Regions of Recent Star Formation*

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Included in these symposium proceedings are 63 papers, representing nearly all of the 42 talks given at the conference and the 23 poster displays. They are grouped into four subject areas: evolution of H II regions, dynamical interactions, infrared and maser sources, and chemistry in active regions. Each of these sections opens with a comprehensive review lecture. Many papers are followed by a brief summary of the discussion from the floor. The book concludes with indexes of authors, of astronomical objects (the nebulae, clusters, and associations mentioned in the text), and of subjects.

In the initial review, G. Tenorio-Tagle (Max-Planck-Institut, Garching) considers some general topics in the dynamical evolution of H II regions embedded in cool, dense gas having a nonuniform density distribution. Two stages in the evolution of H II regions are outlined: a) formation, from the time the early-type star heats up until the ionization front reaches the boundary of the Strömgren zone; b) expansion, the phase when the H II zone expands at supersonic speed into the surrounding H I cloud, forming a dense shell between the two shock fronts. Complications may develop in this simple picture if the ionization front should reach the boundary of the dense cloud and emerge into the rarefied intercloud medium. At that point the "champagne phase" will begin, with the ionized gas from the Strömgren zone streaming into the hole formed at the cloud boundary, the cloud itself acquiring an impetus in the opposite direction. As the hot star's ultraviolet photons escape into the hole that has developed, they will ionize the gas at the boundary of the adjacent clouds, thereby producing the observed bright rims. At the boundary of the cool cloud the outflowing hot gas will form an extensive H II region. It will grow like a blister at a rate of $(2–3) \cdot 10^{-3}\ M_{\odot}/yr$, so that once this process has set in the cool cloud will survive no longer than 10^7 yr.

Detailed calculations of the champagne phase are presented by H. W. Yorke (Göttingen) et al. If, for example, in a cloud 30 pc in diameter and with $3 \cdot 10^5\ M_{\odot}$ a single type O5 star (Lyman-continuum flux $7.6 \cdot 10^{48}$ photons/sec) should be born 5 pc from the edge of the cloud, then after $2.6 \cdot 10^6$ yr an appreciable fraction of the cloud ($\approx 7\%$ by mass) will have been heated and will begin to flow off at parabolic velocity, forming an expanding H II region. At this stage the cloud will be losing 0.008 $M_{\odot}$/r. Generally speaking the total mass loss by the cloud will depend not so much on its initial mass as on the number and especially the position of the ionizing stars in the cloud. Conditions will be most effective for disruption of the cloud if the hot star is located at its edge. If instead the star is centrally placed, then the champagne phase will not begin at all. Rotation will hasten the destruction of the cloud, if other factors are the same.

By combining radio observations made with single-dish antennas and with aperture-synthesis systems, R. H. Harten (Dwingeloo) and M. Felli (Arcetri) have obtained uniform data on 77 H II regions, enabling the evolution of these objects to be studied statistically. As the mean electron density in the H II zone diminishes, the contribution of compact, dense regions to the radio emission decreases in comparison with the diffuse rarefied gas. This decrease is particularly abrupt if $n_e \leq 200\ cm^{-3}$, in good accord with the prediction of the champagne model. The histogram for the distribution of H II regions with respect to $\bar{n}_e$ has a curious form: the ratio of the number of dense regions to the number of rarefied ones is well above that inferred from the simple model of a Strömgren zone advancing into a homogeneous medium. But the picture observed fits in nicely with the champagne model, which predicts that the evolution of an H II zone will rapidly speed up after it breaks through the edge of the cloud.

One other argument for the champagne model is that the Strömgren zones around the earliest-type stars tend to have a large size and a low electron density. The reason may be that the early evolution of such H II regions accelerates considerably when they enter the champagne phase. The bipolar nebula S201 illustrates a rare version of the champagne model: it developed after a hot star was formed at the center of a thin molecular cloud.

By taking advantage of the high angular resolution of an aperture-synthesis array, one can attempt to detect near the edge of H II regions the dense gas condensations whose existence is predicted by B. G. Elmegreen and C. J. Lada's 1977 theory of successive star formation. Among 13 large H II regions only one, S184, contains such condensations. Evidently one explanation of why these objects occur so rarely is that the process of successive star formation can be triggered only by stars of moderate temperature and luminosity. While we cannot tell as yet how common the process of stimulated successive star formation is in the Galaxy, individual examples of the process have been studied in some detail. H. E. Matthews (Ottawa) describes the region around the thermal radio source W1, which coincides with the bright H II region S171 and is located 845 pc away from the sun. Also in this field is the OB association Cepheus IV, which contains about 40 OB stars. Some of them form the compact cluster Berkeley 59, while the remainder are strewn over a 5° field. The whole star formation region, including the Cep IV association, is $\approx 2 \cdot 10^6$ yr old. But Berkeley 59 is a good deal younger ($5 \cdot 10^5$ yr old) and it shows fairly clear evidence that star formation is being triggered there by the neighboring older regions.

