The effects of interaction on the kinematics and abundance of AM 2229–735

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ABSTRACT

This observational study is about the effects of interaction on the kinematics and chemical abundance of the component galaxies of AM 2229–735. This system is formed by a disc galaxy, NED01, and a compact perturbed Sb(s)-like galaxy, NED02, the latter showing a tail and counter-tail arc-shaped feature. This system could be a progenitor of a polar ring galaxy. The sky-projected tail is very luminous and seems to connect the galaxies. Our study was based on *BVRI* broad-band imagery as well as long-slit spectroscopy in the wavelength range 4240–8700 Å. We estimated heliocentric radial velocities of 17 518 ± 25 km s⁻¹ (NED01) and 17 326 ± 27 km s⁻¹ (NED02). Standard diagnostic diagrams were used to classify the main ionizing source of selected emission-line regions. It turns out that all regions are mainly ionized by massive stars. Using two empirical methods, we found that the H II regions in AM 2229–735 have high metallicity: $12 + \log(O/H) = 8.3-8.6$ dex.

Key words: galaxies: individual: AM 2229–735 – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: peculiar – galaxies: photometry – galaxies: spiral.

1 INTRODUCTION

The accretion scenario among interacting galaxies in the local Universe is a measurable phenomenon reported in catalogues by several authors (e.g. Vorontsov-Velyaminov 1959, 1977; Arp & Madore 1977, 1986; Whitmore et al. 1990; Moiseev et al. 2011). Interactions and mergers between galaxies at early stages of evolution of the Universe were probably among the main processes leading to the observed properties of the galaxies in the local Universe (Spinrad et al. 1998). Even at the present epoch, at least 5–10 per cent of galaxies are members of interacting systems (Reshet-nikov & Sotnikova 1997). Many other galaxies retain signs in their structure of past interactions and merging. Examples of these signs are seen on the Polar Ring Galaxies (PRGs), where large-scale rings of stars, gas and dust orbit on the polar plane of early-type galaxies.

With the aim of investigating what scenario could trigger the PRG phenomenon, we have selected interacting galaxies that might become PRGs. We used the catalogues of PRGs presented by Whitmore et al. (1990), Vorontsov-Velyaminov (1977), Arp & Madore (1977) and Arp & Madore (1986), which provide samples of peculiar galaxies and associations. From this analysis, the

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AM 2229–735 galaxy was selected as a key object because of its well-defined morphological structure. AM 2229–735 is a system formed by a spiral galaxy and a compact Sb(s) galaxy connected by a very luminous bridge.

Ferreiro & Pastoriza (2004), using optical photometry, found that the very disturbed main galaxy has a typical exponential luminosity profile. Ferreiro, Pastoriza & Rickes (2008) found in the primary component a nucleus and six H II regions, whose ages are in the range 5–7 Myr. Pastoriza, Donzelli & Bonatto (1999) investigated the nuclear activity and stellar population in the galaxy pairs. These authors, using optical diagnostic diagrams (DDs), concluded that the nucleus of the main component of AM 2229–735 has a composite spectrum, with emission from an AGN and H II region. Moreover, Bournaud & Combes (2003) and Reshetnikov et al. (2006) presented *N*-body simulations to explore the formation of PRGs. The morphologies shown in some stages of their simulations, after the first perigalacticum, are quite similar to the one seen in AM 2229–735, indicating that this system could be the progenitor of a PRG.

PRGs are systems with two main structures, a central host galaxy and an outer ring composed of gas, dust and stars aligned almost perpendicular to the main plane of the host galaxy (Schweizer, Whitmore & Rubin 1983; Whitmore et al. 1990; Casertano, Sackett & Briggs 1991). Whitmore et al. (1990) presented an atlas of PRGs and pointed out that, in general, their host galaxies are S0, despite only 5 per cent of S0 galaxies present a polar ring. In PRGs, the polar ring appears to be younger than the host galaxies as indicated by H1 radio observations (Richter, Sackett & Sparke 1994; van Driel et al. 2000, 2002), near-infrared photometry (Iodice et al. 2002b, c) and optical photometry (Myrrha et al. 1999; Freitas-Lemes et al. 2012a).

