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HIGH-MASS STAR FORMATION DUE TO CLOUD-CLOUD COLLISIONS

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ABSTRACT

New CO data from the high-resolution Massachusetts–Stony Brook survey are analyzed to understand the mechanisms responsible for high-mass OB star formation. For a sample of 94 giant molecular clouds associated with high-luminosity radio H II regions, the efficiency (per unit mass of H_2) for OB star formation decreases significantly with increasing cloud mass over the range 10^5 to 3×10^6 $M_\odot$. We conclude therefore that massive star formation is generally *not* stimulated by an *internal* mechanism such as expanding H II regions in sequential star formation models, which should have a higher efficiency in larger clouds.

It is proposed that OB stars form as a result of cloud-cloud collisions. This is suggested by the observed quadratic dependence of the galactic H II region distribution on the local density of H_2. The preference of OB star formation to spiral arms is then naturally accounted for by orbit crowding and the increased collision frequency of clouds in the spiral arms. However, lower mass stars must be formed predominantly by a different mechanism since observations of external galaxies show a linear correlation between the disk light due to low- to intermediate-mass stars and the CO emission (i.e., the H_2 abundance) at each radius.

We suggest that cloud-cloud collisions can also account for high rates of massive star formation in the nuclei of high-luminosity infrared galaxies. Many of these galaxies exhibit optical morphology indicative of a recent merger, and most have extraordinarily large concentrations of molecular gas; they will therefore have high rates of cloud-cloud collisions.

Subject headings: galaxies: internal motions — interstellar: matter — stars: formation

I. INTRODUCTION

Extensive CO line surveys in the disk of our Galaxy have shown that over 90% of the star-forming gas (3×10^9 $M_\odot$) resides in giant molecular clouds (GMC) of mass 10^5–10^6 $M_\odot$ and typical size 10–80 pc (cf. Sanders, Scoville, and Solomon 1985). Yet, despite the short free-fall collapse time (3×10^6 yr) implied by the densities of the GMCs, the overall star formation rate for the Galaxy is only 5–10 $M_\odot$ yr^{-1}, i.e., 1% of the rate if they collapsed on a free-fall time scale. Suggested mechanisms for initiating condensations within the clouds include the compression due to expansion of H II regions and supernova remnants (e.g., Elmegreen and Lada 1977; Herbst and Assousa 1977) and external triggers such as the shock waves associated with Galactic spiral arms.

In this *Letter* we present observational evidence for an alternative process—the compression of molecular gas in the interface between colliding clouds. We propose that this is the dominant mode for *high-mass star* formation in the Galaxy. The high efficiency for OB star formation in spiral arms is then due to the convergence of cloud orbits in the spiral potential. Although GMCs of similar mass and density exist in interarm regions, their OB star formation is reduced due to the relatively large cloud-cloud mean free path.

The molecular gas in the Milky Way is concentrated in a ringlike distribution at Galactic radii 5–8 kpc where the overabundance of H_2 relative to H I, by a factor of 3–5, implies that the molecules must not be confined to a narrow range of azimuths, i.e., spiral arms (Scoville and Hersh 1979). The presence of molecular clouds in the interarm regions has also been inferred from recent high-resolution mapping of both CO and H I in several external galaxies. In M51, the CO emission is clearly peaked along the spiral arm loci, yet the intensity of the emission from the interarm regions is more than 50% of that seen in the arm peaks (Rydbeck, Hjalmarson, and Rydbeck 1985). In M83, Allen, Atherton, and Tilanus (1986) found the H I emission peak downstream from the dust lanes, and they point out that the absence of H I emission from either the dust lanes or the upstream side of the spiral arms implies that the pre-arm gas must be largely molecular.

Evidence has also accumulated that star formation is a *bimodal* process—with different mechanisms for high-mass and low-mass stars (cf. Larson 1986). This is supported by both the discontinuous slope of the initial mass function and by observations of nearby dark clouds with a high abundance of low-mass pre–main-sequence stars but virtually no high-mass stars. We note also that there are approximately 4000 giant molecular clouds with mass greater than $10^5\ M_{\odot}$ (Sanders, Scoville, and Solomon 1985) yet only 100 giant H II regions (Downes *et al.* 1980), and often the H II regions are clustered within single clouds. Thus high-mass stars must form only in select clouds with extraordinary characteristics (e.g., larger mass or density), or via an external stimulus (associated with the spiral arms). In this *Letter* we analyze the sites of H II region formation within the individual clouds and variations in the cloud properties between arm and interarm regions and suggest that most massive star formation results from cloud-cloud collisions.

