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STELLAR VELOCITY DISPERSION IN ARP 220 AND NGC 6240: ELLIPTICAL GALAXIES IN FORMATION

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ABSTRACT

We present high-resolution ($R \sim 7000$) spectra of the 2.3 μm CO absorption bandhead of two luminous merging galaxies, NGC 6240 and Arp 220, obtained with CGS4 on the United Kingdom Infrared Telescope. We have also secured subarcsecond images of NGC 6240 at 2.2 μm using the Montreal Infrared Camera (MONICA) on the Canada-France-Hawaii Telescope (CFHT). The velocity dispersion ($\sigma_{\rm obs}$ = FWHM/2.354) inferred from the broadening of the CO bandhead in the central 2″ of the brightest nucleus of NGC 6240 is 359 ± 21 km s^{-1}, which is among the highest values ever found in the center of a galaxy. Arp 220 shows a velocity dispersion of 150 ± 21 km s^{-1}. The infrared light profile of NGC 6240 beyond a radius of 0″.7 is well fitted by an $r^{1/4}$ law, but the overall brightness distribution is best represented by a shallower profile such as a King (1966) profile with a core radius of 0.20 kpc. Both Arp 220 and NGC 6240 have mass densities, velocity dispersions, and central surface brightnesses consistent with the fundamental parameter plane of elliptical galaxies.

Subject headings: galaxies: interactions — galaxies: general — infrared: general

1. INTRODUCTION

Arp 220 and NGC 6240 are among a special class of galaxies which emit more than 90% of their bolometric luminosity in the far-infrared (Soifer et al. 1984). Both objects show strong optical and near-infrared recombination lines (Sanders et al. 1988; Fried & Schulz 1983; Rieke et al. 1985) and conspicuous molecular hydrogen emission (Joseph, Wright, & Wade 1984). The source of this activity is still controversial, but possible mechanisms include an intense episode of star formation activity (starburst), an active galactic nucleus, or cloud-cloud collisions on a galaxy-wide scale. The very disturbed optical morphology and the presence of two closely spaced nuclei in the near-infrared (Arp 220: Graham et al. 1990; NGC 6240: e.g., Thronson et al. 1990) strongly suggest that these galaxies are dusty merging systems.

Although a wealth of observations have been accumulated on Arp 220 and NGC 6240, little is known about the *stellar* kinematics—more precisely the velocity dispersion—in the central regions of these galaxies. Velocity dispersions can be obtained from analysis of emission-line and/or absorption-line profiles. A method using absorption lines is clearly favored to probe the gravitational potential, since the gas can be subject to nongravitational motions, especially in mergers. To date, most measurements of velocity dispersion in galaxies have been obtained in the optical, but such techniques are inadequate for violent systems such as ultraluminous *IRAS* galaxies which generally exhibit large extinctions.

The strong CO band absorption at 2.3 μm provides a very good tool for estimating the stellar velocity dispersion in heavily extinguished galaxies, since this feature arises from the atmosphere of late-type giants which dominate the stellar population of galaxies in general. The use of the CO band for studying stellar kinematics is a well-proved method; it has already provided important results in the Galactic center (McGinn et al. 1989; Sellgren et al. 1991; Rieke & Rieke 1988), the nearby starburst galaxies M82 (Gaffney, Lester, & Telesco 1993), and the more distant galaxy NGC 6240 (Lester & Gaffney 1994). In this *Letter* we report velocity dispersion measurements based on the 2.3 μm CO band in Arp 220 and NGC 6240. We also present an analysis of the *K*-band light profile of NGC 6240.

2. OBSERVATIONS AND RESULTS

2.1. *Spectroscopy*

High-resolution spectra of the 2.3 μm CO band absorption were obtained on the United Kingdom Infrared Telescope (UKIRT) on the nights UT 1992 August 5–7. The instrument used was the long-slit cooled grating spectrometer CGS4 (Mountain et al. 1990) configured with the echelle grating and the 300 mm focal-length camera. A 2 pixel wide slit (2″.2) was used, yielding a resolving power of 7000 at 2.3 μm. The spectra were sampled with 2 pixels per resolution element. The spatial resolution was 2″.2 along the slit. For NGC 6240, the slit was set to a position angle of 17° with respect to the line joining the two IR nuclei, separated by 1″.8. Arp 220 was observed with the slit aligned in the north-south direction, which was including both nuclei in the CGS4 aperture. The observations were obtained by nodding the telescope 26″.5 along the slit, an offset small enough to keep the object spectrum on all frames.

