THE DETECTION OF MASSIVE MOLECULAR COMPLEXES IN THE RING GALAXY SYSTEM ARP 143

JAMES L. HIGDON
CSIRO/Australia Telescope National Facility, Paul Wild Observatory, Locked Bag 194, Narrabri, NSW 2390; jhigdon@atnf.csiro.au

RICHARD J. RAND
Department of Physics and Astronomy, University of New Mexico, 800 Yale Boulevard NE, Albuquerque, NM 87131; rjr@gromit.phys.unm.edu

AND

STEVEN D. LORD
IPAC/Caltech, MS 100-22, Pasadena, CA 91125; lord@ipac.caltech.edu

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ABSTRACT

We have imaged the kiloparsec-scale distribution of 12CO(J = 1–0) emission in the ring galaxy system Arp 143 (NGC 2444/2445) using the OVRO millimeter array. We find two giant molecular complexes in the ring component (NGC 2445) and a bright central source. The ring complexes represent 20%–60% of the detected $M_{HI}$, depending on the relative $I_{12CO}/N_{HI}$ for the ring and nucleus. Their individual $H_2$ masses and surface densities ($\Sigma_{HI}$) exceed typical spiral arm giant molecular clouds and associations regardless of the conversion factor. Both are associated with a 6 kpc ridge of peak $\Sigma_{HI}$ and massive star formation activity. H\alpha imaging shows a patchy ring of $H_\beta$ regions situated along the outer edge of the $H_\alpha$ ring. The kinematics of the $H_\beta$ ring show clear signs of expansion. A simple rotating-expanding ring model ($V_{exp} = 118 \pm 30 \text{ km s}^{-1}$) fits the data reasonably well, which implies a ring age of $60 \pm 15$ Myr. NGC 2445’s ring is able to form very large molecular complexes promptly in a metal-poor ISM and trigger massive star formation.

Nearly 80% of the detected $^{13}$CO(1–0) flux originates in a resolved central source that is slightly offset from NGC 2445’s starburst nucleus. We find an ordered velocity field in this component. Assuming an inclined disk, we argue that it is dynamically stable. The central $\Sigma_{HI}$ (9 × 10 $M_\odot$ pc$^{-2}$) significantly exceeds $\Sigma_{HI}$ values commonly found in normal spirals but is much smaller than values derived in similar sized regions of IR-luminous galaxies. The nuclear $H_2$ may be the result of a previous encounter with NGC 2444. 12CO(1–0) emission in ring galaxies may be dominated by the nucleus, which could bias the interpretation of single-dish measurements.

Subject headings: galaxies: individual (Arp 143, NGC 2445) — galaxies: interactions — galaxies: ISM — galaxies: starburst — ISM: molecules

1. INTRODUCTION

$H_\alpha$ studies of such archetype ring galaxies as the Cartwheel and AM 0644–741 show that ~90% of the neutral atomic ISM is concentrated in the narrow orbit crowded rings for at least 40 Myr (Higdon 1996; Higdon et al. 1997b). This is thought to create an environment conducive to the formation of massive cloud complexes and the triggering of massive star formation (MSF) through elevated collision rates. However, we know little of the molecular interstellar matter (ISM) in these systems, which is unfortunate since massive stars in normal galaxies form exclusively in giant molecular clouds and associations (GMAs). Investigations of the molecular component of ring galaxies through the prominent 115 GHz 12CO(J = 1–0) transition have proved difficult owing to their ~1° angular size, which is comparable to the beams of most single-dish millimeter-wave telescopes, and typically low 12CO(1–0) fluxes (Horellou et al. 1995; Higdon, Lord, & Rand 1997a). This has led to speculation that MSF in ring galaxies occurs in a primarily atomic ISM (Higdon 1996). In this Letter we present the first aperture synthesis 12CO(J = 1–0) observations of a putative ring galaxy system—Arp 143 (NGC 2444/2445), which possesses the largest 115 GHz line flux in our ring galaxy survey. Complementary $H_\alpha$ and H$\alpha$ data are also presented to explore the relationship between the neutral ISM and MSF on similar spatial scales. We will show that NGC 2445 is indeed a young ring galaxy, whose ring is forming unusually large GMAs in a metal-poor ISM and triggering MSF.

