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THE INTERSTELLAR MEDIUM IN STAR BURST GALAXIES

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We report far-infrared observations of [O I], [C II] and [O III] fine structure emission lines toward the nuclei of M82 and 7 other galaxies with a high rate of star formation. The far-infrared line emission is bright, contains about 0.5% of the bolometric luminosity in the central 60", and is spatially concentrated toward the nuclei. In these galaxies between 10 and 30% of the interstellar gas near the nuclei is contained in a warm, atomic component. This atomic gas is probably located at the UV photodissociated surfaces of molecular clouds. The neutral gas in M82 has a temperature of $\sim$ 200 K, hydrogen density of $\sim 3 \times 10^4$ cm^{-3} and is very clumpy, indicating that the interstellar medium in this star burst galaxy is very different from that in the disk of our own galaxy. We discuss the implications of the infrared observations for the interpretation of mm molecular lines and for star formation at the nuclei of star burst galaxies.

A 200 pc RING OF MOLECULAR GAS AND AN OUTBURST IN THE GALAXY M82

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ABSTRACT. The CO (J=1-0) emission in M82 has been mapped with the Nobeyama 45-m telescope. The CO intensity distribution in the central re-

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gion is resolved into two peaks. An axisymmetric model reveals a ring structure of molecular gas at a distance of 80-400 pc (centered near 200 pc) from the nucleus. This "200-pc ring" corresponds to just the region of a star formation burst. The molecular gas in M82 is also expanding out of the galactic plane with a velocity of 100-500 km s^{-1}. The expansion energy of (0.1-1.4) × 10^{56} erg can be explained by the energy supply of supernovae in the central region.

1. INTRODUCTION

M82 is a well-known peculiar galaxy at a distance of 3.25 Mpc (Tammann and Sandage 1968). Remarkable Hα filaments extend perpendicularly to the galactic plane (Lynds and Sandage 1963). The nuclear region of the galaxy shows strong emission from the radio to the X-ray wavelength range and violent star formation is suggested for the region.

The galactic gas dynamics has been optically studied in the past 20 years. Optical light, however, is affected by obscuration and scattering because M82 is dusty and is seen almost edge-on. In order to avoid these effects, radio or infrared line observations are required to allow a direct measurement of the true velocity field in the galaxy.

Under this situation, we made new observations of the CO emission with a high angular resolution using the Nobeyama 45-m telescope. We report the results, discuss the structure and dynamics of the molecular gas, and propose a model for the behavior of the gas in M82.

2. OBSERVATIONS

The observations were made during May and June 1984, and March 1985 using the 45-m telescope of the Nobeyama Radio Observatory. The HPBW was 14" (220 pc at the distance of M82, 3.25 Mpc) and the frequency resolution was 250 kHz (0.65 km s^{-1} at the CO J = 1-0 frequency). The mapping area was 1.5' square around the galactic nucleus ($09^h51^m43.9^s$, 69°55'01"; Rieke *et al.* 1980) and the grid spacing was 7.5" in the central 30"×30" and 15" in the outer part. A total of 73 points were observed. Figure 1 shows examples of CO spectra. The intensity scale is the antenna temperature, T_A^*, corrected for atmospheric and antenna ohmic losses, but not for the beam efficiency of the antenna.

3. A 200 pc MOLECULAR RING

Figure 2 shows the map of the integrated intensity $I_{CO} = \int T_A^*(CO)dv$ of the CO line emission. The CO distribution in the central region is resolved into two peaks and is depleted just at the nucleus. The positions of the CO peaks correspond just to the peaks of the 10 μm infrared and radio continuum emission which indicate the region of current star formation.

The intensity distribution of the CO gas in Figure 2 is roughly symmetrical about the minor axis. Thus, it is possible to determine a three-

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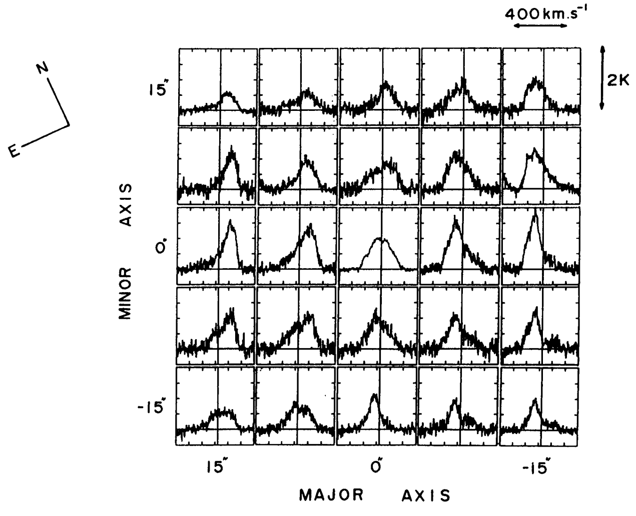

