DISTRIBUTION AND MOTION OF CO IN M31

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ABSTRACT

M31 is among the few galaxies whose solid angle is more than 100 times the beam area of currently operational millimeter-wave telescopes. Roughly 10% of its area has been mapped in the J=1→0 line of CO with the 7-m telescope at Bell Laboratories. The data lie on the major and minor axes and in a filled 20' by 15' field. The average CO emissivity is less than 1/5 that of the Milky Way Galaxy, and the inferred H_2 column densities are less than 10% of the HI column densities at the same positions. Thus M31 has a predominantly atomic interstellar medium, whereas our Galaxy seems to have a predominantly molecular interstellar medium. The molecular emission is strongly concentrated in spiral-arm segments, with greater than ?25:1 contrast between arm and interarm regions. Overall, the CO emission is well correlated with the HI emission, but shows greater concentration to the spiral arms. There is no evidence for a spatial separation of the HI and CO arms to within our resolution (∿1'): all the spiral-arm tracers are spatially coincident. Almost all the gas on the minor axis exhibits non-circular velocities of about 20 km s^{-1}. There are systematic streaming motions as large as 80 km s^{-1} associated with spiral arms.

INTRODUCTION

Detection of spiral structure in a galaxy requires spatial resolution finer than about 500 pc. Since operational millimeter-wave telescopes have beam sizes $\gtrsim$30", the presence or absence of spiral structure in CO emission can be seen only within the Local Group. Combes et al. (1977a, b) have shown that the CO line is detectable only towards dust lanes in M31; Boulanger, Stark and Combes (1981) made a filled 20-point map to show that CO and HI are well correlated, the CO having a somewhat greater contrast and concentration to the spiral arms. Observations of ^{13}CO towards a northern spiral-arm region (Encrenaz et al. 1979) showed ratios $T_A^*(^{12}CO)/T_A^*(^{13}CO) \approx 10$, roughly twice the average value for the Milky Way Galaxy, MWG (Stark, Penzias and Beckman 1983).

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More than 200 CO spectra of M31 have been obtained so far with the 7-m telescope at Bell Laboratories (Stark, Frerking and Linke 1979; Stark, Linke and Frerking 1981; Linke 1981): these data include a filled 20'x15' field on the SW major axis and a strip map of the minor axis.

A FILLED MAP OF A SPIRAL-ARM REGION IN M31

The existence of spiral structure in the CO line is shown clearly in Figure 1. There is > 25:1 contrast between the brightest and faintest map points - the point (-34, 6.5) shows no emission at the 5-mK rms noise level in 1-MHz filters. Projected onto the disk of M31, the telescope-beam half-power circle is an ellipse 200pc x 900pc in size. The beams located on the spiral arms have on the order of 10 giant molecular clouds in them, while the beams on the interarm regions have none. The CO emission is well correlated with all spiral-arm tracers: HI, HII regions, and dust. There are 35 Baade and Arp (1964) HII regions within the bounds of Figure 1, and only 5 lie outside the 1 K km s^{-1} contour where a random distribution would put $\sim$20.

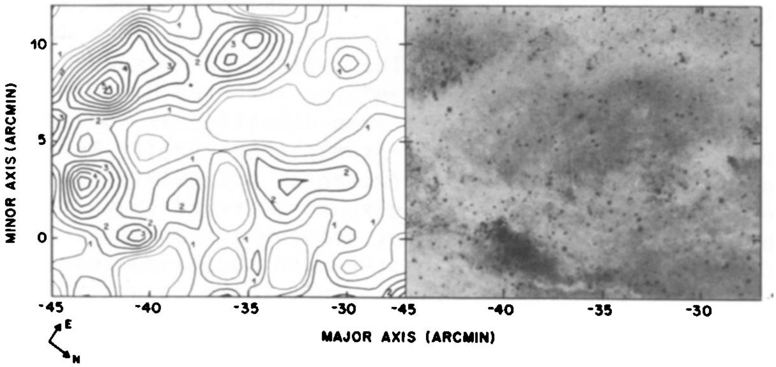

Figure 1. (Left) Integrated ^{12}CO brightness of a field in M31, sampled on a 1.5' square grid (Stark, Linke and Frerking 1981). Contours are labeled in K km s^{-1}. The coördinate system is that of Baade and Arp (1964). (Right) Blue photograph of the same region, showing the correlation of dust and CO.