1 ATNF Fellow.

Optical images of NGC 2445, the southern component in Arp 143, show a compact nucleus surrounded by a number of blue knots that are in fact low-metallicity $H_\beta$ regions (Burbidge & Burbidge 1959; Jeske 1986). Appleton, Schombert, & Robson (1992) found that most of the knots have optical/NIR colors consistent with very young (age $\leq$ 10 Myr) stellar populations and are located along the outer edge of an $H_\beta$ crescent, the distribution expected in ring galaxies created in an off-centered “intruder” passage. They proposed that NGC 2445 represented a young “prestarburst” ring galaxy. The $H_\beta$ crescent’s kinematics were not discussed, and no ring expansion—the sine qua non for a collisional ring galaxy—was reported. We presented $^{13}$CO(1–0) single-dish results for Arp 143 in Higdon et al. (1995) and noted an enhancement in line emission northwest of NGC 2445’s nucleus. We proposed that this was due to molecular gas in the $H_\alpha$ crescent.

2 OBSERVATIONS AND DATA REDUCTION

12CO(J = 1–0) observations of Arp 143 were made using the six-element Owens Valley Radio Observatory millimeter-wave interferometer on 1995 May 2 and 20 in the compact A-configuration (20.8–200 m baseline range). Each 10.4 m antenna was equipped with an SIS receiver cooled to 4 K. Single-sideband $T_{sys}$ were between 300 and 500 K at 113 GHz. The correlator was configured for 120 channels separated by 2 MHz (5.2 km s$^{-1}$), which gave a usable velocity range of 660 km s$^{-1}$. The array tracked a position near NGC 2445’s optical
nucleus for two 12 hr runs. Time-dependent amplitude and phase variations were monitored through frequent observations of QSO 0642+449, while 3C 273 was used to define the flux scale and correlator bandpass shape. We estimate the flux calibration uncertainty to be 10%. The UV data were processed using the OVRO reduction package MMA (Scoville et al. 1992). Channel maps were made using both natural ($\theta_{\text{FWHM}} = 5''$, $1 \sigma = 12$ mJy beam$^{-1}$, $\Delta V = 10.4$ km s$^{-1}$) and uniform ($\theta_{\text{FWHM}} = 3''$, $1 \sigma = 14$ mJy beam$^{-1}$, $\Delta V = 20.8$ km s$^{-1}$) weighting in AIPS, and CLEANed. The naturally weighted maps were further convolved to increase sensitivity ($\theta_{\text{FWHM}} = 8''$, $1 \sigma = 10$ mJy beam$^{-1}$). At the assumed distance of 40 Mpc ($H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$), this corresponds to a spatial resolution of 1.6 kpc. Integrated $^{12}$CO(1-0) maps were made by summing emission that exceeded the 3 $\sigma$ map noise, showed spatial and velocity continuity over at least three consecutive channels, and was within 150 km s$^{-1}$ of the local H I velocities. The final maps were corrected for primary beam attenuation. No continuum emission was detected.

Arp 143 was observed with the Very Large Array$^3$ on 1995 December 27 in the B-configuration to image H I emission with velocity and spatial resolution comparable with the OVRO data. Details of those observations will be presented elsewhere. Naturally weighted channel maps ($\theta_{\text{FWHM}} = 5''$, $1 \sigma = 0.3$ mJy beam$^{-1}$, $\Delta V = 10.6$ km s$^{-1}$) were used to construct H I moment maps using routines in AIPS. IDL programs were used to analyze the H I kinematics.

