MOLECULAR CLOUDS IN EXTERNAL GALAXIES

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1. INTRODUCTION

Observations of the large-scale distribution of molecular clouds in external galaxies offer a unique opportunity for investigating galactic evolution. New generations of stars form in these dense regions, and the most massive of these stars recycle their processed interiors into the interstellar medium. Early observations of the CO distribution in the Milky Way (Scoville and Solomon 1975; Burton and Gordon 1976) indicated that there is intense emission at the center of our Galaxy, very little gas between 1 and 4 kpc radius, and a "molecular ring" feature between 4 and 8 kpc. Observations of molecular clouds in external galaxies of a variety of Hubble types and luminosities will enable us to more clearly understand the origin of this distribution. Although no other galaxies are observed to contain CO distributions precisely like that in the Milky Way, the differences which are present provide important clues to the structure and evolution of galaxies.

I have been conducting a large observational program in collaboration with Nick Scoville investigating the molecular contents of galaxies using the 14-m telescope of the Five College Radio Astronomy Observatory (HPBW = 50"). The aims of this program are to determine (1) the radial distributions of molecular gas in particular galaxies, (2) the relative CO content in galaxies as a function of Hubble type and luminosity, (3) the relative confinement of molecular clouds to spiral arms, and (4) the CO contents of active galaxy nuclei. To date we have observed 77 galaxies--including spirals, ellipticals and irregulars--detected 40 and mapped 23.

II. CO DISTRIBUTIONS IN SPIRAL GALAXIES

Of all spiral galaxies, the Sc's have been found to be the most abundant in molecular clouds. We have detected 21 out of 27 Sc galaxies observed out to the distance of the Virgo Cluster. Observations of several luminous, relatively nearby Sc galaxies--IC 342, NGC 6946, and

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M51--indicate that the CO peaks at the centers and decreases with radius, following the exponential luminosity profile of the disk out to ~ 10 kpc (Young and Scoville 1982a; Scoville and Young 1983). In each of these high-luminosity galaxies, the abundance of H_2 at the center is found to be much greater than that of HI, while in the outer parts the H_2/HI ratio falls close to or below unity. The molecular masses out to radii of ~ 10 kpc in these galaxies were found to be comparable to the HI masses of the entire disk (out to > 25 kpc radius).

While the HI distributions in late-type galaxies are all very similar (i.e. relatively flat profiles with surface densities of ~ 10^{21} atoms cm^{-2} across the disk; cf. Rogstad and Shostak 1972), this was not found to be the case for the molecular distributions. This is dramatically shown in Figure 1, illustrating the H_2 and HI distributions in the high-luminosity galaxies IC 342 and NGC 6946 as well as the low-luminosity Sc galaxies M33 and NGC 2403. Although the HI distributions in these galaxies are all very similar, the surface densities of H_2 vary tremendously.

All observations of Sc galaxies made by us or reported in the literature indicate that the strongest emission in these late-type galaxies originates at their centers. The systematics for Sb galaxies, however, are not as well defined. We have observed 21 galaxies of this

