NUCLEAR STAR FORMATION ON 100 PARSEC SCALES: 10″ RESOLUTION RADIO CONTINUUM, HI, AND CO OBSERVATIONS

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ABSTRACT

We report on a program of radio line and continuum studies of star formation in nearby (< 10 Mpc) spiral galaxies. The objective is a search for hot gas and peculiar dynamics in spiral nuclei with 10″ to 30″ angular resolution. Vigorous star formation is found to be a common phenomenon in the inner kpc of spirals. Arcsecond-resolution observations of radio continuum emission at 6 and 2 cm have been used to separate the thermal and nonthermal radio components. We find that thermal and nonthermal emission are well-mixed even on sizescales of 10 pc. To understand the reason for the increased level of star formation activity in spiral nuclei, we are studying HI and CO emission in these galaxies. The CO ($J = 3 \rightarrow 2$) transition has been detected in M51, M82, NGC 253, NGC 6946 and IC 342 with $T_a^* \sim$0.5–2.0 K, at 20″ angular resolution. The dynamics and spatial distribution of nuclear gas are being studied using VLA HI maps with 30″ synthesized beams. Evidence for noncircular motions in HI has been found in the nucleus of IC 342.

INTRODUCTION

It is clear that nuclear activity is common in spiral galaxies, as evidenced by strong radio continuum (*e.g.* Hummel 1981), infrared (*e.g.* Telesco and Harper 1980), and optical (*e.g.* Keel 1980) emission. In many cases, the emission regions resemble regions of intense star formation activity (Rieke *et al.* 1980). A useful approach toward understanding the "starburst" phenomenon is to study nearby galaxies, where the nuclear emission can be studied with great sensitivity and spatial resolution. We describe a program of radio observations of the ionized and neutral gas in spiral galaxies closer than 10 Mpc, where we can resolve regions of 100-200 pc extent. We use radio continuum emission to trace the ionized regions in these nuclei; dual-frequency observations allow estimates of the thermal emission, and hence the number of young stars and their spatial distribution. The hot molecular component associated with these OB stars can be studied using higher transitions of CO. The enormous numbers of young stars posited for these sources imply high rates of mass consumption. A central issue becomes: is this activity in the nucleus fed from gas in the disk? This question can be addressed with high resolution aperture synthesis maps of HI.

RADIO CONTINUUM STUDIES OF NEARBY SPIRAL NUCLEI

In order to accurately measure thermal radio continuum fluxes in spiral galaxies, it is desirable to spatially resolve out the extended synchrotron emission that dominates single-dish radio continuum observations (Klein and Emerson 1981). Observations of seventeen nearby spiral galaxies were made with the NRAO Very Large Array, at 1″ resolution, corresponding to roughly 10 – 20 pc linear extent. Matched beam observations were obtained at 6 and 2 cm to allow spectral separation of the thermal and nonthermal emission (Turner and Ho 1983).

We detected nuclear radio continuum emission in sixteen of the seventeen galaxies. The nuclei show a range of activity, from 1 mJy in M101 at 7.2 Mpc, to 2 Jy in NGC 253 at 2.5 Mpc, a factor of more than 200 in luminosity. Spectral index maps show that the radio emission is usually dominated by nonthermal emission, even on 10 parsec sizescales. Spectral indices of -1.2 to -0.8 are common. However, flat and positive spectral indices have also been observed (M83; IC 342), possibly indicating the presence of large complexes of compact HII regions in the nuclei. In a number of cases, including Maffei 2, NGC 253, and NGC 4736, the radio continuum knots are organized in one-dimensional structures. In NGC 253, at 0.1″ resolution, there is a string of compact knots aligned to within a degree on the sky, and 5 degrees in the plane of the galaxy; this 100 pc jet-like structure may be related to ejection from the central compact (< 0.6 pc) nonthermal ($> 10^5$ K) nucleus (Turner and Ho 1985).

Even for our small sample of nearby spirals, the range in activity and the variety of morphologies are impressive. The overall impression is that nuclei in general are very active.

CO ($J = 2 \rightarrow 1$) AND CO ($J = 3 \rightarrow 2$) OBSERVATIONS

The goal of the CO observations is to detect molecular gas that has been heated by star formation in spiral nuclei, and to study the dynamics of this gas. High excitation CO lines have two advantages over the CO ($J = 1 \rightarrow 0$) transition for studying warm gas in the nucleus: if the gas is optically thin, the warm gas will have significantly higher line intensities in CO ($J = 2 \rightarrow 1$) and ($3 \rightarrow 2$); if the gas is optically thick, the smaller beamsizes afforded by the higher observing frequencies will decrease beam dilution effects. The CO ($J = 2 \rightarrow 1$) and ($3 \rightarrow 2$) observations were made with the NRAO 12m telescope, with system temperatures of 2000 K and 12000 K and beamsizes of 35″ and 22″ at 230 and 345 GHz, respectively.

