Photometry and Dynamics of the Minor Merger AM 1219-430 with Gemini GMOS-S

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ABSTRACT

We present an observational study of the interaction effect on the dynamics and morphology of the minor merger AM 1219-430. This work is based on $r'$ and $g'$ images and long-slit spectra obtained with the Gemini Multi-Object Spectrograph at the Gemini South Telescope. We detected a tidal tail in the main galaxy (AM 1219A) and a bridge of material connecting the galaxies. In luminosity, AM 1219A is about 3.8 times brighter than the secondary (AM 1219B). The surface brightness profile of AM 1219A was decomposed into bulge and disc components. The profile shows a light excess of $\sim 53\%$ due to the contribution of star-forming regions, which is typical of starburst galaxies. On the other hand, the surface brightness profile of AM 1219B shows a lens structure in addition to the bulge and disc. The scale lengths and central magnitudes of the disc structure of both galaxies agree with the average values derived for galaxies with no sign of ongoing interaction or disturbed morphology. The Sérsic index ($n < 2$), the effective and scale radii of the bulge of both galaxies are typical of pseudo-bulges. The rotation curve of AM 1219A derived from the emission line of ionized gas is quite asymmetric, suggesting a gas perturbed by interaction. We explore all possible values of stellar and dark matter masses. The overall best-fitting solution for the mass distribution of AM 1219A was found with $M/L$ for bulge and disc of $\Upsilon_b = 2.8^{+0.4}_{-0.4}$ and $\Upsilon_d = 2.4^{+0.3}_{-0.2}$, respectively, and a Navarro, Frenk & White profile of $M_{200} = 2.0^{+0.5}_{-0.4} \times 10^{12} M_\odot$ and $c = 16.0^{+1.2}_{-1.1}$. The estimated dynamical mass is $1.6 \times 10^{11} M_\odot$, within a radius of $\sim 10.6$ kpc.

Key words: galaxies: general – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: photometry

1 INTRODUCTION

Since the pioneering works of Vorontsov-Velyaminov (1959) and Arp (1966) classifying hundreds of “peculiar galaxies”, now known as interacting and merger galaxies, the number of studies on the nature of these objects has grown exponentially. Now it is clear that interactions and merger events represent important mechanisms for driving the evolution of galaxies (see review of Struck 2006). They can lead to the formation of morphological structure, such as tidal tails like those detected in Superantennae (Mirabel, Lutz & Maza 1991, see the review of Duc & Florent 2013); bridges of stars and gas like that observed in M51 (Lee et al. 2012). In addition, the velocity fields of interacting galaxies show asymmetries and irregularities due to the interaction with the companion galaxy (e.g., Rubin et al. 1991, 1993, Dale et al. 2001, Mendes de Oliveira et al. 2003, Fuentes-Carrera et al. 2004, Presotto et al. 2010). The kinematic disturbances are expected to disappear in about 1 Gyr after the first encounter (Kronberger et al. 2009). One signature of perturbation is the so called “bifurcation”, when the rotation curve in one side of the disc declines while the other side remains steady (Pedrosa et al. 2008).

Interaction events can be divided into major and minor mergers. In major mergers, the masses of the involved galaxies are comparable. On the other hand, minor merg-
ers are those in which a large galaxy interacts with a dwarf or low-mass galaxy. Although major mergers are a striking phenomena and have received most of the attention (Schwarzkopf & Dettman 2008), they are less common than minor mergers. In fact, minor mergers of galaxies occur at least an order of magnitude more often than major mergers (Hernquist & Mihos 1995). In addition, hierarchical models of cosmological structure formation predict that galaxies grow by accreting other galaxies, more frequently minor companions (e.g., Cole et al. 2000; Wechler et al. 2002; Bédorf & Portegies Zwart 2013).

Obtaining photometric and kinematic information on minor merger systems is useful for understanding the effect that interaction may have on each component. The decomposition of the surface brightness profile into bulge and disc components (Fathi et al. 2010), for instance, allows us to infer the stellar mass distribution. This information, together with the rotation curve, is used to constrain models of dark matter distribution (van Albada et al. 1985; Carignan 1988; Kenz 1987; Blais-Ouellette et al. 2001). These parameters are important to test the predictions of minor merger simulations and thus, to reconstruct their dynamical history (e.g., Salo & Laurikainen 1993; Mihos & Bothun 1996; Rodrigues et al. 1999; Díaz et al. 2000; Thies & Kohle 2001; Krabbe et al. 2008, 2011, and see Barnes & Hibbard 2009 for a partial list of system modelled).

In order to understand the effect of the interaction on the kinematic and photometric properties of minor merger components, we have conducted long-slit spectroscopy and $g'$ and $r'$ images observations with Gemini Multi-Object Spectrograph (GMOS) at Gemini South Telescope. The pair systems were selected from Donzelli & Pastoriza’s (1997) sample. The first results of this programme have been presented for AM 1206–721 (Krabbe et al. 2008) and AM 2322–821 (Krabbe et al. 2011). In this work, we study the system AM 1219–430, shown in Fig. 1. This pair is among those presented for AM 2306–721 (Krabbe et al. 2008) and AM 2322–821 (Krabbe et al. 2008, 2011). In this paper, we adopt the Hubble constant as $H_0=73\text{km s}^{-1}\text{Mpc}^{-1}$ (Spergel et al. 2007).

