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CO OBSERVATIONS OF GALAXIES WITH THE NOBEYAMA 45-M TELESCOPE

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ABSTRACT

High-resolution (15"), filled aperture maps of the CO (J=1-0) line emission have been obtained of several nearby, CO-bright galaxies like M82, M83, IC342, NGC891, etc. in order to study star forming activity in these galaxies.

1. INTRODUCTION

Star formation in galaxies is intimately related to their molecular hydrogen content from which stars form. In order to obtain high-resolution, high-sensitivity and filled aperture maps of H_2 gas in spiral galaxies, we have conducted a survey of the CO (J=1-0) line emission at 115 GHz using the 45-m telescope at the Nobeyama Radio Observatory. The survey already includes nearby, CO-bright galaxies like M82, M83, M51, NGC253, NGC891, IC342, and NGC6946. We have obtained an almost complete map of M82, a map of the bar and central region of M83, a map of the central region of IC342, high-sensitivity scans along the major and minor axes of the edge-on galaxy NGC891, and several incomplete maps of the other galaxies. The survey is being extended to more galaxies. In this paper we report the results for NGC891, M83, IC342, and M82.

2. NGC891

The large-scale distribution of the CO line emission in disk galaxies has an important implication for understanding the structure and dynamics of gaseous content and the evolution of star-forming activity on a galactic scale. In the case of edge-on galaxies, one dimensional scan maps can give fairly complete information about the large-scale CO distribution in a realistic observing time.

NGC891, a typical edge-on Sb, shows a very similar property to our Galaxy. It has been observed in CO using the FCRAO 14-m telescope with a resolution of 45" (Solomon 1981;1983). The CO intensity distribution is characterised by a ring-like concentration at radius 5 kpc and a central hole. It is well known that the Milky Way, a typical Sb galaxy, has a strong central concentration of molecular gas forming a dense nuclear disk (e.g. Liszt and Burton 1978). It is therefore interesting to clarify by high-resolution observations whether Sb galaxies like NGC891 have a nuclear molecular disk. Another important implication of the CO observations of edge-on galaxies is to derive a rotation curve of molecular gas without the ambiguity of inclination angle. A CO rotation curve is especially important to see the dynamics of the central region, for the HI emission has a depression, giving poor information about the central region (Sancisi and Allen 1979).

Observed CO line spectra along the major axis are shown in figure 1. The intensities are corrected antenna temperature calibrated with respect to Ori A

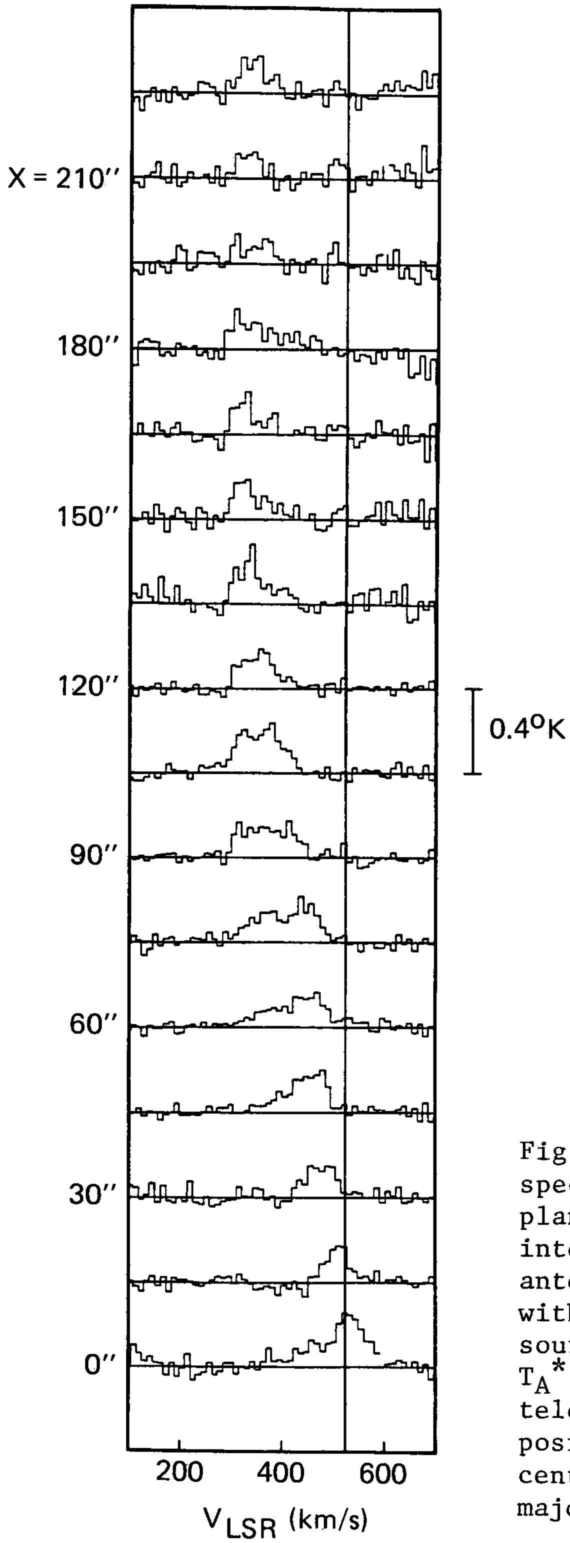

Fig. 1. ^{12}CO (J=1-0) line spectra along the galactic plane of NGC891. The intensity is the corrected antenna temperature T_A^* with respect to a standard source Ori KL which had T_A^* = 35 K with the 45-m telescope. Here X is the position off-set from the centre toward NE along the major axis.

with $T_A^* = 35$ K. Figure 2 shows a position-velocity diagram along the major axis. The rotation curve as derived from the terminal velocities (as drawn with the dashed line) coincides with the HI rotation curve of Sancisi and Allen (1979). From the rotation curve the dynamical mass contained within 15 kpc (225") is estimated to be 2×10^{11} $M_\odot$. The diagram shows that there exist many clumpy structures, which we identify with tangential directions of spiral arms, except for the central strong peak.

The distribution of integrated CO intensity is shown in figure 3. We find that the radial CO distribution is composed of two components: a broadly spread main-disk with the maximum at 60" (5 kpc) radius, tailing as far as to 15 kpc from the center, and a strong concentration toward the center, having a sharp peak of I_{CO} = 26 K km s^{-1}, which we refer to as the nuclear disk.

The main disk is distributed on a broad ring of radius 5-15 kpc with its peak at about 5 kpc. This well resembles that of our Galaxy which has the 5-kpc molecular ring. The main disk is well visible at least up to 15 kpc and appears to extend further beyond this radius. The total mass of molecular hydrogen gas, as derived using the same conversion factor as that used in Solomon (1983) but taking care of the difference between the antenna temperature of Ori A for the 45-m telescope and the 14-m telescope, is about 7×10^9 $M_\odot$. This shares 4 percent of the dynamical mass and this fraction is comparable to that in our Galaxy.