We have mapped CO ($J = 2 \rightarrow 1$) in the nuclei of the nearby spiral galaxies IC 342, M51, NGC 253, and NGC 6946. The beam-diluted brightness temperature, which ranges from $T_a^*(2 \rightarrow 1)$ ~0.2 K in M51 to 1.4 K in NGC 253, is in each case similar to the CO ($J = 1 \rightarrow 0$) temperature (*e.g.* Young and Scoville 1982). Since the ($2 \rightarrow 1$) beam is four times smaller than the ($1 \rightarrow 0$) beam, the CO most likely is optically thick, clumpy with respect to 30″, but with a total angular extent greater than the telescope beams. Mapping shows that the CO ($J = 2 \rightarrow 1$) extent is confined to roughly the inner two kpc. The extent of the ($2 \rightarrow 1$) emission in the nucleus of IC 342 is $\sim 2' \times 1'$, somewhat larger than that mapped interferometrically by Lo *et al.* (1984), but in agreement with the ($1 \rightarrow 0$) Nobeyama map of Sofue (1986). The ($2 \rightarrow 1$) maps also show that the rotation curve in these galaxies rises very steeply out of the nucleus: in NGC 253 the velocity centroid shifts by 150 km s^{-1} over 30″ (~360 pc), implying an enclosed mass of 2×10^8 $M_\odot$.

CO ($J = 3 \rightarrow 2$) was detected in M82, NGC 253, IC 342, M51, and NGC 6946. These observations represent the first detection of extragalactic CO ($J = 3 \rightarrow 2$). The peak antenna temperatures $T_a^*(3 \rightarrow 2)$ range from 0.7 K in NGC 6946, ~1 K in NGC 253, IC 342, and M51, to ~2 K in M82. In all cases, $T_a^*(3 \rightarrow 2)$ is very similar to $T_a^*(2 \rightarrow 1)$. This supports the implications from the $(2 \rightarrow 1)/\ (1 \rightarrow 0)$ ratio that we are observing well-distributed but clumpy molecular gas. Even for modest clumping factors, the detected CO temperatures are higher than the values commonly found in Galactic giant molecular clouds. For example, if the molecular scale length is 100 pc in M82, we deduce a gas temperature of ~30 K.

With the increasing angular resolution achieved by studying the higher frequency CO lines, we can begin to define the morphology and kinematics in the nuclear regions. However, it appears that arcsecond angular resolution will be needed to define the hotter gas component that is heated by star formation activity.

VLA HI MAPPING OF NEARBY SPIRAL NUCLEI: IC 342

The objective of HI mapping of nearby spiral nuclei is to study the relation of the disk gas (HI) and the molecular gas found in the nucleus, as described above. From the large numbers of stars derived for many spiral nuclei (e.g. Beck, Turner, and Ho 1986) it is clear that not many generations of such star formation activity can proceed before the nucleus is exhausted of gas. Is the nuclear gas replenished from the disk? Can we see evidence for nuclear feeding in the HI velocity distribution? To study this problem, we have observed IC 342 in HI with the C and D configurations of the VLA. The preliminary maps have 30″ angular resolution and 10 km s^{-1} velocity resolution.

The integrated intensity distribution in IC 342 shows a flat HI disk distribution and a ~2′ central HI hole, as shown in Westerbork (Rogstad, Shostak, and Rots 1973) and Cambridge (Newton 1980) maps. The higher resolution of the VLA map, however, reveals that the central hole is not completely devoid of HI. There are faint HI features in the nucleus. One HI filament lines up with the inner portion of a spiral arm, as traced by radio continuum emission. Another HI filament appears at the center of the nuclear region, slightly offset from the nuclear radio continuum source and the CO bar of Lo *et al.* (1984). This nuclear HI filament has an extent of roughly 2′ × 1′, oriented north-south. This feature is very similar in extent to the CO $(J = 2 \rightarrow 1)$ feature mentioned in the previous section and the Nobeyama maps of Sofue (1986). The mass of this HI bar is $\sim 1\text{–}2 \times 10^6\ M_{\odot}$, or approximately 1% of the CO mass (Lo *et al.* 1984). The north-south orientation of the HI bar is ~20° different from the more northwesterly orientation of the disk HI gas at the same velocity.

The HI velocities also indicate that the central HI bar feature is not simply a continuation of the HI disk. Deviations from circular rotation appear in the central 2′. The HI bar rotates nearly north-south, with velocities similar in both direction and magnitude with those of CO (Lo *et al.* 1984). In contrast, the disk HI at these velocities (near the systemic velocity of IC 342) define a rotating structure with a position angle ~45° east of north. Other deviations from circular rotation appear at the edges of the HI hole near the ends of the bar. The deviations from circular motion are ~10 to 30 km s^{-1}.

The high angular resolution HI synthesis maps show that the molecular gas in the nucleus can be connected to the disk atomic gas. The correspondence between the HI filament and the CO bar, and the presence of noncircular velocities suggest flows into the nucleus and concurrent conversion of atomic gas to molecular form.

SUMMARY

We report here on a program of radio continuum, CO, and HI studies at high angular resolution in order to examine the kinematics and spatial distribution of key tracers of young star formation. These studies have been most fruitful and promising in demonstrating a link between the nuclear and the disk environments in the case of IC 342.

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DISCUSSION

APPLETON:

Can you be sure that the weak HI feature you see near the center of IC 342 is not a result of incomplete continuum subtraction from the line-containing maps? It seems suspicious to me that this weak HI feature corresponds so closely to the continuum emission.

TURNER:

The feature only shows up in four or five channel maps: it is clearly a spectral and not a continuum feature.