2 OBSERVATIONS AND DATA REDUCTION

This paper is based on $g'$ and $r'$ images and long-slit spectra obtained in 2007; February 12 and May 23 with the GMOS at Gemini South Telescope, as part of the poor weather programme GS-2007A-Q-76. We obtained science quality (slow readout) sets of short exposure time $r'$ and $g'$ images. The images were binned by 2 pixels, resulting in a spatial scale of 0.146 arcsec pixel$^{-1}$. They were processed using standard procedures (bias subtraction and flat-fielding) and combined to obtain the final $g'$ and $r'$ images. Seeings of $\sim 0.99$ and $\sim 1.26$ arcsec were estimated for $g'$ and $r'$, respectively. The seeing was calculated by fitting a Gaussian profile to the field star images. The journal of observations is presented in Table 1.

| Date (UT) | Exposure time (s) | Filter | $\Delta\lambda$ (Å) |
|-----------|-------------------|--------|---------------------|
| 2007–12–02 | 5×30 | $g'$ (G0325) | 3980–5520 |
| 2007–12–02 | 4×30 | $r'$ (G0326) | 4562–6980 |

Spectra in the range 4 280 - 7 130 Å were obtained with the B600 grating, plus the 1 arcsec slit, which gives a spectral resolution of 5.5Å. The frames were binned on-chip by 4 and 2 pixels in the spatial and wavelength directions, respectively, resulting in a spatial scale of 0.288 arcsec pixel$^{-1}$, and 0.9 Å pixel$^{-1}$ dispersion.

Spectra at two different position angles (PA) were taken: PA=$162^\circ$ and $25^\circ$, which correspond to the position along the apparent major axis of AM1219A and the minor axis of AM1219B, respectively. The exposure time of each single frame was limited to 700 s to minimize the effects of cosmic rays, with four frames being obtained for each slit position to achieve suitable signal-to-noise ratio. The slit positions are shown in Fig. 1 superimposed on the $r'$-band image of the pair. Table 2 gives the journal of spectroscopic observations.

The spectroscopic data reduction was carried out using...
A study of the interacting system AM 1219-430

Figure 1. AM 1219-430 $r'$ image with the observed slit positions. The striking bridge of material between the galaxies and tidal arms shows up by isophotes with 2$\sigma$ (blue) and 3$\sigma$ (red) above the sky value.

2.1 Photometric calibration

In order to calibrate the $r'$ and $g'$ images, we used seven foreground stars present in the GMOS field, which are in the United States Naval Observatory-B1.0 Catalogue (USNO-B; Monet et al. 2003). Aperture photometry of these stars was carried out using the PHOT task within IRAF/DAOPHOT. The aperture radii of 3.7 arcsec (25 pixel) and 4.4 arcsec (30 pixel) were used for the $g'$ and $r'$ images, respectively. We applied the bandpass transformation given by Monet et al. (2003) to convert the J and F photographic magnitudes to the $g'$ and $r'$ magnitudes in the SDSS system. Then, the zero-points for the $g'$ and $r'$ images were found according to:

$$g' = 28.52 \pm 0.31 - 2.5 \log(C/t)$$

$$r' = 28.29 \pm 0.24 - 2.5 \log(C/t),$$

where $C$ is the integrated counts within 3.7 and 4.4 arcsec aperture radii in $g'$ and $r'$ images, respectively, and $t$ is the exposure time.

2.2 Sky background

The sky background levels of the $g'$ and $r'$ images were adopted as the mean value of several boxes of 60 x 60 pixels. The selected regions are far from stars and galaxies, so that the mean value is not biased by any residual emission. The statistical standard deviation ($\sigma$) of the sky background around the mean value was also computed for these regions. $\sigma$ is an estimate of the sky noise, and the value of $1 \sigma$ determines the physical limit for galaxy extension. Table 3 gives the detection limits, in magnitudes per square arcsecond, of the $g'$ and $r'$ images measured at 1, 2, and 3 $\sigma$.

The striking bridge of material connecting the galaxies and tidal arms was detected by drawing isophotes with levels corresponding to 2$\sigma$ and 3$\sigma$ over the sky background (Fig. 1).

Table 4 gives the integrated magnitudes $m_{r'}$ and $m_{g'}$ as well as the absolute magnitudes and luminosities of both galaxies. Magnitudes were calculated by integrating the flux...
inside the isophote with an intensity brighter than that of the tidal arms and the bridge between galaxies. The surface brightness of these isophotes ($\mu_{\text{lim}}$) is also given in Table 4. The absolute magnitudes were corrected for the Galactic extinction, adopting $A_g = 0.25$ and $A_r = 0.36$ (Schlafly & Finkbeiner 2011). Finally, the luminosities were estimated from the solar absolute magnitudes in $g'$ (5.45) and $r'$ (4.76) bands (Blanton et al. 2003). These values, in turn, were used to derive the integrated and absolute magnitudes, and luminosity for the $B$ band in the Johnson system, using the Fukugita et al. (1996) transformations (adopting $A_B=0.397$ and $M_\odot (B) = 5.48$). These values are also listed in Table 4 and they will be useful to calculate the M/L in Section 3.

