The Astrophysical Journal, 433:L9–L12, 1994 September 20

A COMPARISON OF DYNAMICAL AND MOLECULAR GAS MASSES IN VERY LUMINOUS INFRARED GALAXIES

L. M. Shier, M. J. Rieke, and G. H. Rieke
Steward Observatory, University of Arizona, Tucson, AZ 87521
Received 1994 May 16; accepted 1994 July 1

ABSTRACT

Observations of the 2.3 μm bands of CO have been used to measure the central stellar velocity dispersions in NGC 1614 and IC 694. K-band images were used to constrain models of the stellar mass distribution. With these data and a spectrum of Arp 220 from the literature, we have determined the total mass within the central regions of all three galaxies. The central molecular gas masses inferred from ^{12}CO $J = 1$–0 fluxes are larger than the total masses determined from stellar kinematics. Subtraction of the likely stellar mass from the total mass yields upper limits for the H_2 mass that are 4–10 times less than the previously reported masses. This result supports other arguments that the I_{CO}/M_{H_2} ratio is not the same in ultraluminous galaxies as it is in Milky Way giant molecular clouds.

Subject headings: galaxies: ISM — galaxies: kinematics and dynamics

1. INTRODUCTION

Very luminous infrared galaxies also have large luminosities in the ^{12}CO $J = 1$–0 rotation transition which have been interpreted to mean that the galaxies contain enormous amounts of molecular gas, especially in their centers (Sargent & Welch 1993; Scoville et al. 1991). The H_2 mass is usually determined by applying a conversion between ^{12}CO $J = 1$–0 flux and H_2 mass determined from observations of giant molecular clouds in the Milky Way (Young & Scoville 1991). However, there is some controversy about the large inferred H_2 masses because the I_{CO}/M_{H_2} ratio in luminous infrared galaxies, and especially in their centers, may be very different from the giant molecular clouds of the Milky Way disk (Maloney & Black 1988; Aalto et al. 1991; Downes, Solomon, & Radford 1993).

One obvious limit to the H_2 mass is that it may not exceed the total mass present. Stellar kinematics can provide mass estimates free from large systematic errors. The stellar velocities are not affected by nongravitational influences—supernova shocks, gas infall, and massive stellar winds—which perturb the kinematics of the ionized gas. Stellar kinematic measurements at visible wavelengths are compromised in infrared galaxies due to their high optical extinction, but near-infrared observations are not seriously affected. The 2.3 μm bands of CO are ideal for the study of stellar kinematics in infrared galaxies. These bands are the strongest stellar absorption features in the near-infrared spectra of normal and starburst galaxies.

In this *Letter* we measure the velocity dispersions of the 2.3 μm bands and compare the total dynamical masses of three galaxies with their previously deduced H_2 contents to provide an observational test of the methods for measuring the H_2 mass. The total masses derived from stellar kinematics are lower in all three cases than the H_2 masses obtained from millimeter wave interferometry.

2. OBSERVATIONS

Two types of data were acquired for this project: spectra of the nuclei of IC 694 and NGC 1614 and broadband images of these galaxies and of Arp 220. The images are used to compensate for the lack of spatial information in the spectra.

Spectroscopic observations were made at the Steward 2.3 m telescope on Kitt Peak on the nights of 1993 May 8 (IC 694), and 1993 September 30 and October 1 (NGC 1614). FSpec, a new near-infrared spectrometer, was used for all these observations. FSpec has a NICMOS3 HgCdTe detector array and a 2".4 × 90" slit (Williams et al. 1993). It was used with the high-resolution grating giving a resolution of 3500 = 80 km s^{-1} (Nyquist sampled). Since the nuclei of both galaxies are only a few arcseconds in extent, the sky background and the galaxy were monitored simultaneously. The galaxies were moved to a new location on the slit at an interval of no more than 4 minutes. The total integration time was 2.1 hr for IC 694 and 4.2 hr for NGC 1614. Approximately every half hour, a star of spectral type A V–G V was observed to sample the terrestrial absorption spectrum. Intermediate dwarf stars have nearly featureless near-infrared continua in the region near 2.3 μm. Stars of type K5 III–M2 III were observed as templates for cross-correlation.

