MASSIVE STAR FORMATION IN SPIRAL ARMS AND INTERARMS

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ABSTRACT. The CO emission from the almost entire disk of M51 was mapped with the Nobeyama 45-m telescope. Using the high spatial resolution and high sensitivity data, we examine formation mechanisms of massive stars and molecular clouds both in arms and in interarms. The N(H_2)/CO ratio is also evaluated in the galaxy.

1. Introduction and Observations

Observations of carbon monoxide in disks of spiral galaxies provide a crucial key to understand formation mechanisms of stars and molecular clouds in arms and interarms, as well as to investigate structure and dynamics of molecular arms themselves. The observations for the purposes require some conditions: firstly, spatial resolution of better than one kpc to distinguish between spiral arms and interarms, secondly, high sensitivity to detect the emission from interarm regions, and thirdly, large field mapping to get statistically meaningful results. We mapped ^{12}CO(1-0) emission in the region of > 5' x 5' of the grand-design spiral galaxy M51 with the Nobeyama 45-m telescope. The HPBW was 17" corresponding to 790 pc at the distance of 9.6 Mpc. The aperture and main beam efficiencies were 0.26 and 0.45, respectively. Figure 1 shows the CO integrated intensity map. Two molecular arms elongate along dust lanes. The beam-corrected arm width is 800 pc to 1400 pc. The arm-interarm intensity ratio is typically two (inner part) to five (outer part).

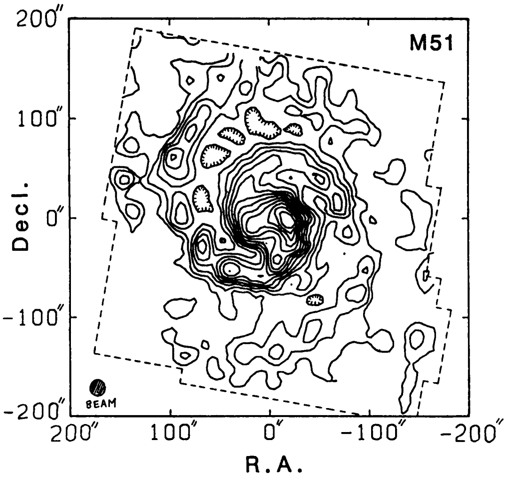

Figure 1. The CO integrated intensity map, $I_{CO} \equiv \int T_A{}^*dv$, of M51. The first contour and contour interval are 2 K km/s. The mapping region is indicated by dotted lines.

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2. Formation Mechanisms of Massive Stars

Here we examine the possibility of massive star formation induced by random cloud-cloud collisions. We assume that most of molecular gas is in the form of Giant Molecular Clouds (GMCs) with $T_{ex} \approx 10$ K, $\tau >> 1$, and a diameter $D \approx 50$ pc as in our Galaxy. In spiral arms, the measured brightness temperature $T_{mb} \approx 0.6$ K indicates the filling factor of $f \approx 0.10$ and thus the number density of GMCs, $N_c \approx 49$ GMC kpc^{-2}. Assuming two dimensional distribution of GMCs because the D is comparable with these scale height, the time scale for the collision is $t_{coll} \approx (N_c \cdot D \cdot \Delta V)^{-1} \approx 4 \times 10^7$ yr, where ΔV is the velocity dispersion ($\approx$ 10 km/s). The molecular arm crossing time is $t_{cross} \approx d_{arm} / V_{cross} \approx 1.0 \times 10^8$ yr, where d_{arm} is the arm width (typically 1000 pc) and V_{cross} the velocity component perpendicular to the arm ($\approx$ 10 km/s; Hausman and Roberts 1984). Therefore, $t_{coll} < t_{cross}$, indicating that random cloud-cloud collisions can occur in spiral arms.

In interarm regions, $T_{mb} \leq 0.2$ K and thus $f \leq 0.03$. Using the same manner as above, the time scale for the random collision is $t_{coll} \geq 1.2 \times 10^8$ yr. The interarm passage time is $t_{pass} \approx d_{inter} / (V_{rot} - R \cdot \Omega_p)$, where d_{inter} ($\approx \pi \cdot R - d_{arm}/\sin\alpha$) is the interarm length along the azimuthal direction, V_{rot} the rotation velocity, R the distance from the center, Ω_p the pattern speed, and α the pitch angle (21°). The t_{pass} is the order of 10^7 yr. For instance, at $R = 3$ kpc, $V_{rot} \approx 210$ km/s (Kuno et al. in this proceeding) and $\Omega_p \approx 14$ km/s/kpc (Kimura 1986), then $t_{pass} \approx 3.7 \times 10^7$ yr. Therefore, $t_{coll} > t_{pass}$, indicating difficulty of random cloud-cloud collisions in interarms. Another mechanism such as self-gravitational instability is required.