The following scenarios have been proposed to explain the origin of a polar ring around a pre-existing galaxy (Iodice et al. 2002a; see also Reshetnikov & Sotnikova 1997; Bekki 1998; Bournaud & Combes 2003; Combes 2006; Macciò, Moore & Stadel 2006):

(i) *the merging scenario*, proposed by Bekki (1997, 1998) and revised by Bournaud & Combes (2003), in which two orthogonal spiral galaxies had a head-on collision;

(ii) the accretion scenario, where gas and particles are pulled off from the donor object by the host (e.g. Schweizer et al. 1983; Reshetnikov & Sotnikova 1997; see also Bournaud & Combes 2003). The accretion scenario assumes that the interacting galaxies would not necessarily be merged, but can experience tidal interaction with formation of loops, rings, rims and gas bridges. This phenomenon of tidal interaction is seen in tidal loops in late-type spirals, such as in UGC 7388 (Faúndez-Abans et al. 2009), in the kinematically confirmed PRG with a spiral host ESO 576-G69 (Reshetnikov, Faúndez-Abans & de Oliveira-Abans 2001) and in some new PRG candidates (Reshetnikov, Faúndez-Abans & de Oliveira-Abans 2011). In the accretion scenario, the formation of a polar ring requires that the donor galaxy is on an almost polar orbit with respect to the host galaxy;

(iii) *the cold accretion* proposed by Macciò et al. (2006) for the formation of isolated PRGs: a polar ring may form through cold gas accretion along a filament into the virialized dark matter halo. In this scenario, there are no limits to the mass of the accreted material, thus a very massive polar disc may develop around either a stellar disc or a spheroid. This idea is supported by numerical simulations (Brook et al. 2008).

In an earlier paper, Freitas-Lemes et al. (2012a) presented BVRI broad-band imagery and long-slit spectroscopy of the PRG AM 2020-504 in order to investigate which of the scenarios above are favoured. They found that (i) (B - R) colour map shows that the ring is bluer than the host galaxy, indicating that the ring is a younger structure; (ii) presence of an oxygen gradient across the ring of this object; and (iii) AM 2020-504 follows the metallicity-luminosity relation of spiral galaxies (Spavone & Iodice 2013). These results support the accretion scenario for this object. A similar work was done by Pérez-Montero et al. (2009) for the PRG IIZw71, a blue compact dwarf galaxy. They found a uniform oxygen abundance across the polar ring, with values around 1/10 of the solar value. This object also supports the accretion scenario, because the material comes from IIZw70, another metal-poor blue compact dwarf, through an H I bridge. Although there has been a large number of PRGs catalogued, only a few of them have been studied in detail, which makes it impossible to determine statistically the prevalence of each formation scenario.

In this paper, we report a study of the proto-PRG candidate AM 2229–735 (ESO 048-IG26), based on broad-band images and long-slit spectroscopy performed at the Pico dos Dias Observatory, Brazil. This paper is organized as follows. Section 2 summarizes the observations and the data reduction. In Section 3, the results and a discussion are presented, while the conclusions are in Section 4.

Table 1. Log of broad-band observations.

Date	Reference	Exposure	Mean air mass	Seeing
		(s)	un muss	(arcsec)
Sep-12-2012	Filter B	5×600	1.6	1.3
Sep-12-2012	Filter V	5×420	1.6	1.2
Sep-14-2012	Filter R	5×360	1.7	1.1
Sep-14-2012	Filter I	5×120	1.6	1.2

Table 2. Log of spectroscopic observations.

AM 2229–735 Reference	Date	λ_c (Å)	PA	Exp. time (s)	Seeing (arcsec)
NED01	Aug-31-2011	6400	0	1800	1.2
NED02	Aug-31-2011	6400	30	1800	1.3

2 OBSERVATION AND DATA REDUCTION

2.1 Broad-band optical imagery

Broad-band optical imagery data were obtained with the 1.6-m telescope at the Observatório do Pico dos Dias (OPD) – Laboratório Nacional de Astrofísica, Brazil. The direct CCD camera with *BVRI* Kron–Cousins filters (Bessell 1990) and a 1024 × 1024 pix² chip was used. This resulted in a scale of 0.284 arcsec pixel⁻¹. Five frames in each filter were taken under a mean seeing of 1.2 arcsec and mean air masses of 1.6–1.7. Table 1 is the journal of the photometric observations. The standard stars, Mark-A and PG13223-086, from the Landolt (1992) catalogue, taken at similar air masses, were used for extinction and calibration purposes throughout the night. We also used imagery data obtained with the Gemini Multi-Objects Spectrograph (GMOS-S) attached to the telescope 8-m Gemini South, Chile, as part of poor weather program GS-2006A-DD-6 (taken from the Gemini Science Archive).

