THE DISTRIBUTION OF MOLECULAR CLOUDS IN SPIRAL GALAXIES

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The use of millimeter wave CO emission as a tracer of molecular hydrogen in the Galaxy (Scoville and Solomon 1975) showed that most of the H_2 unlike HI is concentrated in the inner part of the Galaxy in a "ring" between 4-8 kpc and in the inner 1 kpc. Subsequent surveys (Gordon and Burton 1976, Cohen and Thaddeus 1977, Solomon et al. 1979) confirmed this picture with more extensive data. The molecular interstellar medium was shown to be dominated by Giant Molecular Clouds with individual masses between 10^5 and $3 \cdot 10^6 M_\odot$ (Solomon et al. 1979, Solomon and Sanders 1980). The GMC's confined to a layer with a half thickness of only 60 pc are an important component of the galactic disk, and the most massive objects in the galaxy. They affect the dynamics of the disk by contributing significantly to the surface density and through their individual gravitational interactions with stars.

During the past two years significant progress has been made in measuring the CO emission from the disks of external galaxies. In this review I will concentrate on those galaxies which have been mapped sufficiently to determine the radial distribution of CO emission. For several of these systems, Sc and Scd galaxies, it has been shown that the average CO emission is a monotonically decreasing function of radius with a strong correlation between the CO integrated intensity $I = \int T_A dv$ and the blue surface brightness.

M101 (N5457)

M101 has the largest angular extent of any face on Sc I galaxy. We use this as an example. Solomon et al. (1982a) obtained observations of CO emission at λ = 2.6 mm, from 40 locations in M101 and compared the radial dependence of CO surface emission with the optical emission and the HI distribution (Schweizer 1976, Allen and Goss, 1979). Figure 1 shows a spatial velocity map of CO emission near the major axis. The strong emission 2' south of the center is at a spiral arm crossing. Figure 2 shows the CO integrated intensity I, as a function of galactocentric radius in M101. All of the strongest emission was from the central 6 kpc although weak emission was found in one of the points at

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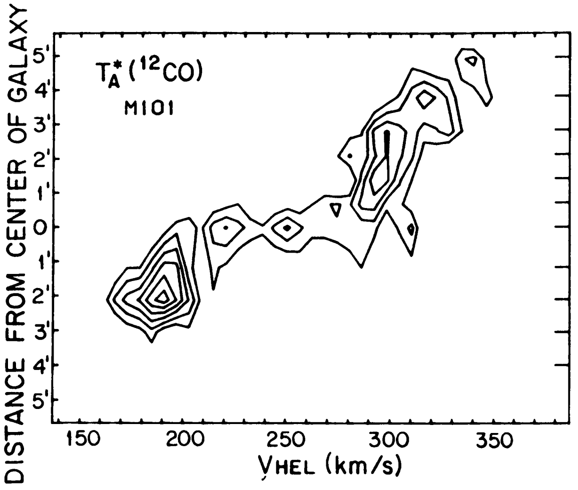
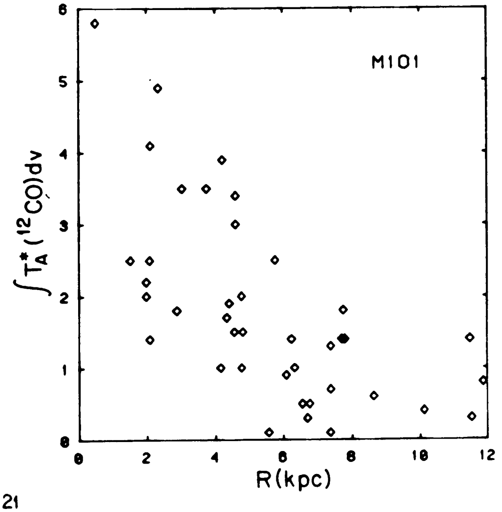


FIG. 1. CO EMISSION NEAR THE MAJOR AXIS OF M101. (SOLOMON ET AL. 1982).

FIG. 2. INTEGRATED INTENSITY I, FOR INDIVIDUAL POINTS IN M101. BEAM DIAMETER = 1.5 kpc.