The nuclear disk has a radius of about 0.5 kpc, but the thickness is not resolved. This component has been detected for the first time for an external Sb galaxy, which confirms that NGC891 has a similar characteristics to our Galaxy, as the size and mass, 3×10^8 $M_\odot$, of molecular gas, are comparable to the nuclear disk in our Galaxy. The velocity dispersion near the center of this component is more than 100 km s^{-1}. The high dispersion may be partly due to internal motion of gas and partly to the steep gradient of the rotation curve. From the velocity dispersion a dynamical mass of 10^9 $M_\odot$ is derived. This leads to a fractional mass of molecular gas in the nuclear disk as high as 30 percent, much higher than that observed in the main disk. This suggests either that the molecular gas is really rich or that the conversion factor from I_{CO} to H_2 mass adopted here (Solomon 1983; Young and Scoville 1982) was too large. If the latter is the case, we have a higher rate of production of heavy elements in the central region than in the main disk: if the molecular mass shares $\sim$10% of the dynamical mass as in the main disk, the CO abundance in the nuclear region is about three times as large as that in the main disk.

Figure 3 compares the CO distribution with those of HI (Sancisi and Allen 1979) and radio continuum (Allen et al. 1979). The CO main disk has a similar distribution to that of the broad disk of the continuum emission. The HI gas is more widely distributed than CO and continuum. The CO nuclear disk coincides well in position with the central peak of continuum. This shows a significant correlation between the nuclear activity and the existence of a dense molecular disk in the center. A detailed description is given in Sofue et al. (1986).

2. M83

The SABc galaxy M83 is the nearest barred spiral (3.7 Mpc distance). The bar structure in a galaxy gives a deep nonlinear potential wave in the rotating material. The interstellar gas suffers a strong shock wave in such a deep

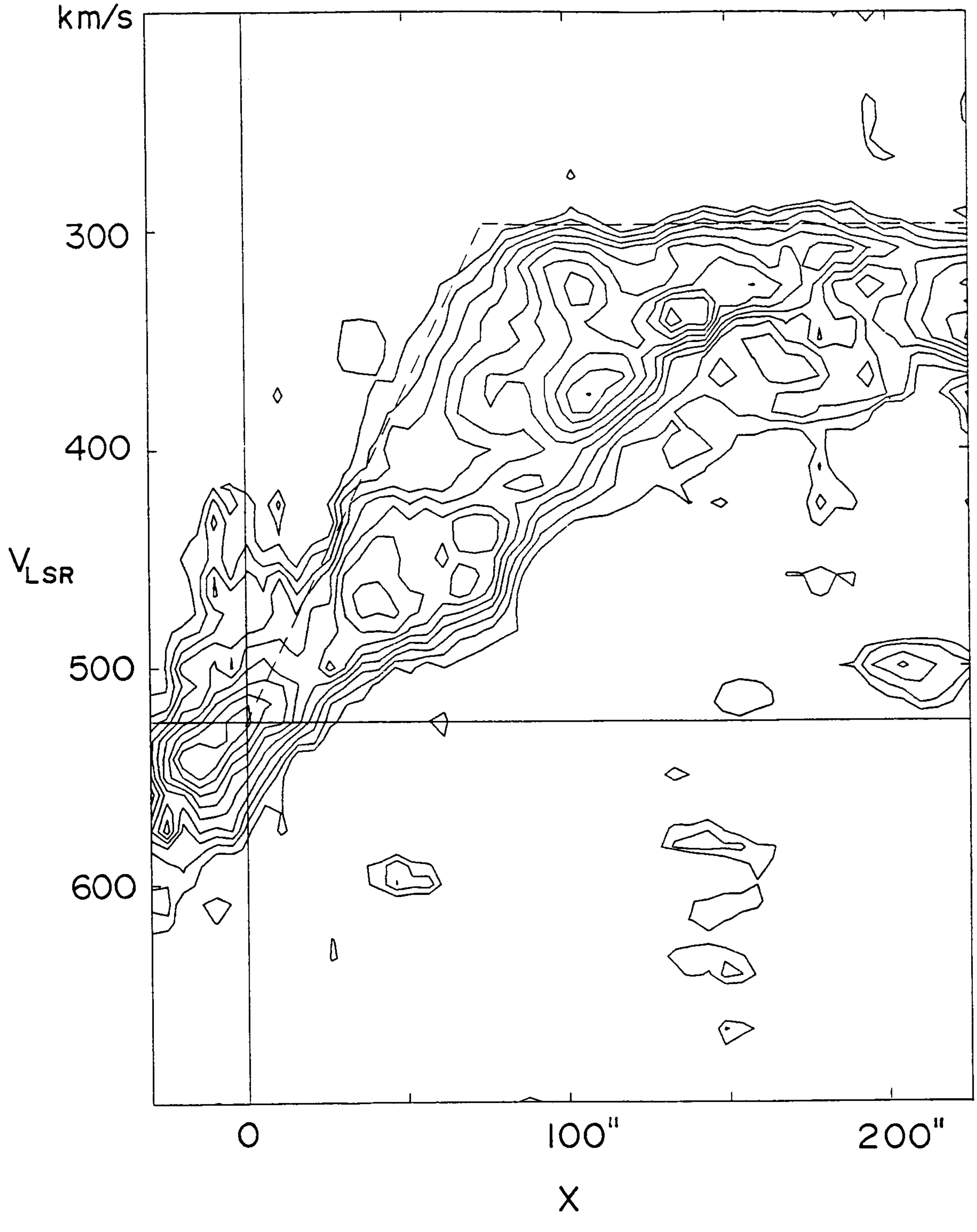

Fig. 2. Position-velocity diagram along the galactic plane of NGC891. The contours are in steps of 20 m K T_A^* and the lowest contour is at 40 m K.