Fig. 1. Examples of CO spectra in the central region of M82. The velocity resolution is 2.6 km s^{-1}. The vertical line indicates the adopted systemic velocity (220 km s^{-1}). The intensity scale is the antenna temperature, T_A^*, corrected for atmospheric and antenna ohmic losses, but not for the beam efficiency of the antenna.

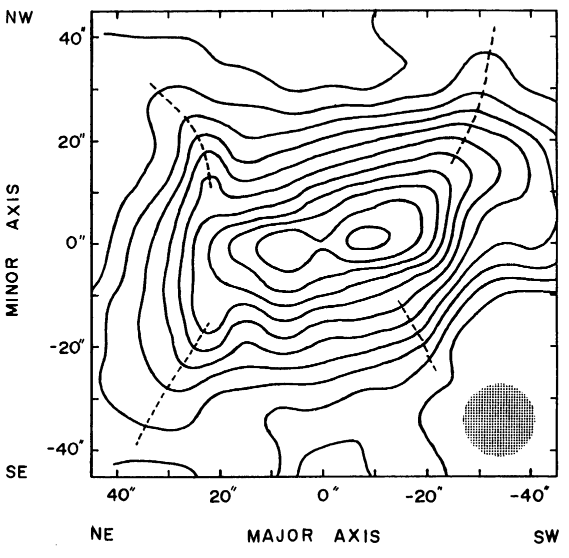

Fig. 2. A map of the integrated intensity of the CO emission, $I_{CO} = \int T_A^*(CO)dv$. The lowest contour level and the contour intervals are 20 K km s^{-1}. The maximum intensity is 230 K km s^{-1}. The dotted circle represents the beam size (HPBW) of the telescope.

dimensional distribution of the molecular gas in M82 based on a simple axisymmetric model. Figure 3 shows the resulting distribution of the volume number density n H_2 cm^{-3}, where an abundance ratio of $[CO]/[H_2] \cong 5 \times 10^{-5}$ and an excitation temperature of $T_{ex}(CO) \cong 40$ K are assumed. The denser region ($n \cong 6$ H_2 cm^{-3}) of the molecular gas exists at radii of 80-400 pc (centered near 200 pc) and shows a ring structure. The mass of the molecular gas in this "200-pc ring" is 3×10^7 $M_\odot$ within z = ±100 pc. Inside the ring we find clearly a "central hole" of the molecular gas ($n < 2$ H_2 cm^{-3}).

The ring structure of the molecular gas is based on an axisymmetric

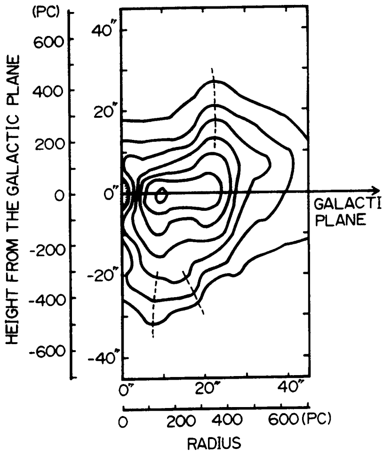

Fig. 3. A map of the volume number density of the hydrogen molecule calculated based on an axisymmetric model from Fig. 2. An abundance ratio of $[CO]/[H_2] \cong 5 \times 10^{-5}$ and an excitation temperature of $T_{ex}(CO) \cong 40$ K were assumed to calculate the density of the CO molecule and to convert it into the density of the hydrogen molecule. The first contour and the contour intervals are 1 H_2 cm^{-3}.

distribution and is not unique. Other models such as bipolar distribution could be considered, but an axisymmetric model is the simplest and at least the depletion of the molecular gas in the nuclear region is real.

4. OUTFLOW OF MOLECULAR GAS

Other prominent features in figures 2 and 3 are spur-like structures extending up to ≧30" (500 pc) from the galactic plane toward the halo (dotted curves). These spurs suggest cavity walls or cylinders of the molecular gas perpendicular to the galactic plane. Hot plasma, which produces the Hα-filaments and the X-ray emission, is distributed just inside the molecular walls (Lynds and Sandage 1963, Watson *et al.* 1984, Kronberg *et al.* 1985).

