The Dense Interstellar Medium and the Birthplaces of OB Stars

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Abstract

We review Bengt Strömgren's research interests in the relationships among ionized, atomic, and molecular hydrogen in the Galaxy and the spatial distribution and kinematics of OB stars. Our current perception of these problems owes much to Strömgren's deep influence and early insight.

I. *Introduction*

In 1939, Bengt Strömgren wrote perhaps his most celebrated paper, introducing the seminal notion that ionizing radiation from luminous OB stars sharply partitions the regions of interstellar hydrogen into two forms, H I and H II. As a measure of the care Strömgren invested in this landmark work, I should mention that he briefly considered the possibility (suggested by Eddington) that the hydrogen might also exist in molecular form (Strömgren 1939, p. 541). Strömgren rejected the idea on the grounds that if molecular hydrogen were created and destroyed by processes similar to those he had analyzed for atomic hydrogen, then negligible amounts of H_2 would be found in interstellar space. Today, we consider this last conclusion wrong – molecular clouds *do* indeed constitute the third great resevoir for interstellar gas – but only because H_2 is formed and destroyed by processes entirely different than those known to astronomers fifty years ago.

Although the parallel idea of the formation of OB stars from the neutral gas which they subsequently ionize must have occurred to Strömgren, he refrained from direcly speculating on the exact connection. It was only after the development of his narrow-band photometric system (see the review of Strömgren 1966), when he had in hand a quantitative tool to measure the ages of the B stars, that he turned again the full force of his attention to this problem. In 1961, he organized a meeting at the Institute for Advanced Study in Princeton on the distribution and motion of interstellar matter (Woltjer 1962). C. C. Lin, a hydrodynamicist on sabbatical leave from M.I.T. at the Institute for the year, attended the conference at Strömgren's invitation. As part of the program, Per Olof Lindblad gave a description of some computer simulations which supported the ideas of Bertil Lindblad concerning spiral structure in disk galaxies. This work, plus the succinct description given by Jan Oort of the problem, caught Lin's imagination, and from that interest grew the modern theory of spiral density waves.

Almost from the start, Strömgren (1967) saw to the heart of the central thesis of density-wave theory, the implication that the pattern of the formation of OB stars in a spiral galaxy should rotate at a constant angular speed Ω_p, which differs generally from the mean material speed $\Omega(r)$ of the interstellar gas. If one combines measured space motions of B stars with their ages deduced from narrow-band photometery, one could integrate the equations of motion backward in time (with some adopted Galactic potential) to find the birthplaces of these B stars. On the other hand, one could also rotate the present-day spiral pattern backwards in time at a constant angular rate Ω_p to deduce the theoretical location of spiral arms at the time of the births of the corresponding stars. If the birthplaces of B stars deduced by the star-migration calculation agreed with the location of spiral arms determined by the modal picture, the entire undertaking would gain credence.

The initial results proved ambiguous if one only took into account the kinematical aspects of the problem. Yuan (see Lin, Yuan, and Shu 1969) found better fits by including the focusing of stellar orbits by the perturbational gravitational field associated with the spiral arms. Within the uncertainties of the age and space-motion determinations, one could then force all of the then-known sample stars to have birthplaces inside spiral arms with reasonable choices for the parameters of the Galactic density-wave pattern. Later study by Yuan and Grosbøl (1981) extended these results to assess the expected color variations and surface brightnesses across spiral arms, but definitive conclusions belong to the future and will probably come only with completion of Preben Grosbøl's ongoing program to obtain the space motions and ages of a very large number of B stars.

II. *Triggered Star Formation*

In the interim, theorists began to examine in detail how spiral structure could help to trigger OB star formation. Motivated by the calculations of Fujimoto (1968), Roberts (1969) championed the idea of a central role for *galactic shocks*, regions of high compression (identified with dust lanes) that follow the supersonic flow of interstellar gas into the spiral potential minima defined by the disk stars. In a cloudy model for the interstellar medium, however, the increase in average gas density arises merely by the bringing of the centers of individual clouds closer together. Why should such a process by itself lead to enhanced star formation? Shu et al. (1972) adopted the two-phase models of Field, Goldsmith, and Habing (1969) and Spitzer and Scott (1969) to compute that a true hydrodynamic shock in a warm intercloud medium could cause the implosion of normal H I clouds, leading possibly to gravitational collapse and star formation (see also Woodward 1976). Beneath the train of thought during this period lay the assumption that star formation proceeds from atomic hydrogen clouds, which, because they lack appreciable self-gravitation to begin with, had to be imploded by an increase of the external pressure load in order to give star formation.