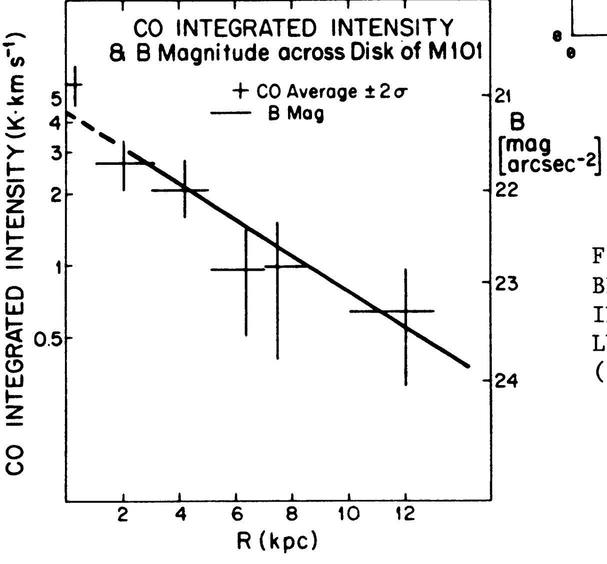


FIG. 3. CORRESPONENCE BETWEEN CO INTEGRATED INTENSITY AND BLUE LUMINOSITY IN M101. (SOLOMON ET AL. 1982).

12 kpc. The general trend of increasing I with decreasing R is obvious. There is, however, a great deal of real scatter which shows a contrast as high as a factor of four between points at the same R. Of the 40 positions observed, 25 show positive CO detections, 21 of these are stronger than CO observed at an H II region in the outer part of M101 by Blitz _et al_. (1982). Clearly the outer regions of M101 are weak in CO emission.

Figure 3 shows the _average_ CO integrated intensity as a function of radius on a semi-log plot employing all 40 observations. The mean integrated intensity shows a clear decrease with radius by about a factor of eight from the center to 12 kiloparsecs radius. Since the central point may be affected by peculiar activity associated with the nuclear region, the distribution of CO emission may be better indicated by the points between 2 and 12 kpc; over this range the mean CO integrated intensity declines by a factor of four. This systematic decline is completely unlike the 21 cm emission. The solid line in Figure 3 shows the blue surface brightness normalized to the CO integrated intensity at R = 4 kpc. There is a strong correlation between the CO emission and the exponential falloff of the optical disk indicated by the blue surface brightness first demonstrated for spirals by Freeman. The scale length of the CO emission is the same as the optical emission to within the errors of the determination. From Figure 4 which shows HI and H_2 surface densities, it is clear that in the inner part of M101 ($R<6$ kpc) the interstellar medium is predominantly in the form of molecular hydrogen. The surface density of molecular hydrogen has been determined from the CO surface brightness using the expression

$$N_{H_2} = 3.6 \times 10^{20} \int T_A^* \, dv \qquad (\mathrm{cm}^{-2})$$

The predominance of H_2 will remain true even if the conversion factor were decreased by a factor of 4 or more. Thus these CO observations show that there is no deficiency of interstellar matter in the inner disk as suggested by HI measurements.

IC 342 and NGC 6946

Young and Scoville (1982a) have convincingly demonstrated the correspondence between blue luminosity and CO integrated intensity for the two Scd galaxies IC 342 and NGC 6946. They show a monotonic decrease of CO integrated intensity across the disks of these galaxies along both the major and minor axis as can be seen for IC 342 in Fig. 5. A different interpretation based on independent data has been given for these galaxies by Rickard and Palmer (1981) who state that a nuclear source plus a flat disk will fit the radial distribution equally well. Actually a close inspection of the IC 342 data does show a flat stretch between 3 and 6 kpc but the CO data of Young and Scoville which goes out to 9 kpc correlates very well with the optical emission. Young and Scoville find a factor of 20 times more surface density in H_2 than HI in the center of N 6946 (see Fig. 6) with H_2 dominating the interstellar medium inside of 10 kpc.

