Astronomy with Millimeter and Submillimeter Wave Interferometry
ASP Conference Series, Vol. 59, 1994
M. Ishiguro and Wm. J. Welch (eds.)

MOLECULAR GAS IN THE CENTERS OF BARRED AND STARBURST GALAXIES

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ABSTRACT

High resolution interferometric CO maps of the circumnuclear regions of several barred galaxies show intense CO emission arising from twin peaks, which are oriented perpendicular to the large-scale stellar bars and located where dust lanes intersect nuclear rings of HII regions. These twin gas concentrations can be explained by the crowding of gas streamlines near stellar inner Lindblad resonances. In the barred nuclear starburst galaxy NGC 3504, a large concentration of molecular gas is centered on the nucleus, apparently inside an inner Lindblad resonance. Star formation is consuming the gas most rapidly where the rotation curve is nearly solid body, suggesting that tidal shear helps control the rate of star formation. A comparison with M82 and NGC 1068 suggests that the starburst in NGC 3504 is in an early phase of its evolution, and that starburst evolution is strongly influenced by shear.

INTRODUCTION

The circumnuclear regions of galaxies harbor starbursts and other unique activity. Millimeter interferometry makes it possible to study the molecular gas in these regions with a resolution of tens to hundreds of parsecs in large numbers of galaxies. Observations of the gas distributions and kinematics reveal that bars, resonances, tidal shear, and gravitational stability of gas all seem to play important roles in driving the evolution of circumnuclear regions. In this paper, we summarize recent high resolution CO maps of the central regions of strongly barred, weakly barred, and starburst galaxies and discuss evidence that gas distributions and specific rates of star formation depend strongly on the strength of stellar bars, and the shape of the rotation curve.

GAS NEAR INNER LINDBLAD RESONANCES

A large fraction of nearby spiral galaxies have "bar-like" central gas concentrations accompanied by non-circular gas motions, suggesting that significant radial inflow is common in spiral galaxies (Lo *et al.* 1984; Ball *et al.* 1985; Ishiguro *et al.* 1989; Handa *et al.* 1990; Hurt & Turner 1991) Bar-driven inward flows of gas in galaxies have been suggested to trigger nuclear starbursts, feed active galactic nuclei, and grow bulges (Kormendy 1980; Simkin, Su & Schwarz 1980; Scoville *et al.* 1985; Hawarden *et al.* 1986; Pfenniger & Norman 1990). Yet observations

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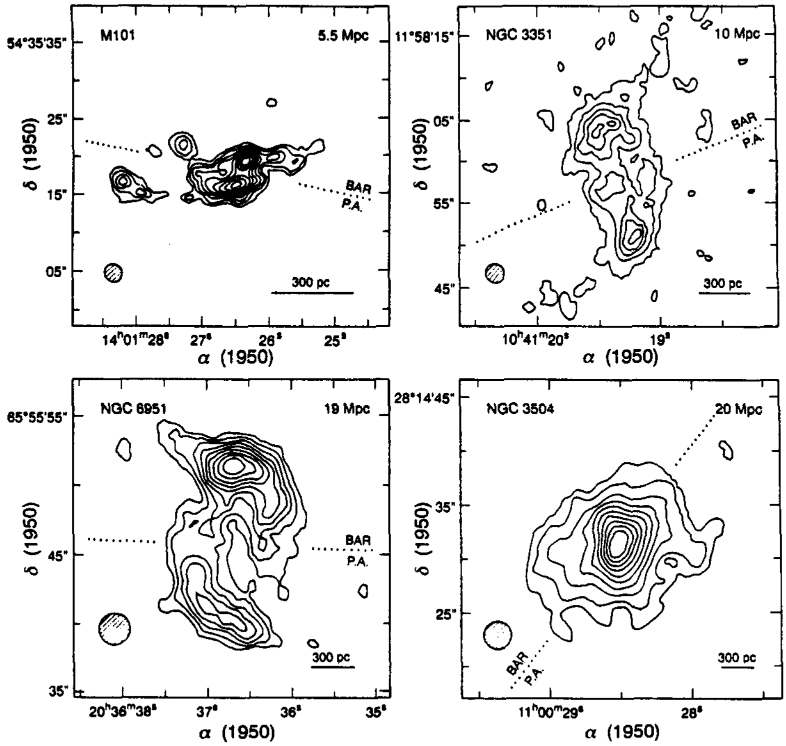

