HIGH RESOLUTION CO OBSERVATIONS OF BARRED GALAXIES

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ABSTRACT. Several different gas dynamical phenomena in barred galaxies are examined with new high resolution CO observations from the OVRO millimeter-wave interferometer. In M101, a gas bar is discovered which is offset in position angle by 24° from a weak stellar bar. In M83, the morphology and kinematics of a large molecular gas complex in a bar-spiral arm transition region suggest that it is formed by the combined action of orbit crowding and shocks. CO maps of 2 barred galaxies with nuclear Hα rings show bright CO emission near the ends of the rings, where shockfronts intersect the rings.

1. RESULTS

1.1 The Offset Gaseous and Stellar Bars in M101

M101 has an unusual bar in its center. A CO map at $55''$ resolution obtained at the NRAO 12-meter telescope shows a barlike feature or ridge of molecular gas with a length of about $2'$ (Kenney, Scoville, and Wilson 1991). A mosaic CO map at $8''$ resolution from OVRO shows that the CO emission is not uniform along the bar, but that there are concentrations at the nucleus, at the ends of the bar, and at sites along the bar (Kenney, Scoville, and Wilson, in prep.). The position angle of the CO ridge in both the single dish and interferometer maps is $102 \pm 3°$. M101 was not previously known to have a stellar bar, but R-band images of the galaxy show that an oval distortion or weak bar exists over radii from $30\text{-}60''$. The interesting thing about the stellar bar is that it is at a position angle of 78°, which is offset by 24° from the molecular gas ridge.

Gas bars which are offset in position angle from the stellar bars have been produced in barred galaxy simulations by at least two groups. An offset is formed if corotation is located significantly beyond the end of the stellar bar and there exists at least one inner Lindblad resonance (ILR) (Sanders and Tubbs 1980; Combes and Gerin 1985). While strong bars are sometimes assumed to end near corotation (Sellwood and Sparke 1988), the position angle offset between the CO ridge and stellar bar in M101 provides evidence that weak bars can end far inside the corotation radius (Petrou and Papayannopoulos 1986).

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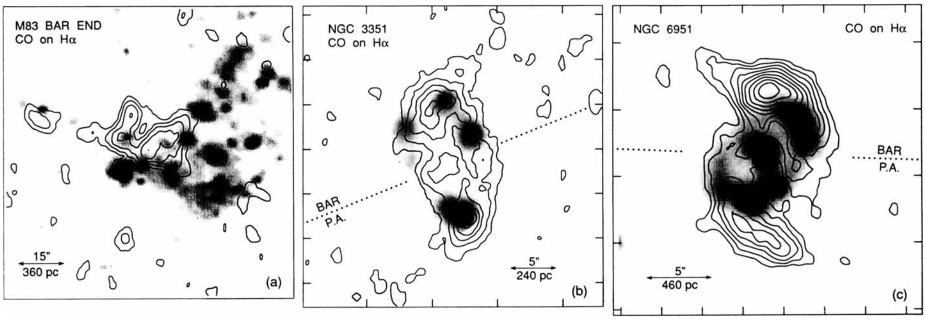

Figure 1. CO contours on Hα grey scale maps of a bar-spiral arm transition zone in M83 (a), and the nuclear regions of NGC 3351 (b) and NGC 6951 (c).

1.2 Gas Dynamics at the Bar End in M83

Barred spiral galaxies often have vigorous star formation occurring near the end of the bar. In order to study the gas dynamical processes responsible for triggering star formation in such a region, we have mapped CO at $\sim 7''$ resolution in the southern bar-spiral transition region of M83 (Kenney and Lord 1991). Figure 1a shows the CO contour map on a grey scale map of Hα emission. The Hα morphology is pipe-shaped, with weak emission along the bar, and luminous HII regions along the start of the spiral arm and in the bar-spiral arm transition zone. The CO complex is located right in the transition region, where the shockfront bends sharply from following the bar to following the spiral arm.