The results mentioned above can be supported by the relation between star formation rate (SFR) and molecular hydrogen density $\sigma(H_2)$. Figure 2 shows the SFR ($\times 10^{-3}$ $M_\odot$/yr/1.7kpc^2) obtained from Hα emission (Tully 1974) versus $\sigma(H_2)$ ($M_\odot$/pc^2) in logarithmic scale. Although it is possible to fit with a linear function whose inclination is $n \approx 1$, the gradient seems to be changed at $\sigma(H_2) \approx 90$ $M_\odot$/pc^2, namely, $n = 0.5 \pm 0.8$ at $\sigma(H_2) < 90$ $M_\odot$/pc^2 and $n = 1.5 \pm 0.8$ at $\sigma(H_2) > 90$ $M_\odot$/pc^2 where SFR $\propto$

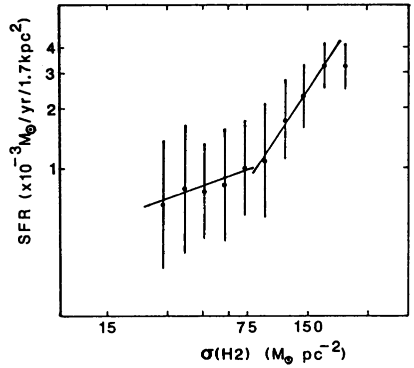

Figure 2. The relation between the H_2 density and the star formation rate.

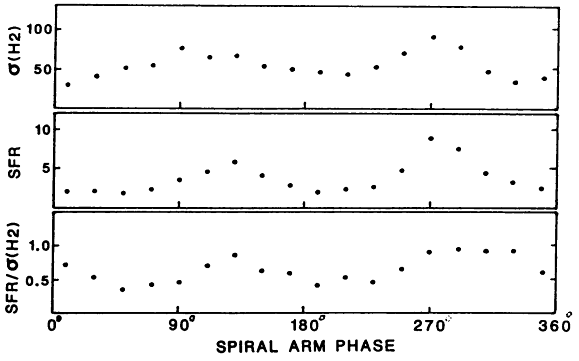

Figure 3. The H_2 density, star formation rate and star formation efficiency along spiral arm phase.

$\sigma(H_2)^n$. If the value of n = 1.5 at > 90 $M_\odot/pc^2$ which is in arm and central regions is real, it suggests mixture of star formation induced by cloud-cloud collisions and by another mechanism in isolated clouds. Since the difference of n is not statistically significant, the confirmation is required using more sensitive Hα and CO data and including HI data. The non-linear effect on star formation is also supported by figure 3. The figure shows the variation of SFR/$\sigma(H_2)$, i.e., of star formation efficiency (SFE), along the azimuthal direction or spiral arm phase. The SFE is not constant but enhanced on spiral arms. This could be due to cloud-cloud collisions in arms.

3. Formation Mechanisms of GMCs

In our Galaxy, most of molecular gas is in the form of GMCs and GMCs are thought to be massive star forming regions. So far, several mechanisms of GMC formation are proposed such as cloud coagulation, Parker instability, and gravitational instability (e.g. Elmegreen 1990). We here examined the possibility of random collisional agglomeration of small clouds into GMCs. We assume that small molecular clouds (SMCs) with the diameter of $D \approx 5$ pc coagulate into a GMC with $D \approx 50$ pc. Using same manner as section 2 but treating three dimensional distribution (D << scale height), the time scale for a collision in arms is $t_{coll} \approx 1.2 \times 10^8$ yr, while the arm crossing time is $t_{cross} \approx 4.8 \times 10^7$ yr, so that $t_{coll} > t_{cross}$. More over, to form a GMC from SMCs, hundreds or thousands collisions are required. Thus it is impossible for a GMC to be formed by random collisions of SMCs during one passage through an arm, and the time scale of 10^9 yr to 10^{10}yr is required. Perhaps GMCs are formed by other mechanisms such as gravitational instability.

4. The $N(H_2)$/CO Ratio

van der Hulst et al. (1988) obtained the extinction Av from thermal radio continuum emission and Hα emission in the disk of M51. Adopting the gas-to-dust ratio, 1.9×10^{21} H/mag, the column density $N(HI + 2 \cdot H_2)$ can be evaluated. Figure 4 show the relation between the CO integrated intensity I_{CO} and the H_2 column density $N(H_2)$, correcting the HI column density. The mean conversion factor is $N(H_2)/I_{CO} \approx (2.3 \pm 1.7) \times 10^{20}$ H_2 (K km/s)$^{-1}$, which is in the range of Galactic value.

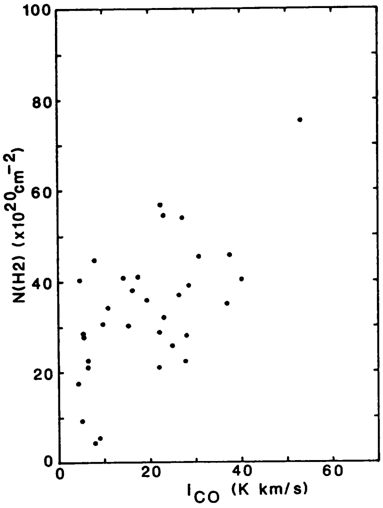

Figure 4. Relation between the CO integrated intensity and the H_2 column density.

References

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Simon White winks at the photographer (Bruce Elmegreen).