FIGURE I OVRO CO contour maps at 2″ resolution for central regions of 4 barred galaxies (Kenney *et al.* 1992). The large scale stellar bars are 2-3 times larger than the size of each frame, and are oriented perpendicular to the line connecting the CO 'twin peaks' in M101, NGC 3351, and NGC 6951.

to date with sufficient resolution to delineate the gas morphology in the central regions of galaxies show that the linear bar-like gas morphology does not continue all the way into the nucleus, and the gas surface density generally peaks some distance away from the nucleus (Ishizuki *et al.* 1990; Kenney *et al.* 1992). This suggests that the inflow may be slowed down or stopped at certain radii. Observations, theory, and models all suggest that gas slows its inward descent and piles up, at least temporarily, near stellar inner Lindblad resonances (ILR) (Combes 1988; Shlosman, Frank & Begelman 1989).

Figure 1 shows the CO(J=1→0) morphologies of 4 spiral galaxies mapped at ~2″ resolution with the 3-element Owens Valley Radio Observatory millimeter-wave interferometer (Kenney *et al.* 1992). NGC 3351 is classified as a strongly barred galaxy, while NGC 3504 and NGC 6951 contain bars of intermediate strength, and M101 has only a weak stellar bar. In M101, NGC 3351, and NGC 6951, the strongest CO emission arises from *twin peaks*, located symmetrically

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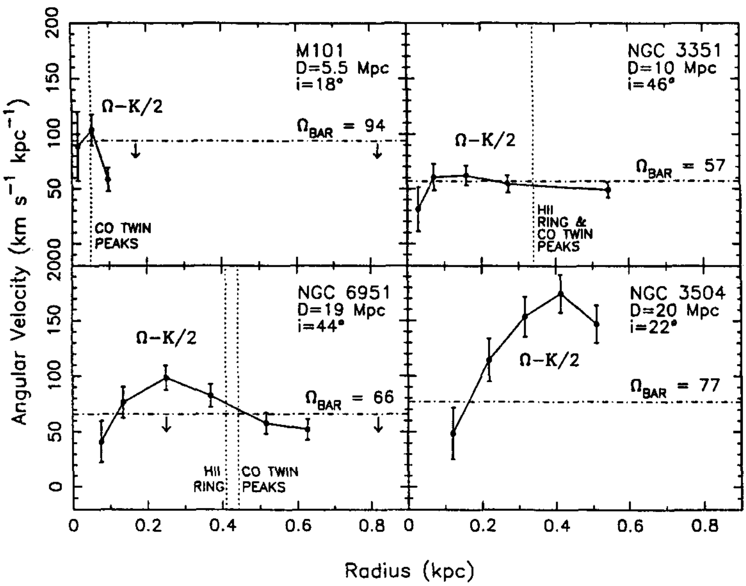

FIGURE II $\Omega_{\rm bar}$ **versus** Ω-$\kappa/2$ **diagram for barred galaxies, derived from CO rotation curves (Kenney** ***et al.*** **1992). ILRs are predicted wherever** $\Omega_{\rm bar}$=Ω-$\kappa/2$.

about the nucleus and oriented nearly perpendicular to the large-scale stellar bars. Comparisons with broad-band optical images shows that CO emission lies along the dust lanes that are located along the leading edges of the stellar bars in NGC 3351 and NGC 6951. These dust lane components form two linear or slightly curved offset ridges which are oriented nearly parallel to the large scale stellar bars, and connect directly to the twin peaks.