Two developments in the 1970s served to undermine this point of view. First, ultraviolet and x-ray observations led to the picture (Cox and Smith 1974, McKee and Ostriker 1977) that much of the volume of interstellar space might be filled with gas too hot to contain continuum galactic shocks of the type envisaged by density-wave theorists. Discrete clouds could still respond in a sufficiently nonlinear manner as to yield a "shocklike" distribution, but the pressure of the hot intercloud medium would not suffer a sharp upward jump inside a dust lane. Second, molecular-line studies (see, e.g., the review of Burton 1976), particularly in the $J = 1\text{-}0$ transition of CO, demonstrated that OB star formation occurred almost exclusively in giant molecular clouds (GMCs). Unlike H I clouds prevented from free expansion by the surface pressure of an external medium, GMCs represent gravitationally bound objects. Thus, GMCs do not need external triggering to undergo star formation *spontaneously*; indeed, the theoretical difficulty lies, as we shall se in the next section, entirely in the opposite direction. Nevertheless, the concept that star formation needs to be *induced* became a fixed idea in the thinking of many astrophysicists, and it led to a torrent of ingenious new proposals long after the original motivation (the birth of stars from non-self-gravitating H I clouds) had vanished.

III. *The Mechanical Support of Molecular Clouds*

Zuckerman and Evans (1974) first gave voice to the crucial issue. The actual mass of a typical GMC much exceeds its Jeans mass; thus, unless agents of support other than thermal pressure exist, a GMC should collapse gravitationally on the order of a free-fall time to convert its entire mass into stars. Such a scenario would yield star formation rates in the Galaxy two to three orders of magnitude larger than the observed value. The central dynamical problem with GMCs consists, therefore, not of how to induce them to form stars, but of how to prevent them from doing it as fast as natural processes would seemingly dictate.

When viewed in this light, the problem of star formation in molecular clouds acquires a completely different perspective. Whatever constitutes the agent of molecular cloud support, it must (1) be difficult to dissipate (or else, star formation would proceed much more efficiently than it actually does), and (2) be present at a dynamically significant level over the wide range of scales in which molecular cloud structures are observed to be self-gravitating. Given these two criteria, of the three mechanisms conventionally invoked to supplement thermal pressure in cloud support – rotation, turbulence, and magnetic fields – we can now single out magnetic fields for special consideration.

If a cloud has internal temperature T and is subject to an external pressure P_{ext}, we may use the results of Mouschovias and Spitzer (1976) to show that the maximum mass $M_{\rm cr}$ that a cloud can support against its own gravity satisfies the equation,

$$M_{\rm cr}\left[1-(M_\Phi/M_{\rm cr})^2\right]^{3/2}=M_{\rm BE}, \tag{1}$$

where $M_{\rm BE}$ is the Bonnor-Ebert mass

$$M_{\rm BE}\equiv 1.4\,\frac{(kT/m)^2}{G^{3/2}P_{\rm ext}^{1/2}}. \tag{2}$$

We have followed Mouschovias and Spitzer in modifying the numerical coefficient in eq. (2) from that given by Ebert (1955) and Bonnor (1956) to provide better overall agreement with the nonspherical models of Mouschovias (1976). In equation (1), we have defined the magnetic critical mass M_Φ as

$$M_\Phi = 0.13\,\frac{\Phi}{G^{1/2}}, \tag{3}$$

with Φ equalling the total magnetic flux that threads the electrically conducting cloud. In the field freezing approximation, Φ is a conserved quality in the mechanical evolution of an isolated cloud.

Gravitational collapse occurs for $M > M_{\rm cr}$; whereas the cloud is stable if its mass $M < M_{\rm cr}$. If we can ignore magnetic effects, i.e., if we can set $M_\Phi = 0$, we would get the critical mass from equation (1) as $M_{\rm BE}$. The typical parameter regime that applies to actual molecular clouds corresponds to $M_\Phi \approx 10^5\ M_\odot$ for $B = 30\ \mu$G and $R = 20$ pc, whereas $M_{\rm BE} \approx 6\ M_\odot$ for $T = 10$ K and $P_{\rm ext}/k = 10^4$ cm^{-3} K. As a consequence, equation (1) has the approximate solution,

$$M_{\rm cr}\approx M_\Phi\left[1+\frac{1}{2}\left(\frac{M_{\rm BE}}{M_\Phi}\right)^{2/3}\right]\approx M_\Phi, \tag{4}$$

when $M_\Phi \gg M_{\rm BE}$. Except for small dense cores, thermal support plays a relatively minor role in comparison with magnetic (and, possibly, turbulent) support in molecular clouds. Moreover, provided cloud masses do not rise with increasing size faster than $M \propto R^2$ (e.g., as indicated by the observations of Solomon et al. 1987), support by magnetic fields of a given strength B can keep pace with gravity at all scales since $M_\Phi \propto \Phi \propto BR^2$ also increases as R^2 for fixed B. (The characteristic mass associated with the "turbulence" observed in molecular clouds also has this property and may have an explanation in MHD fluctuations being self-regulated at some fixed fraction of the Alfvén speed; see, e.g., Lizano and Shu 1989). These conclusions have, as we shall see below, some dramatic consequences for the process of stimulated star formation.