The frames of a given pair "object-sky" were subtracted from each other and the result flat-fielded with a "flat" frame obtained by illuminating the array with a blackbody. Only the brightest row of the detector was used to extract the spectra. The atmospheric transmission and the instrument response were corrected by dividing the co-added spectra by that of an early-type star (BS 6629 and BS 5793, both A0 V). The wavelength calibration was achieved by taking a krypton lamp spectrum before the galaxy observations. The late-type star BS 8008 (K4 III) was observed at three grating positions to

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form a template spectrum used in the convolution analysis (see below). An uncertainty of 25 km s^{-1} was estimated for the absolute wavelength calibration based on the shift observed between the CO bandhead of two independently calibrated spectra of BS 8008. The final reduced spectra are shown in Figure 1. The broadening of the CO band due to velocity dispersion is clearly detected in both galaxies. The "ripples" seen in the spectrum of Arp 220 could be due to a fringing problem in CGS4, but this is far from clear, since these features are not detected in the spectrum of NGC 6240. The spectra were not corrected for a possible fringing problem, but this should have a negligible effect on the analysis, since the ripples' frequency is much higher compared with the general slope of the CO bandhead in the spectrum of Arp 220.

A three-parameter model was used to fit the template spectrum to the two galaxy spectra near the CO bandhead by minimization of χ^2: (1) the template spectrum was shifted in wavelength to obtain the heliocentric velocity $V_{\odot}$; (2) it was convolved with a Gaussian to obtain the velocity dispersion σ_{obs}, and (3) the equivalent width of the CO band in the template was varied by adding a constant c (always greater than -1) to the rectified template spectrum. The new CO band equivalent width W'_{CO} is related to the original value W_{CO} by the following expression: $W'_{CO} = f_{CO} W_{CO}$, where $f_{CO} = (1 + c)^{-1}$. The spectral coverage of the template spectrum of BS 8008 turned out to be too small to achieve a proper analysis of the very broad CO band in NGC 6240. It was therefore decided to use the high-resolution K-band spectrum of γ Dra (K5 III) taken from the Kleinmann & Hall (1986) atlas. This star has a CO index of 0.15 (Doyon, Joseph, & Wright 1994), which is the same as the average value (0.15 ± 0.02) found in normal galaxies (Frogel et al. 1978). Thus a normal galaxy should have $f_{CO} = 1 \pm 0.02$ when compared with γ Dra. It was determined that γ Dra has an instrumental broadening corresponding to a velocity dispersion σ_{cor} of 42 ± 5 km s^{-1} compared with the CGS4 spectrum of BS 8008 (see Fig. 1). This was taken into account in the analysis. As seen in Figure 1, γ Dra shows a residual slope compared with the CGS4 spectrum, but this has a negligible effect on the determination of the velocity dispersion. An average error was assigned to every point in the galaxy spectrum as determined by the local scatter. The standard errors were estimated by (1) varying each parameter in turn from its best-fit value until $\Delta\chi^2 = 1$ and (2) from a Monte Carlo simulation. The uncertainties derived from the two methods were found to be very similar. The fitted parameters are listed in Table 1.