Figure 4(a) and (b) shows the iso-velocity map and the position-velocity diagram along the minor axis, respectively. It is apparent that there are velocity shifts along the minor axis which are not expected from the galactic rotation. The values of the velocity shifts against the systemic velocity of the galaxy (220 km s^{-1}) are +30 km s^{-1} at the NW side and -40 km s^{-1} at the SE side.

The above facts: i) cavity walls of the molecular gas perpendicular to the galactic plane, and ii) velocity shifts along the minor axis, suggest that the molecular gas in M82 is expanding out of the galactic plane (Figure 5), where the northwestern side of the galactic plane is assumed to be the near side (Chesterman and Pallister 1980). Assuming 70° - 85° (90° is edge-on) as the inclination angle of the plane (Lynds and Sandage 1963, Notni and Bronkalla 1983), the expansion velocity is 100-500 km s^{-1} which is comparable with or exceeds the escape velocity. The mass and energy of the expanding molecular gas is 5.4×10^7 $M_\odot$ and $(0.1\text{-}1.4) \times 10^{56}$ erg, respectively. If the H I gas and the ionized gas as well as the molecular gas are considered, the total energy of the expanding gas is about twice the energy of the expanding molecular gas.

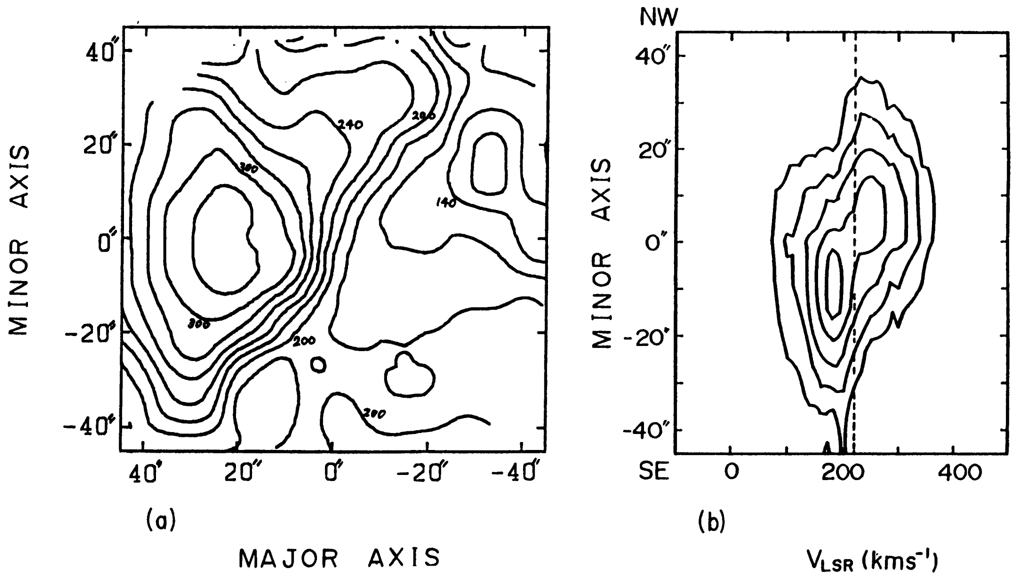

Fig. 4. (a) An iso-velocity map made from peak velocities. The unit of the contour numbers is in km s^{-1}. (b) A position-velocity diagram of the CO line emission along the minor axis. The contour intervals are 0.2 K. The dotted line indicates the systemic velocity of M82, V_{LSR} = 220 km s^{-1}.

The most suitable origin of the gas outflow is an energy supply from supernova explosions in the galactic disk. The total kinetic energy E_{kin} (SN) released into the interstellar space during t_s by supernova explosions is