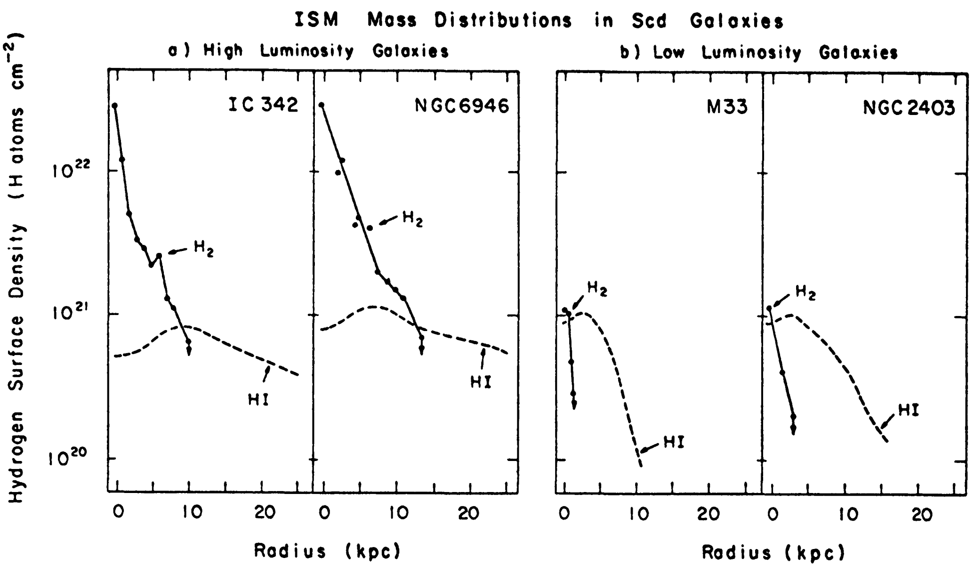

FIGURE 1. Comparison of H_2 and HI distributions in 4 Scd galaxies, two with high luminosities (NGC 6946 and IC 342) and two with low luminosities (M33 and MGC 2403). Although these galaxies all have similar HI distributions across their disks, the amounts of H_2 present vary by 2 orders of magnitude, such that only the high-luminosity galaxies have plentiful supplies of molecular clouds with which to form stars.

type and detected 11. Of the Sb galaxies whose radial distributions we have mapped, 2 were observed to have CO profiles which peak at their centers--NGC 3627 and NGC 3628 (Young, Tacconi and Scoville 1983) -- while the centers of NGC 7331 and NGC 2841 were found to contain less CO than at 5 kpc radius (Young and Scoville 1982b). Since the galaxies with central CO holes are also ones with significant nuclear bulges, we suggest that the CO hole in the early galaxies may be due to the depletion of gas in order to form stars in the nuclear bulge.

In order to test the hypothesis that central CO holes are present only in galaxies with significant nuclear bulges, we have observed a sample of 16 Sa and Sab galaxies and detected 6 of type Sab for a detection rate of 38%, relative to 78% for the Sc's. We did not detect CO in the center of NGC 4594, the Sombrero Galaxy. In two Sa galaxies which we mapped--NGC 3623 and NGC 7814--no CO was detected at any point in the disk. On the other hand, we detected and mapped the CO emission in the Sab galaxies NGC 4736 (M94) and MGC 4826 (M64). Curiously enough, in both galaxies the CO distributions show central peaks. Clearly, more observations of Sa galaxies with large bulges are needed to determine if central CO holes are present in Sa galaxies.

III. CO CONTENTS AS A FUNCTION OF HUBBLE TYPE AND LUMINOSITY

The correlation of the CO distributions and optical luminosity profiles within particular galaxies, and of the molecular content with galaxy luminosity led us to investigate a large sample of galaxies in order to elucidate the interplay between the molecular-gas contents of galaxies and their luminosities. We have observed the CO emission in a sample of Sc galaxies covering a wide range in luminosity both in the Virgo Cluster and in the field. Since it is most meaningful to compare regions of the same size in a variety of galaxies, we have mapped the CO distributions over the central 5 kpc in each galaxy and compared the CO luminosity with the optical luminosity in the same region. For the Sc galaxies we found that over 2 orders of magnitude in luminosity the optical luminosity of a galaxy increases in direct proportion to the CO content (Young and Scoville 1982c; Brady and Young 1982). If the CO emission is assumed to trace the abundance of H_2, and if the blue luminosity is taken to be mostly from Population I stars (thereby indicating the amount of star formation over the last $\sim 2\times10^9$ years), the correlation of CO intensity with B luminosity suggests that the amount of star formation is proportional to the amount of gas present. Thus, we infer that the star-formation rate per nucleon is approximately constant in Sc galaxies.