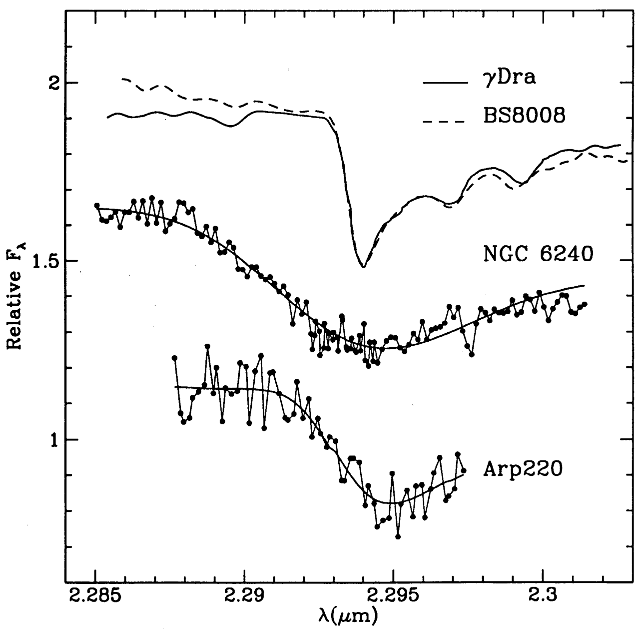

FIG. 1.—Spectra of the CO bandhead at 2.2935 μm. The spectra of Arp 220 and NGC 6240 are shown in the rest frame. The thick solid line superposed on each spectrum is the best fit obtained. The solid spectrum at the top is that of the giant star γ Dra taken from the Kleinmann & Hall (1986) atlas. The dashed spectrum is that of the star BS 8008 (K4 III) obtained with CGS4 after convolution with an instrumental velocity dispersion of 42 km s^{-1} (see text).

NGC 6240 has a velocity dispersion of 359 ± 21 km s^{-1}, which is among the highest ever measured in a galaxy (see the velocity dispersion catalog of Whitmore, McElroy, & Tonry 1985 for comparison). For a Gaussian profile this corresponds to a FWHM of 845 ± 50 km s^{-1}, which is the highest ever reported for NGC 6240 (see Table III of Herbst et al. 1990 for a summary). Recently, Bland-Hawthorn (1994) have secured Ca II triplet ($\lambda \approx 8500$ Å) spectra of NGC 6240 and derived $\sigma_{obs} = 340$ km s^{-1} in the central 2″, in very good agreement with our measurement. Our velocity dispersion is also consistent with that derived by Lester & Gaffney (1994) from similar observations. The heliocentric velocity of NGC 6240 inferred from the CO band (7473 ± 30 km s^{-1}) is significantly redshifted compared with the optically based value of 7351 ± 44 km s^{-1} quoted in the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991, hereafter RC3). The convolution analysis yielded a CO band strength factor $f_{CO} = 1.75 \pm 0.08$ which is significantly stronger than the CO band of a normal galaxy.

The velocity dispersion found in Arp 220 is $\sigma_{obs} = 150 \pm 21$ km s^{-1}. The heliocentric velocity inferred from the CO band (5453 ± 30 km s^{-1}) is, within the uncertainties, consistent with both the optical and the H I values quoted in RC3. The CO band strength factor f_{CO} of 1.18 ± 0.08 is probably a lower limit, since the CO band of Arp 220 is likely to be diluted with ~20% of hot dust emission, as suggested by the JHK colors measured in the central 2″.5 of the nucleus (Carico et al. 1990). Correcting for this dilution effect brings f_{CO} to 1.48. Thus, like NGC 6240, the CO band of Arp 220 is significantly stronger than a normal galaxy.

2.2. *Near-Infrared Imaging*

An image of NGC 6240 was also obtained on the Canada-France-Hawaii Telescope (CFHT) with the Montréal Infrared Camera (MONICA) (Nadeau et al. 1994) on UT 1992 August 10. This instrument is equipped with a 256 × 256 NICMOS3 array with a pixel size of 0″.25. NGC 6240 was observed with a 1.4% circular variable filter (CVF) at seven different wave-

TABLE 1

FITTED PARAMETERS

Galaxy	$V_{\odot}$[a] (km s^{-1})	σ_{obs}[b] (km s^{-1})	f_{CO}[c]
Arp 220	5453 ± 30	150 ± 21	1.18 ± 0.08
NGC 6240......	7473 ± 30	359 ± 21	1.75 ± 0.08

[a] Heliocentric velocity. The errors include both the uncertainties in the fit and the absolute wavelength calibration.
[b] Velocity dispersion.
[c] CO band strength factor (see text).