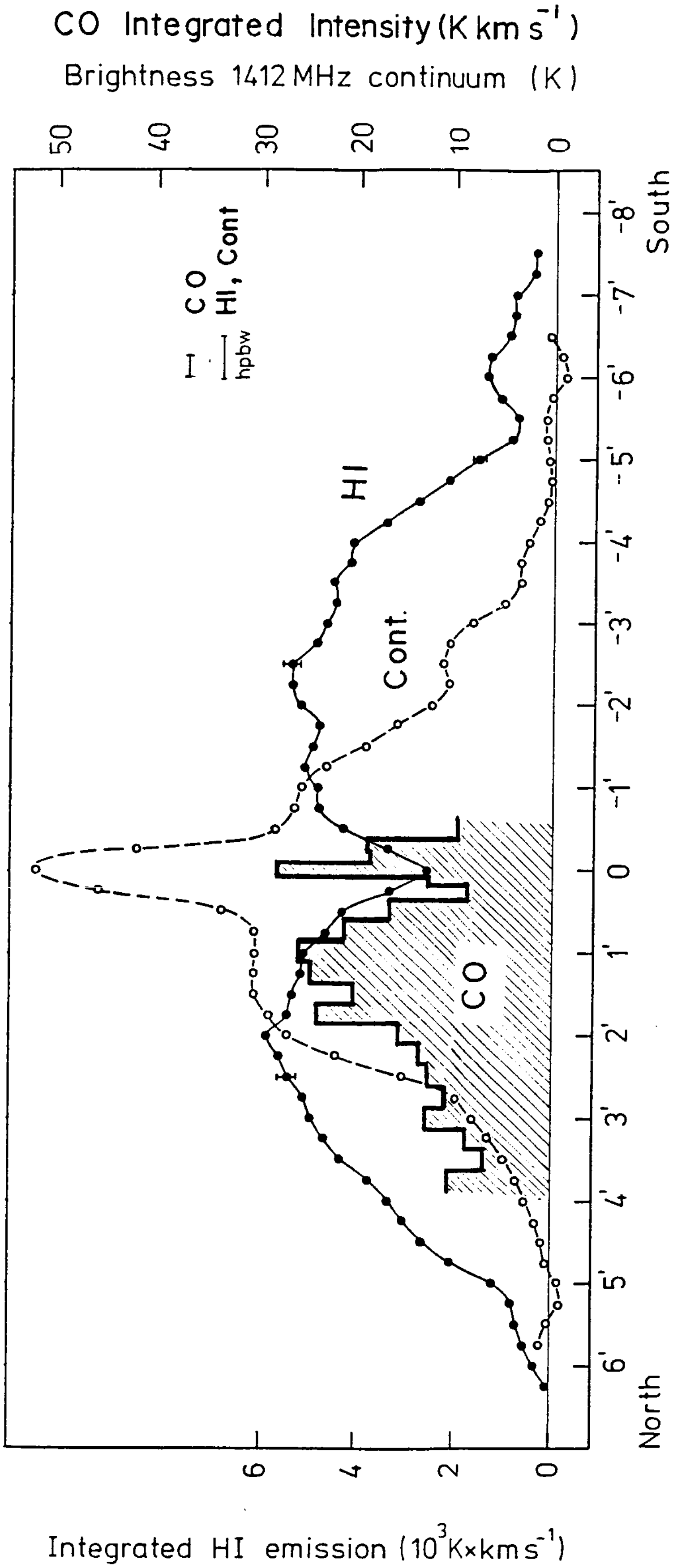

Fig. 3. Intensity distribution of the integrated CO line emission along X (hatched diagram). The HI (Sancisi and Allen 1979) and radio continuum (Allen et al. 1978) intensity distributions are superposed for a comparison. Note the coincidence of the CO main disk with the continuum disk and of the CO nuclear emission with the continuum nuclear emission.

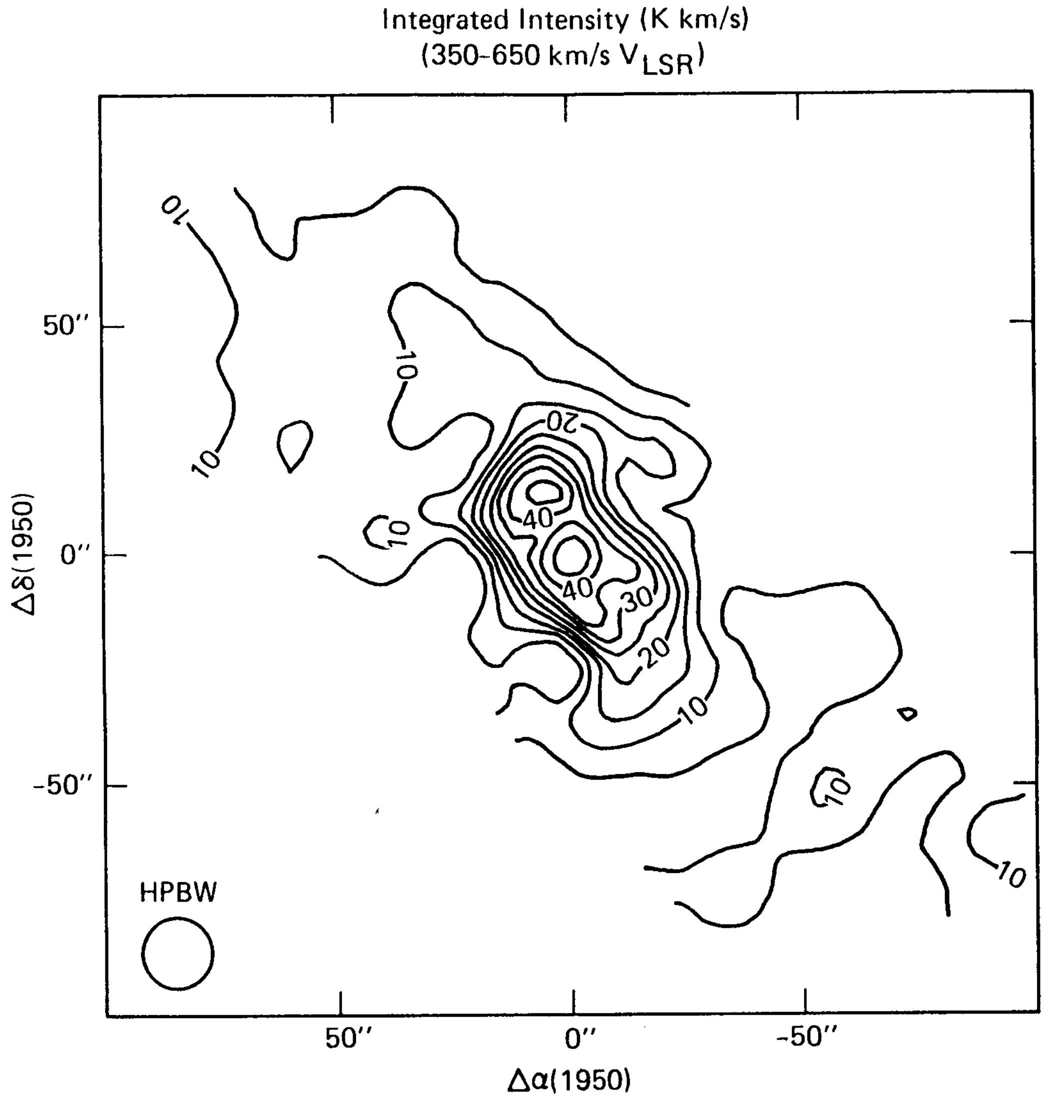

Fig. 4. CO intensity map of the barred region of M83. Note the strong concentration in the central 20".