We obtained H$\alpha$+[N II] and Johnson B-band CCD images of Arp 143 with the McDonald Observatory 0.76 m telescope on 1992 March 10–12 using the T2 CCD located at the Cassegrain focus (0''58 pixel$^{-1}$). Line emission was isolated using an 80 Å FWHM filter centered at 6650 Å, while line-free continuum was mapped using a wider (120 Å FWHM) filter centered blueward of H$\alpha$. The CCD reduction was routine and was performed in IRAF. The line map was calibrated using extinction-corrected H I region line fluxes from Jeske (1986) and is believed accurate to ~25%, except in the nucleus where the images saturated. The H$\alpha$ image was smoothed ($\theta_{\text{FWHM}} = 5''$) to improve sensitivity and to match better the $^{12}$CO(1-0) and H I data. Measured field star positions were used to define an astronomical coordinate system in the optical images to an accuracy of 1″ (Benedict & Shelus 1978).

### Table 1: Molecular Gas Properties

| Region       | $\overline{S}$ ($\text{Jy km s}^{-1}$) | $M_{\text{HI}}$ ($10^5$ $M_\odot$) | $\Sigma_{i_{21}}$ ($M_\odot$ pc$^{-2}$) | $\Delta V_{\text{FWHM}}$ (km s$^{-1}$) |
|--------------|-------------------------------|-------------------------------|---------------------------------|---------------------------------|
| Arp 143 “a”  | 6.2 ± 0.3                     | 16.9 ± 0.7                    | 16 ± 0.7                        | ~52±315.3                      |
| Arp 143 “b”  | 1.6 ± 0.2                     | 4.1 ± 0.2                     | 1.0 ± 0.1                       | ~12±73.3                       |
| Arp 143 “c”  | 1.3 ± 0.2                     | 2.7 ± 0.6                     | 0.9 ± 0.1                       | ~17±100.0                      |
| M100 GMAs    |                               | 7.4 ± 0.4                     | 1.0 ± 0.1                       | ~7.0                           |
| M51 GMAs     |                               | 5.0 ± 0.8                     | 0.8 ± 0.1                       | ~12±80.0                       |
| Arp 143 nuclei | 27.6 ± 1.6 | 11.3 ± 1.2 | 1.0 ± 0.1 | ~9.0 ± 6.2 |
| Virgo spiral nuclei | 15.9 ± 2.1 | 0.8 ± 0.1 | 1.0 ± 0.1 | ~20.0 ± 10.0 |
| LIR galaxy nuclei | 2200.0 | ~10       | ~10       | ~10       |

* The range of values corresponds to the use of $X_{\text{MC}}$ and $X_{\text{MC}}$. $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ is assumed throughout.

* Rand 1995.

* Rand 1993.

* Quoted values derived from uniformly weighted data assuming $X_{\text{MC}}$.

* Average of eight Virgo galaxies (Canzian 1990). Standard deviations for $M_{\text{HI}}$ and $\Sigma_{i_{21}}$ are 7.1 x $10^5$ $M_\odot$ and 88 $M_\odot$ pc$^{-2}$.

* Average of 24 LIR galaxies from Sanders & Mirabel 1996.