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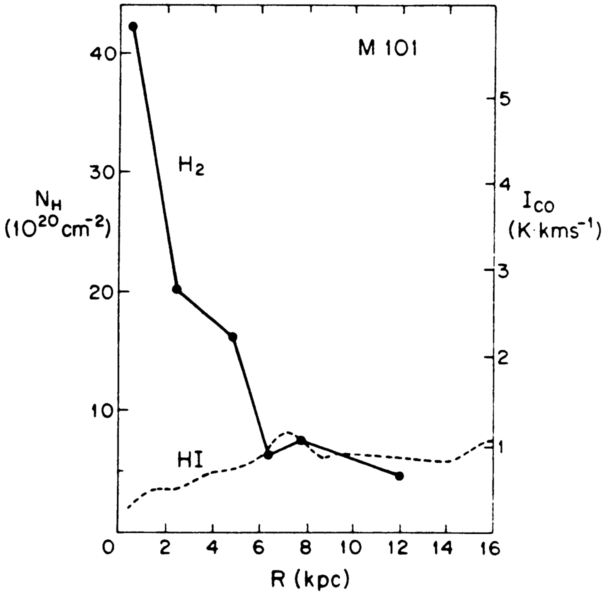
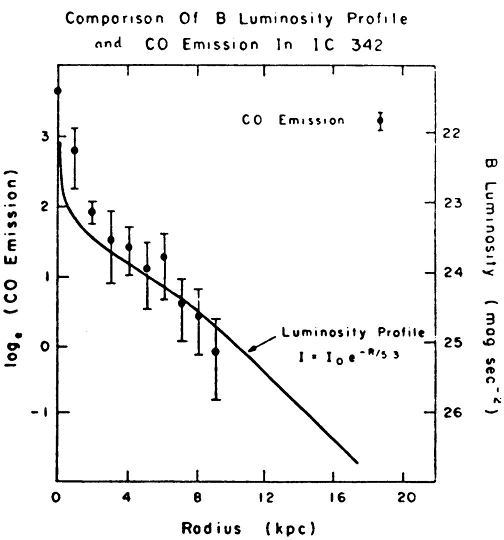
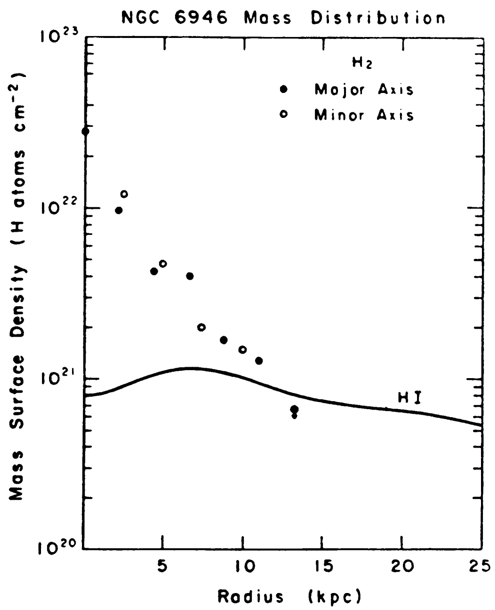


FIG. 4. COMPARISON OF H_2 AND HI SURFACE DENSITIES IN M101 (SOLOMON ET AL. 1982)





FIGS. 5 and 6. (YOUNG AND SCOVILLE 1982)

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M51

M51 has been observed by Rickard and Palmer (1981) and Scoville and Young (1982). Scoville and Young have shown that the CO emission, Far I.R. and radio continuum all correlate strongly, with a scale length of 3.9 kpc. This galaxy has 3/4 of all interstellar matter in H_2. From Fig. 7 the HI appears to be a very minor constituent in the inner few kpc.

Sc and Scd systems

The four galaxies discussed above are all Sc I or Scd I systems. They have in common a linear relationship between CO emission and optical surface brightness. This has been interpreted by Young and Scoville (1982) and Solomon et al. (1982) as indicating that the star formation rate is proportional to the first, rather than the second, power of the average molecular density. This generalization must be regarded as preliminary in view of the small sample. In N628 (Solomon 1983) there is some indication that CO falls off more slowly than the optical light.

NGC 891

N891 is an edge on (i = 88°) Sb I galaxy which is often compared to the Milky Way. The CO emission across the disk has been measured by Solomon et al. (1982 The large line of sight through the disk enables the observer to determine the radial distribution of emission from relatively strong signals by assuming an axisymmetrick disk. The average CO emission as a function of radius from the galaxy, NGC 891, can be determined out to 15 kpc by 11 observations spaced every 0!75 (3 kpc if D = 14 Mpc) along the major axis. These CO observations are approximately analgous to observing our Galaxy with a very small (~ 1 cm) antenna or just a feed horn. The difference between the HI and H_2 distribution is given in Fig. 8 which depicts the integrated intensity of CO, HI (Sancisi and Allen 1979) and nonthermal radio continuum as a function of distance along the major axis. The half power projected radius of the CO emission is only 2!5 corresponding to less than half of the size of the optical disk while the HI extends out to 4!5 to its half power points. The CO emission has a half power size close to that of the nonthermal radio continuum, and both are concentrated in the inner galaxy. The central dip in Fig. 8 in HI and possibly CO is effected by overlapping clouds at the same velocity along the line of site.

The total mass of molecular hydrogen, H_2, in N891 inferred from the total integrated intensity across the disk assuming D = 14 Mpc is $M(H_2) = 7 \times 10^9\ M_\odot$. Sancisi and Allen (1979) find for total atomic H mass, $M(HI) = 8 \cdot 10^9 M_\odot$. Thus approximately one half of all ISM in N891 is in the form of H_2 but the two components have completely different radial distributions. The inner half of N891 has an ISM dominated by H_2 and the outer half dominated by HI.