We have expanded this investigation of the interdependence of CO content and luminosity to include galaxies with earlier Hubble types. For a sample of 26 galaxies from the Virgo cluster--8 Sa's, 7 Sb's, 9 Sc's, and 2 ellipticals (M86 and M87)--we detected the centers in 13 at greater than the 4σ level (4 Sa's, 2 Sb's, and 7 Sc's). Within this sample we have compared the CO and optical luminosities in the central

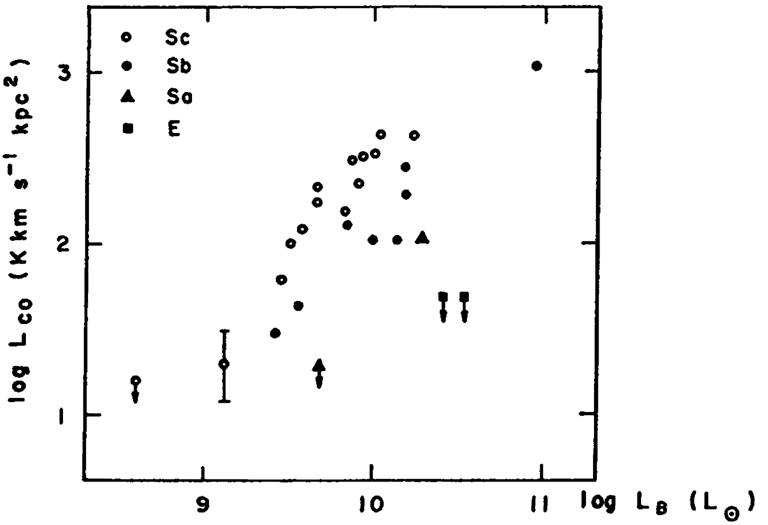

Figure 2. Comparison of CO and B luminosities of the central 5 kpc for galaxies in the Virgo Cluster and in the field. The Sb and Sc galaxies show a linear correlation over almost 2 orders of magnitude. For a given B luminosity the Sc galaxies have the most CO; for a given amount of CO the early-type galaxies are the brightest.

5 kpc of the galaxies for which B luminosities were available in the literature. Figure 2 shows this comparison for the Sa, Sb, Sc, and E galaxies in the Virgo Cluster and in the field. This figure dramatically illustrates several points. First, within each Hubble type the galaxies with high CO luminosities have the highest B luminosities. Second, at a given CO luminosity the E and Sa galaxies are more luminous than the Sb's and Sc's. And third, for a given optical luminosity the Sc galaxies have more CO than the Sa's and Sb's. The differences occurring from one type to another may simply be due to the presence of nuclear bulges -- the earlier types have higher luminosities at the centers due to the presence of the bulges (i.e., the blue luminosity is contaminated by Population II stars), and the gas contents may additionally be low as a result of gas consumption to form stars in the bulge. In order to determine the differences among the CO contents of the disk components of the various Hubble types, it will be necessary to observe CO in the Virgo-Cluster galaxies outside of the nuclear-bulge regions, out to radii of $\sim$ 10 kpc.

IV. IRREGULAR GALAXIES

Although the molecular contents of spiral galaxies are becoming fairly well understood, the link between CO luminosity and large-scale star-formation properties in irregular galaxies remains less clear. In particular, irregular galaxies often display high star-formation rates and other young structural features such as OB associations and HII regions commonly found in spirals, but most irregulars have proven