### Table 3. Sky background levels

| Filter | 1σ | 2σ | 3σ |
|--------|----|----|----|
| $g'$   | 26.09 | 25.34 | 24.89 |
| $r'$   | 26.05 | 25.30 | 24.86 |

### Table 4. Total magnitudes and luminosities

| Galaxy   | Filter | $m_T$  | $M_T$   | $L/L_\odot$ | $\mu_{\text{lim}}$ (mag/arcsec$^2$) |
|----------|--------|--------|---------|-------------|-----------------------------------|
| AM 1219A | $g'$   | 14.48  | $-20.76$ | $3.07 \times 10^{10}$ | 25.31                             |
|          | $r'$   | 13.43  | $-21.71$ | $3.87 \times 10^{10}$ | 23.78                             |
|          | $B$    | 15.13  | $-20.15$ | $1.79 \times 10^{10}$ | 25.17                             |
| AM 1219B | $g'$   | 16.00  | $-19.25$ | $7.57 \times 10^{9}$  | 25.25                             |
|          | $r'$   | 14.84  | $-20.30$ | $1.05 \times 10^{10}$ | 24.01                             |
|          | $B$    | 16.70  | $-18.58$ | $4.23 \times 10^{9}$  | 25.98                             |

## 3 IMAGE RESTORATION

In order to improve the identification of H II regions, we deconvolved the $g'$ and $r'$ images using Lucy–Richardson (L-R) algorithm (Richardson 1972; Lucy 1974). The first step is to create a synthetic point spread function (PSF) from the calibration stars using the PSF task of IRAF/DAOPHOT. We choose a 2D elliptical Gaussian for the functional form of the analytic component of the PSF model. Briefly, the algorithm computes the parameters of the analytic function by fitting all the stars weighted by their signal-to-noise ratio using a non-linear square fitting technique. The reader is referred to Stetson (1987) for more details. Then, we deconvolved the images using the LUCY task within IRAF/STSDAS. The L-R algorithm generates a restored (or deconvolved) image through an iterative method. The essence of L-R is as follows: at the end of each iteration, the resulting reconstructed image is convolved with the PSF and compared to the observed image. A correction image is generated by the ratio of the observed image to its PSF-convolved reconstruction, which measures the fractional deviation between the model and the observed. This information is then used to refine the reconstruction process during the next iteration. This correction and comparison process is repeated until the correction image no longer changes significantly (Pogge & Martini 2002). The restored data will be properly normalized, and the integrated flux in the image is conserved. The total flux for a particular object should also be conserved. The deconvolved $r'$ image of AM 1219A is present in the left-panel of Fig. 3. This procedure resolved the compact nucleus in several H II regions. In addition, we can see that the spiral arms start at the very centre of the galaxy, and the giant H II region of the strong perturbed north-east arm is resolved in H II region complexes. The deconvolved $r'$ image of AM 1219B is present in the left-panel of Fig. 4. This image shows no significant difference from the original one. We also did not detected H II region complexes as in the main galaxy.

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**Figure 2.** Normalized spectra showing the lines Hα and [N ii] from long-slit apertures along the apparent major axis of AM 1219A.
3.1 Elmegreen method

To verify the level of the morphological distortions introduced by the interaction, we applied the symmetrization method of Elmegreen, Elmegreen & Montenegro (1992) to the galaxies. This method is based on the $m$-fold symmetry concept: if the spiral structure remains invariant under a rotation of $2\pi/m$ around the image centre ($m$ is the number of arms), the galaxy has $m$ dominant arms. In most galaxies, the dominant symmetry is $m = 2$. Following this procedure, we have separated both the two-fold symmetric and non-symmetric parts of the spiral galaxy pattern, by making successive image rotations and subtractions. The non-symmetric image (hereafter $A_2$) is obtained by subtracting from the observed image the same image rotated by $\pi$. If $I(r, \theta)$ is the original image in polar coordinates, then

$$A_2 = |I(r, \theta) - I(r, \theta + \pi)|,$$

where the subscript $\tau$ stands for truncation, meaning that pixels with negative intensities are set to 0. On the other hand, the symmetric image (hereafter $S_2$) is obtained by subtracting the asymmetric image from the observed one. The $S_2$ image shows what should be the “original disc” and the non-perturbed spiral pattern. Therefore, the symmetric images correspond to

$$S_2 = I(r, \theta) - A_2(r, \theta).$$

The results for AM 1219A and AM 1219B are displayed in Figs 3 and 4, respectively. The left-hand panels show the deconvolved images of the galaxies in $r'$, the middle panels the $A_2$ images and the right-hand panels the $S_2$ images. The $A_2$ image of AM 1219A shows a one-arm structure, with several H II region complexes along it. The $S_2$ image “dig up” the non-perturbed spiral pattern of AM 1219A, from which we can classify the non-perturbed structure of AM 1219A as Sbc galaxy type. On the other hand, the $A_2$ image of AM 1219B does not show any significant asymmetry, just a small overdensity in the north-west arm. There is no significant difference between the deconvolved and $S_2$ images.