R. M. Crutcher and Y.-H. Chu (Berkeley) have thoroughly investigated the source W40 and the associated molecular cloud. This cloud now contains 3 $M_{\odot}$ of ionized gas, 30 $M_{\odot}$ of stars, and $10^4\ M_{\odot}$ of molecular gas. From all indications the star formation process began there $2 \cdot 10^6$ yr ago, when the cloud was subjected to a sudden one-dimensional compression due to a nearby supernova outburst or else the passage of a spiral-arm shock. The cloud is still continuing to contract at 3 km/sec, but hot gas is flowing at 8 km/sec from the central part of the cloud through the holes formed in the cool, dense gas.

D. A. Naylor et al. (Noordwijk and London) have observed the Orion Nebula interferometrically in a far-infrared balloon experiment. They confirm the earlier finding, based on radio recombination lines, that the electron density undergoes large variations (from a few hundred to more than 10^4 cm^{-3}) and that the nebula itself is cup-shaped. It has approximately the same oxygen abundance as the sun but seems to be twice as rich in nitrogen, although this last estimate is none too accurate.

In the second part of the proceedings, J. M. Shull (Boulder) and S. Edwards and R. L. Snell (Northampton and Amherst) discuss interactions between stellar winds and the interstellar medium. Observations with the Copernicus and IUE ultraviolet satellites yield for 37 type O stars the following relation between mass-loss rate and luminosity:

$$\dot{M} = (3.8 \cdot 10^{-6} \cdot M_\odot/\mathrm{yr})\,(L/10^6 L_\odot)^{1.73}.$$

The gas is being thrown out at velocities of $(1-3.5) \cdot 10^3$ km/sec. During its $\approx 10^6$ yr life on the main sequence, an O star will deliver to the ISM 10^{49}–10^{50} erg of mechanical energy, producing effects comparable with a supernova explosion. But a stellar wind inside a dense cloud will have distinctive consequences of its own. For example, Herbig–Haro objects, which often travel outward from a common center at speeds of 100–350 km/sec, appear to be dense gaseous condensations caught in a flow of stellar wind and moving radially under the impact of that wind (by analogy to the H_2O masers moving through the Orion Nebula). Some of these condensations may turn into stars which will, of course retain the fast radial motion.

The joint action of OB stars and supernovae upon the ambient ISM will give rise to "superbubbles" hundreds of parsecs in diameter. The most spectacular examples are the "supershells" of neutral hydrogen swept up as such a bubble expands. In the Magellanic Clouds, superbubbles are observed in optical lines, and one of the superbubbles closest to us, a region 450 pc across in Cygnus, emits prominent x rays. This superbubble is filled with $2 \cdot 10^6$°K plasma carrying 10^{52} erg of energy. Apparently it originated in company with the Cygnus OB 2 association, which is $2 \cdot 10^6$ yr old; the energy output of its five O stars is $5 \cdot 10^{38}$ erg/sec.

J. G. Stacy and P. D. Jackson (University of Maryland) have observed neutral hydrogen in a transparent Milky Way window in the constellation Puppis. Four giant shells have been found there, 130–240 pc in diameter $(5-10) \cdot 10^4$ $M_\odot$ in mass, some of them related to regions of hot gas and OB associations. Star formation regions generally will often display looped or ring-shaped gaseous structures. Young stars seem to be the prime source of turbulent motion in the ISM.

The distribution of giant molecular clouds in the galactic plane has been observed by W. L. H. Shuter and A. Szabo (Vancouver), who record 71 clouds toward l = 29°–46°. Taking the ratio of H_2 and ^{13}CO molecules to be 10^6, these authors find that an average cloud has a mass of $1.5 \cdot 10^5$ $M_\odot$, an effective radius of 13.3 ± 0.9 pc, and a one-dimensional internal velocity dispersion of 6.3 km/sec. These parameters yield a mean virial mass of $7 \cdot 10^5$ $M_\odot$ for a cloud, indicating that the mass derived from the ^{13}CO line intensity is underestimated. The reason evidently lies in the lower excitation temperature (≈ 4°K) in the cloud than had been assumed in calculations (10°K). Clouds of $\approx 5 \cdot 10^5$ $M_\odot$ form a ring in the Galaxy with radii R/R_0 of about 0.5 and 0.7; less massive ($\approx 5 \cdot 10^4$ M) clouds are distributed more uniformly.

The infrared source in NGS 2071, located 500 pc away from us and forming part of the Orion B molecular cloud, is an interesting example of a star formation site. J. Bally (Bell Laboratories) has detected here a pair of gas streams moving in opposite directions at more than 70 km/sec. Altogether they contain 22 $M_\odot$ of gas and $6 \cdot 10^{46}$ erg of kinetic energy; they are ≈ 1 pc long and have a dynamical lifetime of ≈ 10^4 yr. This bipolar flow most likely stems from an efflux of gas along the rotation axis of a cool, flattened cloud having a star formation region at its center.

