MOLECULAR GAS IN THE CENTRAL REGIONS OF GALAXIES

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ABSTRACT

High-spatial-resolution CO observations of galaxies have shown detailed distribution and dynamics of the molecular gas in spiral galaxies. We review observations, and show that the molecular gas distributions in the nuclear regions can be classified into three types: a core type with high concentration toward the nucleus; compact-ring type with ring radius of ~200 pc; and a broad-ring type with ring radius of several hundred pc to ~1 kpc. We also discuss their implications.

1. ITRODUCTION

Molecular clouds are the major sites of star formation in galaxies. The molecular clouds in galaxies are studied by observing molecular lines, and the CO line observations have been most common. CO observations may be categorized into the following investigations: (a) Statistical relationships with various constituents, which can be studied with relatively low (~1–10 kpc) resolution observations; (b) Molecular clouds, spiral arms, and their relationship to star formation, which can be studied by high (~100 pc to 1 kpc) resolution observations; and (c) Central regions of individual galaxies, for which we need also high-resolution (~100 pc) observations. In the present review, we mainly discuss category (c) for the central regions. In this review we concentrate oursefves on spiral galaxies.

2. HIGH-SPATIAL-RESOLUTION OBSERVATIONS

Detailed distributions of CO emission in galaxies have been studied by using large-aperture single dishes like the 45-m telescope at Nobeyama and IRAM 30-m telescope. At the frequency of ^{12}CO($J = 1 - 0$) line (115 GHz) the 45-m and 30-m telescopes attains resolutions of 17″ and 21″, respectively. At the ^{12}CO($J = 2 - 1$) frequency (230 GHz), the IRAM 30-m telescope has a resolution of 13″. These angular resolutions corresponds to linear resolution of a few hundred pc for nearby galaxies, e.g. for those at distances less than 10 Mpc. Interferometers have become available for observations for CO bright galaxies. The Owens-Valley mm interferometer has been used to map galaxies at a resolution of a few arc seconds (e.g. Lo et al. 1984). The Nobeyama mm Array (NMA) has worked at 115 GHz,

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and CO maps with a resolution of 4-8″ have been obtained (e.g. Ishisguro et al 1989).

3. DISTRIBUTIONS OF MOLECULAR GAS IN SPIRAL GALAXIES – MAIN-DISK PLUS NUCLEAR-DISK STRUCTURES

(a) S0/Sa Galaxies

These types of galaxies contain small amount of molecular gas, an order of magnetitude smaller than that in late type galaxies of Sb and Sc. Thronson et al (1989) have surveyed the CO emission from this type of galaxies, and shown that the SFR in these galaxies are below that found in later type galaxies. They further argue taht the present ISM is the remnant of earlier epoch star formation, enriched by evolved stars. No systematic search and mapping with high angular resolutions have been made as yet.

(b) Sb Galaxies

Sb/c galaxies are most extensively studied in the CO line, and many maps have been published. Generally, Sb galaxies show a large-radius (a few to 10 kpc) molecular ring plus nuclear rotating disk.

The Galaxy: The Milky Way is a typical edge-on Sb galaxy. The whole galactic plane survey in CO (Dame et al 1987) have shown that the CO intensity shows broad peaks at $l \sim 20 - 30°$corresponding to the 4-kpc gaseous ring, and a high concentration within a few hundred pc of the galactic center. The moleclear gas distribution near the center is most complicated (e.g. Bally et al 1987): The gas distribution is clumpy, consisting of a large number of clouds. The gas near the center within 100–200 pc has a large velocity dispersion as large as 300–500 km s^{-1} . An expanding ring of 200-pc radius is superposed, and many other expanding/contracting ring/shell structures are found.

NGC 891: An edge-on Sb galaxy, NGC 891, has been mapped along the galactic plane at high resolutions ($13 - 20''$: Sofue et al 1987; Guelin et al 1990). The radial CO distribution is similar to that found in our Galaxy: CO emission has a sharp peak near the center, and has a ring-like enhancement at a few kpc radius.

M31: This galaxy contains smaller amount of CO compared to our Galaxy or to NGC 891. The molecular gas is well distributed in the 10-kpc ring, and shows a clumpy structures composed of super-clouds (Combes et al 1977; Boulanger 1984). Because of its proximity, the galaxy provides the best opportunity to resolve giant molcular clouds in individual arms and star forming regions (Nakano et al 1987; Lada et al 1988). The nuclear region of M31 seems to contain little molecular gas (Sandqvist et al. 1989).