II. GIANT MOLECULAR CLOUDS WITH H II REGIONS IN THE INNER GALAXY

From the Massachusetts–Stony Brook CO Survey (cf. Sanders *et al.* 1986*a*), Scoville *et al.* (1987) have cataloged molecular clouds with and without associated radio H II regions. The former sample comprises 95 GMCs containing 171 radio H II regions from the surveys of Downes *et al.* (1981) and Lockman (1986).

In Figure 1, we show the distribution of virial masses for the 73 H II region clouds with resolved distance ambiguities. The distribution of masses for these clouds is approximately $N(M) \propto M^{-1.0 \pm 0.4}$ as compared with a power-law index of -1.6 for all GMCs (Sanders, Scoville, and Solomon 1985). Thus, the H II regions tend to be found in high-mass clouds with a higher probability than in low-mass clouds. Also shown are the efficiencies for massive star formation estimated from the H II region free-free luminosity ($S_{6\text{ cm}} d^2$) and alternatively, from the number of high-luminosity H II regions (with luminosity exceeding 30 Jy kpc^2), as a function of the overall H_2 mass in discrete mass bins. The figure clearly demonstrates that the efficiency (per unit H_2 mass) for both *UV emission* and formation of distinct *OB associations* decreases at the high end of the cloud mass spectrum. Hence, the rate of massive star formation is not simply proportional to the cloud mass but instead must depend on the cloud surface area, internal properties such as the density, or *external* stimuli—all of which could yield a higher OB star formation *efficiency* (per unit mass) in the smaller clouds. *Internally* generated stimuli such as the expanding shocks of H II regions (e.g., Elmegreen and Lada 1977) are disfavored since their efficiency should increase in higher mass clouds where there is more surrounding material to be stimulated.

In order to evaluate the possibility that clouds with H II regions are systematically denser than normal GMCs, we show in Figure 2 the internal velocity dispersions as a function of the GMCs with and without H II regions. Both samples exhibit the same velocity dispersion for diameters above 20 pc implying that the virial densities ($\rho \propto v^2/r^2$) are approximately equal for H II region clouds and non–H II region clouds. (However, at smaller diameters, those with H II regions do have greater velocity dispersion as discussed below. The clouds with H II regions also exhibit higher peak CO temperatures, but this is probably an *effect* of the high luminosity stars, rather than a *cause* of high-mass star formation [see Scoville *et al.* 1987]).

The *external* stimulus responsible for massive star formation may be constrained from analysis of the H II region locations within their GMCs. Waller *et al.* (1987) and Scoville *et al.* (1987) found that the apparent distribution of H II region locations is centrally peaked. This is inconsistent with the apparent limb-brightened distribution expected if OB star formation were stimulated solely on the surface of GMCs.

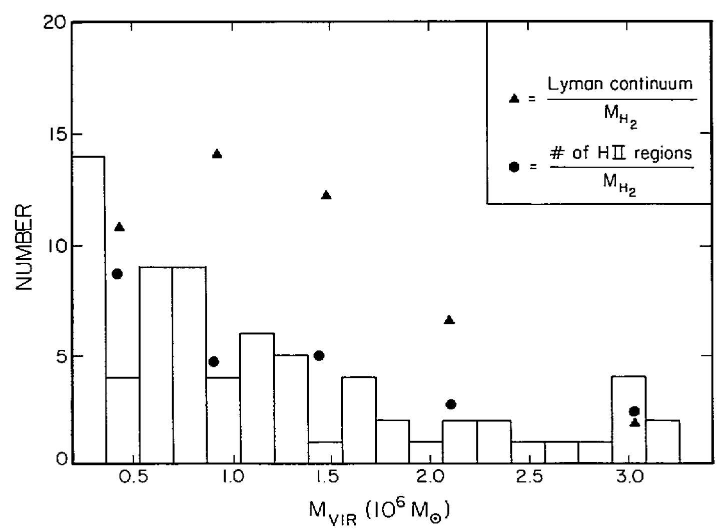

FIG. 1.—The distribution of virial masses for a sample of 73 GMCs associated with 102 radio H II regions in the first Galactic quadrant. Also shown is the relative efficiency for Lyman-continuum luminosity and OB star cluster formation per unit mass of H_2 in different cloud mass bins (Scoville *et al.* 1987). (The mass bins, of nominal width $5 \times 10^5\ M_{\odot}$ were expanded for the two high-mass bins in order to include a minimum of eight clouds in each bin.)