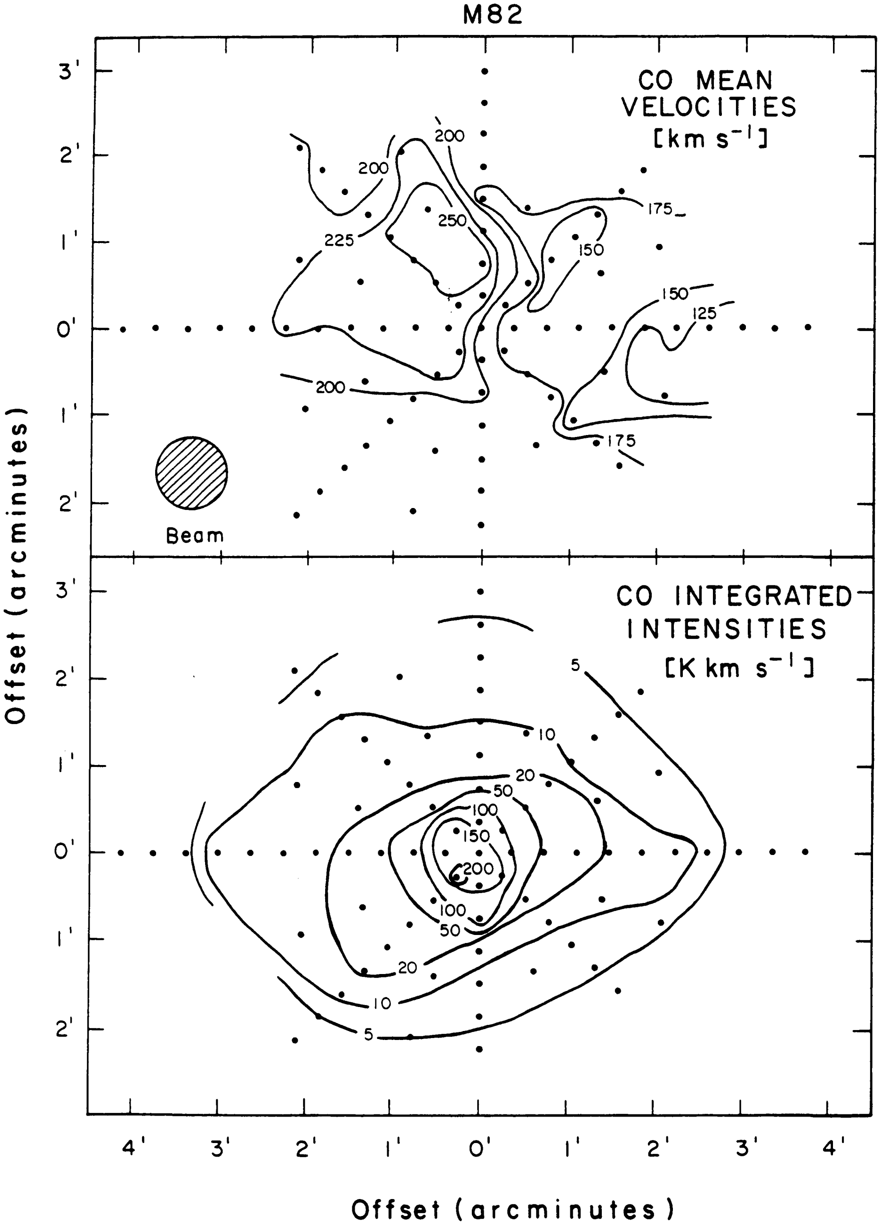

FIGURE 3. Contour maps indicating (a) the mean CO velocities and (b) the integrated intensities in M82. The velocity contours indicate that the kinematic major axis in the NE is rotated 45° to the optical major axis, an effect which can be caused by radial motions of ~ 50 km s^{-1} in the disk. The integrated intensities decrease smoothly away from the center in all directions, showing evidence for molecular clouds in the vicinity of the optical filaments located above and below the disk.

surprisingly deficient in CO emission (Elmegreen, Elmegreen, and Morris 1980). In order to more clearly define the relationship between CO luminosity and star-formation processes in irregulars, we have undertaken a program to observe CO in several irregular galaxies.