A comparison of the CO distributions with Hα distributions shows that in NGC 3351 and NGC 6951, the twin CO peaks lie at or near the ends of elliptical rings of HII regions. HII region complexes do not uniformly fill the elliptical annuli which we refer to as "rings": indeed, the brightest HII complexes in the "rings" are located along the major axis of the ellipse and near the CO twin peaks. CO emission can be found over portions of the rings defined by the HII regions, although away from the twin peaks CO emission is weak or undetected. The strongest Hα emission from the center of M101 arises from two Hα peaks located close to the CO peaks.

The CO rotation curves derived from the OVRO data show that the CO twin peaks and Hα rings are located near the predicted location of stellar ILRs. The locations of the ILRs are defined in the case of a weak bar to be the radii where the value of Ω-$\kappa/2$, which is the angular speed of the stars Ω minus half of the epicyclic frequency κ, is equal to the bar pattern speed $\Omega_{\rm bar}$ (Binney & Tremaine 1987). Figure 2 shows $\Omega_{\rm bar}$ and Ω-$\kappa/2$ versus radius for the 4 galaxies shown in Figure 1, where we have assumed that Ω is the same for the gas and the stars. The locations of the CO twin peaks in M101, NGC 3351, and NGC

6951 agree, within the uncertainties, with the locations of stellar ILRs or OILRs predicted from the gas kinematics.

Evidence from both optical images and CO kinematics indicates that the twin peaks are located where the dust lanes associated with the leading edges of the stellar bars curve inwards and intersect rings of HII regions in the vicinity of ILRs/OILRs. Twin gas concentrations may be expected to form due to the crowding of gas streamlines near the OILR, since this is where the dominant periodic stellar orbits change from being elongated in a direction parallel to the stellar bar (x_1 orbits, which dominate between corotation and the OILR) to being elongated perpendicular to the bar (x_2 orbits, which dominate between the OILR and the IILR) (Contopoulos & Mertzanides 1977). Models of gas in barred potentials show that the gradual shift of the orientation of the gas flow lines from that of the x_1 orbits to that of the x_2 (Schwarz 1984; Combes & Gerin 1985; Athanassoula 1992) cause a crowding of gas streamlines in patterns similar to what is observed in NGC 3351 and NGC 6951.

The Milky Way and several other galaxies exhibit evidence for orbit crowding near ILRs. In the center of the Milky Way, for which there is growing evidence of a central bar (Blitz & Spergal 1991), the strongest CO emission appears to originate near an inner Lindblad resonance (Binney *et al.* 1991). In the weakly barred spiral IC342, CO arises from narrow offset dust lanes which curve around to form a ring-like feature near the nucleus (Ishizuki *et al.* 1990). The strongest CO emission lies along the dust lane component further from the center than the ring-like feature, so that the 'twin peaks' in this galaxy are not quite perpendicular to the large-scale stellar bar. In weakly barred galaxies, gas is not driven radially inward as rapidly as in strongly barred galaxies, so the 'dust lane component' is bound to have a higher gas surface density. Variations in the strength and loci of maximum orbit crowding from galaxy to galaxy are expected from differences in the detailed mass distributions (Athanassoula 1992).

STARBURST GALAXIES

The presence of bars in the nearby starburst galaxies M82, NGC 253, and NGC 1068 (Telesco *et al.* 1991; Canzian, Mundy & Scoville 1988; Scoville *et al.* 1985) suggest that bars play an important role in the starburst phenomenon. However the relationship between bars and starbursts is not simple, since not all barred galaxies are undergoing starbursts, nor do all galaxies with starbursts have obvious stellar bars (Pompea & Rieke 1990). It is not yet known whether there are dynamical differences between starburst and non-starburst galaxies, or whether most galaxies undergo short-lived starburst episodes, perhaps triggered by interactions. While these basic questions remain unanswered, recent high resolution CO observations have started to clarify the anatomy of starbursts, and the role of dynamics in their evolution.