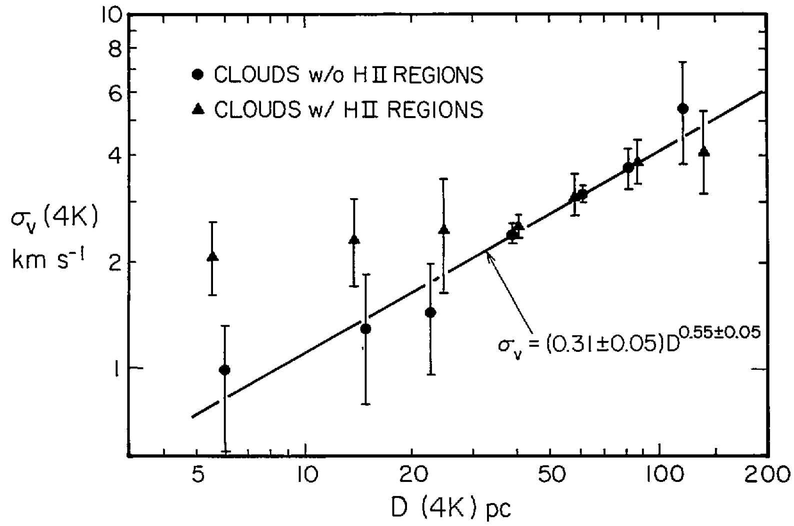

FIG. 2.—The dependence of the internal velocity dispersion on the cloud diameter is shown for clouds with and without radio H II regions (Scoville *et al.* 1987). Both samples of clouds are consistent with the same size–line width relation at $D > 20$ pc, but for smaller sizes the H II regions have systematically higher dispersions, perhaps due to cloud-cloud collisions.

Schemes for OB star formation must therefore account for both the formation of stars deep in the interior of clouds and the lower efficiency in high-mass clouds. A model, consistent with both of the above, is one in which massive star formation is triggered in the interface region between colliding GMCs. The resulting OB star clusters will then appear sometimes near the edge but often near the center of the merged complex depending upon both the encounter geometry and the relative masses of the colliding clouds. At the same time the lower mass GMCs can have a higher OB star formation efficiency due to their larger surface area–to–volume ratio. (In fact, the OB star formation efficiency per unit mass appears to fall faster than $M^{-1/3}$ in Fig. 1, but it is not clear if this difference is significant.)

If massive star formation is associated with the collision of GMCs and the GMC mass spectrum is invariant across the Galaxy, then the local density of H II regions should vary with the frequency of cloud-cloud collisions, i.e., quadratically with the number density of clouds. Clemens, Sanders, and Scoville (1986) have recently analyzed the high-resolution Massachusetts–Stony Brook CO survey to derive an approximate "face-on" H_2 distribution, resolving the near-far distance ambiguities with scale-height information. Comparison of the deduced H_2 distribution with that of H II regions (shown in Fig. 3) indicates that the density of H II regions varies as $\langle n_{H_2} \rangle^{1.9 \pm 0.2}$ where $\langle n_{H_2} \rangle$ is the midplane H_2 density averaged over 300 pc.

The cloud-cloud collision model also allows for the existence of some interarm H II regions. Based on the relative contrast for the CO emission between the arm and interarm regions (3 : 1; Sanders 1981 and Clemens, Sanders, and Scoville 1986), one expects a 9 : 1 arm-interarm contrast in the H II regions. This is in accord with the results of Mezger and Smith (1977) who find 15% of the giant H II regions in classic interarm regions.

III. DISCUSSION

In spiral galaxies the confinement of the H II regions to narrow, coherent spiral arms should depend on two factors: the amplitude of the spiral potential perturbation and the overall abundance of molecular clouds. For the model proposed here with massive star formation resulting from cloud-cloud collisions it is natural to expect bimodal star formation —*massive stars formed where the collision frequency is high and lower mass stars formed from individual clouds at a rate proportional to the cloud mass.* Theoretical calculations for clouds on ballistic trajectories through a spiral potential of amplitude 5% indicate an increase in the number density of clouds by a factor of 4 in the spiral arms (Kwan and Valdes 1983). The resulting factor of 16 increase in the cloud collision frequency will produce a strong clustering of the resultant H II regions in the arms.

The formation of lower mass stars, at a rate proportional to the mass density of H_2, will be less concentrated in the arms if a significant fraction of the H_2 exists in interarm regions. The light from this lower mass population will then exhibit a linear dependence on the mass of H_2 as a function of Galactic radius and on the integrated mass of H_2 from one galaxy to another. This is in good agreement with the observed correlation between CO emission and the blue light from late-type spiral galaxies (Young and Scoville 1982; Scoville and Young 1983).