3.2 Luminosity profile

We derived the $g'$ and $r'$ surface brightness profiles of the $S_2$ images to estimate the bulge and disc photometric parameters of the pair components. The ISOPHOTE task of IRAF/STSDAS was used (Jedrzejewski 1987). In this task, the isophotal contour of a galaxy is fitted with a mean ellipse and parametrized using values of PA, ellipticity and coordinates of the centre. The centres of the ellipses were kept fixed while the other parameters were allowed to vary at each iteration step. During the fitting process, we adopted a clipping factor of 20% for the brightest pixels in each annulus to avoid the pixels of star formation regions. The adopted bulge and disc luminosity profiles are the Sérsic (1968) and Freeman (1970) profiles, respectively:

$$I(r) = I_0 \exp \left[-\left(\frac{r}{r_e}\right)^{1/n}\right], \quad k_n = 2n - 0.324,$$

$$I(r) = I_d \exp \left[-\left(\frac{r}{r_d}\right)^{1/n}\right].$$

In Sérsic’s equation, $I_0$ is the central intensity and $r_e$ is the effective radius, which encloses half of the total bulge luminosity, and the $k$ relation can be estimated for $n \geq 1$ with an error lower than 0.1% (Ciotti 1991). $I_d$ is the disc central intensity and $r_d$ the scale length of the disc component in Freeman’s profile.

In general terms, we followed the method described by Aguirre (1994), Prieto et al. (2003) and Cabrera-Lavers & Garzón (2004). We made a first approximation assuming that the surface brightness profile is the sum of bulge and disc components. Then, the routine begins by fitting the parameters for the bulge and disc over different ranges of the profile radius. We fitted the disc with the Orthogonal Distance Regression method (Boggs & Rogers 1994) using a routine in PYTHON, and then we subtracted the disc from the original profile and fitted the bulge component to the residuals. When the bulge was fitted, we again subtracted the bulge from the original profile, and the process was repeated. After some iterations, we obtain the disc and bulge parameters.

In Fig. 5, we present the decomposition of the surface brightness profiles of AM 1219A into bulge and disc structural components in both filters. The sum of these components does not fit the observed profile between 2.9 arcsec ($\sim 1.3$ kpc) and 20.7 arcsec ($\sim 9.5$ kpc), where there is an excess of light ($\sim 53\%$) due to the contribution of the star formation along the spiral arm (see Fig 5). This excess of $\sim 53\%$ is a typical value for starburst galaxies, and is in agreement with the classification by Pastoriza et al. (1998) for this galaxy.

The surface brightness profile of the secondary galaxy is decomposed in bulge, disc, and lens-like structures. The latter component was modelled by a Duval & Athanassoula (1983) profile, given by

$$I(r) = I_0 \left[1 - \left(\frac{r}{r_l}\right)^2\right].$$

The secondary galaxy surface brightness profile decomposition is presented in Fig. 6. The sum of the adopted components (bulge, disc and lens) fits well the observed profile, with a lower $\chi^2$ of 8.2 and 8.0 in the $g'$ and $r'$ bands, respectively.

The structural parameters of AM 1219A and AM 1219B in $g'$ and $r'$ are listed in Table 5. The scale lengths in the $r'$ band are $2.22 \pm 0.05$ and $1.89 \pm 0.02$ kpc for AM 1219A and AM 1219B, respectively. Our scale lengths and disc central magnitudes agree with the average values: $r_e = 3.8 \pm 2.1$ kpc and $\mu_d = 20.2 \pm 0.7$ mag/arcsec$^2$ derived by Fathi et al. (2010) and Fathi (2010) for $\sim 30000$ galaxies with no sign of ongoing interaction or disturbed morphology. This indicates that the interaction has not affected the stellar disc structure. On the other hand, the Sérsic index $(n)$ in the bulge structures is $< 2$ for both galaxies. These values are typical of pseudo bulge (Kormendy & Kennicutt 2004). The $r_e$ values in $r'$ are $0.76 \pm 0.02$ and $0.68 \pm 0.05$ kpc for the main and secondary galaxies, respectively. These values agree with the average value for pseudo-bulge found by Gadotti (2009). The pseudo-bulges are systematically flatter than classical bulges, and their morphologies often have nuclear spirals, rings, bars, and patchiness. In addition, they have intense star formation activity (Kormendy & Kennicutt 2004).
Figure 3. Elmegreen method applied to AM 1219A. The left-hand panel shows the deconvolved image in the $r'$ band, the middle panel shows the $A_2$ image and the right-hand panel the $S_2$ image.

Figure 4. Same as Fig. 3 for AM 1219B.

Figure 5. Structural decomposition of the surface brightness profiles of AM 1219A, with $g'$ (left) and $r'$ (right).
only the Hα regions, as can be seen in the deconvolved image in the left-hand panel of Fig. 3.

In addition to the analysis of the surface brightness profiles, we determined the position angle (PA) and inclination (i) of the discs of both galaxies, assuming the mean PA and i values of the most external ellipses, where the disc component dominates the radial profile and the isophotes are not affected by the spiral structure. PA and i calculated are listed in Table 6.

