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DISSOCIATION AND IONIZATION OF MOLECULAR GAS IN THE SPIRAL ARMS OF M51

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Abstract

We derive the star formation rate and efficiency in the arm and interarm regions of M51 from observations of the molecular (Lo *et al.* 1987) and ionized (van der Hulst *et al.* 1988) phases of the interstellar medium, and show that the HI observations of Tilanus and Allen (1989) are consistent with dissociation of molecular gas by these young, massive stars if $n_H \geq 200$ cm^{-2}. However, these stars are not able to dissociate or ionize all the gas, and at least 60% must remain molecular in the interarm regions. The efficiency of star formation in M51 seems to be similar to that in the Galaxy, and does not appear to be enhanced in the spiral arms. Therefore, the effect of the strong density wave may be only to concentrate the gas, and hence the young stars, to the arm regions.

n sub H greater than or equal to 200

Introduction

The inner regions of the Whirlpool Galaxy, M51, ($r < 1' = 2.8$ kpc, at a distance of 9.6 Mpc) have been mapped at high resolution in HI (Tilanus and Allen. 1989), CO emission (Lo *et al.* 1987), and Hα and thermal radio emission (van der Hulst *et al.* 1988), with resolutions of 12, 7, and 8 arcseconds respectively. Van der Hulst *et al.* identified giant HII regions and derived their physical properties, such as the rms electron density, $\overline{n_e^2}$, and excitation parameter, U. Assuming a volume filling factor for the ionized gas of $\delta = 1$, they then derived the total HII mass. Lo *et al.* (1987) calculated the column density of molecular gas using the Galactic conversion factor $N(H_2) = 3.6 \times 10^{20} I_{CO}$ cm^{-2}. They found the average column density in the arms to be 2×10^{22} cm^{-2}, and the interarm column density to be in the range (1.4–3.4)$\times 10^{21}$ cm^{-2}. In this paper, we calculate the amount of molecular gas which could be dissociated by the young stars which are responsible for the Hα and thermal radio emission, as a function of electron density in the ionized gas, and hydrogen density in the region immediately surrounding it. The HI column density so derived is then compared to the HI observations of Tilanus and Allen (1989), in order to determine the physical conditions of the interstellar medium in the spiral arms, such as volume density and filling factor.

Star Formation Rate and Radiation Field

Assuming an intial mass function (IMF) appropriate for the most massive stars ($dN/dM \propto M^{-2.5}$), we calculate the total number of stars of spectral type B2 or earlier, $N_\star$, from the excitation parameter, $U \propto N_\star^{1/3}$, for each HII region. In the inner spiral arms, there must be 1400 such stars per kiloparsec of arm length, but because the giant HII regions account for only 34% of the total disk thermal emission, this number could be increased by up to a factor of 3. Since the arms have a typical width of 500 pc, this implies a surface density of (2.8–8.4)$\times 10^{-3}$ OB stars pc^{-2}. Hence, the star formation rate (and radiation field, if the stars have the same scale height as in the Galaxy) in the spiral arms is 4–13 times that in the solar neighborhood. In the interarm regions, the upper limit to the surface density of young stars is 3.6×10^{-4} pc^{-2} (using the total Hα flux given by Kennicutt and Kent (1983)), about half the density near the sun. So the arm contrast in young stars is at least 8. This can be compared to the CO arm contrast of between 3 and 15 (Lo *et al.* 1987).

If we assume the IMF used above extends to a lower mass limit of $0.4 M_\odot$, then we can calculate the total mass of newly-formed stars in the spiral arms, $M_\star$, and compare this to the gas mass to derive a star formation efficiency, $\epsilon \equiv M_\star/(M_\star + M_{gas})$. We find $\epsilon \approx$ 0.15–0.4% in the arms, and $\epsilon \leq$ 0.25% between the arms. This is comparable to the efficiencies of 0.2–5% found for Galactic giant molecular clouds (Wilking and Lada. 1985). Thus, star formation does not appear to be more efficient in M51 than in the Galaxy, and the efficiency is not necessarily enhanced in the spiral arms by the strong density wave.

Dissociation by Young Stars

Using the number of OB stars inferred above, we can find the total flux of dissociating photons. This should be fairly insensitive to the slope of the IMF. The mass of gas dissociated, however, depends not only on the volume density of the neutral gas, but also on the density within the HII region (since this affects the Strömgren radius), and the detailed geometry. Assuming the stars are in a single spherical OB association, completely embedded in molecular gas (so that no photons escape), we find that the mass of gas dissociated is $M(HI) = 2.9 \times 10^6 N_\star^{7/6} n_e^{2/3} n_H^{-3/2}\ M_\odot$. If, instead, the stars are uniformly distributed in the arm, the HI mass is typically half this value, and if the stars are strung out along the arm ("cylindrical" geometry), the HI mass differs by ±50% for densities of interest. So the mean HI column density in the arms is typically $N(HI) \approx 7.3 \times 10^{20} N_\star^{7/6} n_e^{2/3} n_H^{-3/2}$ cm^{-2}. The electron density given by van der Hulst *et al.* (1988) is $n_e = 1.57\ \delta^{-1/2}$ cm^{-3}, where δ is the HII volume filling factor. Tilanus and Allen (1989) find that the mean HI column density in the arms is about 7×10^{20} cm^{-2}. Therefore, if $\delta = 1$, we need $n_H \approx 200$ cm^{-3}, and if $\delta = 0.1$, $n_H \approx 400$ cm^{-3}. Typically, $n_H \approx 100 n_e$ is needed to explain the low HI column densities.

Alternatively, if the stars are not too deeply embedded within the molecular gas, then we can consider the molecular clouds to be immersed in an interstellar radiation field 4–13 times larger than in the solar neighborhood. Then, the atomic envelopes of molecular clouds will have a column density $N(HI)_{env} = 2.3 \times 10^{23} G^{1.5} n_H^{-1.5}$ cm^{-2}, where $G = 4$–13 (Federman *et al.* 1979). If each line of sight passes through one cloud, and if the density in the atomic gas is $n_H \approx 200$–600 cm^{-3}, then the observed HI could be simply explained as the envelopes of molecular clouds along the line of sight, as proposed generally by Shaya and Federman (1987).

Finally, since the giant HII regions are so large ($d \approx 450$ pc), they may burst through the molecular cloud layer, creating wormholes, and much of the dissociating radiation could escape into the halo. In this case, n_H could be much lower and still agree with the observations.

The Interstellar Medium in Interarm Regions

The observations referenced above also allow us to place limits on the fraction of the molecular gas in the arms which is ionized or dissociated by the young stars. The column density of H$_2$ in the arms is 2×10^{22} cm^{-2}, whereas that of the HII and HI is only observed to be $\leq 7 \times 10^{21}$ cm^{-2} and 7×10^{20} cm^{-2} respectively. In the interarm region, the molecular gas still dominates, with $N(H_2) = (1.4$–$3.4) \times 10^{21}$ cm^{-2}, $N(HI) \leq 6 \times 10^{20}$ cm^{-2} and $N(e) \leq 10^{20}$ cm^{-2}. Therefore, the interstellar medium in the interarm regions must be at least 60% molecular. However, the molecular gas cannot be gathered into large complexes like those seen in the spiral arms, because the CO brightness temperature, averaged over 300 pc, is less than $0.6K$ in the interarm regions (Lo *et al.* 1987).

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