Data reductions were performed in the standard manner using the $IRAF^1$ package. This included dark and bias subtraction, and flat-field correction (we used a mean of several dome flats taken in the appropriate filter). All frames of AM 2229–735 were aligned using four isolated foreground stars and then collapsed for each filter using the task IMCOMBINE. The photometric standard stars were calibrated to the standard *BVRI* photometric system in the usual way (see e.g. Reshetnikov 1994; Myrrha et al. 1999).

2.2 Spectral observations

The spectroscopic observations were also performed with the 1.6-m telescope at OPD equipped with a Cassegrain spectrograph and an Ikon back-illuminated 2048 × 2048 CCD. A diffraction grating of 300 lines mm⁻¹ was used. We obtained a spectral coverage of 4240–8700 Å ($\lambda_{central} = 6400$ Å), and air mass for the slits of 1.5 were measured along both galaxies of the AM 2229–735 system. The log of spectroscopic observations is given in Table 2. Although differential atmospheric refraction effects can be important in slit positions out of the parallactic angle at the air masses of our spectroscopic observations, these do not affect neither our results regarding the rotation curve nor the diagnostics and derivation of abundances

¹ Image Reduction and Analysis Facility is developed and maintained by the National Optical Astronomy Observatories.



Figure 1. GMOS-S *r*-band image of AM 2229–735 with the observed slit positions: $PA = 0^{\circ}$ and 120° , respectively. The label NED01 (host galaxy) and NED02 (companion) are designated.

in the studied H $\scriptstyle\rm II$ regions, as this analysis was performed using emission-line ratios with very close wavelength baseline.

We retrieved a 30 s Gemini Observatory acquisition image of AM 2229–735 (r-G0326 with 630 nm effective wavelength), presented in Fig. 1. The two component galaxies NED01 and NED02 are shown, and the slit positions are overplotted. The widths of the slits were both set at 1.6 arcsec. Slit-1 was positioned at position angle (PA) = 0°, close to the photometric major axis of NED01; Slit-2, centred at NED02, was placed along PA = 120° .

Data reductions were performed in the standard manner using IRAF routines to carry out bias, flat-fielding and cosmic ray subtraction. The wavelength calibration was established using a He–Ar lamp. 1D spectra were extracted each 2 arcsec from the 2D image, and sky subtracted. The 1D spectra were then flux calibrated and extinction corrected using five tertiary standard stars from Baldwin & Stone (1984), as revised by (Hamuy et al. 1992, see also Hamuy et al. 1994). A Galactic extinction correction of E(B - V) = 0.027 (Schlegel, Finkbeiner & Davis 1998) was applied using the standard IRAF routines. The emission-line intensities were measured using the IRAF SPLOT routine after a Gaussian line profile fitting.

These measured radial velocities were checked with the EMSAO package using the composite emission-line template 'femtemp97' distributed by RVSAO/IRAF external package. We adopted the redshift value from the highest correlated coefficient template. We thus derive a heliocentric velocity of 17518 ± 25 km s⁻¹ (see also Section 3.3), which corresponds to a distance of 240 Mpc for AM 2229–735, assuming $H_0 = 73$ km s⁻¹ Mpc⁻¹ (Spergel et al. 2007), resulting in a scale of 1 arcsec = 1.16 Kpc.

3 RESULTS AND DISCUSSION

3.1 Aperture photometry

We carried out circular aperture photometry at the positions labelled in Fig. 2. Table 3 presents the measured magnitudes in B, (B - V), (B - R), (V - R) and (V - I) for the labelled regions (assuming a radius of 2 arcsec ≈ 2.3 kpc), some of which were measured almost in the same places selected by Ferreiro et al. (2008).

The blue absolute magnitude measured in aperture 13, corresponding to the nuclear region of NED 01, is $M_B = -19.58 \pm 0.2$, which is in agreement with the value $M_B = -19.49 \pm 0.4$ derived



Figure 2. Positions used for aperture photometry are labelled over a GMOS-S *r*-band image. Measured magnitudes are presented in Table 3.

Table 3. Aperture photometry data. All measurements were done with r = 2 arcsec aperture radii. ID's correspond to the positions marked in Fig. 2.