### 3. Results

#### 3.1. The Neutral ISM of NGC 2445

Contours of integrated $^{12}$CO(1-0) and H I line intensity are shown superposed on the Arp 143 B-band image in Figures 1a and 1b (Plate L10). We find (1.25 ± 0.08) x $10^4$ M$_\odot$ of atomic hydrogen concentrated into an ~15 kpc diameter ring in NGC 2445’s disk. Though we detect only 25% of the single-dish 21 cm flux (Shostak 1978), our data provide a high-resolution view of the H I ring, the most conspicuous component in Appleton et al.’s (1992) C- and D-array VLA maps. The highest $\Sigma_{i_{21}}$ is found in a quasi-linear ridge west of the ring’s optical nucleus (30–60 M$_\odot$ pc$^{-2}$). Surface densities between 3 and 20 M$_\odot$ pc$^{-2}$ typify the rest of the H I crescent. We do not detect H I in NGC 2445’s nucleus or in NGC 2444. By contrast, $^{12}$CO(1-0) emission in NGC 2445 is dominated by a slightly resolved nuclear source, plus two large complexes (“a” and “b”) ~10” to the west and northwest. Both are associated with the ring’s high $\Sigma_{i_{21}}$ ridge. A third elongated source (“c”) extends southeast from the nucleus into a low $\Sigma_{i_{21}}$ region. Their emission properties are listed in Table 1. Altogether, we measure a $^{12}$CO(1-0) flux integral of 36.7 ± 2.1 Jy km s$^{-1}$ within the OVRO primary beam, or 33% of the single-dish value (Higdon et al. 1995). Adopting a Galactic $I_{\text{c,CO}}$-N$_H$ conversion factor ($X_{\text{c,MC}}$) Bloemen et al. (1986) leads to a total H$_2$ mass of (1.2 ± 0.1) x $10^9$ M$_\odot$. But given the LMC-like metallicity of the ring, use of an LMC conversion factor ($X_{\text{c,MC}}$ Cohen et al. 1988) may be more appropriate for “a” and “b,” in which case the total $M_{\text{HI}}$ becomes (2.2 ± 0.2) x $10^8$ M$_\odot$. The two ring GMAs would then represent 60% of the total molecular gas detected by the array. We will dodge the uncertain conversion factor issue by listing a range of $M_{\text{HI}}$ and $\Sigma_{i_{21}}$ values corresponding to the two choices of $X$.

The two molecular complexes of the ring contribute 19% of the observed $^{12}$CO(1-0) emission. Their individual H$_2$ masses are 1.6–9.7 x $10^4$ M$_\odot$ (“a”) and 0.4–2.5 x $10^4$ M$_\odot$ (“b”). Compared with the GMAs in M100 and M51, mapped with 700 pc resolution by Rand (1995, 1993), NGC 2445’s complexes are more massive with a comparable range in $\Sigma_{i_{21}}$ assuming $X_{\text{c,MC}}$ (Table 1). NGC 2445’s $\Sigma_{i_{21}}$ values are no doubt lower limits owing to the 1.6 kpc naturally weighted synthesized beam. At higher resolution they might break up into less massive GMAs as well. However, if $X_{\text{c,MC}}$ applies, their $M_{\text{HI}}$ and $\Sigma_{i_{21}}$ values significantly exceed the GMAs in M100 and M51, even when making allowances for differing resolutions. Both “a” and “b” are found in high $\Sigma_{i_{21}}$ regions (~50–60 M$_\odot$ pc$^{-2}$), although H I and $^{12}$CO(1-0) peaks do not coincide. Regions in which $\Sigma_{i_{21}} > 20$ M$_\odot$ pc$^{-2}$ and in which no $^{12}$CO(1-0) emission is detected are found within the OVRO primary beam. H I may, of course, be present here as our map noise sets a point source $M_{\text{HI}}$ detection limit of 1.8 x $10^2$ M$_\odot$ (3 $\sigma$) for $\Delta V$ of 30 km s$^{-1}$ and $X_{\text{c,MC}}$. Significant differences between the $^{12}$CO(1-0) and H I velocities were found in the ring, with $\Delta V_{\text{CO,H}}$ equal to ~38 km s$^{-1}$ for “a” and ~40 km s$^{-1}$ for “b.” Both are located in regions of large H I velocity dispersion or streaming, so it is difficult to attribute the offsets to an obvious systematic effect.

