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Molecular Gas in the Edge-On Galaxy NGC 4013

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Abstract. Our OVRO observations at 300 pc resolution of the molecular gas disk in the edge-on spiral galaxy NGC 4013 show no evidence for extraplanar material at our sensitivity limit. The observed molecular gas kinematics are in agreement with gas motion in a barred potential.

1. Introduction

Optical images of edge-on spiral galaxies show the presence of large dust bands running across the body of the galaxies. Recently, Howk & Savage (1999) found a correlation between the presence of extra-planar dust filaments and DIG which is suggesting massive star formation as the main cause for both features. Several mechanisms are considered to create this off-plane material: (1) hydrodynamic or magneto-hydrodynamic flows such as a fountain (e.g. Shapiro & Field 1976) or chimney (e.g. Norman & Ikeuchi 1989), (2) flows driven by magnetic field instabilities (Parker 1992). All these mechanisms require the ejection of dusty/molecular material from the thin galaxy disk. Therefore star formation and its associated resulting energy input into the ISM should play a significant role. Other possible explanations are warped or flared molecular gas disks. Due to the geometry of the galaxy on the sky, a flared gas layer could mimic extra-planar gas. In galaxies with boxy/peanut bulges, such as NGC 4013, the presence of a stellar bar can cause a vertical resonance that thickens the stellar bulge (e.g. Friedli & Benz 1993) and might allow the transport of molecular gas to higher z. However, this thickening occurs only at privileged positions along the bar (i.e. at the ILR).

2. Results for NGC 4013

NGC4013 is an edge-on warped spiral galaxy which shows prominent extra-planar DIG seen in Hα line emission (Rand 1996) as well as extra-planar dust features along the whole disk (Howk & Savage 1999, Alton et al. 2000). Two of the most prominent features are 6" - 8" away from the plane of the galaxy with inferred gas masses of about a few times $10^5 M_\odot$ (Howk & Savage 1999). 30m single dish observations of both CO lines already showed that the molecular gas disk can be traced till a radius of ~100" (8.2kpc) on the eastern side close to the beginning of the warp of the outer HI disk (Garcia-Burillo et al. 1999).

NGC4013 was observed in the CO(1-0) line with the Owens Valley Radio Observatory (OVRO) mm-interferometer using a 7-point mosaic to cover the entire optical disk (3.3'=16.5kpc). Obtained in the C, L and H (U) configurations, the data have a spatial resolution of ~3.6" (300pc) for the entire disk and 2.3" (190pc) for the inner arcminute. We recover about 70% of the total CO mass detected with single dish observations, or about $1.4 \times 10^9 M_\odot$ within the disk.

Molecular gas is detected along the dust lane and is unresolved at our resolution of 2.3" (190pc) resulting in widths of about 60-100pc, similar to other galaxies such as NGC891 (Scoville et al. 1993) or NGC5907 (Garcia-Burillo et al. 1997). Our observations confirm that NGC4013 hosts a large-scale stellar bar as already suggested by Garcia-Burillo et al. (1999). The observed gas kinematics as seen in the pv diagram along the major axis are in excellent agreement with theoretical predictions for gas motion in a barred potential. Detailed comparison to models for various angles of the bar to the line-of-sight by Athanassoula & Bureau (1999) suggest that the bar in NGC4013 is seen more side-on. There is a z-offset between the CO and Hα emission. Observations of more face-on systems in Hα and CO have shown that the Hα is usually offset toward the leading side of the CO emission by about 300-500pc (Sheth et al. 2002). This implies that most of the Hα emission detected is connected to the gas lanes in the bar potential. The strong non-circular motions in the inner ~5" (410pc) mark the region of the Inner Lindblad Resonance (ILR), and thus the presence of x_2 orbits. Our data provides no strong evidence for extra-planar molecular gas in NGC 4013: The H shaped Hα feature at the nucleus of NGC4013 seems to be originating from the high density CO ring. Since such CO rings are quite often associated with circumnuclear starburst rings, it seems very likely that the Hα feature is a super-wind, similar to the one seen in NGC3079. Recently, Garcia-Burillo et al. (1999) found evidence for extra-planar molecular gas (at 3" resolution) using the PdBI interferometer. We detect no extra-planar CO emission down to our sensitivity limit of 0.8 Jy beam^{-1} km s^{-1}, or about $1.4 \times 10^6 M_\odot$, at ~3.6" resolution. However, our local upper limit is consistent with the PdBI data. Since we miss about 30% of the total gas mass detected by the 30m telescope, diffuse high-z gas can still be present in NGC 4013.

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