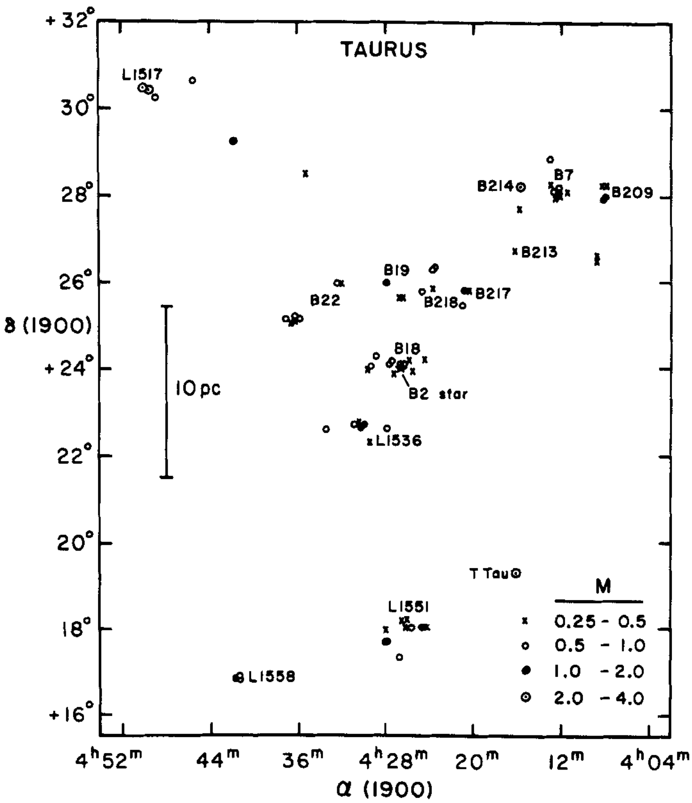

FIGURE 1. The spatial distribution of the Cohen-Kuhi stars in Taurus, coded by mass, as indicated in the lower right. The positions of the associated Barnard and Lynds dark clouds are also indicated, as is the position of the star of earliest spectral type, a heavily obscured B2 star.

stars.[9,10] To determine whether there is also evidence that the more massive stars in Orion have formed with a more compact spatial distribution than the less massive ones, we have shown, in FIGURE 4, only those T Tauri stars that have ages less than 10^6 y and are still seen close to their places of formation; although the statistical significance of the result is not large, the more massive T Tauri stars in FIGURE 4 are, in fact, considerably more spatially concentrated than the less massive ones. It is particularly