ID	В	(B - V)	(B-R)	(V-R)	(V - I)
1	20.64	0.69	0.85	0.16	1.20
2	19.47	0.58	0.76	0.18	1.08
3	18.15	0.53	0.72	0.19	1.09
4	18.23	0.59	0.79	0.20	1.15
5	19.49	0.60	0.8	0.20	1.10
6	19.52	0.54	0.72	0.18	1.03
7	19.49	0.71	0.83	0.12	1.15
8	19.45	0.73	0.88	0.15	1.13
9	19.07	0.78	0.86	0.08	1.32
10	19.44	0.73	0.84	0.11	1.14
11	18.98	0.74	0.8	0.06	1.26
12	18.99	0.75	0.84	0.09	1.24
13	17.32	0.64	0.86	0.22	1.17
14	18.45	0.58	0.86	0.18	1.17
15	18.46	0.63	0.85	0.13	1.18
16	18.42	0.60	0.87	0.11	1.18
17	18.43	0.60	0.85	0.05	1.19
18	22.35	0.65	0.8	0.15	1.25



Figure 3. (I) $(V - I) \times (B - V)$ diagram, data from Ferreiro et al. (2008); (II) $(V - I) \times (B - V)$ diagram, data from this work; and (III) $(B - R) \times (B - V)$ diagram, data from this work.

by Ferreiro et al. (2008). Also for the central aperture of NED 02 (position 3) we measured $M_B = -18.75 \pm 0.2$, also agrees with their value of $M_B = -18.69 \pm 0.4$.

In Fig. 3, the colour distribution suggests that the southern region of NED01 is bluer than the northern one, with the blob object 9 being the reddest object in the colour–colour diagrams. The nucleus of NED02 is bluer than the one of NED01 (panels II and III). (B - R) colour index in the central aperture of NED01 is about 0.5 mag higher than in NED02. The whole NED02 appears bluer than NED01, and the object '6' in the NE line-of-sight path between both galaxies is bluer than all the regions of NED02, with colours more similar to NED01. The (\triangle) and (\blacksquare) are field objects ('1' and '18') with characteristics of dwarf galaxies, as derived from their point spread function. In panel I, the data quoted by Ferreiro et al. (2008) are plotted with the same symbols for comparison with our own data. Although the positions of our apertures do not match up exactly with those of Pastoriza et al. (1999), our results are in agreement with these previous values.

3.2 Image enhancement

To extract as much information as possible from the images, we applied STSDAS/IRAF external package techniques of image enhancement on the *BVRI* frames, and transform processing described in Faúndez-Abans & de Oliveira-Abans (1998). The Figs 1 and 2 show a high-pass filter applied to the *R* image of AM2229–735 which has better signal to noise ratio. With the filtering process, some hidden features become apparent. The north arm and disc of NED01 spread in a low-brightness bridge between NED02 and NED01. NED01 seems to be a warped SAB(s) galaxy viewed nearly edgeon (78°) in our line of sight. There is slight evidence of a bar, which appears asymmetrical. The whole object appears perturbed by the tidal interaction. NED02 seems to be a Sb(s) galaxy.

Fig. 4 is the residual image of the Gaussian filtered frame subtracted from the original GMOS r-G0326 image. This image confirms the warped general structure of NED01. It is also evident the presence of a bar extending about 3 arcsec from the nucleus, seen



Figure 4. GMOS r-G0326 image, after a high-pass filtering.

almost in the north–south direction and more evident in the north part. Two adjacent structures are present, which suggest that there may be an inner ring of radius $r \sim 3.5$ kpc.

3.3 Kinematics

In Fig. 5, the nuclear spectra of NED01 (top panel) and NED02 (bottom panel) are shown. The following emission lines can be discerned from left to right: H β , [O III] λ 4959, [O III] λ 5007, [N II] λ 6548 blended with H α , [N II] λ 6584 and [S II](λ 6716 + λ 6731) lines. The redshift of NED01 is z = 0.0573, corresponding to a line-of-sight velocity of 17 518 ± 25 km s⁻¹, and the redshift of NED02 is z = 0.0583, corresponding to a line-of-sight velocity of 17 326 ± 27 km s⁻¹. Redshift values were measured using H α emission line.

Fig. 6 shows the rotation profile of the central part of NED01, which encompasses the nucleus and the bulge along the emission



Figure 5. Optical nuclear spectra of NED01 and NED02 in units of erg sec^{-1} cm⁻² Å⁻¹. Identification of main emission features are overplotted.