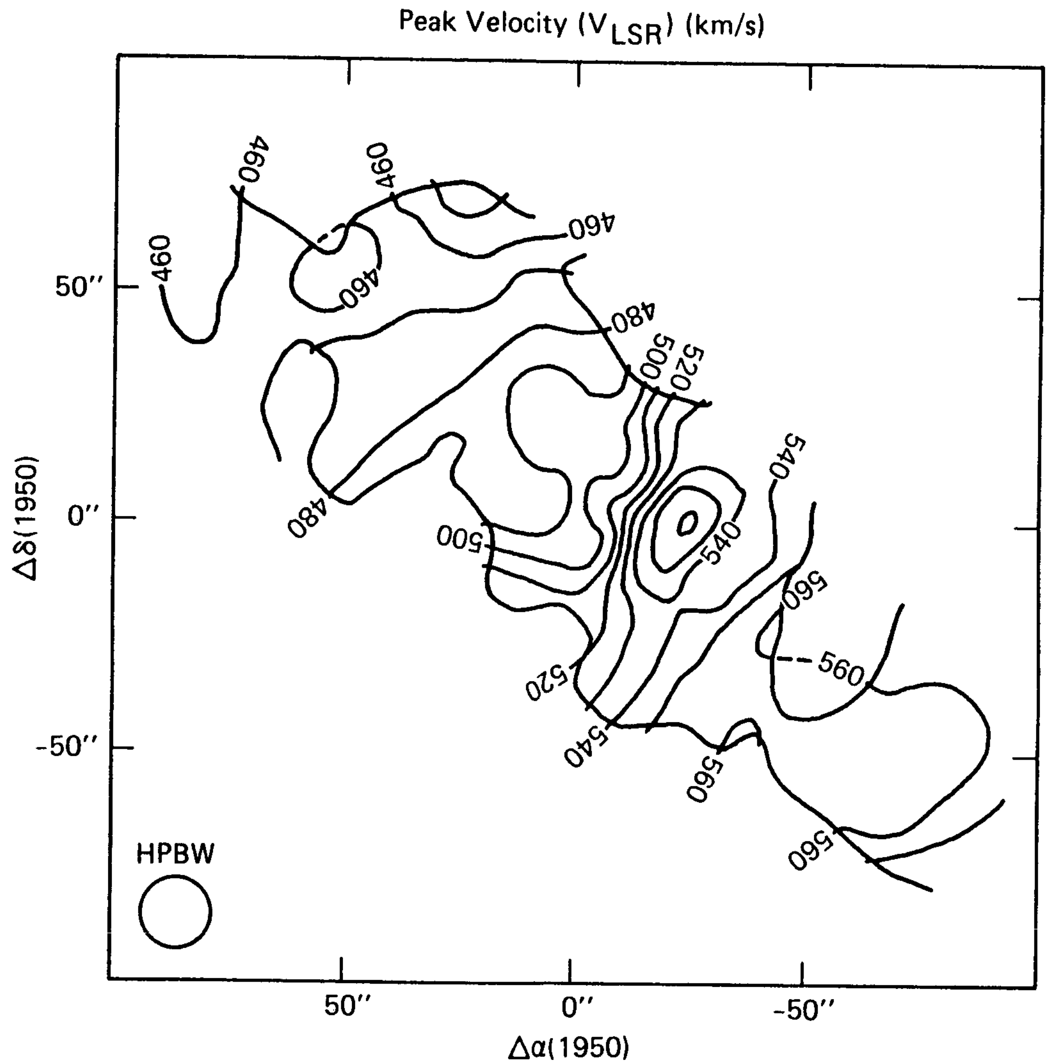

Fig. 5. Peak velocity distribution of CO gas in the bar of M83. A non-circular motion of 20 - 30 km s^{-1} is seen near the center.

potential (Sørensen et al. 1976; Roberts et al. 1979). In fact well developed dark lanes are found along the leading sides of the bar of M83 indicative of a shocked concentration of molecular gas. The strong shock will cause loss of angular momentum, leading to an accumulation onto the galactic center. Infall of gas toward the center may result in a high rate of star bursting, which is observed as the strong radio continuum emission near the center (Ondrechen 1985). The radio continuum observations show evidence of nonthermal emission along the barred shocked region. It is therefore important to investigate the motion of gas in and around the central barred region.

The high resolution map of HI line emission by Allen et al. (1986) shows, however, a depression in the central region including the bar, giving no information about the motion of gas there. In order to see the motion in the bar and gaseous concentration toward the center we have performed a survey of the CO line emission as the tracer of the molecular hydrogen gas. Our CO map covers a region of 3.5' x 1' along the bar, where most of the bar is included. Figures 4 and 5 show the distributions of total intensity, namely the H_2 column density, and the velocity field, respectively (Handa et al.1986).

The gas is concentrated in the central 1' x 0.5' (1 x 0.5 kpc) region, where about 40% of the gas in the observed region is found. The central gas distribution is elongated roughly along the bar, but shows an S-shaped ridge with two strong peaks, one is associated with the center, and the other is more shifted from the center by 10" (200 pc).

In the barred region a rather broad CO distribution is found, and the peak positions of the CO intensity runs approximately along the leading sides of the bar.

A clear noncircular motion is found in the central 1' (1 kpc). The amount of the noncircular motion subtracted for the circular rotation is about 20-30 km s^{-1}. This may be a superposition of deceleration by the shock and the infall motion. Beyond 1' from the center the velocity field resembles the circular rotation, although the sensitivity of the present observations might not be enough to detect weak noncircular motion.

The strong concentration of molecular hydrogen toward the center and its noncircular motion is suggestive of the infall of matter due to the barred shock wave, and must be intimately related to the activity of star formation observed in optical, infrared, UV, X-ray, and radio observations (Rieke 1976; Bohlin et al. 1983; Trinchieri et al. 1986; Ondrechen 1985).

4. IC 342

Extensive CO line observations of this bright S_{cd} galaxy have been made by Rickard and Palmer (1981) and Young and Scoville (1982). IC342 has a bright optical nucleus with a dark lane elongated in the north-south direction. A prominent molecular bar has been found lying on the dark lane using the Owens Valley interferometer (Lo et al. 1984). Their field of view was spatially limited by the primary beam as well as by the velocity coverage of the spectrometer. It is therefore not known whether the molecular bar is connected to the outer spiral arms, whether the bar is surrounded by more broad gas distribution, etc. We have made a highest resolution CO map accessible by a single-dish with