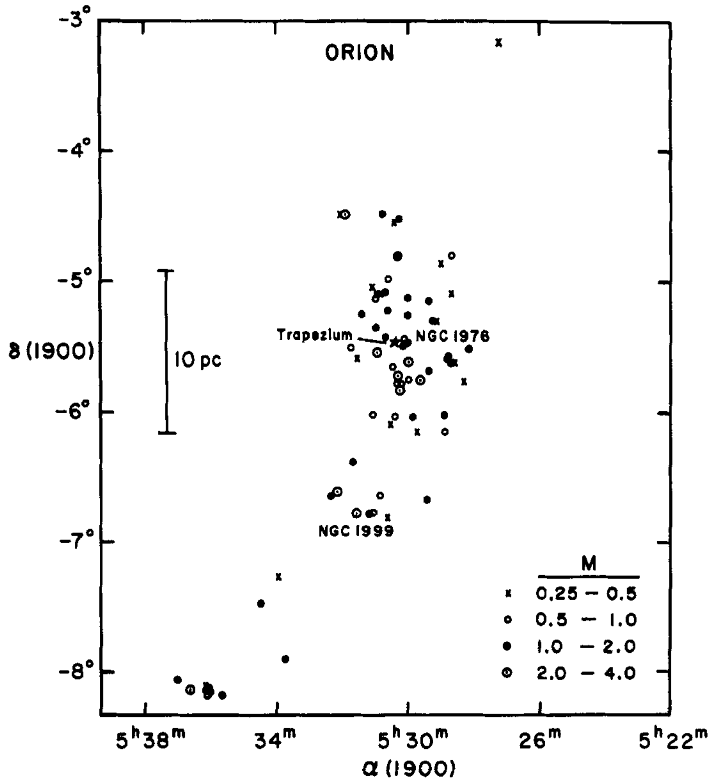

FIGURE 2. The spatial distribution of the Cohen-Kuhi stars in Orion, plotted on nearly the same linear scale as that used in FIGURE 2. The Orion Nebula (NGC 1976) and the associated young cluster are centered on the Trapezium, which contains the most massive star in the region.

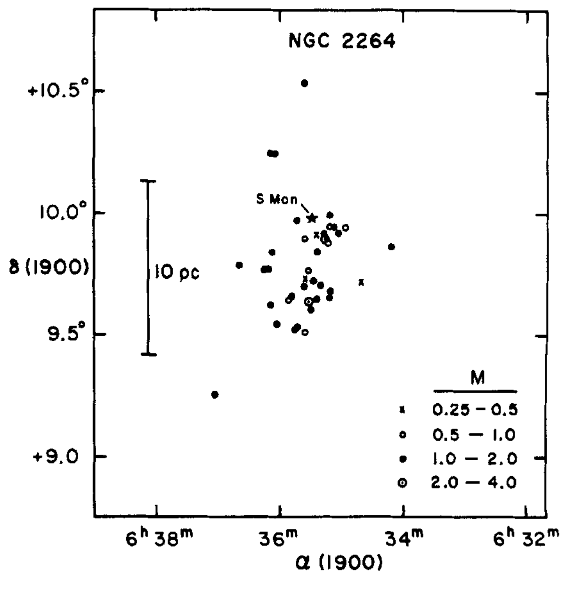

FIGURE 3. The spatial distribution of the emission-line stars in NGC 2264. The position of the most massive star, the O7 star S Mon, is also indicated.

striking that the most massive star in the Orion region, θ^1C Ori in the Trapezium, is right at the center of the Orion cluster.

The formation of massive stars is continuing at present in the dense core of the Orion Molecular Cloud OMC1, whose compact cluster of luminous infrared sources (the BN-KL cluster) is also centrally located and has a projected distance from the Trapezium of only about 0.1 pc. When the stars in the infrared cluster blow away their surrounding gas and become visible, as will probably soon happen, they will appear as a

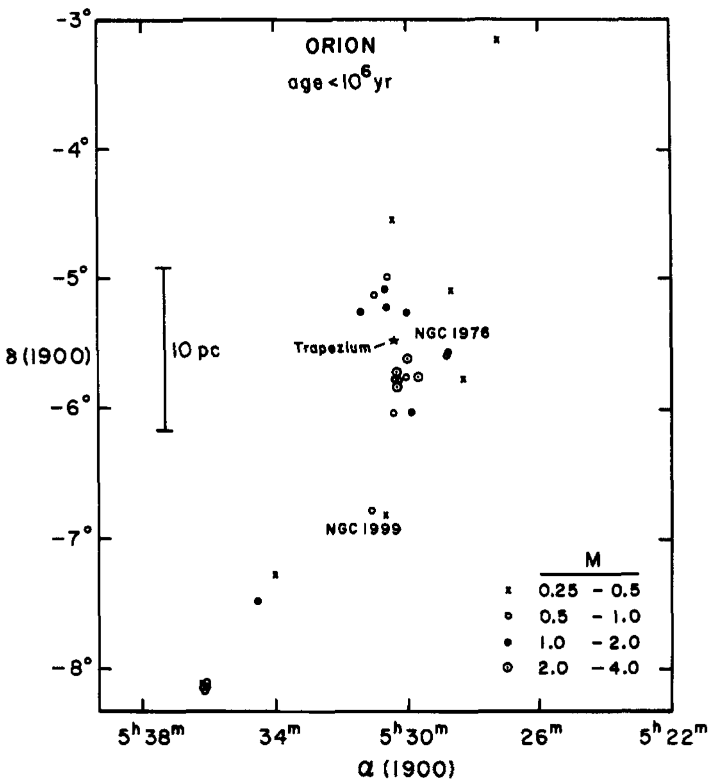

FIGURE 4. The spatial distribution of the emission-line stars in Orion that have ages less than 10^6 y.

new Trapezium-like subgroup of massive stars near the center of the Orion Nebula cluster. The infrared objects in OMC2 apparently represent a group of less massive stars forming further away from the center of the Orion cluster.