$$E_{kin}(SN) = \int_{-t_s}^{0} \gamma_{SN}(t)\ E_0(SN)\ p\ dt,$$

where $\gamma_{SN}(t)$ is the supernova rate, $E_0(SN)$ is the initial total energy of a supernova event and p is the ratio of the kinetic energy released into the interstellar space to $E_0(SN)$. We adopt 10^{51} erg for $E_0(SN)$ and 0.03 for p (Chevalier 1974), and the duration time of star formation $t_s \cong 5 \times 10^{7}$ yr and $\gamma_{SN}(t) = \gamma_0 \exp(-t/\alpha)$ ($\gamma_0 \cong 0.3$ SN yr^{-1}; the present rate of supernova events, $\alpha \cong 2 \times 10^7$ yr) according to the star burst model of Rieke *et al.* (1980) in M82. The $E_{kin}(SN)$ is 2×10^{57} erg and well exceeds the observed outflowing energy of the molecular gas ((0.1-1.4) $\times 10^{56}$ erg). The outflowing gas with the velocity of 100-500 km s^{-1} requires a time of (1-5) $\times 10^6$ yr, to travel from the galactic plane up to the observed area (z = 500 pc). Even if for t_s = (1-5) $\times 10^6$ yr, E_{kin} (SN) is (0.2-1.2) $\times 10^{56}$ erg and is comparable with the observed outflowing energy. Therefore the kinetic energy given to the interstellar gas by supernovae in M82 is enough to blow up the observed molecular gas into the halo.

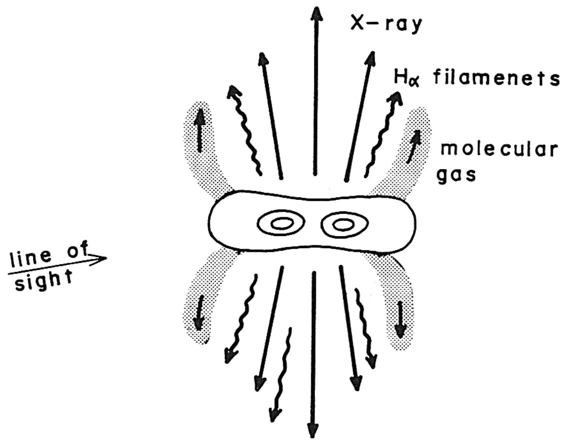

Fig. 5. A schematic view of the molecular gas and of the hot plasma emitting the X-ray and the Hα photons from the filaments in M82.

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DOPITA: I seem to recall that H I and dust observations suggest that an H I cloud is falling into M82. Is this still thought to be the case, and could this be the trigger of the star-burst?

NAKAI: Our CO observations within the mapping area of 90" square could not indicate inflow of the molecular gas. The redshifted and blue-shifted emission above and below the galactic plane may be caused by gas expanding with a velocity of 100-500 km s^{-1} perpendicular to the plane or by infalling gas with 30-40 km s^{-1} in the plane. However, the former is a more reasonable explanation because the distribution of the molecular gas shows a cylindrical structure nearly perpendicular to the plane.

PUDRITZ: Have you surveyed the immediate environs of M82 for CO emission?

NAKAI: We have mapped only in the region of 90" square because of the smaller beam size, the weaker emission of CO in the outer region, and the limited observing time. Stark and Carlson (1984, Astrophys. J. 279, 122) and Young and Scoville (1984, Astrophys. J. 287, 153) have surveyed up to 2' - 3' from the galactic plane.

COMBES: I would like to mention that dynamical models computing the behaviour of molecular gas in a bar potential reveal the formation of molecular rings close to the center, when the bar angular velocity is low. These rings could in fact be elliptical and the gas would then be observed in non-circular-motions. This is a possible interpretation for the molecular ring in M82.

LO: While the CO observations of M82 are only confined to the central region and therefore do not address directly whether gas is flowing inwards or out, it is clear that the latest site of star formation occurs at the region of high gas concentration: the inner 1 kpc. Since accretion does not directly explain the confinement of gas to the nuclear region, some additional mechanism must be involved. Furthermore, NGC 253, as a star-burst galaxy with properties very similar to M82, does not have a companion, indicating accretion alone does not necessarily account for star-burst. However, for the $10^{12} L_{\odot}$ galaxies such as Arp 220, the extent and the amount of gas required for the star-burst indicate that direct "face-on" collisions of galaxies are necessary.

HEIDMANN: Following the last comment by Lo, in the same direction it can be said that it is difficult to invoke infall to explain the active star formation in the clumps of clumply galaxies as they are scattered all over the body of these galaxies.

MOLECULAR GAS IN THE NUCLEUS OF M82

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7"-resolution CO (1-0) observations of M82 with the Owens Valley millimeter-wave interferometer have resolved 2 components of molecular gas in the central 1.5 arcmin of the galaxy: (1) a high plane of M82, and (2) shell-like or filamentary structures of molecular gas, with size-scale as large as 400 pc, extending most likely out of the plane of the galaxy.