The data reduction required several steps. The background emission was removed by subtracting two temporally adjacent images. This procedure also removes the dark current. The images were flat-fielded with dome flats. The spectrograph was set to the same wavelength when observing the flat-field screen as when observing the galaxies to minimize the effects of fringing. Before flat-fielding, the fringes have an amplitude of $\sim 1\%$. All of the images from each half-hour period between observations of the dwarf star were combined and the bad pixels rejected in the process. The IRAF twodspec package was used to extract a spectrum from a 2".4 × 4".8 region centered on the galaxy nucleus. The dwarf star spectra were reduced in a similar manner. The galaxy spectrum was then divided by the dwarf spectrum to remove terrestrial absorption effects. It was not possible to wavelength-calibrate these spectra from atmospheric lines because the OH air glow does not extend past $\lambda > 2.27$ μm. Xenon lamp spectra were used for the May run and NeKr lamp spectra for the fall run for wavelength calibration. No attempt was made to flux-calibrate the spectra. The spectra are shown in Figure 1; the signal-to-noise ratio is 22 for IC 694 and 28 for NGC 1614.

J (1.25 μm), H (1.65 μm), and K (2.2 μm) images of IC 694 and Arp 220 were obtained at the 2.3 m Steward Observatory

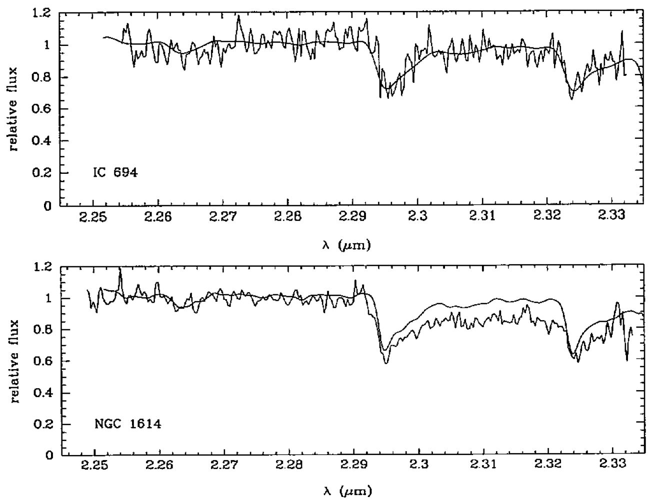

FIG. 1.—Spectra of NGC 1614 and IC 694. The spectra have been corrected to zero redshift. Spectra of HR 7800 broadened by the dispersion of each galaxy have been superposed.

telescope on 1992 March 17. NGC 1614 was observed through J, H, and K_s filters at the same telescope on 1992 November 3. A NICMOS3 (Rieke et al. 1989) camera was used at a plate scale of 0"24 in March and 0"66 in November. The seeing was 0"8 in March and 1"2 in November. The telescope was beam-switched once per minute to monitor sky brightness changes. Blank sky images were subtracted from galaxy images to remove the sky background and dark current. The data were flat fielded with flats constructed from blank sky images. None of the imaging was done under photometric conditions. The aperture photometry of Carico et al. (1990) was used to calibrate the images of Arp 220 and NGC 1614. Aperture photometry from Nakagawa et al. (1989) was used to calibrate the images of IC 694.

3. ANALYSIS

The CO-band spectra were used to measure the stellar velocity dispersions as described in § 3.1. Luminosity profiles were extracted from the K and K_s band images. The luminosity profiles were used to determine whether the galaxies are best described as dispersion supported or rotationally supported. The luminosity profiles, galaxy models, and derived masses are discussed in § 3.2.

3.1. *Velocity Dispersions*

The two methods most commonly used for measuring the redshift and velocity dispersion of galaxies are the cross-correlation technique described by Tonry & Davis (1979) and the Fourier quotient technique of Sargent et al. (1978). The cross-correlation method was used to measure the velocity dispersions in IC 694 and NGC 1614 because it is more accurate in cases where the velocity dispersion is less than 150 km s^{-1} (Larsen et al. 1983).

The spectra in Figure 1 were used to measure velocity dispersions in the nuclei of NGC 1614 and IC 694. Due to the small size of the nuclei (2"–3") and the relatively large pixels of the spectrograph (1"2), we were only able to obtain a single nuclear spectrum for each galaxy.

The CO index was used to choose template stars with a band strength close to that of the galaxies. The CO index was measured from the galaxy spectra using the method described in Kleinmann & Hall (1986) to convert to the index from the depth of the CO(2,0) band. A small correction was applied to account for the change in spectroscopic CO index with velocity dispersion. The CO index in all three galaxies is stronger than in normal galaxies, indicating that supergiants must be contributing some of the 2.3 μm light. HR 7405 (M0 III) and HR 7800 (K7 III) were used as templates for NGC 1614. Template stars for IC 694 were 41 Com (K5 III) and SAO 120744 (M2 III).