M82 and NGC 1068 are among the best-studied nearby starburst galaxies, and both have been mapped in CO at high resolution. The starburst in M82, which is highly inclined to the line of sight, exhibits 2 strong $^{12}CO(J=1\rightarrow0)$ peaks which straddle the nucleus, suggesting either a 'twin peaks' morphology, or a ring viewed edge-on (Lo *et al.* 1987; Carlstrom 1988). While multi-transition molecular line studies suggest that the peak gas surface density may be at a smaller radius than the $^{12}CO(J=1\rightarrow0)$ peak (Wild 1990), the relative distribution of near-infrared, far-infrared, and molecular line emission suggests that the starburst in M82 evolved from the inside out: late-type giant stars peak near the nucleus, tracers of young massive stars peak at a radius of ~100 pc, and a (partial?) ring of molecular gas extends from 100-200 pc (Carlstrom 1988; Telesco *et al.* 1991). The morphology and evolution of the starburst appears to be related to the rotation curve. The CO ring is located near the turnover point of the rotation curve, and the most intense star formation has occurred inside this radius. The apparent inside-out evolutionary history as well as the relationship between the starburst morphology and the rotation curve appears similar in NGC 1068 (Wynn-Williams, Becklin & Scoville 1985; Telesco & Decher 1988; Planesas, Scoville & Myers 1991). These features of M82 and NGC 1068 raise the following questions: Why do starbursts happen only near the nucleus? What determines the extent of starburst regions? Why do starbursts evolve from the inside out? Why do evolved starbursts have rings of gas near the turnover points of the rotation curves?

Observations of the little-known starburst galaxy NGC 3504 have begun to provide answers to some of these questions (Kenney, Carlstrom & Young 1993). The early type barred spiral galaxy NGC 3504 hosts a nuclear starburst of intensity comparable to that observed in M82 (Balzano 1983; Heckman *et al.* 1983; Devereux 1989; Puxley, Hawarden & Mountain 1990). While NGC 3351, NGC 6951 and NGC 3504 all have similar bar sizes, the central Hα and radio continuum luminosities in NGC 3504 are 6-12 times higher than those in NGC 3351 and NGC 6951, and the ratios of Hα or radio continuum luminosities to CO luminosity are 2-5 times higher in NGC 3504 than in the other 2 galaxies (Kenney *et al.* 1992). The CO morphology in NGC 3504 is completely different from the non-starburst barred galaxies in Figure 1, as it has a CO surface brightness that is nearly azimuthally symmetric and increases monotonically toward the nucleus. The rotation curve and the ratio of Hα/CO versus radius are shown in Figure 3a-b. The ratio of Hα/CO, which is probably proportional to the rate at which molecular clouds form massive stars, is high and approximately constant on the solid-body part of NGC 3504's rotation curve, but drops by a factor of ~4 where the rotation curve turns over at R~4″ (Kenney, Carlstrom & Young 1993). Apparently the rate of massive star formation per unit gas mass is closely related to the rotation curve, and the most intense part of the starburst is restricted to the region of low shear. What physical mechanism might explain this relationship?

One possible candidate is the gravitational stability of the gas. Kennicutt (1989) has shown that the existence of star formation in the outer regions of many spiral galaxies depends on the value of $Q=\Sigma_{crit}/\Sigma_{gas}$ (Toomre 1964; Binney & Tremaine 1987). In this expression, Σ_{gas} is the actual gas surface density, and $\Sigma_{crit} = \kappa\sigma/\pi G$ is a theoretical critical gas surface density which depends on the gas velocity dispersion σ and the epicyclic frequency κ (which in turn depends on the rotation curve). This is a ratio between gas self-gravity and the centrifugal and coriolis forces which can support gas from collapse. In the outer disks of spirals, Kennicutt (1989) found star formation suppressed wherever Q>1.4 and a nearly linear relationship between the star formation rate and the gas surface density where Q<1.4. The values of Σ_{crit}, Σ_{gas}, and their ratio are shown versus

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radius for NGC 3504 in Figure 3c-d. Q is less than one and approximately constant within the central 6″ (600 pc). Thus the central gas disk should be unstable to the formation of lumps, and this is consistent with the existence of star formation throughout the central molecular disk.