MASS SPECTRA OF YOUNG STARS

Because most of the T Tauri stars studied by Cohen and Kuhi lie on nearly vertical Hayashi tracks in the HR diagram,[6] their estimated masses depend primarily on their spectral types and their derived mass spectra are not grossly affected by magnitude-dependent selection effects. There are striking differences in the distribution of spectral types of the T Tauri stars in Taurus, Orion, and NGC 2264. FIGURE 5 shows the ratio of the numbers of stars with spectra earlier or later than K6.5 (corresponding to masses larger or smaller than about 1 $M_\odot$) and brighter than various limiting apparent magnitudes, plotted as if all stars were placed at the distance of Orion. It is evident that, regardless of the limiting magnitude chosen, a large difference persists between Taurus and the other two regions. Even after corrections are made for the different median ages of the stars in these regions,[7] the difference remains significant at about the 3σ level.

The mass spectra of the Cohen-Kuhi stars in Taurus and Orion are shown in FIGURE 6. Here the difference between Taurus and Orion appears as a turndown in the Orion mass spectrum at masses below 1 $M_\odot$ This deficiency of low-mass stars may not apply to the entire population of young stars in Orion, which includes the numerous faint flare stars that are widely dispersed throughout the region, but it is nevertheless characteristic of the youngest stars that have just recently formed in the Orion Nebula cluster. It is noteworthy that the Taurus mass spectrum is very similar to the initial mass spectrum of field stars,[11] while the Orion mass spectrum is similar to that of many open clusters, which often show a deficiency of low-mass stars.[12] Thus, Taurus may be a typical site for the formation of field stars, while in Orion we see the formation of a typical open cluster.

POSSIBLE INFERENCES FOR STAR FORMATION

The data discussed above are all consistent with an evolutionary picture in which the properties of a large star-forming complex change systematically with time while stars continue to form for a period of at least $\sim 10^7$ y. At an early stage, a star-forming region may resemble the Taurus dark clouds, where the average density is relatively

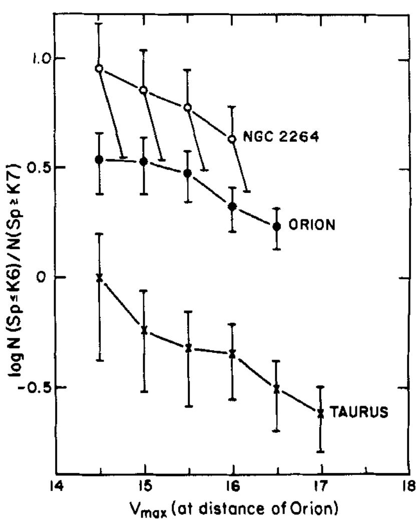

FIGURE 5. The ratio of the number of emission-line stars with spectral types of K6 and earlier to the number with spectral type K7 and later plotted against the limiting magnitude that the stars would have if all were placed at the distance of Orion.

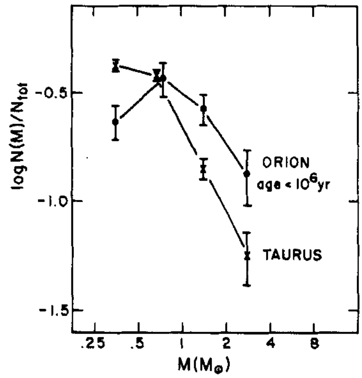

FIGURE 6. The mass spectra of the emission-line stars in Taurus and Orion. Plotted are the numbers of stars in the equal logarithmic mass intervals 0.25–0.5, 0.5–1.0, 1.0–2.0, and 2.0–4.0 $M_\odot$, normalized by the total number of stars in each region. The error bars give $N^{1/2}$ statistical errors.