Uncertainties were derived by Monte Carlo simulations of a spectrum with the same velocity dispersion, signal-to-noise ratio, and line strength as the galaxies. The measured dispersions and CO indices are listed in Table 1.

3.2. *Models*

Models of the galaxies are needed to infer masses from the aperture dispersions described in § 3.1. Two galaxies with the same aperture dispersion may have different masses if their degrees of rotational support, mass distribution, or extinction are different.

Merging galaxies evolve into elliptical-like remnants (Hernquist 1993) and spiral galaxy bulges have high velocity dispersions, so the η-models of Tremaine et al. (1994) have been used to infer the masses within the central regions from the aperture dispersions. These models assume that the galaxy is spherical and has a constant mass-to-light ratio. The model galaxies are nonrotating and possess isotropic velocity dispersions. The models have a density of the form $\rho(r/r_s) = k/[r^{3-\eta}(r+1)^{1+\eta}]$. For the sake of simplicity, the $\eta = 3$ model was chosen. In this model, the light is dominated by stars near the scale radius. The mass interior to the scale radius is $(15/7)(r_s \sigma_{\rm los}^2/G)$.

The K-band images were used to measure the light profiles of the galaxies. The K-band light is an accurate tracer of the mass distribution in spiral galaxies (Rix 1993), and the K band is less affected by dust emission and absorption than shorter wavelengths. The morphologies of IC 694, NGC 1614 and Arp 220 are different. IC 694 has a single, axisymmetric nucleus. A

TABLE 1

RESULTS FOR PROGRAM GALAXIES

Galaxy	Distance (Mpc)	Velocity Dispersion (km s^{-1})	Mass ($r < r_{CO}$) (10^9 $M_\odot$)	r_{CO} (pc)	CO Index (mag)
NGC 1614	63	75 ± 12	2.0 ± 0.4	600	0.17 ± 0.02
IC 694	41	135 ± 30	2.6 ± 1.0	250	0.20 ± 0.02
Arp 220	73	125 ± 30[a]	1.8 ± 0.8	350	0.20 ± 0.05[b]

a Doyon et al. 1993.
b Rieke et al. 1985.

disk is visible, but its surface brightness is much lower than that of the nucleus, so it does not affect the light profile within a radius of 3 kpc. The center of NGC 1614 has two midinfrared nuclei separated by 0".6 (Keto et al. 1992). These nuclei are too close to be resolved in our K_s band images. The bright knot to the north of the nucleus is not included in our aperture. Arp 220 has two nuclei separated by $\sim 1''$ (Graham et al. 1990), which are not clearly resolved in our images.

The value of r_s may be determined by fitting projections of the Tremaine et al. (1994) model convolved with a Gaussian seeing disk to the luminosity profile of each galaxy. There is a range in the values of r_s: 1".1 in IC 694, 1".5 in NGC 1614, and 2".0 in the circumnuclear regions of Arp 220. The last value gives a half-light radius in good agreement with that found by Wright et al. (1990). The half-light radius for NGC 1614 is 12% larger than that found by Forbes et al. (1992). For $H_0 = 75$ km s^{-1}, the scale radii are 220 pc in IC 694, 460 pc in NGC 1614, and 660 pc in Arp 220.

The above assumptions allow the velocity dispersion and luminosity density to be computed at each point in the galaxy. Aperture dispersions may be computed for any size aperture by integrating over the aperture and through the line of sight. We have computed aperture dispersions for the rectangular apertures used for our observations. Masses for the regions of high ^{12}CO $J = 1$–0 emission derived from the aperture dispersions and the scale radii are presented in Table 1. The quoted uncertainties in the masses were calculated from the uncertainties in the velocity dispersions.