When young stars or spiral arms interact with dense interstellar clouds, shock waves will be generated there. G. F. Mitchell and T. J. Deveau (Halifax) have calculated the change in the chemical composition of interstellar gas after it is traversed by a weak shock. The initial gas density was taken to be 10^4 cm^{-3}; the velocity of the compression wave, 10 km/sec. The calculations included 1423 chemical reactions involving 105 elements and compounds. Cosmic-ray heating was taken into account, as well as the heat released through the formation of H_2 molecules on grains and the cooling of the gas by various molecules and ions. After 10^4 yr following passage of the shock, the composition of the gas will have changed as follows: the NH_3 abundance increases by 180 times, H_2O by 34, CN and OCN by 13, HS by 8.1, H by 6, and OH, HCO, H_2S, OCS by 2 times. The remaining elements and ions drop in abundance: O_2 by 50 times, O by 600, S and NH_2 by 4, NH by 2, Mg^+ by 3, and HCO^+ and N_2H^+ by 170 times.

In a review paper, W. D. Watson and C. M. Walmsley (Urbana) examine more broadly the chemistry of interstellar gas subjected to shock waves, cosmic rays, and radiation emanating from star formation regions. Even though dense clouds in the vicinity of star formation zones will have a much higher temperature (≈ 50–100°K) than ordinary isolated clouds (≈10°K), their chemical composition will not differ significantly. The theory of gas-phase ion–molecule reactions is fully adequate for describing the observed distribution of elements in molecular clouds. Evidently it is only when calculating the formation of the most widespread molecule in the universe, the hydrogen molecule, that one needs to allow for reactions on grain surfaces.

G. Sandell (Stockholm and Helinski) finds a close correlation between the abundance of CH molecules and the optical absorption in dark clouds: $N_{CH} = (2\text{-}7) \cdot 10^{13} A_B$ cm^{-2} (A_B in magnitudes). F. P. Israel et al. (Noordwijk) have recorded ^{12}CO (J = 2 – 1) emission near 30 Doradus in the Large Magellanic Cloud. The complex of giant molecular clouds associated with the H II regions N159 and N160A resembles complexes in our Galaxy.

Using the VLA system, B. E. Turner (Charlottesville) has observed 22 OH masers and the accompanying continuum sources. All the type I masers are associated with ultracompact sources of continuum emission, whereas the type II(a) (1720 MHz) masers probably are not. Turner discusses some possible mechanisms for pumping the two types of masers.

In an excellent review on infrared and maser sources in star formation regions; R. Genzel (Berkeley) and D. Downes (Grenoble) devote most of their attention to the process whereby protostars and young stars associated with compact infrared and maser sources lose mass. They thoroughly consider the structure and physical conditions in the Orion-KL region, which contains a cluster of infrared sources, masers, and high-speed gas flows. Two contiguous, orthogonal gas streams are observed in this region, one moving at 18 and the other at ≈ 100 km/sec. Both flows carry roughly the same amount of mass, 10^{-3}-10^{-2} $M_{\odot}$/yr. The infrared cluster might serve as their energy source, but only if the optical depth τ_{IR} with respect to infrared radiation exceeds 10, so that the photons will be multiply scattered.

Summing up the current picture of research on star formation regions. Genzel and Downes write that until now there has been no chance of observing true protostars during their collapse phase. Around such an object the absorption A_V might amount to more than 100 magnitudes, ruling out not only optical but also near-infrared observations. In the far infrared, on the other hand, good-quality observations are still blocked by poor angular resolution. Possibly some of the observed low-velocity H_2O masers are associated with the final collapse phase of protostars.

The stages directly following the collapse of a protostar, however, have no become observable. Once thermonuclear reactions have begun at the center of a massive protostar, it will outwardly resemble a late-type giant or supergiant. The growth in luminosity, rotation, and magnetic field strength (and perhaps the action of a companion star) will cause a protostar envelope to become unstable and to start flowing out at low velocity (from 10 to ≈ 300 km/sec), but even so a large amount of material will be lost. One of the most interesting properties of the mass flow could be an apparent anisotropy, such as encountered in the Orion-KL region, where low- and high-velocity flows are juxtaposed. Such a state could result from an anisotropic gas distribution in the neighborhood (within $\approx 10^{16}$ cm) of the protostar; for instance, an accretion disk might be present. As it interacts with density irregularities in the cool ambient gas, the outflowing gas could generate high-excitation molecular lines and give rise to bright H_2O masers and Herbig–Haro objects.

After the mass-loss phase has ended (in $\approx 10^4$ yr), a compact H II region will have formed around the young star. So long as its size remains small, it should be observable in broad-winged Brackett α, γ lines, as in the BN object. Later this region will become a radio-continuum emitter. In the cool gas surrounding the H II region, OH masers will appear and the 18-cm radio background will begin to strengthen. At this stage H_2O masers will still be observed in the H II zone. They will vanish later on, when the H II region, $(2\text{-}15)\cdot 10^4$ yr old, has expanded to $\geq 10^{17}$ cm. Even later, after the H II region has begun to grow optically thin and has reached the site of the OH masers, they too will disappear. Strictly speaking, that is the stage when we will observe the stellar wind blowing from main-sequence O stars.

From the concise sampling given above, it is plain that the volume under review will be extremely useful to anyone who wants to know how stars are born. The book has been received by the library of the Shternberg Astronomical Institute in Moscow.

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