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MOLECULAR GAS DISTRIBUTIONS IN NEARBY STARBURSTS

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RESUMEN

Se describen las relaciones entre la actividad de formación estelar y las distribuciones de gas molecular en las regiones centrales de galaxias espirales, con y sin brotes de formación estelar.

ABSTRACT

A comparison of molecular gas distributions in the central regions of nearby spiral galaxies shows that the starburst galaxies have their gas most centrally concentrated. The largest gas concentrations in most barred galaxies are near or between inner Lindblad resonances, although in some of the most intense starbursts a significant amount of gas appears to be near or inside inner inner Lindblad resonances. Inside the star-forming rings of some "hot spot" galaxies, there are extremely low levels of massive star formation, despite inferred molecular gas surface densities of 600–800 $M_\odot$ pc^{-2}, indicating that there is a high threshold gas density required for star formation in the circumnuclear regions of galaxies. The Toomre gravitational instability parameter Q is close to 1 throughout the starburst regions of NGC 3504 and NGC 4102 and in the star-forming ring of NGC 4314, yet Q>1 inside the star-forming ring of NGC 4314. This suggests that gravitational instabilities are relevant for understanding both ongoing central starbursts, and the lack of star formation inside "hot spot" rings. I also speculate on possible evolutionary relationships among the galaxies.

Key words: **GALAXIES: INDIVIDUAL: NGC 3504, NGC 4102, NGC 4314 — GALAXIES: SPIRAL — GALAXIES: STARBURST — INSTABILITIES — RADIO LINES: GALAXIES**

1. CIRCUMNUCLEAR MOLECULAR GAS DISTRIBUTIONS IN SPIRAL GALAXIES

In order to understand the starburst phenomenon, it is important to understand the striking variety of molecular gas morphologies found in the centers of both starburst and non-starburst galaxies. This variety is illustrated in Figure 1 by the OVRO CO maps of 8 nearby, relatively undisturbed spiral galaxies with bars of at least moderate strength (Kenney 1996). Sc galaxies, particularly those with weaker stellar bars, have strong CO emission along the leading edges of the bars, forming ridges which lead into the circumnuclear regions (M101, M83). The Sa (NGC 4314) and Sb (NGC 3351, NGC 3504, NGC 4102, NGC 6951) galaxies tend to have weaker CO emission along the bar, and have strong CO emission in the circumnuclear region inside the bar. There are CO rings (NGC 4314), spiral arms (NGC 6951), or "twin peaks" (NGC 3351), located near inner Lindblad resonances (ILRs), yet also galaxies with centrally peaked exponential disks (NGC 3504, NGC 4102).

What accounts for the variety in gas morphologies? Many features of the gas distributions can be understood by the dynamical behavior of gas in the vicinity of ILRs (Combes 1996; Kenney 1996; Elmegreen 1994, 1996). There is good evidence that the star-forming rings and the maximum molecular gas surface densities in many barred galaxies are located somewhere between the 2 resonances of a double ILR, in many cases probably closer to the outer ILR (OILR). Yet even the galaxies with centrally peaked (at $\sim$ 100 pc resolution) gas distributions, NGC 3504 and NGC 4102, clearly seems to have ILRs, with the peak gas surface density located deep inside the OILR, and perhaps even inside the inner ILR (IILR). Some of the differences may be evolutionary. In simulations (Knapen et al. 1995; Shlosman 1996), gas distributions in the vicinity of a double ILR evolve rapidly, and gas concentrations can form near both the OILR and IILR, and even get inside the IILR. A major uncertainty in such simulations is the behavior of star formation. The evolution of the gas distribution depends sensitively on the local rate of star formation, and the resulting energy input into the ISM, which are poorly understood.