low and small groups of low-mass stars are forming in scattered small molecular clumps and filaments. With time, the gas may become progressively more condensed into massive, dense clouds or cloud cores like OMC1, forming stars in larger and more centrally concentrated clusters, with a mass spectrum that increasingly favors massive stars. The most massive stars may form as a result of rapid accumulation processes in the dense central cores of these contracting clouds or forming star clusters. The culmination of this type of evolution may be represented by the present Orion Nebula region, where a dense cluster with very massive stars at its center has been forming for the past $\sim 10^7$ y and where the formation of massive stars is continuing near the center.

The fact that the most massive stars appear to form only in a small region of very high density at the center of a forming star cluster is not easily explained by the traditional fragmentation theory of star formation, but suggests that accretive build up processes are involved. Moreover, the massive stars appear to form after, and perhaps as a result of, the previous formation of large groups of less massive stars; a possible explanation is that the gravitational field of a cluster of mostly low-mass stars helps to concentrate the remaining gas to the high densities required to form the more massive stars.

The observations of gas flows associated with obscured young objects in Orion and elsewhere show, however, that no sooner does a massive star form than it begins to produce a strong stellar wind that blows away the gas in its vicinity, probably cutting off further accretion and star formation processes and exposing the newly formed stars to view. The formation of a massive star therefore requires that a large amount of gas be accumulated rapidly into a star before a wind can blow it away; this may explain why massive stars appear to form only in very dense regions, since only there can the required very high accretion rate be attained. Clouds or clumps of lower density can only produce lower accretion rates and, therefore, could only form less massive stars, in agreement with what is observed.

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DISCUSSION OF THE PAPER

J. PAZMINO (*New York, N.Y.*): Is the difference between the cohesiveness of the Orion and Taurus clouds due to a difference in tidal forces caused by Orion being out of the Galactic plane?

LARSON: It is possible that Taurus is being dispersed by tidal forces and Orion is not, but I don't see what it has to do with Orion's location out of the plane. The real problem is how Orion got there in the first place.

A. STARK (*Bell Telephone Laboratories, Holmdel, N.J.*): The problem of how Orion got so far out of the Galactic plane can be rephrased in terms of velocity: If you accept the age of 12 million years for the complex, how did Orion get such a high velocity (~ 15 km s^{-1}) perpendicular to the Galactic plane when it passed through (or originated in) the plane center? This is a remarkably high velocity for such a massive object.

T. MOUSCHOVIAS (*University of Illinois, Urbana, Ill.*): A comment on the spatial separation of low- and high-mass stars: We should be careful in making a direct association between the Jeans mass (as a function of position in a cloud) and the mass of the star that will form out of that fragment. The fact that M_J is larger in the envelope of a cloud does not imply that, once a fragment begins to collapse, a collapsing fragment will not itself fragment further. The three-dimensional numerical calculations do not yet have a good enough resolution grid to address this issue properly.

LARSON: In general, I agree with your remarks. However, the theoretical demonstration of successive fragmentation still has to be made.

A. E. GLASSGOLD (*New York University, New York, N.Y.*): Do you believe that propagating star formation occurs within a cloud?

LARSON: Although the subgroups of the Orion association are considered the prototypes for propagating star formation, I have certain reservations about this picture. First, the geometry is really much more complex than linear propagation along a single cloud. Second, the stars around the Orion Nebula itself have a large range in age. My general opinion is that propagation may be relevant for the formation of massive stars but does not apply to low-mass stars.

M. L. KUTNER (*Rensselaer Polytechnic Institute, Troy, N.Y.*): On the question of sequential star formation, I agree with your statement that the sequence from Ia to Id is a questionable one. Since the Orion association is the prototypical one for which sequential formation of subgroups is argued, the case for coherent sequential formation over a scale of tens of parsecs is weak, at best, for any association.