Can this same simple theory predict the radial variation in SFR/M_{gas}? The timescale for the growth of gravitational instabilities in a thin disk is approximately (Larson 1987; Silk 1988) $\tau \sim \sigma/\pi G \Sigma_{gas} \sim \kappa/Q$, which for a constant value of Q is $\tau \sim \kappa$. Since κ is constant in regions of solid body rotation but decreases as R^{-1} for a flat rotation curve, this timescale is approximately constant in the central 4″ of NGC 3504 but decreases significantly at radii beyond the turnover point in the rotation curve. Figure 3f shows that the shape of the τ versus radius curve for NGC 3504 is very similar to the shape of the $H\alpha/CO$ versus radius curve in Figure 3b, consistent with the idea that rapid cloud growth in the central few arcseconds results in rapid star formation. However, the predicted timescale does not match the timescale estimated from the SFR/M_{gas} ratio. The star formation timescale in the central 3″ is $\sim 6 \times 10^8$ yrs, whereas the cloud growth timescale is $\sim 5 \times 10^5$ yrs, or a factor of 10^3 shorter. The efficiency for converting gas mass into stars is believed to be a few percent in local Milky Way clouds, and perhaps even higher in starburst regions (Larson 1987), so it is hard to reconcile this difference without some other effect(s) being important. Furthermore, in the outer star-forming regions of galaxies where the rotation curve is flat and Q is nearly constant (Kennicutt 1989), $\tau \sim \kappa$ predicts a cloud formation timescale which varies as $\sim R^{-1}$, whereas the observed star formation timescale is closer to being constant with radius. This prompts us to consider other shear-related mechanisms for regulating the star formation rate.

Tidal shear may also help control the star formation rate by controlling the cloud destruction rate or the cloud re-formation rate. The star formation timescale for a given value of Q may be controlled in part by the ratio of the azimuthally averaged gas surface density Σ_{gas} to the critical tidal surface density Σ_{tide}, below which tidal shear will rip apart an already formed, non-shearing, non-collapsing cloud (Kenney, Carlstrom & Young 1993). While $\Sigma_{crit}/\Sigma_{gas}$ describes whether a uniform shearing layer of gas is unstable to the formation of lumps, $\Sigma_{tide}/\Sigma_{gas}$ describes whether an already formed lump of gas can survive the tidal shear of the galaxy. Star-forming molecular clouds are denser than the local values of Σ_{crit} and Σ_{tide}, but the energy injected into clouds by star formation may ultimately make them expand or lose mass and become less dense. If the potential has non-axisymmetric features such as a bar or spiral arms, clouds may form in regions of low Q and low shear but be destroyed when they flow into regions of higher shear (Athanassoula 1992; Rand 1993). In either case, tidal shear might conceivably end the star-forming life of a molecular cloud. The likelihood of tidal destruction depends strongly on the shape of the rotation curve. In regions where the rotation curve is nearly flat, $\Sigma_{crit} \sim \Sigma_{tide}$, so a lump of gas with $\Sigma_{gas} \sim \Sigma_{crit}$ has a density close to the range where tidal shear can shred it. However, in regions where the rotation curve is nearly solid body, $\Sigma_{crit} >> \Sigma_{tide}$, so a lump of gas with $\Sigma_{gas} \sim \Sigma_{crit}$ has a density much greater than that which is susceptible to tidal shear. Figures 3c and 3e show that $\Sigma_{tide} << \Sigma_{gas} \sim \Sigma_{crit}$ in the central part of NGC 3504, but that $\Sigma_{tide} \sim \Sigma_{gas} \sim \Sigma_{crit}$ beyond $R \sim 4''$. Therefore starbursts may occur predominantly in the nearly solid body cores of galaxies since this is the only location where tidal shear is insignificant for an entire orbit