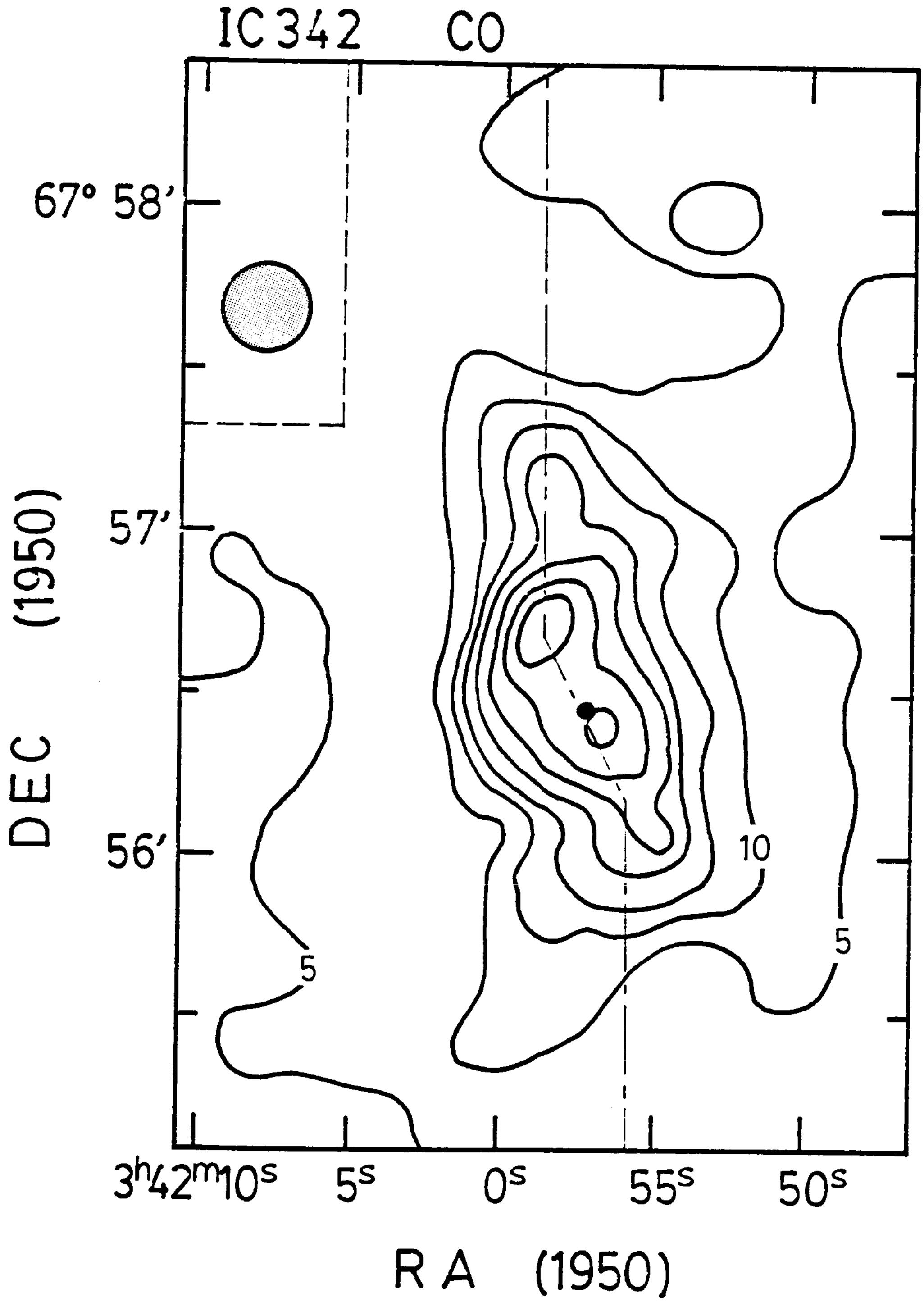

Fig. 6. Distribution of the integrated CO intensity of the bar of IC342. The 2.2 μm peak position is marked with the dark circle. Contour unit is in K km s^{-1}.

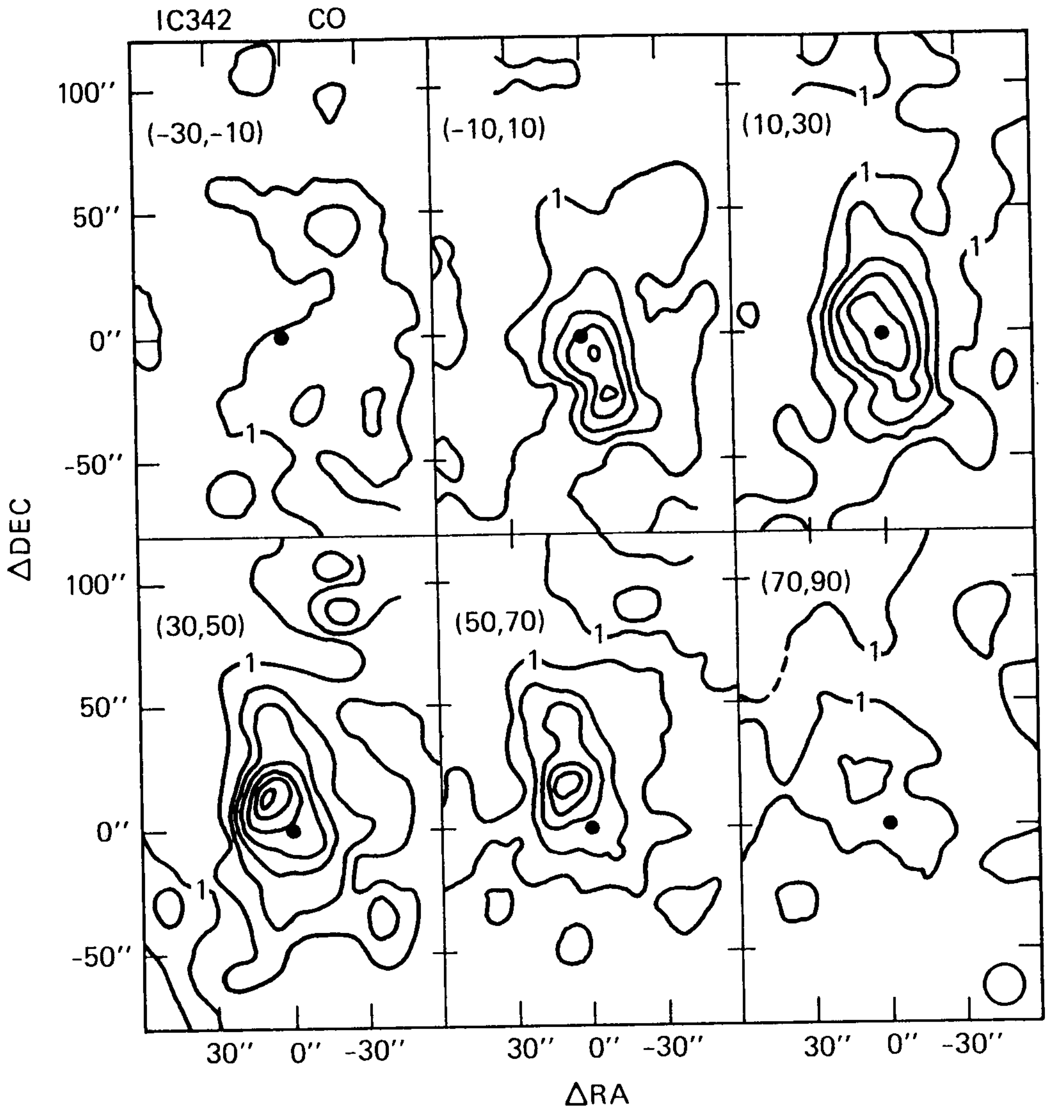

Fig. 7. Equal-velocity integrated CO intensities of IC342.

a sufficient velocity coverage (Hayashi et al. 1986).