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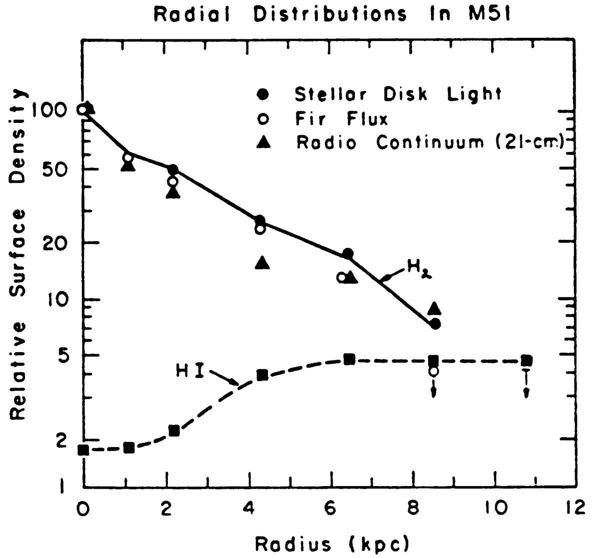

FIG. 7. COMPARISON OF CO, FAR I.R., RADIO CONTINUUM AND HI IN M51. (SCOVILLE AND YOUNG 1982)

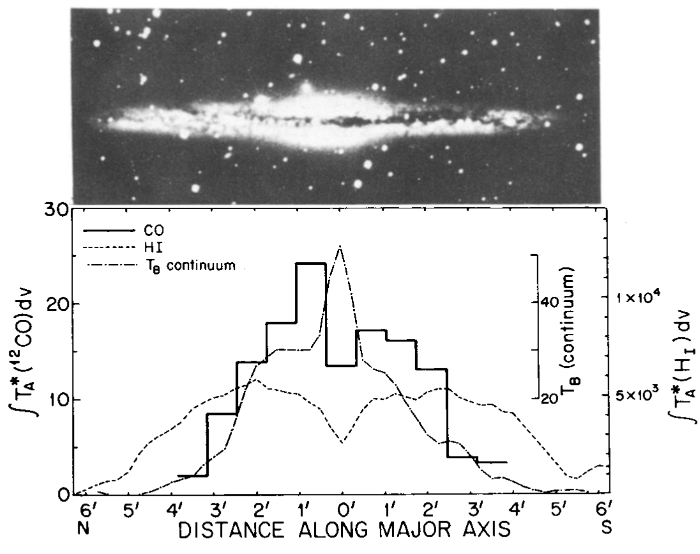

FIG 8. COMPARISON OF CO, HI AND RADIO CONTINUUM IN N891 (SOLOMON ET AL. 1982).

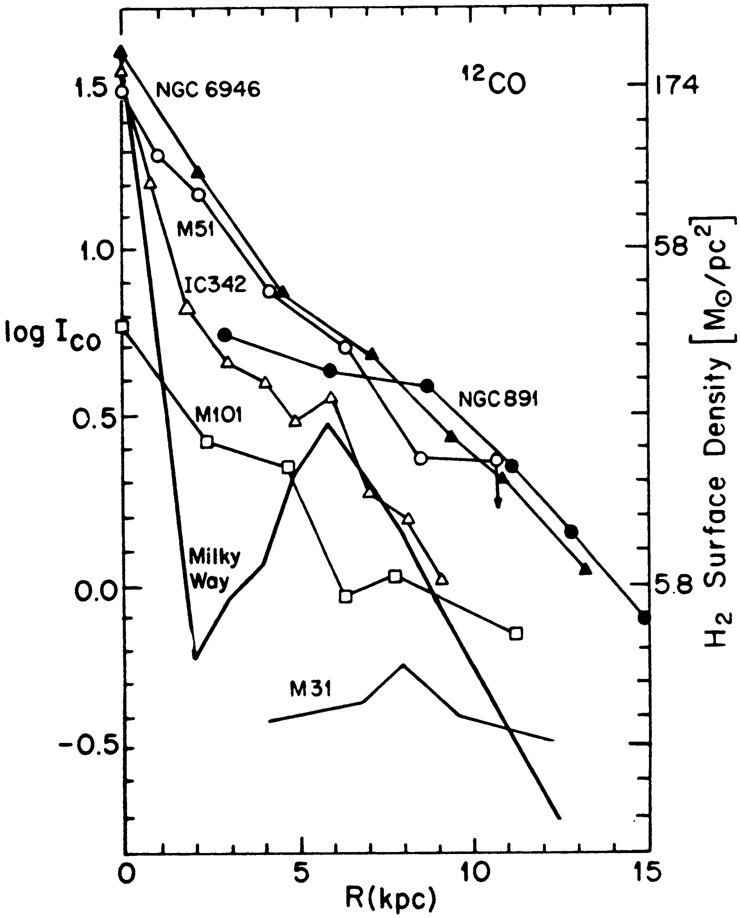

FIG. 9. RADIAL DISTRIBUTION OF CO EMISSION IN 6 GALAXIES COMPARED WITH THE MILKY WAY.