(c) Sc Galaxies

The molecular gas is ditributed obeying the exponential-law with a scale radius of a few kpc, on which a nuclear disk with smaller scale radius and spiral arms are superimposed (Young and Scoville 1982; Tacconi and Young 1986; Sofue 1987). The nuclear disk is usually elongated, showing an oval or a bar structure.

M51: A number of CO surveys have been made of this galaxy (e.g. Young 1988). High-resolution ^{12}CO($J = 1 - 0$) mapping of the entire galaxy ($6' \times 6'$ region) was recently completed by Nakai et al (1990) at a resolution of 17″using the 45-m telescope, and by Guelin et al (1990) at a resolution of 21″using the IRAM 30-m telescope. The CO maps show clear two-armed spirals, tracing the optical (dust lanes) and radio arms. The arms are patchy, and individual clumps correspond to active star forming regions. The molecular gas is well detected in the interarm regions. The arm-interarm (azimuthal) distribution agrees with the galactic shock wave theory, while the velocity discontinuity (~ 70 km s^{-1}) at the shock is much larger than predicted from the theory. The gas density sharply increases toward the center. However, the very nuclear region shows a depression, and the more inner region lacks the molecular gas. This situation is better seen in the higher resolution maps obtained with the Owens Valley (7″) and NMA (4″) observations (Lo et al. 1987; Tosaki et al 1990).

NGC 6946: The CO distribution in the disk at $r > 2$ kpc obeys approximately an exponentially decreasing law,

$$I_{\rm CO} = I_{\rm MD} \exp(-r/5{\rm kpc}),$$

while the inner 2 kpc region can be described as

$$I_{\rm CO} = I_{\rm ND} \exp(-r/0.9{\rm kpc}),$$

where $I_{\rm MD} = 20$ K km s^{-1} and $I_{\rm ND} = 110$ K km s^{-1} are the coefficeints for the main disk and the nuclear disk components, respectively (Tacconi and Young 1986; Weliachev et al. 1988; Sofue et al. 1988). The molecular gas distribution is well correlated with the blue light distribution. Radio continuum emission shows also a good correlation with CO. The innermost CO gas is distributed elongated, composing a molecular bar. There has been no indication of a ring or a central depression. The velocity field shows noncircular motion, suggesting a bar-shock accretion. The nuclear region has been resolved with NMA (Ishizuki et al 1990): The intensity of the central core reaches as high as $I_{\rm CO} = 10^3$ K km s^{-1} , which is an order of magnitude greater than $I_{\rm ND}$.

IC 342: The overall distribution of molecular gas is similar to that observed in NGC 6946 (e.g. Young 1987). The central region shows a molecular bar structure (Lo et al 1984; Hayashi et al 1987). Higher resolution observations (Ishizuki et al. 1990) show that the bar splits into two symmetrical spirals of large pitch angle. The spirals end near a ring. The nuclear ~ 100 pc region has CO depression. The molecular ring positionally coincides the radio continuum ring (Turner and Ho 1983). The motion of molecular gas near the center is highly noncircular, suggesting a bar-shock inflow. This may fuel the gas toward the central high-density ring, where high star formation is enhanced.

(d) Barred Spiral Galaxies

Barred spiral galaxies provide an opportunity to investigate the theoretical prediction that a bar potential causes non-circular motion of gas via the shock, which results in an angular momentum loss and rapid accretion toward the nucleus (Sϕrensen et al 1976; Noguchi 1988; Combes 1990).

A good CO map has been obtained for M83 (Handa et al 1990), which showed molecular gas elongated along the leading edges of the bar. The molecular bar is connected to a high-density nuclear core of molecular gas, where an active star formation is taking place. The velocity field in the bar and near the nucleus is highly noncircular. The high concentration toward the center and the relatively small amount of gas along the bar indicate that the accretion is very rapid.

Besides the barred galaxies like M83, there have been many galaxies, in the central regions of which bar-like molecular gas distributions are found, although not classified as barred galaxies: NGC 6946, IC 342 (see above), NGC 253 (Canzian et al 1988), Maffei 2 (Ishiguro et al 1989), etc.. These galaxies all show high density molecular gas disk near their centers.