More than 80% of the total $^{12}$CO(1-0) flux, or (7.1 ± 1.6) x $10^4$ M$_\odot$ of H$_2$ ($X_{\text{c,MC}}$), is emitted by the nucleus of NGC 2445. The $^{12}$CO(1-0) peak is displaced 5” (0.8 kpc) southwest of...
of the optical center. A uniformly weighted $^{12}$CO(1–0) map of this region is presented in Figure 2a and shows the emission to be clearly elongated along a position angle of 71°, with a minor/major axis ratio of ~2/3. NGC 2445’s peak $\Sigma_{\text{H}_2}$ (910 M$_\odot$ pc$^{-2}$, $X_{\text{tot}}$) is significantly larger than $\Sigma_{\text{H}_2}$ inferred in the nuclei of normal spirals ($\Sigma_{\text{H}_2}$ = 190 M$_\odot$ pc$^{-2}$ in eight Virgo spirals, with an 88 M$_\odot$ pc$^{-2}$ rms; Canzian 1990) and some mergers (e.g., NGC 4038/39; Stanford et al. 1990). However, NGC 2445’s central $M_{\text{HI}}$ and $\Sigma_{\text{H}_2}$ are far outclassed by the centers of IR-luminous galaxies such as Mrk 273 ($\Sigma_{\text{H}_2}$ = 3.8 $\times$ 10$^4$ M$_\odot$ pc$^{-2}$; Yun & Scoville 1995). These comparisons are summarized in Table 1.

The velocity field of the nuclear $^{12}$CO(1–0) emission (Fig. 2b) shows ordered motions which suggest a disk geometry. We estimated its dynamical mass assuming a radius of 490 pc and 45° ± 10° inclination to be

$$M_{\text{dyn}} = \frac{RV_{\text{sys}}}{G \sin i} = (3.3 \pm 1.3) \times 10^9 M_\odot.$$  

The ratio of molecular to dynamical mass $M_{\text{HI}}/M_{\text{dyn}}$ is 0.2 ± 0.1 using $X_{\text{tot}}$ and is consistent with a system in equilibrium given the uncertainties. This is also similar to values determined for the nuclei of normal spirals, as opposed to the molecular masses and $M_{\text{HI}}/M_{\text{dyn}}$ typically found in IR-luminous galaxies (Yun, Scoville, & Knop 1994). Finally, we tentatively identify the elongated source “c” with a faint dust lane visible in the Arp atlas (1966) photograph.

### 3.2. Massive Star Formation and the ISM in NGC 2445

Figure 1c shows the distribution of H~I~ regions in Arp 143 with $L_{\text{H}\alpha}$ between 0.6 and 15. $\times$ 10$^{38}$ ergs s$^{-1}$. All are found in NGC 2445. Apart from the nucleus, MSF is concentrated along a patchy ellipse with the same general shape as the H~I~ crescent in Figure 1b. The three most luminous H~I~ regions form an ~6 kpc complex associated with both the GMAs “a” and “b” and the high $\Sigma_{\text{H}_2}$ ridge of the ring. We estimate the ring’s SFR to be 0.5 $M_\odot$ yr$^{-1}$ based on its $L_{\text{H}\alpha}$, which is 25% of the nuclear SFR (Kennicutt 1983; Jeske 1986). This is only 25% of the average SFR for four similarly sized ring galaxies in Marston & Appleton’s (1995) survey and less than 1% of that of the Cartwheel (Higdon 1995). The global relationship between H~I~, $^{12}$CO(1–0), and H$\alpha$ emission is illustrated in Figure 1d. Note that with one exception H~I~ regions are situated along the outer edge of the $\Sigma_{\text{H}_2}$ > 10 M$_\odot$ pc$^{-2}$ ring. This is most pronounced in the south and east but is also true in the H~I~ ridge west of the nucleus. We detect no H~I~ regions with $L_{\text{H}\alpha}$ above 3 $\times$ 10$^{38}$ ergs s$^{-1}$ (3 $\sigma$) in NGC 2445 apart from the nucleus and ring, or in NGC 2444.