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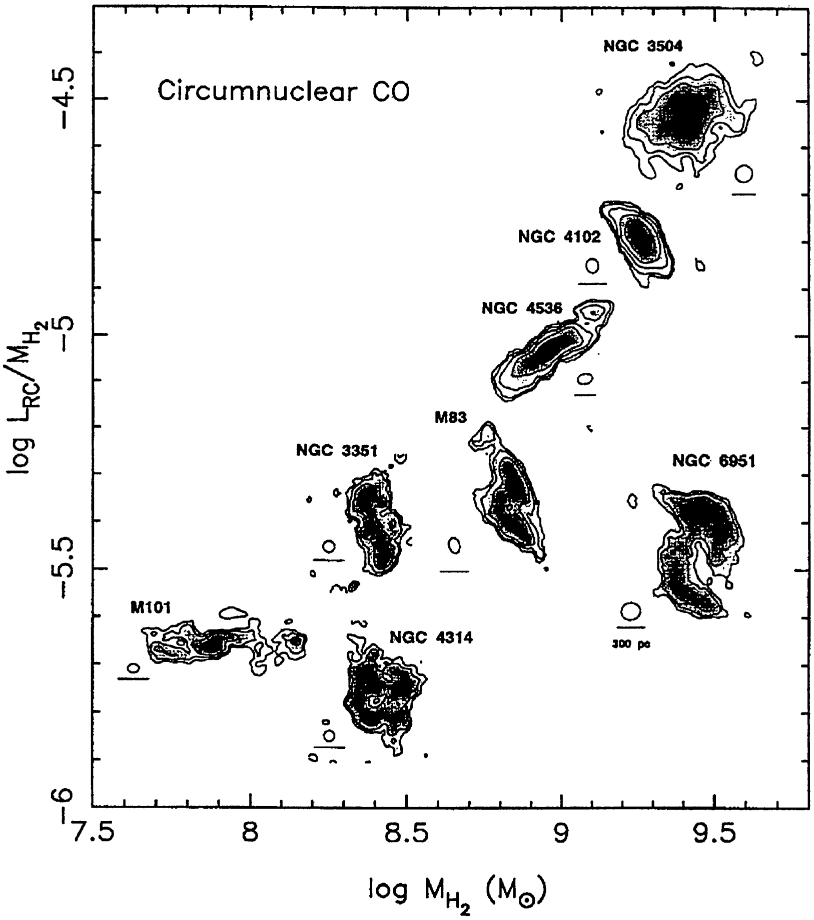

Fig. 1. CO maps of the circumnuclear (1 kpc) regions of 8 spiral galaxies, plotted in a diagram of molecular gas mass versus the ratio of 1.4 GHz radio continuum luminosity to molecular gas mass, which is a measure of the star formation rate per unit gas mass. This diagram illustrates that the intensity of circumnuclear star formation is correlated with the gas morphology. In most of these galaxies (NGC 3351, NGC 6951, NGC 4314, M101, and M83), the largest concentrations of molecular gas are located close to the Inner Lindblad Resonances. However in the starbursts NGC 3504 and NGC 4102 the gas is centrally concentrated, probably inside ILRs. Beamsizes, which are typically 2-3″, are shown as ellipses. The horizontal line associated with each galaxy is 300 pc in length. All galaxies have large-scale stellar bars which extend beyond the areas shown in these maps.

2. STARBURSTS AND INHIBITED STAR FORMATION

Star formation rates are clearly related to gas morphologies. Figure 1 shows the CO maps in a plot of molecular gas mass versus the ratio of 1.4 GHz radio continuum luminosity to molecular gas mass, which is a measure of the star formation rate per unit gas mass, or the inverse of the star formation timescale. NGC 3504 and NGC 4102, which have the most centrally concentrated CO distributions, also have the most luminous and shortest-lived starbursts, with starburst luminosities and timescales comparable to M82.