Figure 6 shows a distribution of the integrated intensity of CO line emission. The dark circle is the center of the galaxy as determined by 2.2 μm infrared emission (Becklin et al. 1980). The CO emission is concentrated in the central bar whose size is 1.3x0.6 kpc after being deconvolved from the beam. Little CO emission is seen outside the bar: the molecular bar is localized within the optical bulge and is not connected to the outer spiral arms. The result is consistent with that of Lo et al. (1984), but our result suggests that the bar is more spread in the minor axis direction than the interferometer result. The beam-deconvolved width of the bar is 0.6 kpc and is considerably wider than that measured by Lo et al. (1984). The narrower width of their CO map might be caused by the limited velocity coverage of their spectrometer.

The CO bar has a double-peaked structure with a shallow dip toward the nucleus, being symmetric with respect to it. The two maxima lie about 200 pc away from the nucleus. The molecular hydrogen mass of the nuclear bar is estimated to be 2×10^8 $M_\odot$. Five percent of the total H_2 mass is accumulated in the central small area. This may explain the vigorous star forming activity in the nuclear region of this galaxy (Becklin et al. 1980; Turner and Ho 1983).

Figure 7 shows equal-velocity intensity maps, where intensities at every 20 km s^{-1} are shown in the form of contour maps. At the systemic velocity, the intensity distribution has a symmetric bar structure, whereas at 30 - 50 km s^{-1} there exists a dense complex at 15" to the NE of the center, and no counterpart to this complex is seen at the opposite side at $-10 \sim 10$ km s^{-1}. The velocity distribution shows a significant displacement from a circular rotation consistent with Lo et al. (1984). The noncircular motion may be related to the formation of the bar concentration of gas in the central region.

5. M82

The peculiar edge on galaxy M82 is well known with its filamentary structure running perpendicularly to the galactic plane, which suggests an intensive outflow of gas from the disk (Lynds and Sandage 1963). The dynamic state of the galaxy may be caused by star formation activity near the center (Rieke et al. 1980; Kronberg et al. 1985). The active star formation must be deeply related to the dense molecular hydrogen gas concentrated near the central region (Olofson and Rydbeck 1984; Nakai et al. 1986; Lo et al. 1986).

Figure 8 shows the intensity distribution of the CO line emission in the central 40" of M82 as observed with the 45-m telescope. Figure 9 shows a distribution of volume density of H_2 gas obtained by deconvolving the observed CO intensity on the assumption of a cylindrical symmetry around the rotating axis. It is remarkable that there exists a hole at the center, surrounding which we find a "200-pc ring", or a doughnut-shaped structure. This ring has a steep density gradient toward the center, whereas it is widely spread towards the outer side. The ring is further associated with spur-like protrusions extending toward the halo. The protrusions make a large-scale cylindrical structure with the height 500 pc from the galactic plane.

Velocity variation along the major axis shows a normal rotation of the disk at velocity of 100 km s^{-1}. Along the minor axis and along the cylindrical struc-

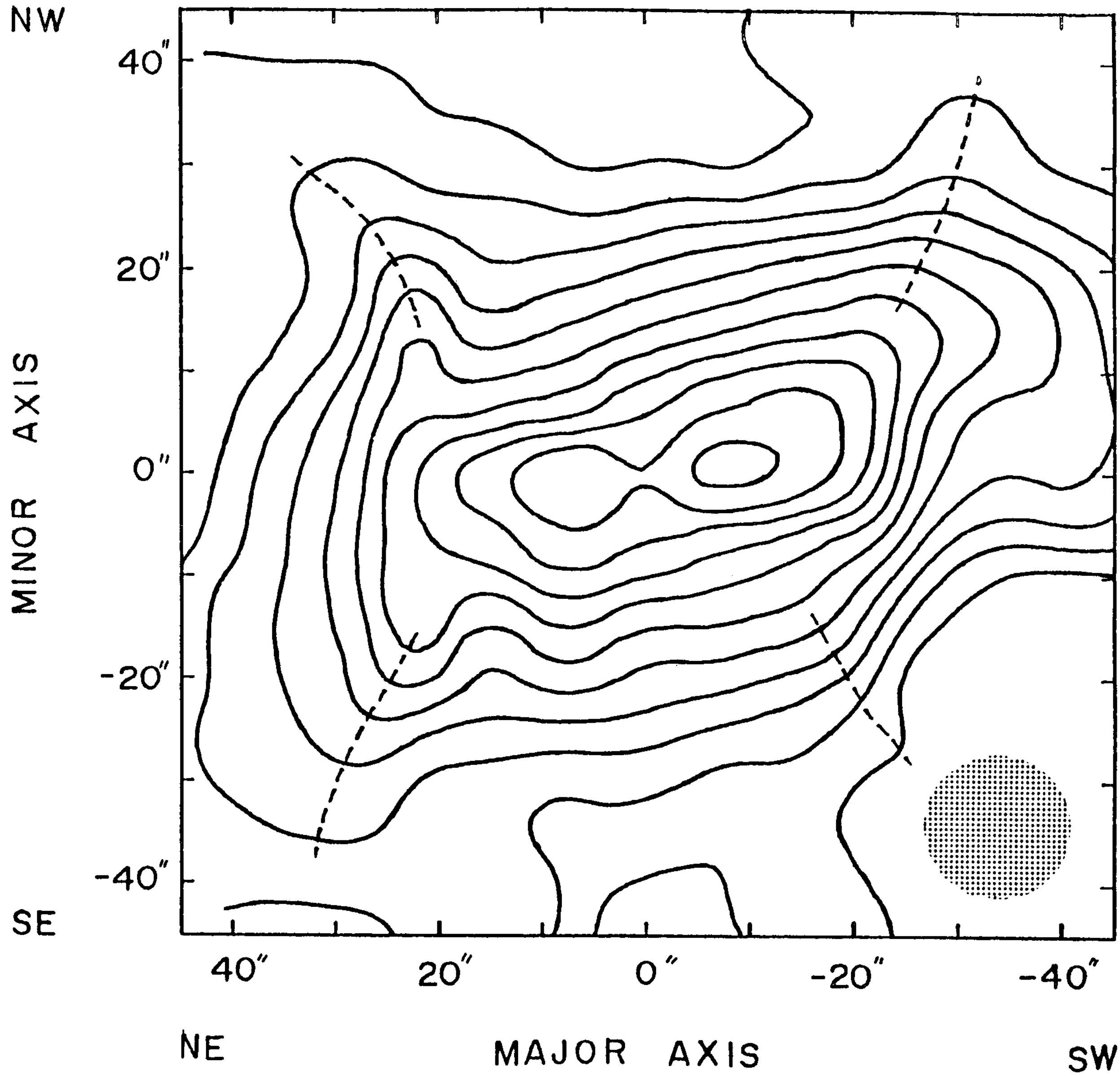

Fig. 8. Integrated intensity of CO line emission of M82. Note the double peaks which indicates the ring-like structure. Dashed lines show CO ridges extending toward the halo, which we interpret as due to cylindrical distribution of molecular gas perpendicular to the galactic plane. The lowest contour level and the contour intervals are 20 K km/s. The maximum intensity is 230 K km s^{-1}.

