STAR FORMATION AND DYNAMICS OF MOLECULAR GAS IN CIRCUMNUCLEAR REGIONS OF BARRED GALAXIES

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1. Introduction

To investigate gas dynamics in bar or oval potentials of galaxies and the relation to star formation in the nuclear and circumnuclear regions, the CO ($J = 1 \rightarrow 0$) emission from nine nearby galaxies (NGC 1530, NGC 2782, NGC 2903, NGC 3504, NGC 4369, NGC 5383, NGC 7479, NGC 7541, & NGC 7714) was mapped using the Nobeyama Millimeter Array with angular resolutions of 4–13 arcseconds. Observations of M 83 by Handa et al. (1994) are included in the following discussion.

2. Categories of CO Morphology

The observations revealed a variety of CO distributions in barred galaxies: in category [1], the CO distribution is elongated parallel to the large-scale stellar bar (NGC 7479 & NGC 2903); in category [2], there is an inner CO bar inscribed in a pair of dust lanes that lie along the large-scale stellar bar (NGC 5383, M83, NGC 1530, & NGC 2782); and in category [3], the CO is concentrated in the nucleus (NGC 3504).

3. Interpretation in Terms of Orbit Resonance Theories

This variation can be interpreted in terms of orbit resonance theories. Category [1] is the case where the x_2-to-x_1 coverage ratio, the ratio of the coverage by orbits in the x_2-family (orientations perpendicular to the large-scale stellar bar) to the coverage by orbits in the x_1-family (parallel to the large-scale stellar bar) is very small. In this case, the radius of the inner Lindblad resonance (ILR) is much smaller than that of the corotation resonance or there is no ILR. The narrow CO distribution parallel to the large-scale stel-

lar bar in NGC 7479 resembles the results of numerical simulations with small x_2-to-x_1 coverage ratios (Athanassoula 1993). In NGC 2903, the CO isovelocity contours are parallel to the large-scale stellar bar, also suggesting a small x_2-to-x_1 coverage ratio.

Category [2] is the case where the x_2-to-x_1 coverage ratio is larger than in the category [1]. In particular, the deviation angles of the inner bars in NGC 1530, M 83, and NGC 5383 with respect to the main stellar bars are close to 45°. This agrees with the prediction of the damped-orbit-resonance theory (Wada 1994).

4. Dynamical Evolution of Inner Bars

There is a variety of CO distributions in the inner bars of galaxies in category [2]. The inner gaseous bar of NGC 5383 (Figure 1) has local peaks of integrated CO intensity at the apocenters and Hα emission spread over the inner gaseous bar. On the other hand, the inner bars of M 83 (Handa et al. 1994; Cowan & Branch 1985) and NGC 1530 (Figures 2,3) have leading ridges of the CO integrated intensity and star forming regions inscribed in the leading ridges. In addition, NGC 2782 (Figure 4) has a pair of circumnuclear CO peaks between the ends of the dust lanes that run along the large-scale stellar bar. The southern CO peak is elongated west toward the inner end of the straight dust lane. This variation suggests that the galaxies are in different stages of dynamical evolution as molecular gas is transported toward the nucleus. NGC 5383 is in the earliest stage and NGC 2782 is in the latest stage. Note the near-infrared image of NGC 2782 shows a weak elongation in the east-west direction (Pompea & Rieke 1990) and the southern CO elongation is on the leading edge of the near-infrared elongation. It is plausible there are oval potentials inside the outer ILRs of the inner-barred galaxies. The gas in the leading ridges may be affected by the gravitational torques exerted by the inner bar and driven toward the nucleus. If dynamical evolution of this kind is real, NGC 3504 may be in the stage after the molecular gas has been transported toward the nucleus by the torques exerted by the inner gaseous bar. This means high density gas in the nuclear region can be realized due to the dual-bar system, the large-scale stellar bar, and the inner gaseous bar.

5. Star Formation in the Circumnuclear Kiloparsec Regions

CO and 20 cm radio continuum data compiled from the literature (Figure 5) reveal galaxies are divided into two classes in terms of the gas depletion time due to star formation, $\tau_{\rm SF}$, the reciprocal of the radio-to-CO intensity ratio (Wright et al. 1988). Galaxies with higher radio-to-CO ratios have $\tau_{\rm SF} \sim 10^8$ years while galaxies with lower ratios have $\tau_{\rm SF} \sim 10^9$ years. The

shorter τ_{SF} is similar to that for well-known starburst galaxies like M 82 and NGC 253. The longer τ_{SF} is similar to that for the normal galaxies (Young et al. 1989; Young this Symposium). Note many hot spot galaxies have long τ_{SF}, indicating their apparent star formation enhancement is a simple result of the piling up of a large amount of molecular gas, not of a starburst. Starbursts are divided into two categories: the "ring starbursts" which occur in a ring with a diameter comparable to the width of the large-scale stellar bar (e.g., NGC 1068, NGC 1097, & NGC 3310), and "nuclear starbursts" which occur inside this diameter. The inner bar mentioned above is a plausible mechanism for fueling the nuclear starburst.

6. Evolution of Kiloparsec Rings and AGNs

After the nucleus is fueled with matter, the resulting mass concentration may disrupt the inner bar and form a ring (Friedli & Martinet 1993). NGC 1097 (Hummel et al. 1987), NGC 3310 (Duric et al. 1986), and NGC 4736 (Pogge 1989) possess rings resembling such a morphology. NGC 1068 has a similar ring with a starburst, although there is a small bar inside the ring (Thronson et al. 1989; Planesas et al. 1991). Optical spectroscopy of the nuclei and starburst rings of NGC 1097 (Talent 1982; Phillips et al. 1984) and NGC 3310 (Terlevich et al. 1990; Kikumoto et al. 1993) suggests star formation occurred in the nuclei before the rings, supporting the scenario of dynamical evolution. It is also suggested (Friedli & Martinet 1993) the morphology of a galaxy changes to an early-type spiral in the final stage of the dynamical evolution. This is consistent with statistics (Balzano 1983) indicating starburst galaxies are often early-type spirals. Note NGC 1068 and NGC 1097 have active nuclei. This is consistent with other statistics that Seyfert galaxies tend to have outer and/or inner rings (Simkin et al. 1987) and to be early-type spiral galaxies (Terlevich et al. 1987).

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