There is much more contrast in the distributions of star formation than in the molecular gas. The H II region ring ("hot spot") galaxies NGC 3351 (Kenney et al. 1992) and NGC 4314 (Benedict et al. 1996) provide an interesting comparison with the centrally concentrated starburst galaxies NGC 3504 (Kenney et al. 1993) and NGC 4102 (Jogee & Kenney 1996). In the central 200 pc of these 4 galaxies, the CO surface brightnesses vary by only a factor of 6, while the Hα and radio continuum surface brightnesses vary by a more than a factor of 100. Inside the star-forming rings of NGC 3351 and NGC 4314, there are extremely low levels of massive star formation, despite inferred molecular gas surface densities of 600–800 $M_\odot$ pc^{-2}. This is evidence for a high threshold gas surface density required for star formation in the circumnuclear regions of galaxies.

Gravitational instabilities seem relevant for understanding both the ongoing central starbursts in NGC 3504 and NGC 4102, and the lack of star formation inside the rings of NGC 3351 and NGC 4314. With the CO data cube, we can measure the gas surface density Σ_{gas} (inferred from the CO surface brightness, assuming the "standard" Milky Way CO-H_2 conversion factor), the critical surface density required to trigger gravitational instabilities Σ_{crit}, and their ratio $Q=\Sigma_{crit}/\Sigma_{gas}$ (Toomre 1964; Kennicutt 1989; Elmegreen 1994). Q is close to 1 throughout the starburst regions of NGC 3504 (Kenney et al. 1993) and NGC 4102 (Jogee & Kenney 1996) and in the star-forming ring of NGC 4314. Yet Q>1 inside the star-forming ring of NGC 4314, which may explain why there is no star formation inside the ring, despite significant quantities of molecular gas (Kenney & Jogee 1997, in preparation). It may be that gas builds up without forming stars until $\Sigma_{gas}(R) > \Sigma_{crit}(R)$, at which point a starburst commences.

3. SPECULATIONS ON EVOLUTIONARY TRENDS

Given the likelihood that circumnuclear gas morphologies evolve, what are the possible evolutionary differences between the galaxies in Fig. 1? Are any of the galaxies in a pre-burst or post-burst phase? One possible pre-burst galaxy is NGC 6951, which has a large central gas mass, yet a relatively low L/M_{gas}. It has a lot of gas in 2 spiral arms which extend beyond the ring of active star formation, probably near the OILR (Kenney et al. 1992). Since the gas in the arms are forming stars inefficiently, most of this gas will probably settle inwards and enter the ring. The gas morphology of NGC 6951 is similar to those seen at an early evolutionary phase of the simulations of Knapen et al. (1995). In the simulations, much of the gas starting in the OILR spiral arms ends up near or inside the IILR. If so, NGC 6951 could evolve into a galaxy with a more intense, more centrally peaked burst (i.e, move upwards in the L/M_{gas} versus M_{gas} plane).

In galaxies presently experiencing intense, centrally concentrated bursts, the gas consumption timescale due to star formation is shortest in the center (Kenney et al. 1993), which is also where starburst outflows preferentially eject gas. This suggests that at later evolutionary stages, NGC 3504 and NGC 4102 will have thinner rings of molecular gas and star formation, probably located close to their OILRs. As these galaxies deplete their central supply of gas, yet continue to form stars at a more modest rate in the outer parts of their circumnuclear disks, they should evolve downward and to the left in the L/M_{gas} vs. M_{gas} plane.

Are any of the galaxies in the lower left of Fig. 1 post-starburst systems? While it may well be that the centrally concentrated burst systems NGC 3504 and NGC 4102 evolve to become something like the "hot spot" galaxies NGC 3351 and NGC 4314, it is not necessarily true that all the galaxies in the lower left of Fig. 1 have recently experienced an episode of more intense, more centrally concentrated star formation. Some may be products of slow evolution, with modest yet steady rates of circumnuclear star formation, fueled by modest gas inflow rates from the bar. Ultimately, learning the masses, ages, and spatial extents of compact stellar disks formed from previous episodes of star formation will help us unravel the histories and mysteries of galaxy centers.

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