The origin of the large multi-peaked CO complex located in the center of the field can be partly understood by orbit crowding, in which gas on highly elliptical orbits from the bar region collides with gas on more circular orbits from the spiral arm region. The westernmost component is located at the same galactocentric azimuth, but at a greater galactocentric radius than the bright CO peaks immediately to the east, which is just what is predicted in the orbit crowding model. The gas kinematics also support this model, since the innermost CO components (i.e., closest to the bar) have a tangential velocity which is 60 km s^{-1} less than the outermost component (i.e., closest to the spiral arm). This is simply understood if·the innermost components are on highly elliptical orbits and the outermost components are on more circular orbits. The gas at apocentron on the elliptical orbit must have a slower tangential velocity than gas on a more circular orbit at the same radius, since the gas on the elliptical orbit has an insufficient tangential velocity to achieve a circular orbit, so it instead falls back toward the nucleus. The unobservable but presumably large outward radial motion of the inner gas stream brings it together with the outer gas stream, forming a large gas complex and subsequently leading to massive star formation.

The action of shocks enhance the orbit crowding effect. The spiral arm shock redirects gas inward, so that the outermost component will pass closer to the bar end that it would in the absence of shocks. Shocks may also play a direct role in the formation of the innermost component, by the shock-focussing phenomenon described by Roberts, Huntley, and van Albada (1979). The shockfront bends sharply in the transition zone, changing orientation by roughly 90° in going from the bar to the spiral arm. Because of the way shocks redirect streamlines, a region of streamline convergence is expected downstream from the sharp bend in the shockfront. The eastern component of the large CO complex is located approximately where streamline convergence is expected to be a maximum, and thus it may have formed by shock-focussing.

1.3 Molecular Gas in the Nuclear Ring Galaxies NGC 3351 and NGC 6951

We have mapped CO at $\sim 2''$ resolution in the centers of 2 barred Sb galaxies with nuclear Hα rings (Devereux, Kenney, and Young 1991; Kenney, Devereux, and Young, in prep.). Figures 1b and 1c show CO contour maps superposed on grey scale Hα images of NGC 3351 and NGC 6951. In both galaxies, there is faint CO emission partially tracing the elliptical rings defined by Hα. However, the brightest CO features are lobes or spiral arcs of emission located near the ends of the Hα rings. In NGC 3351, the bright CO is entirely within the ring, but there is faint emission along 2 ridges which are outside of but connecting to the ring and are spatially coincident with dust lanes. In NGC 6951 the bright CO arcs extend out of the ring, connecting with the dust lanes which lie along the leading edges of the stellar bar. Since these dust lanes are generally believed to produced in shockfronts, the bright CO in both galaxies is located near the intersection of the shockfronts and the rings.

The bright CO and the Hα rings are aligned roughly perpendicular to the large scale stellar bars in each galaxy. This can be understood if the rings are located at ILRs, since closed orbits (in the frame of the pattern) change their orientation by 90°at every principle resonance (Contopolous and Mertzanides 1977). Rings may be expected to form here, since torques exerted by the bar cause radial gas motions which create a buildup of gas at the ILR. A full dynamical picture must account for the strong CO emission in the center of NGC 3351's ring, which is not associated with strong Hα emission.

The ends of the rings are bright both because the CO is hot and because the gas surface density is high. The peak brightness temperatures are ~5 K, when averaged over 100-200 pc and 13 km s^{-1}. At higher resolution, the brightness temperatures should exceed the 6-10 K typical of quiescent Milky Way clouds, so the standard CO-H_2 relation may not apply. The bright CO peaks are located along a shockfront, and in general are not coincident with HII regions, so the gas is probably shock-excited. The gas surface density is also expected to peak at the ends of the ring because of orbit crowding, shock deceleration, and the fact that particles on elliptical orbits move more slowly at the apocentron. At present, we don't know which of these effects are most important.

1.4 References

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