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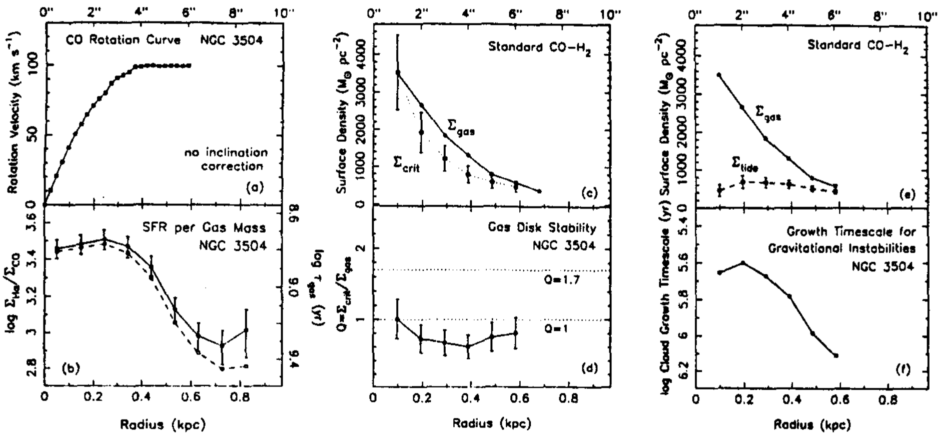

FIGURE III Several quantities plotted versus radius in the center of the nuclear starburst galaxy NGC 3504 (Kenney, Carlstrom & Young 1993). (a) CO rotation curve. (b) Ratio of $H\alpha/CO$ intensity. Numbers along right side are gas consumption timescales. The $H\alpha/CO$ ratio begins to drop at the turnover point in the rotation curve, indicating that some dynamical phenomenon related to the rotation curve helps control the rate of star formation per unit gas mass. (c) Gas surface density and critical gas surface density and (d) their ratio. (e) Gas surface density and critical tidal surface density. (f) Cloud formation timescale in gravitational instability theory.

once enough gas has accumulated to make Q$\sim$1.

The starburst in NGC 3504 can be directly linked to the presence of a large quantity of gas on the nearly solid body of the rotation curve. However, it is not yet clear what makes NGC 3504 different from the non-starburst barred galaxies. The offset dust lane morphology and the rotation curve (Figure 2d) both suggest that ILR(s) exist in the vicinity of the turnover point of the rotation curve at R$\sim$4″. However, there is no enhancement in CO emission at these radii, as there are in other galaxies with ILR(s). Significantly, the observations of NGC 3504 shows that an ILR does *not prevent* a galaxy from experiencing a starburst: a large quantity of gas has reached the nuclear region of NGC 3504 despite the presence of ILR(s). Thus it may be the evolutionary stage rather than the dynamics which is different between the starburst and non-starburst galaxies.

NGC 3504 seems to be in an early and short-lived phase of its starburst. The gas consumption timescale is $\sim$4 times shorter in the central 4″ than beyond the turnover point of the rotation curve. This suggests that the gas distribution will be ringlike in $\sim 6 \times 10^8$ yrs, much like the present gas morphologies of M82 and NGC 1068, and perhaps like NGC 3351 and NGC 6951. Since the gas surface density in NGC 3504 still increases monotonically toward the nucleus, the starburst must be less than $\sim 6 \times 10^8$ yrs old, and at an earlier stage of its evolution than either M82 and NGC 1068. The large quantity of gas indicated by the CO emission also suggests a young starburst. Gas comprises 60% of the dynamical mass within R=100 pc, if the Milky Way CO-H_2 relationship is applicable in NGC 3504. Thus not much more gas could have existed in the recent past, and the gas mass already consumed by star formation is probably less than that which still remains. The discovery of a galaxy in this short-lived phase of the starburst is a valuable find. At later stages of the starburst, the consumption of gas and the enormous release of energy eradicate the dynamical clues which allow us to understand its origin.