(e) Interacting Galaxies

Tidal interaction between galaxies causes oval distortion of the gravitational potential in each galaxy. Nonlinear response of gas against the oval/bar potential results in an angular momentum loss and in an accretion of gas toward the central region (Noguchi 1988; Combes 1990). The accreting gas produces a ring of gas, radius of which is of the order of bar width, and finally causes starburst. This scenario of starburst is based on observations of already on-going star bursters.

In order to clarify if tidal interaction generally enhances the gas accretion and triggers starburst, we need a systematic study of dynamics of molecular gas for unbiased samples of interacting galaxies. For this and to investigate detailed behavior of molecular gas in interacting galaxies, we (Sofue et al 1990) have conducted a CO survey for linteracting galaxies from Arp's Atlas. A preliminary result shows that interacting galaxies have a higher star formation efficiency, while they does not show significant enrichment of CO gas compared to normal galaxies. This result is consistent with Solomon and Sage (1988).

(f) Star Burst/FIRL Galaxies

Many starburst galaxies are FIR luminous galaxies and are shown to be interacting systems. High-density molecular gas has been detected in the central regions of these galaxies (e.g. Scoville 1990; Okumura et al 1990; Taniguchi et al 1990). Examples are seen for M82 (Nakai et al. 1987), Arp 220 (Solomon et al 1990), etc.. High-resolution maps have shown that the gas is highly concentrated in the central regions of radius less than 1 kpc.

3. NUCLEAR DISK STRUCTURE – RINGS AND NONCIRCULAR MOTION

(a) Nuclear Core, Ring and Cavity

High resolution observations of CO bright galaxies have shown that the central regions have a nuclear disk with high concentration of molecular gas. In many cases nuclear disks show a ring structure and a central cavity in CO followed by dense

Table 1: Nuclear rings and disks of molecular gas for CO bright galaxies.

Galaxy	Type	Dist.(Mp)	Nuclear Disk/Ring[b]	Reference[a]
Milky Way	Sb	0.01	r200-pc expa. ring	By1987, Da1987
NGC 891	Sb	14	r500-pc nucl. disk(Un)	So1987
Maf. 2	Sbc	5	r200-pc expa. ring	Ig1989
M31	Sb	0.7	No nucl. disk	Sa1989
M81	Sb	3.2	–	Br1988
NGC 1068	Sb, Sey I	18	r870-pc ring+2-kpc disk	Ka1989, Pa1989
M33	Sc	0.8	r500-pc weak ring	Wi1989
M51	Sc	9.6	r500-pc bar + arms + nucl. cavity	Lo1987, Na1990 To1990
M100	Sc	7	1-kpc nu.disk(Un)	Sm1983
IC 342	Sc	3.9	r100-pc ring+arms	Yo1982, Hy1986 Lo1984, Iz1990a
NGC 6946	Sc	5.5	r50-pc core(Un) + 500-pc bar	Yo82,We87,So88 Ba1985, Iz1990b
NGC 4631	Sc/SBd	5.2	r1-kpc/250-pc rings	So1989, 1990
M83	SABc	3.7	r180-pc core(Un)+bars	Ha1990
NGC 4258	SBb	6.6	r300-pc core	So1989b, Kr1990
NGC 253	SABc	3.4	d640×200-pc bar	Ca1988
NGC 1097	SBbc	17	r450-pc ring	Ge1989
M82	Ir/Burst	3.2	r200-pc ring	Na1987, Ls1990
SBGs	Ir/Burst	~ 100	$r < 1$ kpc dense core(Un)	Ok1990, Sc1990

a) Ba=Ball et al; Br=Brouillet et al.; By=Bally et al; Ca=Canzian et al; Da=Dame et al; Ge=Gerin et al;Ha=Handa et al; Hy=Hayashi et al; Ig=Ishiguro et al; Iz=Ishizuki et al; Ka=Kaneko et al.; Kr=Krause et al; Lo=Lo et al; Ls=Loiseau et al; Na=Nakai; Ok=Okumura et al; Pa=Planesas et al; Sa=Sandqvist et al; Sm=Solomon et al; Sc=Scoville; So=Sofue et al; To=Tosaki et al.; We=Weliachev et al; Wi=Wilson et al.; Yo=Young and Scoville.

b) r=radius; d=diameter.; Un=Unresolved with the current observations.

molecular arms and/or bars. Only a few galaxies show a filled-center structure, or a core type, having no cavity. Table 1 lists galaxies, for which the central regions have been resolved in the CO line. Fig. 1 shows radial distributions of CO intensity for these galaxies. To summarize, we may classify the molecular gas distributions in the following three types:

Core type: The gas is highly concentrated in the central few hundred pc region, and there is no cavity. Examples are NGC 4696, NGC 4258, and M83.