Table 6. Inclination and position angle

| Galaxy     | i (°)    | PA (°) |
|------------|----------|--------|
| AM 1219A   | 39.8° ± 1.5° | 29.0° ± 0.6° |
| AM 1219B   | 49.3° ± 0.2° | −42.0° ± 0.7° |

Fisher & Drory (2010), and reference therein). These features are in agreement with the results in Pastoriza et al. (1999), where they found a strong star formation in the nuclei of both galaxies; furthermore, AM 1219A has several patches of H α regions, as can be seen in the deconvolved image in the left-hand panel of Fig. 3.

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4 IONIZED GAS KINEMATICS

Radial velocities were derived by measuring the centroids of Gaussian curves fitted to the profiles of the strongest emission lines (\([\text{NI}] \lambda 6548.04, \, \text{H} \alpha \lambda 6563, \, [\text{NI}] \lambda 6584 \) and \([\text{SII}] \lambda 6717\)). For spectra with very low signal-to-noise ratio, only the Hα line was used to determine the radial velocity. The final radial velocity for each spectrum was obtained by averaging the individual measurements from the detected emission lines, and the errors correspond to the standard deviation of these measurements around the mean. For radial velocities that were measured with a single emission line, we used Keel’s expression (Keel 1998) to determine the uncertainty. Then, we subtracted from them the systemic velocity. We adopted the radial velocity of the central aperture of each galaxy as systemic velocity, which are 6932 and 6985 km s\(^{-1}\) for the main and secondary galaxies, respectively.

Donzelli & Pastoriza (1997) estimated systemic velocities of 6957 and 6979 km s\(^{-1}\) for AM 1219A and AM 1219B, respectively. Our estimates agree to within 1% with those previous determinations.

Fig. 6 shows the observed rotation curve of AM 1219A and the \(r’\) image with the long-slit apertures. The rotation curve is quite asymmetric, with the south-east (S-E) side being typical of discs, increasing from the centre until reaching a peak at \(\sim 3.2\) kpc and flattening at \(\sim 84\) km s\(^{-1}\). On the other hand, the north-west (N-E) side has the same behaviour as the S-E up to \(\sim 3.5\) kpc, then increasing to reach the velocity of \(\sim 250\) km s\(^{-1}\) at 8.2 kpc. The highest velocities are spatially coincident with the N-E H \(\alpha\) region complexes (see Fig. 7). The non-symmetric behaviour in the rotation curves has also been observed in other interacting pairs (e.g., Rubin et al. 1991, 1999; Dale et al. 2001; Mendes de Oliveira et al. 2003; Puentes-Carrera et al. 2004; Presotto et al. 2010) and predicted by numerical simulation of Pedrosa et al. (2008) and Kronberger et al. (2006) for major and minor mergers, respectively.

The observed rotation curve and the \(r’\) image with the long-slit apertures for AM 1219B are shown in Fig. 8. Clearly, AM 1219B does not present a well-defined and symmetric rotation curve along the observed slit position. The decomposition of the surface brightness profile (Section 3.2) shows that AM 1219B is a disc galaxy. Thus, the fact that we do not detect rotation may be due to the long-slit position (PA =25°), lying almost perpendicular to the line of nodes (\(\sim −42°\), see Table 6).

5 ROTATION CURVE MODELS

The mass distribution in AM 1219A is modelled as sum of the bulge, disc and dark halo components. The bulge and disc mass distributions are assumed to be given by their respective luminosity distributions to within an unknown M/L (Kent 1987). If we assume that the mass distribution of AM 1219A follows the deprojected luminosity distribution with constant M/L for each component, then, we can obtain the mass surface density for bulge and disc from the Sersic...
Table 5. Structural parameters

| Galaxy   | Filter | $\mu_b$ (mag/arcsec$^2$) | $r_e$ (arcsec) | $n$   | $\mu_d$ (mag/arcsec$^2$) | $r_d$ (arcsec) | $\mu_l$ (mag/arcsec$^2$) | $r_l$ (arcsec) |
|----------|--------|---------------------------|---------------|-------|---------------------------|---------------|---------------------------|---------------|
| AM 1219A | $g'$   | 18.11 ± 0.91              | 1.47 ± 0.25   | 1.74 ± 0.17 | 21.04 ± 2.21              | 4.97 ± 0.92  | -                         | -             |
| AM 1219A | $r'$   | 17.60 ± 0.70              | 1.64 ± 0.04   | 1.41 ± 0.16 | 19.72 ± 0.27              | 4.82 ± 0.11  | -                         | -             |
| AM 1219B | $g'$   | 18.74 ± 1.81              | 1.76 ± 0.34   | 1.20 ± 0.47 | 21.81 ± 0.07              | 4.51 ± 0.05  | 21.01 ± 0.07              | 6.07 ± 0.16   |
| AM 1219B | $r'$   | 17.33 ± 1.57              | 1.48 ± 0.12   | 1.17 ± 0.34 | 20.33 ± 0.08              | 4.11 ± 0.04  | 20.56 ± 0.33              | 5.89 ± 0.06   |

Figure 7. Left: kinematics along PA=162° in AM 1219A. The velocity scale corresponds to the observed values after subtraction of the systemic velocity for each galaxy, without correction for inclination on the plane of the sky. Right: the apertures extracted along the slit.