M31

M31 has been mapped in CO emission by Stark (1980) and by Linke (1982) who reports a very close correspondence between the HI "arm" and CO emission. However in sharp contrast to all of the other galaxies discussed here, M31 is a very weak CO emitter, almost an order of magnitude lower in I(CO) than the Galaxy. The CO emission appears to be confined to the region of optical obscuration where HI emission peaks with extremely weak CO emission in the central 6 kpc. Thus there is no region in M31 corresponding to the molecular ring of the Galaxy or to the inner 1 kpc of the Galaxy. The interstellar medium in M31 unlike all of the others discussed here is mainly atomic hydrogen throughout.

Summary of Radial Distribution and Comparison with the Galaxy

Figure 9 shows the radial dependence of CO integrated intensity I, for the 6 galaxies discussed above, compared with that of our Galaxy (determined from the Stony Brook-Massachusetts survey of the Galaxy by Sanders, Solomon and Scoville 1982). In all cases I(CO) is the equivalent face on integrated intensity. The determination of H_2 surface density assumes a constant (with radius) conversion factor given above. The magnitude of I(CO) in the Galaxy is similar to that of M101 and IC 342 at R ~ 6 kpc but the shape of the distribution is clearly different. There is no inner gap in the molecular cloud distribution at 3 or 4 kpc in the disk of the ScI galaxies. The deficiency of molecular clouds at R = 1-4 kpc may be a characteristic of Sb galaxies; N891, which is classified SbI, does show some indication of a turnover in I and there is some evidence of a hole in two Sb galaxies observed by Young and Scoville (1982b).

Another interesting consequence of these observations, which remains to be tested with many more galaxies, is that although the HI surface density of galaxies seldom is more than about 5 $M_\odot/pc^2$ and has a fairly flat distribution (with R) with a central dip, the H_2 varies by more than an order of magnitude. Whenever the total surface density of interstellar matter exceeds about 5 $M_\odot/pc^2$, the excess appears to be in the form of H_2 in molecular clouds (Solomon et al. 1982). From this point of view the most important property of a galactic disk is the total surface density of interstellar matter which determines the star formation rate and luminosity of the galaxy.

References

Allen, R.J. and Goss, W.M., 1979 A. and A. Suppl. 36, 136.
Blitz, L., Israel, F.F., Neugebauer, G., Gatley, I., Lee, T.J., Beattie, D. H., 1981, Ap.J. 249, 76.
Cohen, R.S. and Thaddeus, P., 1977, Ap.J.Letters 217, 155.
Gordon, M.A. and Burton, W.B. 1976, Ap.J. 208, 346.
Linke, R. 1982, NRAO "Symposium on Extragalactic Molecules" ed. M.Kutner.
Rickard, L.J. and Palmer, P. 1981, Astron. Astro. 102, L13.
Sancisi, R. and Allen, R.J., 1979, A.and A.74, 73.
Sanders, D.B., Solomon, P.M. and Scoville, N.Z. 1982 (submitted Ap.J.)
Schweizer, F., 1976, Ap.J. Suppl. 31, 313.
Scoville, N.Z. and Solomon, P.M., 1975, Ap.J. 199, L105.
Scoville, N.Z. and Young J. 1982 (Preprint).
Solomon, P.M., Sanders, D.B., Scoville, N.Z. 1979, IAU Symposium No. 84 ed. B. Burton, p. 35.
Solomon, P.M. and Sanders, D.B., 1980, "Giant Molecular Clouds in the Galaxy" eds. P. Solomon and M. Edmunds, Pergamon Press.
Solomon, P.M., Barrett, J., Sanders D.B. and deZafra, R. 1982a (to be published Ap.J. Letters).
Solomon, P.M., Barrett, J. and deZafra R. 1982b, submitted to Ap.J.
Solomon, P.M. 1983 (to be published).
Stark, A. 1980, Ph.D. Thesis, Princeton University.
Young, J. and Scoville N.Z. 1982a, Ap.J. July 15.
Young, J. and Scoville, N.Z. 1982b (to be published Ap.J. Letters).

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