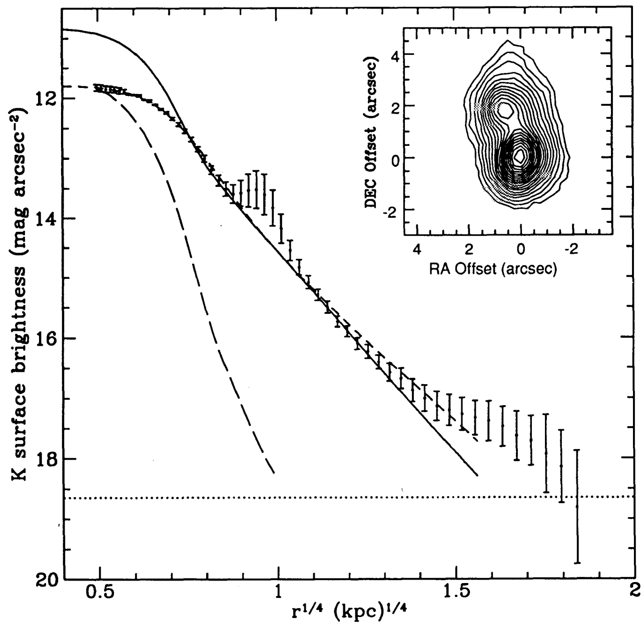

FIG. 2.—*K* surface brightness profile of NGC 6240. The image from which the light profile is derived is shown (*inset*). The contours are drawn on a logarithmic scale, each one separated by a factor of $2^{-1/4}$ (the first contour is $2^{-1/4}$ from the peak). The first isophote is centered on the brightest nucleus. The seeing-convolved $r^{1/4}$ law and the seeing-convolved King (1966) profile ($\log (r_t/r_c) = 2.25$) that best fit the data are represented by solid and short-dashed lines, respectively. The long-dashed line is the radial profile of the PSF, scaled to the same central surface brightness of the galaxy. The dotted line represents a level 3 σ above the sky.

lengths centered on the redshifted transition $v = 1$–0 $S(1)$ of molecular hydrogen.[6] An image of the continuum at 2.17 μm was formed by combining the four images excluding the emission line. The observations were obtained under very good seeing of 0".64 ± 0".02 as derived from the star SAO 121896 observed just before and after NGC 6240. The resulting image is shown in Figure 2 (*inset*). The relative photometry of both nuclei agrees very well with the relative *K*-band photometry of Thronson et al. (1990). Both nuclei are clearly resolved; the brightest nucleus has a FWHM of 0".87 × 1".18.

The 2.2 μm light profile along the major axis, derived from isophote fitting of the image using the "isophote" IRAF task, is shown in Figure 2. All parameters describing the isophotes (center position, position angle and ellipticity) were allowed to vary. The "bump" seen at ~1 kpc (1" = 485 pc; $H_0 = 75$ km s^{-1} Mpc^{-1} adopted throughout) is clearly due to the presence of the second nucleus. The brightness profile of NGC 6240 was fitted with various functions after convolution with a point-spread function (PSF) best representing the seeing disk. The PSF was characterized from the averaged profile of the star SAO 121896 observed just before and after NGC 6240. The resulting radial profile was well fitted with a Gaussian core plus two exponential wings. This analytical PSF is represented by the long-dashed line in Figure 2. The solid line represents the best seeing-convolved $r^{1/4}$ law fit with an effective radius $r_e = 2.9$ kpc. Only the outer regions could be reasonably well fitted with an $r^{1/4}$ law. A better fit to the central regions is obtained with a seeing-convolved King (1966) profile (*short-dashed line*) with $c = 2.25$, where $c = \log (r_t/r_c)$, the ratio of the tidal radius r_t to the core radius r_c. The inferred core radius is 0.20 ± 0.04 kpc. No attempt was made to fit the parameter c, since the surface brightness profiles of ellipticals are generally well described by a King profile with $c = 2.25$ (Kormendy 1977). Both the de Vaucouleurs and the King profiles fail to fit the data at a radius of ~5 kpc, which is not surprising, since this brightness level corresponds to the beginning of the two tidal tails seen in a high-contrast image. These features are well above the sky (cf. Fig. 2), and their brightnesses fall off approximately as an exponential. The main result from this fitting analysis is that *the overall brightness distribution of NGC 6240 is very similar to that of an elliptical galaxy.*

[6] The original goal of this program was to produce a high spatial resolution image of the H_2 emission in NGC 6240. These results will be presented elsewhere.

3. DISCUSSION

The first evidence that the collision of two disk galaxies could produce a mass distribution indistinguishable from that of an elliptical galaxy was provided by Schweizer (1982), who showed that the optical light profile of the merger NGC 7252 is well fitted with the $r^{1/4}$ de Vaucouleurs law. This pioneering work has been extended in the near-infrared by Wright et al. (1990). They showed that the *K* light profiles of two very luminous mergers, Arp 220 and NGC 2623, are very well described by the $r^{1/4}$ law. We argued in § 2.2 that the light profile of NGC 6240 is also very similar to that of an elliptical galaxy. These observations provide strong evidence that elliptical galaxies can indeed be formed out of mergers.