Ring I (compact ring) type: Molecular gas forms a ring of radius of about 200 pc, and a central cavity is found within the ring. Examples are M82, IC 342, Maf. 2, etc..

Ring II (broad ring) type: Molecular gas forms a broad ring of radis of 700

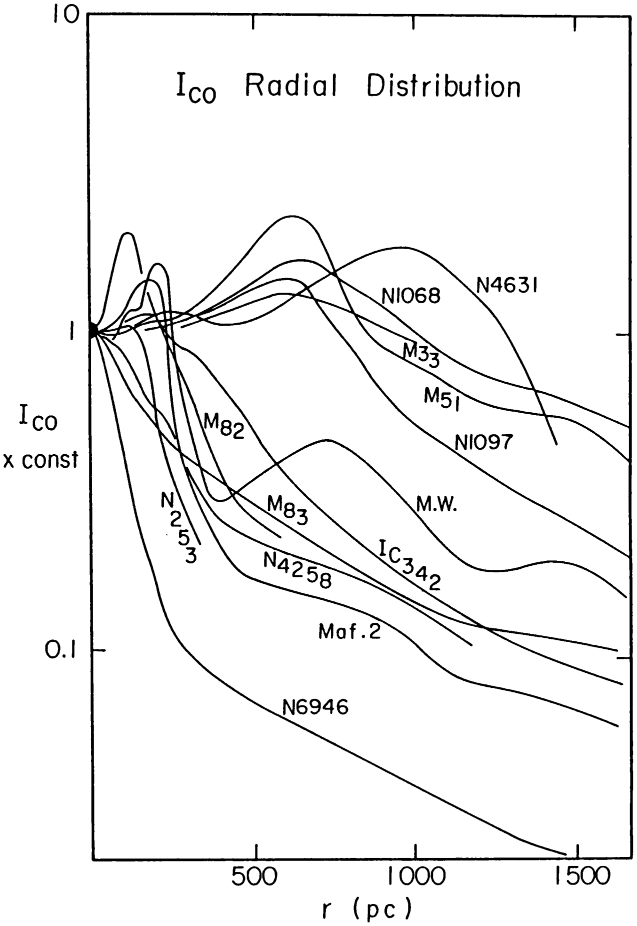

Fig. 1: Radial distributions of CO line intensity for various galaxies. Intensities are normalized by their central values.

pc – 1 kpc. Examples are NGC 4631, NGC 1068, etc..

(b) Formation of the Core, Ring, and Cavity

Ring and core: According to the viscosity-driven angular momentum transfer and on-going star formation model (Yoshii and Sommer-Larsen 1989), the formation of a dense nuclear disk is a natural consequence of an exponential-disk formation when a galaxy was born and contracted from a premeval gas sphere. At such a stage when premeval disk was formed, the radial gas density distribution may have been of a core type. In addition to this initial high-density disk, viscousity and shock-induced angular momentum transfer causes accretion of gas toward the center. This accretion is enhanced if there exists an oval or a bar-like potential (e.g. Noguchi 1988).

Cavity at the nucleus: The star formation efficiency is an increasing function of the gas density, so that the star formation rate becomes extremely high, when the nuclear core is formed. As the consequence of intense star formation near the center, the gas close to the nucleus will be rapidly exhausted, and a cavity of gas is formed. If there exists an AGN, its strong UV will heat and dissociate molecules, forming a cavity around it.

Ring size: It should be noticed that the ring radius is almost constant, $\sim$ 200 pc for Ring I and 700 pc – 1 kpc for Ring II. The reason why the ring size is about constant is not clearly understood yet. However, we may suggest that the ring size could be related to bar width, and the bar size (width) could be common for any galaxies. Finally we mention that, if the size of nulcear molecular rings is really constant, it could be used as a distance indicator.

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