Figure 8. Same as Fig. 7 for AM 1219B and a slit with a PA=25°.
and [Freeman] surface brightness profiles, respectively. The halo mass distribution can be either parametrized or derived from the observed rotation curve. Below we will describe in some detail the mass model for the components and give the expressions for the circular velocity ($V_c$).

For the bulge mass distribution, we use the rotation curve derived for a S´ersic profile density. This profile is obtained by an Abel integral equation ([Binney & Tremaine] 1984, Simonneau & Prada 2004), which relates surface brightness (equation 3) to density:

$$\rho(s) = \frac{k}{\pi n} I_b \int_{s_{\text{min}}}^{s_{\text{max}}} \frac{\exp[-ks^2]}{\sqrt{s^2 - s^2}} \, dz,$$

where $I_b$, $r_e$, $n$ and $k_n$ are those in equation 3 and $s = (r/r_e)$. $\Sigma_d$ is the M/L for the bulge component. For $n > 1$, the integration of this equation has no analytical solution. Thus, we will use an analytical approximation proposed by [Simpson & Prada] 2004 for $\rho(s)$ that allows an easy computation of the mass and gravitational potential to any required degree of precision:

$$\rho(s) = \frac{k}{\pi n - 1} \frac{1}{s_{\text{max}}^{n}} I_b \int_{s_{\text{min}}}^{s_{\text{max}}} \frac{\exp[-ks^2(1-x^2)^{-\frac{1}{n-1}}]}{\sqrt{1 - (1-x^2)^{-\frac{2n}{n-1}}}} \, dx.$$

Equation 4 can be solved by Gaussian numerical integration. The cumulative mass profile is given by

$$M(r) = 4\pi \int_{0}^{r} r^2 \rho(r) \, dr,$$

For a spherical density distribution with S´ersic profile, we may readily evaluate the circular velocity ($V_c$) by equating the gravitational attraction to the centripetal acceleration:

$$V_c^2(r) = \frac{GM(r)}{r},$$

For the disc, the cumulative mass of the exponential profile ([Binney & Tremaine] 1984) is

$$M(r) = 2\pi \Sigma_d I_r r^2 [1 - \exp(-r/r_d)](1 + r/r_d),$$

where $I_d$ and $r_d$ are those in equation 3 and $\Sigma_d$ is the M/L for disc component. The circular velocity ($V_d$) curve derived for an exponential disc is given by the following equation (Freeman 1970):

$$V_d^2(r) = 4\pi G \Sigma_d I_r r^2 \left[I_0(y) K_0(y) - I_1(y) K_1(y)\right],$$

where $y = r/2r_d$, $I_n$ and $K_n$ are modified Bessel functions of the first and second kinds, respectively, $G$ is the gravitational constant.

For the halo mass model, we use the density profile proposed by [Navarro, Frenk & White] 1995, 1996, 1997, hereafter NFW). In this case the dark matter density is given by

$$\rho(r) = \frac{\rho_0 \rho_c}{(r/r_s)(1 + r/r_s)},$$

where $r_s$ is a characteristic radius, $\rho_0$ is the characteristic overdensity and $\rho_c = 3H_0^2/8\pi G$ is the critical density ($H_0$ is the current value of Hubble’s constant). The virial halo mass is usually in the literature as $M_{200b} = \frac{4}{3}\pi 200\rho_c r_{200b}$. It is useful to define a dimensionless parameter $c \equiv r_{200}/r_s$, where $c$ is called the halo concentration. $\rho_0$ can be linked to $c$ by [Navarro, Frenk & White] 1996

$$\rho_0 = \frac{200}{3} g(c); \quad g(c) = \frac{c^3}{\ln(1 + c - c/(1 + c))}.$$  

The circular velocity ($V_c$) in the NFW profile is

$$V_c^2(r) = \frac{GM_{200}}{r} \left[\ln(1 + c r/r_{200}) - \frac{cr/r_{200}}{1 + cr/r_{200}}\right].$$

Then, we can calculate $V_c$ for the NFW profile via the concentration ($c$) and virial mass ($M_{200b}$).

The final rotation curve model is computed from the squared sum of the circular velocities of the bulge, disc and halo components:

$$V_c^2(r) = V_b^2(r) + V_d^2(r) + V_h^2(r).$$

This equation has four free parameters: the bulge and disc M/L ratios, $\Sigma_b$ and $\Sigma_d$, respectively, and the halo parameters, $M_{200b}$ and $c$. The other parameters are photometric, which were determined in Section 3 for the bulge ($I_b$, $r_e$ and $n$) and the disc ($I_d$ and $r_d$) components. We use photometric parameters of the $r'$ band, because it provides a better estimate of the underlying mass distribution than $g'$.