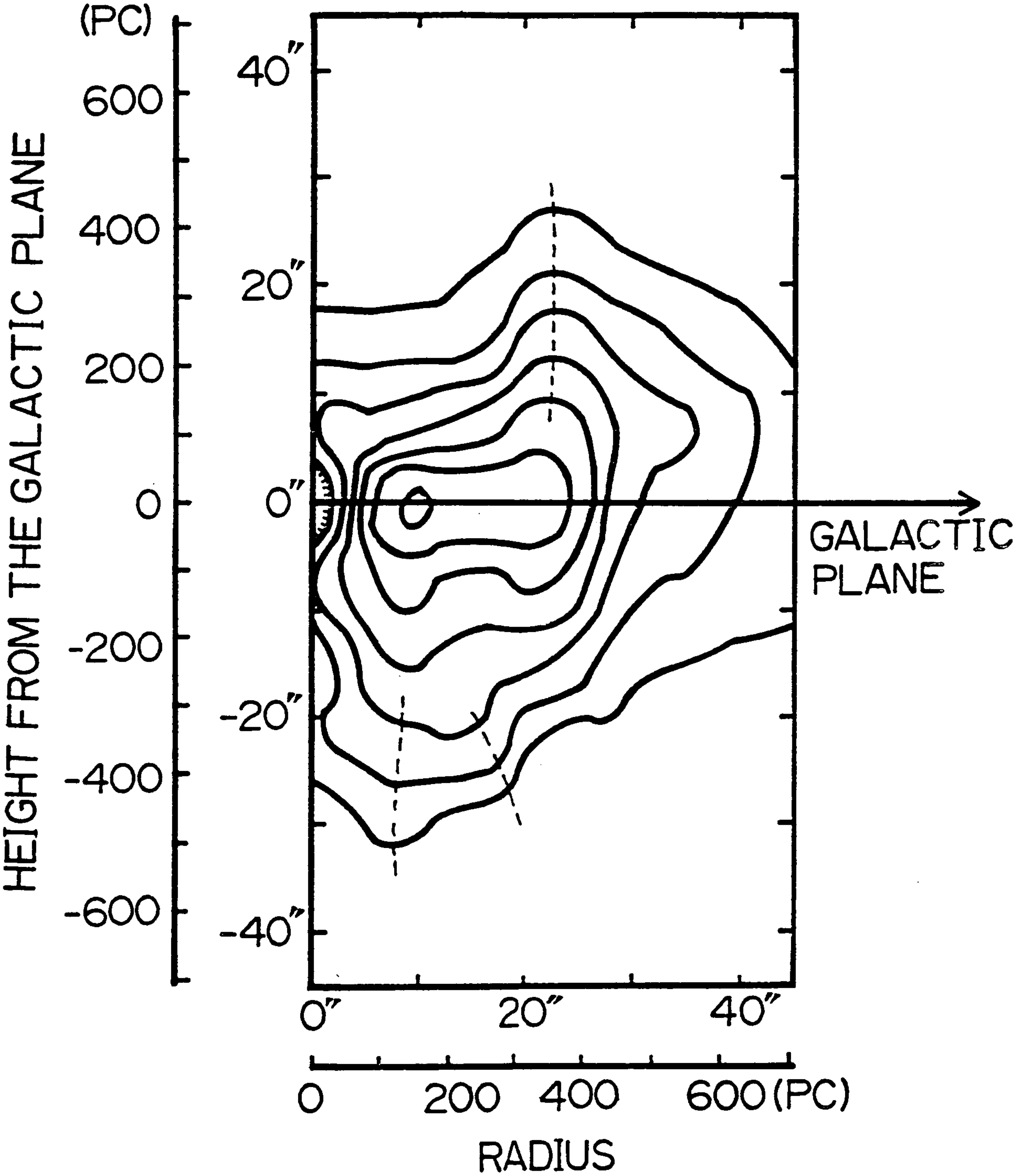

Fig. 9. Distribution of the volume density of molecular hydrogen calculated based on an axisymmetric model from figure 8. The first contour and contour intervals are 1 H_2 cm^{-3}.

ture in the halo we find also a velocity gradient. If we take into account the inclination of the galaxy disk, this gradient is well attributed to an outflow motion of molecular gas. The outflow velocity is from 100 to 500 km s^{-1} perpendicular to the disk plane, depending on the inclination angle, 70°-85°.

As the total mass involved in the cylinder is estimated to be $5x10^7$ Mo, the kinetic energy of the outflow motion is of the order of 0.1-1.4 x 10^{56} ergs. According to the star bursting model of Rieke et al. (1980) the rate of supernova explosions in the central few hundred pc is about 0.3 SN y^{-1} and the duration of the bursting activity is 5 x 10^7 y. Then the total energy released by SN explosions is $2x10^{58}$ ergs for a single SN energy of 10^{51} ergs. If the fraction of energy converted to kinetic energy of the gas is 0.03 (Chevalier 1974), enough energy is given to the gas to drive the outflow motion of the molecular cylinder.

Another fraction of the released SN energy may be used to heat up the ISM to high temperature, and the heated-up gas will expand into the halo, forming an X-ray halo. This is actually observed as an elongated halo of X-ray emission perpendicular to the disk plane (Watson et al. 1984). It must be noticed that the X-ray halo is confined by the wall of the molecular cylinder. It is likely that the interface of the X-ray halo and the molecular cylinder has an intermediate temperature, radiating H alpha emission. The H alpha filamentary structure may be a view of the interface region as seen through the dusty (molecular) cylinder with outflow motion. Figure 10 illustrates this picture.

From the observed facts we may propose the following scenario of evolution of M82: More than 10^7 years ago there appeared a dwarf galaxy ('proto-M82') with very rich content of molecular gas, possibly induced by an inflow of gas from M81 through a tidal interaction. The gas accumulated toward the center and produced a dense molecular disk. In the central region there occurred intensive star formation which propagated outward through the disk. Subsequent SN explosions and mass outflows from stars caused compression of the disk gas into a ring of high density molecular gas. In such a dense ring, especially near the inward shock-compressed side, further star formation occurred. The ring and star bursting sites are now observed as the 200-pc ring and associated nonthermal radio emisson. Plowed HI gas has been accumulated in an HI ring outside the molecular ring (Weliachew et al. 1984).

Released energy through the subsequent SN events escapes into the halo, a part of which goes to heating up the surrounding gas and a part goes to the kinetic energy of the high-velocity outflow of gas perpendicular to the disk, and is readily observed as the X-ray halo and the molecular cylinder as described above.