### 3.3. Kinematics of the H~I~ Ring

In Figure 3 we show a radial velocity–position angle diagram for the H~I~ ring. The data represent averages within 10$^\circ$ segments of a 6° wide annulus fit to the H~I~ distribution. The dashed line shows the best fit to a nonexpanding rotating circular ring model. Strong noncircular motions are seen along the minor axis on both sides of the ring (P.A. = 40°–130° and 250°–340°), which are most easily explained as expansion. The solid line shows a least-squares fit of a rotating-expanding circular ring model, from which we derive $V_{\text{sys}}$ = 4000 ± 10 km
s^{-1}, V_{rot} = 214 \pm 25 \text{ km s}^{-1}, \text{ and } V_{exp} = 118 \pm 30 \text{ km s}^{-1}. \text{ The rotating-expanding ring is not a perfect fit. This may reflect nonplanar motions, tidal interaction with NGC 2444, or departures from circularity. Note that the largest discrepancy occurs near P.A. = 180^\circ, which is where the H\alpha ring splits in two. Nevertheless, expansion is clearly indicated by the data. From the ring’s radius and V_{exp}, we estimate its age to be 60 \pm 15 \text{ Myr, or } 20\% \text{ of that of the Cartwheel (Higdon 1996).} \n
4. DISCUSSION

These observations show that NGC 2445’s ring contains large-scale concentrations of molecular gas. At 1.6 kpc resolution, their M_{H_2} and \Sigma_{H_2} values appear larger than those typically found in spiral arms, especially if X_{LMC} is adopted. Their close association with the highest \Sigma_{H_2} of the ring suggests their formation in the orbit-crowded ring density wave through agglomeration or gravitational instability. The ring is clearly capable of forming large molecular masses out of a metal-poor ISM. Similarly, the concentration of luminous metal-poor H\alpha regions along the gas ring’s outer edge, and the close association between peak \Sigma_{H_2}, \Sigma_{H_2}, and \Sigma_{exp}, implies direct MSF triggering, rather than the simple rearrangement of preexisting star-forming regions (Higdon 1995).

We find the morphology of NGC 2445’s neutral and ionized gas to be in excellent agreement with model ring galaxies formed in off-centered collisions (see Appleton & Struck 1987). Indeed, the absence of a stellar bar makes it very unlikely that the gas ring is a resonance phenomenon. We found strong evidence of expansion in the H\alpha ring, which implies that the ring was formed 60 \pm 15 \text{ Myr ago. Together with the ring’s low metallicity and \sim 10 Myr old clusters, the large M_{H_2}, and } \Sigma_{H_2} \text{ for complexes “a” and “b,” and a low SFR relative to other rings, the body of evidence points to NGC 2445 being a young ring galaxy.}

The origin of the nuclear 12CO(1–0) emission is less certain. The high \Sigma_{H_2} relative to normal spirals coupled with the nuclear starburst suggests a tidal origin. However, the central \Sigma_{H_2} is clearly not in the same class as IR-luminous galaxies. Published ring galaxy simulations do produce large mass buildups in central regions, but not until the ring galaxy is highly evolved (see, e.g., Appleton & Struck 1987; Mihos & Hernquist 1994).

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Fig. 1.—(a) Contours of integrated $^{12}\text{CO}(1-0)$ emission (natural weighting, $\theta_{\text{FWHM}} = 8^\prime$) superposed on a $B$-band CCD image of the Arp 143 system. The dashed circle indicates the OVRO primary beam FWHM. The levels are logarithmic and correspond to 0.45, 0.79, 1.4, 2.5, 4.5, 7.9, 14.1, and 25.1 Jy km s$^{-1}$ beam$^{-1}$.
(b) Contours of $\Sigma_{\text{HII}}$ from the VLA B-array data ($\theta_{\text{FWHM}} = 5.4^\prime$). The levels range from 10 to 50 $M_\odot$ pc$^{-2}$ in steps of 10 $M_\odot$ pc$^{-2}$. Crosses mark the positions of H II region centers.
(c) Contours of $\Sigma_{\text{HII}}$ in Arp 143. Ten logarithmically spaced levels between 7.4 and $3.4 \times 10^{17}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ are shown.
(d) Composite showing relative distribution of $\Sigma_{\text{HII}}$ (gray scale), $\Sigma_{\text{CO}}$ (contours), and H II regions (plus signs).

Higdon, Rand, & Lord (see 489, L134)