6 MASS MODELS

The literature presents basically two approaches to study the mass distribution: the maximum-disc (van Albada et al. 1985, Carignan 1982 and references therein) and the best-fitting method (Kent 1987, and references therein). The first approach assumes that the stellar component (bulge+disc) dominates the mass distribution in the inner part. The bulge and disc M/L ratios are constrained by the rising part of the rotation curve. Any excess in rotation velocity at large radii is then attributed to a dark halo component. On the other hand, the second approach uses a $\chi^2$ analysis to determine the combination of parameters that best fits the observed rotation curve. In this paper, we adopt a general method that includes all possible distributions of values between stellar and dark matter masses. We explore a range of values of $M_{200b}$ and $c$ halo parameters for a grid of M/L ratios of the bulge (1.0 $\leq \Sigma_b$ $\leq$ 3.6) and disc (1.0 $\leq \Sigma_d$ $\leq$ 3.6). We adopt the following ranges for the halo parameters: $-3 \leq \log(M_{200b}/M_\odot)$ $\leq$ 0.69 (where $M_\odot = 1.0 \times 10^{12} M_\odot$) and 5.0 $\leq c \leq$ 25.0 (Navarro, Frenk & White 1996, Bullock et al. 2001). Thus, for these parameters, the minimum disc corresponds to $\Sigma_b = 1.0$ and $\Sigma_d = 1.0$; the maximum disc, however, corresponds to $\Sigma_b = 3.6$ and $\Sigma_d = 3.6$. We developed a PYTHON code to compute for each point of the $\chi^2$ space ($\Sigma_b$, $\Sigma_d$, $\log(M_{200b}/M_\odot)$ and $c$), the circular velocity for each component, the resulting $V_c$ given by equation 17 and the $\chi^2$ model of the rotation curve.

We adopted as observed velocity curve the points along the S-E side of AM 1219A because, as discussed in Section 4, the N-W side of AM 1219A is significantly affected by the presence of AM 1219B. In contrast, the S-E side of the galaxy seems to be relatively undisturbed. The adopted velocity curve has been corrected for Galactic systemic motion, inclination with respect to the plane of the sky (i = 40°), and PA of the line of nodes (PA = 29°) (see Table 6).

The best-fitting model corresponding to the global minimum of $\chi^2$ space was found for the following parameters: $\Sigma_b = 2.8$, $\Sigma_d = 2.4$, $\log(M_{200b}/M_\odot) = 0.3$ and $c = 16.0$. In
order to illustrate the global minimum and its convergence pattern, we present in Fig. 9 the $\chi^2$ space projections in the planes $\log(M_{200}/M_\star)-c$ and $T_b-T_d$ by fixing on the global minimum values. The convergence patterns are smooth and the global minimum is easily identifiable in both projections. The contours indicate the degree of the correlation between parameters. Then, as can be seen in the left-hand panel in Fig. 9, there is a strong correlation between $M_{200}$ and $c$, which is because there is a degeneracy between them: a decrease in $c$ is balanced with an increase in $M_{200}$, and vice versa. This is due to the rotation curve that does not extend to large radii.

Fig. 10 shows the one-dimensional projections of the $\chi^2$ space in the fit parameters: $\log(M_{200}/M_\star)$, $c$, $T_b$, and $T_d$. Each plot is produced by taking global minimum values for all the parameters except for the parameter chosen for the projection, which are allowed to vary within the ranges specified above. Then, we compute $\chi^2$ for the adopted range, but keeping the remaining parameters fixed. In these plots, the $\Delta\chi^2$ variation obeys the $\chi^2$ probability distribution for 1 degree of freedom. So $\Delta\chi^2 = 1$ corresponds to 1\sigma uncertainty or 68\%. In Table 7 are listed the parameters and their errors (at the 1\sigma level) for the model with the global minimum of $\chi^2$, and the cumulative mass for each component and their total sum inside 6.2 kpc, which is the radius of the last velocity point observed.

The observed rotation curve overlaid on the best-fitting model is shown in Fig. 11. The model provides a good match to the observed curve over all radii, with $\chi^2$ of 3.1. The bulge component dominates the inner part ($r \lesssim 1.5$ kpc) of the rotation curve. The disc and halo have equal weights in the middle part ($1.5 \lesssim r \lesssim 3.5$ kpc), and the halo component becomes dominant in the outer parts ($3.5 \lesssim r \text{ kpc}$), where the curve is flat.

In Table 8 we compare the NFW halo parameter obtained for AM 1219A using our general method with those found for Milky Way (Battaglia et al. 2005), M31 (Tamm et al. 2012), and ERIS simulation for the formation of late type galaxies (Guedes et al. 2011). Milky Way and M31 are typical late type galaxies, and we can see that their halo parameters are close to those found for AM 1219A.