ACKNOWLEDGMENTS

Much of this work was done with my collaborators Chris Wilson, Nick Scoville, John Carlstrom, Judy Young, and Nick Devereux. Special thanks to the people at OVRO.

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https://doi.org/10.1017/S0252921100019813 Published online by Cambridge University Press

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QUESTIONS

LO: In explaining the "twin peaks" of CO distribution in your sample galaxies as orbit crowding of x_1 and x_2 families of stellar orbits, have you considered the dissipation that necessarily occurs for the molecular gas?

KENNEY: Models of gas flow with dissipation in barred galaxies by Athanassoula show gas morphologies similar to the CO morphologies of the "twin peaks" galaxies.

LO: In your stability criterion of $\Sigma_{gas} > \Sigma_{crit}$, as applied to NGC 3504, what are the assumptions and uncertainties involved in deriving both Σ_{gas} and Σ_{crit}?

KENNEY: The gas surface density estimate has assumed the Milky Way value of the CO-H_2 ratio, and this is probably uncertain by a factor of ~2 for starburst regions. The critical gas surface density is valid for thin isothermal disks, and depends linearly on the gas velocity dispersion and epicyclic frequency. These 2 quantities are measured directly from the CO data cube, and their uncertainty produces an uncertainty in Σ_{crit} of ~20-50% .

GENZEL: How did you estimate pattern speeds?

KENNEY: In all cases we assumed that the corotation radius was at or slightly beyond the end of the large-scale stellar bar. In some galaxies (e.g., M101 and NGC 6951) this is the only constraint and consequently we have only an upper limit for the pattern speed. In NGC 3351 we assumed that corotation coincided with the stellar ring located somewhat beyond the end of the bar, as predicted by theory. In NGC 3504, we assumed that the outer pseudo-ring coincided with an outer Lindblad resonance, as predicted by models, and this yields an estimate of the pattern speed consistent with the corotation radius near the bar end.

GENZEL: Were the $H\alpha$ and CO data in NGC 3504 at the same resolution?

KENNEY: The original data were not, but the $H\alpha$ map was smoothed to the same resolution as the CO map before making a comparison.

CAMERON: What is the CO column density and corresponding A_V in the central regions of NGC 3504? Such high A_V probably means that $H\alpha$ measurements are highly extinction biased.

KENNEY: A lower limit of 1.3 magnitudes of extinction at $H\alpha$ comes from a comparison of $Br\gamma$ (from Puxley *et al.* 1988) and $H\alpha$ fluxes within a 20″ aperture. Since extinction is bound to be patchy an not uniform as assumed for this calculation, the total extinction is certainly higher. Since the extinction is probably greatest toward the nucleus, where the highest gas surface density (peak $\Sigma(H_2+He)=3500\ M_\odot\ pc^{-2}$) is observed, correcting the $H\alpha$ radial distribution for extinction would probably make the difference in $H\alpha$/CO between R>4″ and R<4″ even greater. It would certainly be useful to map NGC 3504 in near-IR lines which suffer less extinction.

CAMERON: You claim that NGC 3504 is a "starburst caught in an early phase of evolution". If so, this galaxy should emit in the Wolf-Rayet band at 4660Å and possibly in the near-IR 2.06μm HeI line. Does it?

KENNEY: I don't know.

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BOOTH: While it is appropriate to address dynamical aspects from interferometer maps, when you discuss surface densities, I wonder about the effect of missing flux.

KENNEY: In NGC 3504 the CO interferometer map misses ~30% of the single dish flux. We have estimated the possible effect of missing CO flux on the CO radial distribution, and find that the missing flux could contribute an additional 10% at most to the CO brightness at R=4″, and an additional 25% at R=6″. We have taken this missing component into account in our estimate of the CO radial distribution. Since the missing fraction of the total flux increases with radius, correcting the CO radial distribution for the missing flux makes the difference in Hα/CO between R>4″ and R<4″ even greater.

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