The "cooling diagram," i.e., the correlation between mass density and velocity dispersion, provides another important diagnostic to test the idea that the properties of merger remnants closely resemble those of elliptical galaxies. This correlation is a projection on the fundamental parameter plane of elliptical galaxies (Kormendy & Djorgovski 1989). As shown in Figure 3*a*, at a given velocity dispersion, elliptical galaxies,

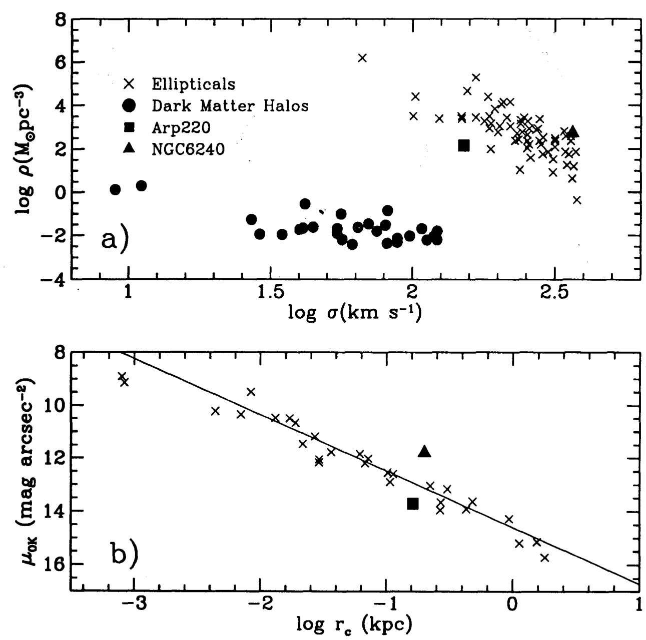

FIG. 3.—(*a*) Mass density vs. velocity dispersion for cores of elliptical galaxies and dark matter halos, adapted from Kormendy & Sanders (1992). (*b*) Central *K*-band surface brightness vs. core radius for bulges and elliptical galaxies, adapted from Kormendy (1985). The symbols have the same meanings as in (*a*). The solid line is a least-squares fit to the elliptical galaxy data.

have relatively high mass densities compared with the dark matter halos of late-type galaxies. Kormendy & Sanders (1992) have used the cooling diagram to show that some ultraluminous *IRAS* galaxies (including Arp 220) have properties typical of elliptical galaxies. Their conclusion was based on velocity dispersions derived from millimeter CO observations. The stellar velocity dispersion measurements presented in this *Letter* can be used to determine the locus of Arp 220 and NGC 6240 in the cooling diagram. For an isothermal sphere, the mas density is given by $\rho_0 = 9\sigma^2/4\pi G r_c^2$ (Richstone & Tremaine 1986), where σ is the velocity dispersion and r_c is the core radius. If unknown, r_c can be approximately determined from the effective radius: $r_c \approx r_e/14$, as derived from the data of Kormendy (1977). Taking $r_e = 3.4$ kpc for Arp 220 (Wright et al. 1990) and scaling it to $H_0 = 75$ km s^{-1} Mpc^{-1} yield $r_c =$ 0.16 kpc. As seen in Figure 3*a*, both Arp 220 and NGC 6240 have mass densities and velocity dispersions similar to those of elliptical galaxies, showing that large dissipation has taken place in both galaxies.

Another projection of the fundamental plane is the central surface brightness versus the core radius. The *K*-band version of this diagram is shown in Figure 3*b*. The *V* surface brightness data were taken from Kormendy (1985) and converted to *K* assuming a typical $V-K$ of 3.25 for elliptical galaxies (Frogel et al. 1978). The central *K*-band surface brightness of NGC 6240 is 11.8 mag arcsec^{-2} (cf. Fig. 2), and the corresponding value for Arp 220 is 13.7 (Wright et al. 1990). As seen in Figure 3*b*, both Arp 220 and NGC 6240 fall reasonably close to the correlation found for elliptical galaxies. These results suggest that both *Arp 220 and NGC 6240 are consistent with the fundamental plane of elliptical galaxies.* These observations strengthen the idea that elliptical galaxies can be formed out of merger remnants.

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