We use the model rotation curve to extrapolate the mass profile at the equivalent radius (10.6 kpc) of the outermost isophote ($\mu_B = 25.2$ mag/arcsec$^2$), see Table 4, finding a mass of $1.6 \times 10^{11}$ M$_\odot$. For the same region, we calculate $M/L = 8.9$. This result is higher compared to the mean value, $M/L = 4.7 \pm 0.4$, for isolated galaxies of the same Hubble type (Sbc) obtained by Faber & Gallagher (1979). However, it agrees with the mean

![Figure 9](image.png)

**Figure 9.** Left: the $\chi^2$ space projections in the plane $\log(M_{200}/M_\star)-c$ by fixing on the global minimum values for $M/L$ ratios ($T_b = 2.8$, $T_d = 2.4$). Right: the $\chi^2$ space projections in the plane $T_b-T_d$ by fixing on the global minimum values for the NFW halo parameters ($\log(M_{200}/M_\star) = 0.3$, $c = 16.0$). Contours of $\Delta\chi^2$ corresponding to a probability of 68.3, 95.4 and 99.7 per cent (1\sigma, 2\sigma, 3\sigma) for 1 degree of freedom. The plus symbol indicates the global minimum $\chi^2$.

| Galaxy               | $c$ | $R_{200}$ (kpc) | $M_{200}/M_\odot$ |
|----------------------|-----|----------------|-------------------|
| AM 1219A ($\chi^2_{\text{min}}$) | 16  | 184           | $2.0^{+0.5}_{-0.4} \times 10^{12}$ |
| Milky Way ($^a$)     | 18  | 186           | $0.8^{+1.2}_{-0.2} \times 10^{12}$ |
| M31 ($^b$)           | 13  | 200           | $1.04 \times 10^{12}$          |
| Simulation Sc ($^c$) | 22  | 239           | $0.79 \times 10^{12}$          |

*Note:* values taken from, ($^a$) Battaglia et al. (2005), ($^b$) Tamm et al. (2012) and ($^c$) ERIS simulation for the formation of late type galaxies (Guedes et al. 2011).
value, $M/L_B = 8.5 \pm 1.1$, derived by Blackman & van Morsel (1984) for binary galaxies.

7 CONCLUSIONS

We present an observational study on the effects of interactions in the morphology and kinematics of the galaxy pair AM 1219-430. The data consist in $g'$ and $r'$ images and long-slit spectra in the wavelength range from 4 280 to 7 130 Å, obtained with the GMOS at Gemini South. The main findings are the following.

(i) We detected a striking bridge of material connecting both galaxies, together with a tidal tail in the secondary galaxy.

(ii) The total apparent and absolute magnitudes in $g'$ and $r'$ for each galaxy were measured. The pair has $\Delta M_{g'} = 1.52$ and $\Delta M_{r'} = 1.41$, which means that in luminosity, the primary galaxy is about 3.8 times brighter than the secondary.

(iii) The symmetric and non-symmetric parts of AM 1219A and AM 1219B were separated using the symmetrization method of Elmegreen, Elmegreen & Montenegro (1992). The symmetric images show what should be the "original disc" and the non-perturbed spiral pattern. From these images, we calculate the PA and $i$ for both galaxies. We found for AM 1219A a PA = $29.0^\circ \pm 0.6^\circ$ and an $i = 40.8^\circ \pm 1.8^\circ$, and AM 1219B has a PA = $-42.0^\circ \pm 0.7^\circ$ and an $i = 49.3^\circ \pm 0.1^\circ$. On the other hand, the non-symmetric image of AM 1219A shows a one-arm structure, with several H II region complexes along it.

(iv) The surface brightness profile of AM 1219A was decomposed into bulge and disc components. The profile shows a light excess of $\sim 53\%$ due to the contribution of star-forming regions in the arms, which is typical of starburst galaxies. On the other hand, the surface brightness profile of AM 1219B reveals the existence a lens structure in addition to the bulge and disc.

(v) The scale lengths and central magnitudes of the disc structure of the galaxies agree with the average values derived for galaxies with no sign of ongoing interaction or disturbed morphology (Fathi et al. 2010, Fathi 2010). This indicates that the interaction has not affected the disc structure. The Sersic index ($n < 2$) and the effective and scale radii in the bulge structures of both galaxies are typical of pseudo-bulge (Kormendy & Kennicutt 2004, Gadotti 2009).

(vi) The rotation curve of AM 1219A, derived from the ionized gas emission line, is quite asymmetric, suggesting that the gas kinematic was perturbed by interaction. The highest velocities of north-west side of the rotation curve are spatially coincident with the H II region complexes.

(vii) A general method was used in order to explore all possible values of the stellar and dark matter masses.
The overall best-fitting solution for the mass distribution of AM 1219A was found with M/L for bulge and disc of $T_b = 2.8_{-0.4}^{+0.4}$ and $T_d = 2.4_{-0.3}^{+0.3}$, respectively, and NFW halo parameters of $M_{200} = 2.0_{-0.5}^{+0.5} \times 10^{12} M_\odot$ and $c = 16.0_{-1.1}^{+1.2}$. The estimated dynamical mass is $1.6 \times 10^{11} M_\odot$ within a radius of $\sim 10.6$ kpc. M/L at that radius is 8.9.

In a forthcoming paper, in order to reconstruct the history of the AM 1219-430 system and predict the evolution of the encounter, we will model the interaction between AM 1219A and AM 1219B through numerical simulations using the N-body/SPH code GADGET-2 (Springel 2005). The model parameters for both galaxies will be constrained by the photometric parameters and kinematic properties derived in this work.

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