The only galaxy classified as an irregular which has been found to be abundant in molecular clouds is M82 (Rickard et al. 1977), and we have recently completed an 81-point map of the radial distribution out to 3' at 22" spacing. Figure 3 shows the mean CO velocities and integrated intensities as a function of position across M82. This irregular is similar to the high-luminosity Sc galaxies in that the H_2 abundance greatly exceeds that in HI out to at least 4' radius on the major and 3' on the minor axis. The CO emission in M82 also exhibits several peculiarities. First, emission is present not only along the major axis, but also off the disk along the minor axis in the vicinity of the tangled system of optical filaments, an aspect which was first observed by Stark (1982). Second, the mean velocities show distinct evidence for warps and irregularities, such that the overall velocity field in M82 is clearly not dominated by rotation. Since the highest velocities lie on an axis which is rotated 45° to the major axis, there must be radial motions present with a magnitude of at least 50 km s^{-1} at a radius of 1 kpc. These CO observations support the view that M82 is presently accreting material; this accretion may be responsible for the present high rate of star formation, radial motions and gas along the minor axis.

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DISCUSSION

W.M. Goss: What do you know about the distribution of CO in M101?

Young: M101 has been mapped by Solomon et al. (1983). They have the radial distribution out to about 10 kpc. It shows the same type of fall-off that we see in the other external galaxies shown here.

J.V. Villumsen: What is the azimuthal variation in CO emission in your sample of external galaxies?

Young: The azimuthal variation was indicated by the vertical bars in my viewgraphs for IC 342 and NGC 6946. The azimuthal variation at one radius is greater than the uncertainties in the measurements. The variations are not entirely random: there are no very low values close to the centre, nor very high values in the outskirts.

M.L. Kutner: Could the interpretation of the correlation between CO luminosity and blue light be the opposite to yours? The sources of blue light may heat the clouds, and by measuring CO brightness one would then measure, in part, the average cloud temperature.

Young: The blue light comes not only from the extremely young stars, which are the ones that are heating the clouds; the light comes from stars that are up to 2 x 10^9 years old, which are well away from the molecular clouds. In addition most of the gas that we see is probably not in the process of forming stars, but rather it is in the outer envelopes of molecular clouds, and at 10 K only. Some gas will be hot, the gas which is associated with the stars presently forming, but that is a very small fraction of the mass of gas that we see.

Kutner: My poster paper shows in our Galaxy a radial gradient of the average temperature of molecular clouds. The conversion from CO luminosity to mass goes as $T^{1.3}$; hence small temperature variations can have large spurious effects on the mass derived.

Young: That's right: if the temperature varies, one will not infer the correct mass for the molecular clouds from the CO observations. On the other hand: we are discussing here the inner 10 kpc of galaxies which may extend much farther (say 25 kpc) in HI. While the temperature may vary with radius, it is not clear that it would vary from one galaxy to another.

H. van Woerden: Your central holes in Sb galaxies - can they be due to saturation (selfabsorption) of the CO emission?

Young: The two Sb's shown (NGC 7331 and 2841) indeed have relatively high inclinations. Solomon et al. find a central hole in the edge-on Sb NGC 891, and they think this may in fact be due to selfabsorption. However, because the rotation curve is so steep, the velocity profile measured at the centre is very wide; hence I think selfabsorption is not much of a problem in those Sb's.

A.I. Sargent: At the Owens Valley Radio Observatory we have observed several of the galaxies you have just described at 230 GHz in the J = 2→1 CO-line. Our resolution is of order 30 arcseconds and is therefore somewhat better than yours. From a preliminary inspection of the data, we agree with the trends you have noted in IC 342. However, in the case of M51 it is not completely certain that the gas falls off as you describe; there are indications that the line intensities may first fall off away from the nucleus, but rise again near the spiral arm. We fail to detect NGC 2403 although, on the basis of your results, it should have been detectable. In addition, our results suggest that the gas is not completely optically thick in several active galaxies, not only in M82.

R.J. Allen: There is a correlation of CO emission with radio continuum emission, as already pointed out by Morris and Rickard (1982). It is the best correlation with radio continuum that I have seen. As an example, NGC 6946 and M101, which have similar morphological types, have nonthermal radio-disk brightnesses differing by almost an order of magnitude - and they now turn out to have a similar difference in CO brightness.