CO ON THE MINOR AXIS OF M31

This data is summarized in Figure 2. The distribution of CO brightness with radius is very different from the Galaxy: there is no detectable central feature in M31 at a level which is a factor of 300 less than the CO surface brightness of the MWG central region (e.g. Sanders, Solomon and Scoville 1983). The radius of M31's "molecular ring" is nearly twice as large as in the MWG. A comparison of surface brightnesses corrected for inclination shows M31 to be weaker by a factor of $\sim$ 5 compared to the MWG (Stark, Linke and Frerking 1981), and weaker by a factor of 10 to 20 with respect to some other galaxies studied in CO (cf. Morris and Rickard 1982). M31 is not, however, an unusually CO-faint galaxy - it is, in fact, typical of Sb spirals of similar luminosity class. This apparent discrepancy results from a selection effect: those galaxies that are well-observed in CO are a special class of objects with high CO surface brightness, chosen because of limits imposed by instrumental sensitivity.

The velocities shown in Figure 2 have some peculiar features. Almost none of the CO emission on the minor axis is at the systemic velocity of -300 km s^{-1} (e.g. Rubin and D'Odorico 1969). The intensity-weighted average of the CO velocities on the minor axis is -321 $\pm$ 5 km s^{-1} indicating a "sloshing" motion of the whole disk. This discrepancy between the gas motion and the systemic velocity was seen in HI by Burke, Turner and Tuve (1963). It is not the typical signature of velocity perturbations by a bar, since both sides of the disk have streaming motions of the same sign. The spiral arm at the -5' position is moving inwards, towards the nucleus of M31, with a radial streaming motion of 80 km s^{-1}. Inward motion cannot be the direct effect of an explosion in the center. The FWHM line widths are typically 25 km s^{-1}, much larger than any single molecular cloud. This width results from the superposition of several clouds, spread out in velocity by a one-dimensional rms cloud-to-cloud velocity dispersion of about 8 km s^{-1} (Stark 1979; Blitz 1981).

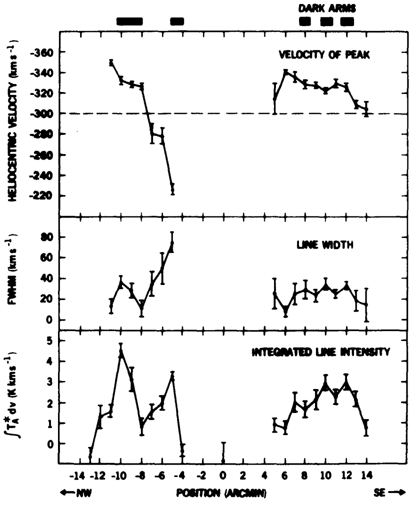

Figure 2. Parameters of CO J=1→0 lines on the minor axis of M31 (Stark, Frerking and Linke 1979). Positions of dust lanes are shown above the frame. (Top) Velocity of the line peak: the systemic velocity is indicated by the dashed line at -300 km s^{-1}. (Middle) Line width (Full width at half-maximum). (Bottom) Line intensity integrated over all velocities. One arcminute corresponds to a radial distance of ≈ 1 kpc. There is no detectable emission between the -4' and +4' positions.

SUMMARY

I) The CO distribution in M31 has a hole in the center - there is little or no emission from the inner 4 kpc. The CO brightness peaks at R ~ 10 kpc.

II) The emission is strongly concentrated to spiral arms, with 25:1 contrast. All spiral-arm tracers are well correlated with CO.

III) M31 has a predominantly atomic ISM, whereas the Galaxy's molecular component is greater than or roughly equal to the atomic component.