Figure 6. Rotation profile of NED01 obtained from the emission lines measured along its major axis (Slit-1).

regions. The radial velocity was estimated from the H α emission line observed and the errors were estimated by the deviation of the individual measurements around the mean, following the procedure considered by Krabbe et al. (2011). We realized that there are three main kinematical subsystems along the observed slit signal: (1) the symmetrical core-bulge section in the $r \leq 10$ kpc central region, encompassing the rigid rotating bar; (2) a decoupled asymmetrical structure in the southern region for r < -10 kpc; and (3) a smooth decoupled region out from 8 kpc in the north, whose point of inflexion coincides with the 'blob' (denoted as 9 in Fig. 2), suggesting an association of kinematics with structural components. The southern section of the rotation profile is receding from us, and the northern one is approaching.

NED02 shows a U-shaped radial velocity profile (see Fig. 7). U-shaped profiles are common in strongly interacting galaxies, as reported in studies of interacting binary-disturbed galaxies (e.g. Borne & Hoessel 1985, 1988; Borne 1990; Bender, Paquet & Nieto 1991; Madejsky 1991; Madejsky, Bender & Moellenhoff 1991). The physical interpretation given by Borne et al. (1994) is that there is a tidal coupling between the orbit of the companion and the resonant stellar orbits in the kinematically disturbed galaxy (Borne & Hoessel 1985; Borne 1988; Balcells, Borne & Hoessel 1989). U-shaped profiles has also been found by Faúndez-Abans et al. (2012) in interacting galaxies at the core of the Abell S0546 cluster,



Figure 7. The U-shaped velocity profile of NED02 obtained from the emission lines measured along the Slit-2.

as a direct observational signature of tidal friction in action. The coupling of NED02 with NED01, and the U-shaped rotation profile of NED02 is thus a direct observational signature of tidal friction in this system.

The disturbed kinematics of NED02, and the morphology of the pair suggest that AM 2229–735 may be a case of proto-PRG. *N*-body simulations presented by Bournaud & Combes (2003) and Reshetnikov et al. (2006) to explore the accretion scenario shows in some stages, after the first perigalacticum, a morphology quite similar to the one seen in AM 2229–735. In this scenario, the polar ring forms out when a donor galaxy is in an almost polar orbit with respect to the accreting host galaxy. After the first perigalacticum, the donor stretches out due to the tidal forces, in a way very similar to that seen in NED02. The tidal tail is then pulled out by the potential well of the host galaxy, wrapping around it to become a ring.

3.4 Metal content and ionization stage of the gas phase

Determination of the metallicity of the gas phase of star-forming regions, traced by oxygen abundance, through strong line ratios has been widely discussed in the literature. Accurate oxygen abundance can only be derived by measuring emission-line ratios sensitive to electron temperature. Unfortunately, these emission lines are weak or non-observable in objects with low excitation. In these cases, calibration between abundances and more easily measured line ratios have to be used to estimate the metal abundances (e.g. Kewley & Dopita 2002; Pérez-Montero & Díaz 2005; Dors et al. 2011).

No emission-line ratio sensitive to the electron temperature was measured in our spectra of AM 2229–735; therefore, we used empirical calibrations involving strong emission lines [O III] λ 5007, [N II] λ 6584, [S II] (λ 6717 + λ 6731) and the Balmer lines H β and H α to determine the metallicity, as explained below.

We had to take into account that the H α flux was contaminated by the [N II] λ 6548 line flux. We used the theoretical relation between the intensity of the emission lines $\frac{I_{[N II]\lambda}65548}{I_{[N II]\lambda}6548} = 2.95$ taken from Osterbrock (1989) and it was corrected by subtracting $F([N II])\lambda$ 6548 = $F([N II])\lambda$ 6584/2.95 from the measured H α flux. This yielded a 16 per cent lower H α flux. The emission-line ratios used throughout the paper are defined in Table 4. The calibration of these strong line ratios with the oxygen abundance has been attempted by several methods, i.e. by using oxygen abundance computed from electron temperature detection (Pilyugin 2001), through photoionization models (e.g. Dors & Copetti 2005), or through mixed methods (see discussion in Kewley & Ellison 2008 and Maiolino et al. 2008). To estimate the metallicity of selected regions of AM 2229–735, we followed the same methodology used in Freitas-Lemes, Rodrigues & Faúndez-Abans (2012b). We

Table 4. The quoted emission-line ratios.