Young: The radio brightnesses in NGC 6946, M51 and M101 indeed fall off with the same scale length as CO.

T.M. Bania: So, is the Milky Way the only galaxy with a molecular annulus?

Young: No: the Sb galaxies NGC 7331 and 2841 have molecular rings. Further, in NGC 253, a very highly inclined Sc galaxy, we have mapped CO out to 5 kpc radius. It shows something like a ring, a factor of 2 less intense than that in our Galaxy, but definitely a maximum in the radial distribution.

Infrared observations by Neugebauer et al. show a bar in the centre of NGC 253. The point has been often made that our Galaxy may have a bar. Maybe these ring distributions are related to the presence of a central bar.

L. Blitz: It is important to remember, when interpreting CO data, that you are using a tracer which has an abundance of $\sim 10^{-4}$ of the H_2 you wish to determine. Therefore small changes in CO abundance (due to metallicity gradients) and/or excitation (due to temperature gradients) will cause large changes in the derived H_2 surface density. What you are observing is a convolution of the number of molecular clouds in the beam with the average properties of the clouds in the beam. Therefore, when you observe CO radial gradients, you may be measuring gradients in the mean properties of the cloud ensemble, rather than gradients in the H_2 distribution.

Consider, for example, the plot (Figure D1) of CO emission versus radial distance for M101 published by Solomon et al. (1983). This galaxy shows the same decline of integrated CO emission with blue light that you have shown for other galaxies. The dots are [O/H] abundances from Smith (1975). The slope of the [O/H] gradient is about one half that of the CO gradient. If the [C/H] gradient is similar to that of [O/H], the CO abundance might be proportional to the square of the O abundance. The gradient of CO emission then could be due entirely to the metallicity gradient, and the H_2 surface density might be constant as a function of radius. Alternatively, possible temperature gradients (such as those observed in Maffei 2 by Rickard and Harvey) combined with [O/H] gradients could produce the observed CO distribution, even if the H_2 surface density is constant with radius. In the light of known and possible temperature and metallicity gradients, we can not now determine the radial H_2 distribution in galaxies with any confidence from CO data, and any conclusions based on an inferred H_2 distribution must be viewed with considerable scepticism.

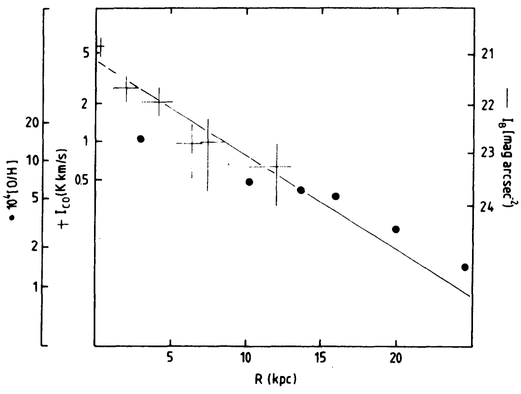

Figure D1. Radial distributions of CO emission (crosses: profile integrals in K km s^{-1}) and blue light (solid line: surface brightness in mag arcsec^{-2}), from P.M. Solomon et al. (1983). The dots represent [O/H] abundance ratios from H.E. Smith (1975).

Young: I shall leave it for Solomon to discuss the CO distribution in M101. As to the effects of abundance variations, let me make the following point. The metallicity at the centre is the same in M101, M51 and M83; yet M101 has a factor 5 lower CO brightness at its centre. Metallicity may have an effect, but we do not know what effect, and it can not have caused the difference between M101 and the other two galaxies. In addition, the metallicity in M33 is constant over the range in radius where we observe CO to fall off. In M51, the metallicity drops by a factor 5 only, the CO emisson by a factor 100. In general, the distributions of CO and O/H are not proportional like in M101. We need good metallicity gradients and a good understanding how C varies with O.

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Top: Anneila Sargent (right) discusses her CO observations of galaxies with Antonella Natta. CFD

Bottom: Leo Blitz in his discussion with Judy Young CFD