Real merging galaxies have large amounts of dust and high extinction to the center. Model galaxies with uniformly mixed dust and stars were used to evaluate the effects of the dust on the colors and observed velocity dispersions. The smooth appearance of our near-infrared images suggests that there is not patchy extinction in the near-infrared on the scale of our resolution element. The $J-H$ and $H-K$ colors of the galaxies were used in combination with the model to estimate A_V. The colors of the galaxies were measured from the images using the same apertures as was used with the spectrograph. IC 694 has $J-H = 1.15$ and $H-K = 0.77$, Arp 220 has $J-H = 1.22$ and $H-K = 0.67$, and NGC 1614 has $J-H = 0.85$ and $H-K_s = 0.53$. Assuming that the stellar population has infrared colors like those of normal galaxies, the $H-K$ colors indicate $A_V = 10$ in IC 694, $A_V = 9$ in Arp 220, and $A_V = 7$ in NGC 1614. Extinction at the level suggested by the near-infrared colors has a negligible effect on the derived mass. The light is dominated by emission from stars near the scale radius, where the line-of-sight velocity distribution is not a strong function of radius, so small changes in the radius that dominates the light have minimal impact on the the observed velocity dispersion.

4. DISCUSSION

The masses derived in this *Letter* provide an upper limit to the mass of any individual component, including H_2. As § 3 demonstrated, the kinematic mass determinations are not subject to large systematic errors. Therefore, we can test the validity of the use of the Galactic I_{CO}/M_{H_2} ratio (Scoville & Sanders 1987) to measure M_{H_2} in the centers of luminous *IRAS* galaxies.

Interferometer observations have been made of the ^{12}CO $J = 1$–0 rotation transition in each galaxy, in each case sampling a volume nearly identical to the one where we have measured the dynamical mass. Sargent & Scoville (1991) observed IC 694 and found strong ^{12}CO $J = 1$–0 emission in the central 2".7 = 500 pc. They used the Galactic I_{CO}/M_{H_2} ratio to infer a H_2 mass of $3.9 \times 10^9\ M_\odot$. Observations of NGC 1614 produced an H_2 mass estimate of $6 \times 10^9\ M_\odot$ for the inner $2'' = 1.2$ kpc (Scoville et al. 1991). Arp 220 was observed by Scoville et al. (1991). They found a 1".4 × 1".9 (500 × 640 pc) core containing an estimated $1.8 \times 10^{10}\ M_\odot$ of H_2.

The upper limits on the total molecular gas content become smaller if we consider the contribution of stars to the total mass. Given that NGC 1614 and IC 694 do not have spectra that are clearly LINER-like (Armus, Heckman, & Miley 1989), stars must be producing the large luminosity of both galaxies. In the far-IR alone, NGC 1614 has a luminosity of 2.5×10^{11} $L_\odot$ and the Arp 299 system (IC 694 + NGC 3690) has a luminosity of $5.5 \times 10^{11}\ L_\odot$ (Soifer et al. 1987). High-resolution far-infrared imaging of the Arp 299 system shows that 60% of the light originates in IC 694, giving it a total far-infrared luminosity of $2.3 \times 10^{11}\ L_\odot$ (Joy et al. 1989). Nearly all of this light originates in the central few arcseconds of the galaxies, as shown by the 12 and 25 μm compactness measurements of Wynn-Williams & Becklin (1993). If the stellar population is like that of the prototypical starburst galaxy M82, then $M/L_{BOL} = 0.005\ M_\odot/L_\odot$ (McLeod et al. 1993). The stellar population must be at least $\sim 1.6 \times 10^9\ M_\odot$ in IC 694 and $\sim 1.3 \times 10^9\ M_\odot$ in NGC 1614. After subtracting the mass of the stellar population, the upper limits on the H_2 mass are $1 \times 10^9\ M_\odot$ in the center of IC 694 and $7 \times 10^8\ M_\odot$ in the center of NGC 1614.

The reported H_2 masses are larger by a factor of 4–10 than the upper limits resulting from subtraction of the probable mass of the stars from the total kinematic masses. The molecular gas mass estimates and the kinematic mass calculations depend on the assumed distances to the galaxies in differing ways, so their ratio goes as H_0. Even if H_0 is 50, the reported molecular gas masses are larger than the dynamical masses by factors of at least 3–6.

5. CONCLUSIONS

Masses have been determined for the central regions of IC 694, NGC 1614, and Arp 220 using stellar dynamics. In all three galaxies, the total dynamical mass of the ^{12}CO $J = 1$–0 core is less than the H_2 mass inferred from the ^{12}CO $J = 1$–0 flux and the standard I_{CO}/M_{H_2} conversion factor. Consideration of the likely mass of the stellar populations in NGC 1614 and IC 694 places even lower limits on the molecular gas mass. The conversion factor found for Milky Way GMCs is evidently not correct for these luminous infrared galaxies. The true H_2 content of these galaxies and the gas mass fraction must be determined by more detailed observations and modeling of the state of the molecular gas.