The shock-compressed 200 pc ring is probably expanding. In fact, the velocity dispersion toward the center of M82 is as high as 200 km s^{-1} in full width. This cannot be attributed to the rotation alone, and suggests an expansion of the ring gas at velocity 100 km s^{-1}. Then the expansion should have begun before 2 x 10^6 years ago, consistent with the duration of star bursting activity. The kinetic energy of the expanding motion is 3 x 10^{54} ergs as the total mass of the ring is 3 x 10^7 Mo, again enough driven by the SN energies.

6. Discussion

The galaxies reported here all show dense molecular disks in their central

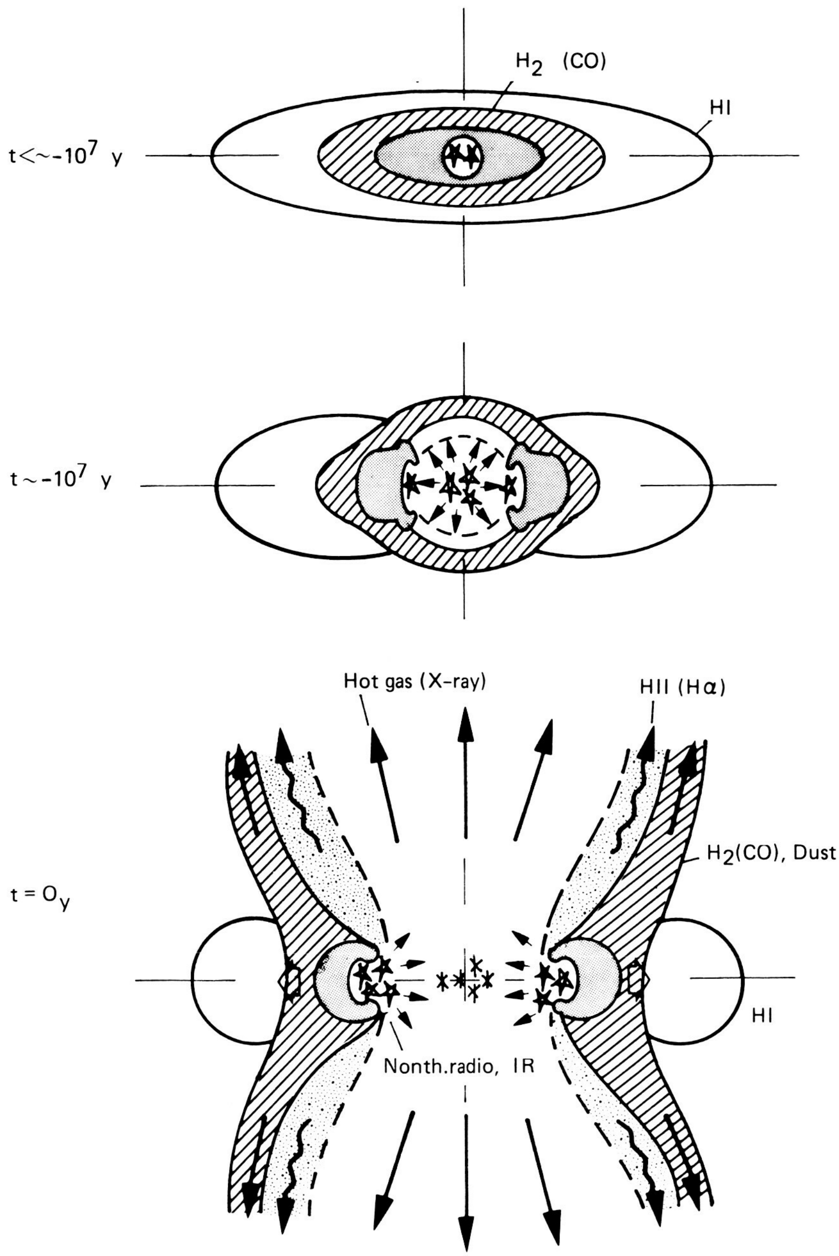

Fig. 10. Schematic illustration of possible evolution of M82.

regions. They show more or less central activity, and some show bursting star formation. Such activity may therefore depend on the molecular gas content in the central regions.

Table 1 lists the molecular to dynamical masses in the central few hundred pc of the galaxies reported here, and compares their ratios of molecular to dynamical masses. Here the molecular mass was estimated using the formula given in Sofue et al. (1986) except for M82 for which we used the value of Nakai et al. (1986). All the galaxies show that the ratio is 0.2-0.3, which is significantly higher than that known for the main disk of NGC891 or than in our Galaxy disk.

Table 1. Molecular and dynamical masses in the central few hundred pc.

Galaxy	Type	Distance	Region	M_{dyn}	M_{H_2}	M_{H_2}/M_{dyn}
NGC891	Sb	14 Mpc	R $\lesssim$ 500 pc	$\sim 10^9$ Mo	$\sim 3 \times 10^8$ Mo	$\sim$ 0.3
M83	SABc	3.7	350	5×10^8	1×10^8	0.2
IC342	Scd	4.5	500	5×10^8	1×10^8	0.2
M82	Pec.	3.3	200	4×10^8	10^8	0.2

It is interesting to note that the ratio is almost constant for these galaxies, which include a normal galaxy such as NGC891, though all of them show some central activity. This implies that the anomalous star bursting activity in M82 is affected not only by the gas density alone, but also by some other mechanism. A hint may come from its ring structure: the 200-pc ring of M82, which likely arises from a shock compression by a more central activity, may play an essential role in the burst. Namely the degree of star forming activity depends on dynamics and morphology of the molecular disk as well. A comparative study in a more quantitative way is in progress. Finally we mention that the difference in the activity might be due to different I_{co} to H_2 conversion rate in those galaxies: the high molecular content in NGC891, IC342 and M83 might be an apparent phenomenon caused by a higher content of heavy elements in their central regions than in M82 or in normal disks of NGC891 and our Galaxy, because we have used the usual conversion factor as noted above.

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DISCUSSION

UNGER:

A VLA map of OH absorption in M82 shows a rotating molecular ring on a scale of a few hundred pc (Weliachew *et al.* 1984, *A and A* **137** 335). How does this relate to your expanding CO ring?

SOFUE:

Positionally it coincides with the CO ring, though I haven't done detailed comparisons. Neither have I checked whether the OH ring is expanding. But it is quite likely that they are both in the same site on a ring, being illuminated and compressed by the star formation burst and the central activity.

HECKMAN:

Pat McCarthy, Wil van Breugel, and I have recently obtained long-slit optical spectrophotometry of the emission-line filaments in M82. These new data strongly support the type of bi-polar wind model you have described. First, we find that the gas pressure in the filaments drops roughly like $1/r^2$, as a simple wind model would predict. Second, the relative emission-line strengths can be well fit by standard shock models. I will be discussing these and other related data during my talk Thursday afternoon.

SOFUE:

That's important information. Thank you for the comments.