IV) The observed line widths imply a one-dimensional root-mean-square cloud-to-cloud velocity dispersion $\sigma_v \approx 8$ km s^{-1}.

V) One arm is streaming inwards at 80 km s^{-1}.

VI) The ISM in the disk of M31 is "sloshing" by 20 km s^{-1} with respect to the systemic velocity.

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DISCUSSION

B.G. Elmegreen: What are the masses of the 4 large CO clouds in the dusty regions?

Stark: I have no ^{13}CO data, so I hesitate to answer, but they are of order 10^6 $M_\odot$, hence comparable to complexes of giant molecular clouds.

T.S. Jaakkola: In your figures, as in those of Brinks, there are features indicating more positive velocities on the far side than in the symmetric position on the near side. It was shown several years ago (T.S. Jaakkola, P. Teerikorpi, K.J. Donner, 1975, Astron. Astrophys. 40, 257) that this is a general effect seen in the iso-velocity data of galaxies (18 positive cases out of 25 available at that time). I do not believe in a general expansion of the disks of spiral galaxies ten times faster than in the Metagalaxy. Rather, there is a systematic effect superposed on the lineshifts due to radial velocities.

Stark: The largest negative velocities occur on the side nearest to us.

H. van Woerden: Your cloud-to-cloud velocity dispersion of 8 km/s, is it the dispersion of cloud motions around the mean, or rather an r.m.s. difference between 2 clouds?

Stark: It is the one-dimensional velocity dispersion (r.m.s.) around the mean.

A. Blaauw: How much of that is due to differential rotation in the system?

Stark: The contribution of differential rotation to the linewidths is small, and has been taken into account in calculating the dispersion.

J.P. Ostriker: In comparing our Galaxy and possibly similar galaxies to M31, you find they do not quite agree and an additional parameter may be needed. Another solution, especially after hearing Hodge's review, is that our Galaxy is really an Sc (and then it agrees rather nicely), rather than an Sbc.

Stark: My point there is that the selection effects in extragalactic CO observations are still very great, hence it is too early to judge the relationships between morphological type and other properties.

C.J. Cesarsky: You give an arm/interarm contrast for CO. If you convert from CO to H_2, and take the HI into account, what arm/interarm contrast do you get then?

Stark: The arm/interarm contrast is entirely dominated by the HI, since the molecular constituent is always less than one-tenth of the total mass, even in the arms, unlike in the central parts of our Galaxy.

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J.S. Young: The low CO abundance in M31 (so that the surface density of HI is greater than that of H_2) is very important for the question of possible confinement of the molecular clouds to spiral arms. In the inner regions of high-luminosity Sc galaxies, where $H_2 >> HI$ (e.g. IC 342, NGC 6946 and M51), one cannot confine the dominant component of the interstellar gas into small areas. In M51, the CO studies at 20" - 45" resolution by Rydbeck, by A. Sargent, and by Scoville and myself show arm/interam contrasts of factors of 2-3, and that only in the outer parts where the HI and H_2 surface densities become comparable.

With regard to the Hubble type of our Galaxy, its smaller size compared to M31 as indicated by Hodge, combined with its lower V_{max}, suggests that our Galaxy has a lower luminosity than M31. If our Galaxy is an Sc, it must be a high-luminosity one (according to the rotation curves of Rubin, Ford and Thonnard); but it does not have as much gas as the high-luminosity Sc's (as I showed on Monday), so the Milky Way is more likely to be an intermediate-luminosity Sb.

Stark: As to M51, I prefer to wait till the Nobeyama telescope maps this galaxy - then I'll believe the story. The arm/interarm contrast in our Galaxy is about 3:1 in CO emissivity and more than 10:1 in the density of giant molecular clouds, even in regions where molecular hydrogen dominates.

B.F. Burke: Considering the high arm/interarm contrast in CO, where would the old CO go to die?

Stark: I suspect it blows up, as we saw for the local spur yesterday. It probably gets destroyed after 30 million years.