We thank NASA for providing support for LMS through the GSRP Fellowship and for providing the NICMOS3 array. The construction of FSpec was supported by the National Science Foundation. We thank John H. Black and Hans-Walter Rix for useful discussions, and the anonymous referee for an exceptionally supportive and helpful report.

REFERENCES

Aalto, S., Black, J. H., Johansson, L. E. B., & Booth, R. S. 1991, A&A, 249, 323
Armus, L., Heckman, T. L., & Miley, G. K. 1989, ApJ, 347, 727
Carico, D. P., Sanders, D. B., Soifer, B. T., Matthews, K., & Neugebauer, G. 1990, AJ, 100, 70
Downes, D., Solomon, P. M., & Radford, S. J. E. 1993, ApJ, 414, L13
Doyon, R., Wells, M., Wright, G. S., & Joseph, R. D. 1993, preprint
Forbes, D. A., Ward, M. J., Depoy, D. L., Boisson, C., & Smith, M. S. 1992, MNRAS, 254, 509
Graham, J. R., Carico, D. P., Mathews, K., Neugebauer, G., Soifer, B. T., & Wilson, T. D. 1990, ApJ, 354, L5
Hernquist, L. 1993, ApJ, 409, 548
Joy, M., Lester, D. F., Harvey, P. M., Telesco, C. M., Decher, R., Rickard, L. J, & Bushouse, H. 1989, ApJ, 339, 100
Keto, E., Ball, R., Arena, J., Jernigan, G., & Meixner, M. 1992, ApJ, 389, 223
Kleinmann, S. G., & Hall, D. N. B. 1986, ApJS, 62, 501
Larsen, N., Nørgaard-Nielson, H. U., Kjægaard, P., & Dickens, R. J. 1983, A&A, 117, 264
Maloney, P., & Black, J. H. 1988, ApJ, 325, 389
McLeod, K. K., Rieke, G. H., Rieke, M. J., & Kelly, D. M. 1993, ApJ, 412, 111
Nakagawa, T., Nagata, T., Geballe, T. R., Okuda, H., Shibai, H., & Matsuhara, H. 1989, ApJ, 340, 729
Rieke, G. H., Cutri, R. M., Black, J. H., Kailey, W. F., McAlary, C. W., Lebofsky, M. J., & Elston, R. 1985, ApJ, 290, 116
Rieke, M. J., Montgomery, E. F., Rieke, G. H., Vural, K., Blessinger, M., & Kleinhaus, W. 1989, in Proc. 3d NASA Ames Infrared Detector Technology Workshop, ed. C. R. McCreight (NASA TM-102209), 311
Rix, H.-W. 1993, PASP, 105, 999
Sargent, A. I., & Scoville, N. Z. 1991, ApJ, 366, L1
Sargent, A. I., & Welch, W. J. 1993, ARA&A, 31, 294
Sargent, W. L. W., Young, P. J., Boksenberg, A., Shortridge, K., Lynds, C. R., & Hartwick, F. D. A. 1978, ApJ, 221, 731
Scoville, N. Z., & Sanders, D. B. 1987, in Interstellar Processes, ed. D. Hollenbach & H. A. Thoronson (Dordrecht: Reidel), 21
Scoville, N. Z., Sargent, A. I., Sanders, D. B., & Soifer, B. T. 1991, ApJ, 366, L5
Soifer, B. T., Sanders, D. B., Madore, B. F., Neugebauer, G., Danielson, G. E., Elias, J. H., Lonsdale, C. J., & Rice, W. L. 1987, 320, 238
Tonry, J., & Davis, M. 1979, AJ, 84, 1511
Tremaine, S., Richstone, D. O., Byun, Y.-I., Dressler, A., Faber, S. M., Grillmair, C., Kormendy, J., & Lauer, T. R. 1994, AJ, 107, 634
Williams, D., Thompson, C. L., Rieke, G. H., & Montgomery, E. F. 1993, Proc. SPIE, Infrared Detectors and Instrumentation, ed. A. M. Fowler, 1308, 482
Wright, R. S., James, P. A., Joseph, R. D., & McLean, I. S. 1990, Nature, 344, 417
Wynn-Williams, C. G., & Becklin, E. E. 1993, ApJ, 412, 535
Young, J. S., & Scoville, N. Z. 1991, ARA&A, 29, 581