We suppose that at the present epoch of galactic evolution almost all clouds have subcritical masses, $M < M_{cr}$, since initially supercritical clouds must have collapsed a long time ago. An increase in the external pressure P_{ext} – due, e.g., to the passage of a galactic or supernova shock – can lower M_{BE} but not M_Φ (if field freezing holds); thus, external inducement of gravitational collapse and star formation cannot occur unless M happens to satisfy: $M_\Phi < M < M_{cr}$, which constitutes an extremely narrow range (cf. eq. [4]) if $M_{BE} \ll M_\Phi$. In this circumstance, the vast majority of molecular clouds must be magnitically subcritical, $M < M_\Phi$, and no amount of external compression can induce a cloud (under the constraint of field freezing) to collapse.

In a sense, magnetic fields play the same role for our theory for molecular clouds that electron degeneracy pressure does for the theory of white dwarfs. In this analogy, M_Φ replaces the Chandrasekhar limiting mass M_{Ch}. No increase of external pressure can cause a magnetically supported cloud, with $M < M_\Phi$, to collapse, any more than it can cause a white dwarf, with $M < \mathrm{M}_{Ch}$, to do so, because the restoring force due to the compressed magnetic fields (or degenerate electrons) rises in direct proportion to the increase in self-gravitation (for a "gas" whose internal "pressure" is proportional to the 4/3 power of the density in three-dimensional compression). Clearly, magnetic fields provide such a formidable obstacle to gravitational collapse that we should no longer be surprised, to zeroth order, that star formation in magnetized molecular clouds proves to be generally a very inefficient process.

IV. *The Relationships among H_2, H I, and H II*

If we accept the arguments of the previous section, we see that there exists logically only two ways for a magnetized molecular cloud to become unstable to gravitational collapse (see also the reviews of Mestel 1985; Shu, Adams, and Lizano 1987). To increase the ratio, M/M_Φ, either we can lower Φ (and therefore M_Φ) at fixed M, or we can increase M relative to M_Φ (i.e., increase the mass-to-flux ratio M/Φ). Because molecular clouds are only lightly ionized (Elmegreen 1979), the first process will occur inexorably via ambipolar diffusion in small dense cores. Current belief holds this to occur for the mode of low-mass star formation. Because GMCs appear to be aggregates of smaller cloud clumps (Blitz 1987), the second process can occur through the agglomeration of clumps, which can enhance the mass to flux ratio M/Φ (if the agglomeration occurs parallel to field lines) and lead to overall gravitational collapse of a relatively large piece of a GMC. Some evidence exists to indicate that this may constitute the mode of high-mass star formation.

The interesting question for the line of research originated by Strömgren then becomes: Does the formation of GMCs and subsequent clump agglomeration due to orbit focusing in spiral arms occur through the collection of small H I clouds or small H_2 clouds?

On this question astronomical opinion remains divided. Part of the difficulty lies in the demonstration by Kaufmann et al. (1987) that the details of the cross-arm distribution of H II regions and other spiral tracers in galaxies like M81 cannot be reproduced by single-component fluid models of the interstellar medium. In any case, the traditional answer, an outgrowth of the ideas outlined in § II, holds in favor of the following pathway: Atomic clouds give rise to molecular clouds; molecular clouds yield luminous OB stars, which then produce the large photoionized regions that show up so dramatically in optical photographs of spiral galaxies. The traditional picture then predicts the following sequence as we follow the gas flow into and out of a galactic shock: well-separated H I clouds → gathered H I superclouds (dust lanes) → H_2 clouds → OB stars → H II regions. More recently, detailed studies of gas-rich galaxies like M83 and M51 (Allen, Atherton, and Tilanus 1986; Lo et al. 1987; Tilanus et al. 1988; Vogel et al. 1988) indicate that the dust lanes are composed of GMCs, and that the atomic gas lies downstream from the dust lanes, well mixed (on a large scale) with the ionized gas. These observations suggest that the H I and H II arise by photodissociation and photoionization of the giant molecular clouds giving birth to young OB stars. In this scheme, we have the sequence; small molecular clouds → GMCs (dust lanes) → OB stars → H I and H II regions.

To complicate the situation, investigations of gas-poor galaxies like M31 (e.g., Lada et al. 1988) suggest that the original scheme involving the formation of H_2 clouds from H I clouds may be more appropriate after all! In the final analysis, it may turn out that both pictures have validity; GMCs may be assembled primarily from pre-existing dwarf molecular clouds in gas-rich galaxies, and from pre-existing H I clouds in gas-poor galaxies. It may even turn out that the inner and outer regions of the *same* galaxy may rely on different formation mechanisms for giant molecular clouds.

I think Bengt Strömgren would have been pleased that the questions he first asked concerning the spatial relationships among ionized, atomic, and molecular hydrogen in the Galaxy and their associated OB stars have had such a bountiful set of implications. It forms a true tribute to his insight and inspiration that these problems continue to excite and fascinate the current generation of observational and theoretical astronomers.

This work has been supported in part by the National Science Foundation through grant No. AST86-14743 and in part under the auspices of a special NASA astrophysics theory program which funds a joint Center for Star Formation Studies at NASA Ames Research Center, UC Berkeley, and UC Santa Cruz.

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