At present there exist few detailed numerical calculations of general relevance to the collision of GMCs. Hausman's work (1981), restricted to atomic hydrogen clouds of small mass and large relative velocity, is not applicable to the GMCs which have much larger binding mass and lower velocity dispersion (comparable to the internal velocity dispersion). For collisions at 4 km s^{-1} (the GMC cloud-cloud velocity dispersion: Liszt and Burton 1981 and Clemens 1985),

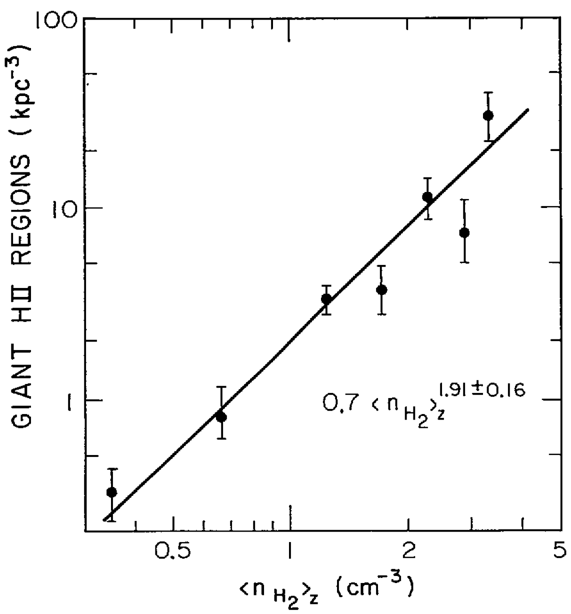

FIG. 3.—The local number density of H II regions in the Galactic disk is shown as a function of the mean H_2 density (averaged over length scales of ~ 300 pc in the Galactic disk and 100 pc in Z). The face-on distribution of H_2 used for this analysis is from Clemens, Sanders, and Scoville (1986).

the shocked interface gas will remain molecular but be heated to a peak temperature 10^3 to 2×10^3 K. Since the Jeans length at the highest temperatures is much greater than the thickness of the hot interface, stars cannot form until the postshock gas has cooled (to ~ 100 K). The highest mass stars will then form first in the cooling gas, perhaps accounting for a favoring of massive stars in the initial mass function.

Depending upon the relative sizes of the two colliding clouds, the interface region (and the stars formed within it) could appear near the surface of the merged cloud (for very unequal cloud masses) or near the center of the merged complex (for equal mass clouds). For a given GMC, collisions will most often occur with smaller clouds since the GMC size distribution is $N(R) \propto R^{-2.5}$ (Sanders, Scoville, and Solomon 1985). If more than one OB cluster is formed during a cloud collision, they will be distributed along the interface plane and separate sites of star formation will exhibit a marching, temporal sequence along the interface. It is noteworthy that the nearest examples of massive star formation in Orion exhibit such a temporal sequence (Elmegreen and Lada 1977) and the sites of most recent OB star formation (M42 and NGC 2024) occur in the top of the southern Orion cloud and the bottom of the northern Orion cloud, close to their possible point of contact (cf. Maddalena *et al.* 1986).

In the model presented here, massive star formation will occur only during a small fraction of the cloud's lifetime. A low duty cycle for massive star formation (< 20%) is expected from comparison of the cloud-cloud merging time with the mean free time between collisions. Based on a typical cloud size of 40 pc and cloud-cloud rms velocity of 4 km s^{-1}, the collision should last 10^7 yr, whereas the mean time between collisions is $\gtrsim 5 \times 10^7$ yr (shortest in the arms at the peak of the molecular cloud ring). The larger velocity dispersion for H II region clouds with $D < 20$ pc (Fig. 2) is consistent with the view that these clouds have recently undergone a collision, resulting in an increase in the internal kinetic energy of the cloud. (Since the typical cloud-cloud velocity dispersion is ~ 4 km s^{-1}, one would not expect to see the enhanced internal velocity dispersion except in the smaller clouds which have internal $\sigma_v < 4$ km s^{-1}.)

The role of cloud-cloud collisions in stimulating a high rate of massive star formation is likely to be particularly relevant to the nuclear regions of high-luminosity infrared galaxies. On the basis of a high preponderance of red supergiants and the low mass-to-light ratio, Rieke *et al.* (1985) have pointed out that the star formation activity inferred for M82 and NGC 253 must be dominated by stars more massive than 3 $M_\odot$. CO observations of both galaxies (Young and Scoville 1984; Scoville *et al.* 1985) suggest a mean mass density of molecular clouds much higher than that in the central region of our galaxy. In addition, the presence of large noncircular motions due to a central bar potential will increase the cloud-cloud collision rate (Scoville *et al.* 1985). More extreme examples of these phenomena are provided by the very high luminosity *IRAS* galaxies which exhibit ratios $L_{IR}/M(H_2)$ a factor of 3–10 greater than normal spirals like the Milky Way (Sanders *et al.* 1986*b*). Over half of these galaxies exhibit optical morphology suggestive of galaxy mergers. If the high-energy output is generated by young stars, the star formation efficiency must be much greater, perhaps a result of the high frequency of cloud-cloud collisions in galaxies with abnormally high molecular abundances and chaotic velocity fields.

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