Symbol	Definition
[Ο π]/Hβ [Ο 1]/Hα [Ν π]/Hα [S π]/Hα N2S2	[O III] λ 5007/H β [O I] λ 6300/H α [N II] λ 6584/H α ([S II] λ 6716+ λ 6731)/H α log $\left(\frac{I([NII])\lambda$ 6584)}{II([SII])\lambda6717.6731)}
O3N2 N2	$ \log \left(\frac{I([O \text{ II}] \lambda 5007)}{I(\text{H}\beta)} \times \frac{I(\text{H}\alpha)}{I([\text{N II}] \lambda 6584)} \right) \\ \log \left(\frac{I([\text{N II}] \lambda 6584)}{I(\text{H}\alpha)} \right) $

investigated what the main ionizing mechanisms are of the observed H II regions of AM 2229–735 system. For that, the DDs [O III]/H β versus [N II]/H α and [S II]/H α ; and [N II]/H α versus [S II]/H α proposed by Baldwin, Phillips & Terlevich (1981), Coziol et al. (1999) and Pérez-Montero et al. (2013) were considered. Oxygen abundance and the total abundance ratio N/O for those regions ionized only by massive stars were derived using the following empirical calibrations for different emission-line ratios given by Pérez-Montero & Contini (2009):

$$12 + \log(O/H) = 8.73 - 0.32 \times O3N2, \tag{1}$$

 $12 + \log(O/H) = 0.57 \times N2 + 9.07$ and (2)

$$\log(N/O) = 1.26 \times N2S2 - 0.86, \tag{3}$$

where O3N2, N2, and N2S2 are defined in Table 4.

The emission-line intensity measurements were normalized to the flux of $H\beta = 100$, and the nebular reddening coefficient $c(H\beta)$ was calculated by comparing the Balmer decrement $H\alpha/H\beta$ to the theoretical value 2.86 given by Osterbrock (1989) for an electron temperature of 10 000 K and considering the interstellar law of Whitford (1958). The observed $H\beta$ flux for each aperture are presented in Table 5. The error associated with the line fluxes were estimated following the same procedure as in Oliveira, Copetti & Krabbe (2008).

First, we used the $[N \Pi]/H\alpha$ versus $[S \Pi]/H\alpha$ DD and the classifications proposed by Pérez-Montero et al. (2013) and Coziol et al. (1999) to separate objects ionized only by massive stars from those containing active nuclei (AGN) and/or shock excited gas. This is shown in Fig. 8. After, for the objects located into the 'star-forming objects' the abundances were determined by using the equations (1)–(3).

As seen in Fig. 8, the measured regions of NED01 are placed in the star-forming objects portion of the plot, considering both classification lines. However, for NED02 the classification is double.

Table 5. Reddening corrected emission-line intensities (relative to $H\beta = 100$) and global properties.

Dist. (kpc)	$\log(F[\mathrm{H}\beta]) \\ (\mathrm{erg}\mathrm{s}^{-1}\mathrm{cm}^2)$	$c(H\beta)$	(Ο III) λ5007	Ηα	(N II) λ6584	(S II) λ6720
		AM 222	29—735 NI	ED01		
-15.75	-15.06	0.67	108 ± 8	234 ± 10	45 ± 9	95 ± 7
-13.50	-15.05	0.52	101 ± 8	236 ± 9	42 ± 8	90 ± 7
-11.25	-15.07	0.61	108 ± 9	235 ± 9	38 ± 6	101 ± 8
-9.00	-15.04	0.52	103 ± 8	236 ± 10	40 ± 7	93 ± 9
-6.75	-15.07	0.51	98 ± 7	236 ± 9	44 ± 8	96 ± 7
-4.50	-15.04	0.58	105 ± 8	235 ± 8	48 ± 7	97 ± 8
-2.25	-15.04	0.46	103 ± 8	237 ± 8	49 ± 7	105 ± 7
0.00	-15.03	0.39	103 ± 7	237 ± 7	52 ± 6	96 ± 6
2.25	-15.02	0.45	102 ± 8	235 ± 7	49 ± 7	90 ± 6
4.50	-15.05	0.53	108 ± 7	235 ± 8	46 ± 7	107 ± 7
6.75	-15.04	0.55	104 ± 9	236 ± 9	44 ± 8	90 ± 7
9.00	-15.06	0.57	109 ± 8	235 ± 10	35 ± 9	103 ± 8
11.25	-15.04	0.59	115 ± 9	236 ± 9	45 ± 7	96 ± 7
13.50	-15.05	0.51	113 ± 9	236 ± 11	48 ± 8	98 ± 7
AM 2229-735 NED02						
-4.50	-15.22	0.16	144 ± 7	235 ± 8	66 ± 7	118 ± 8
-2.25	-15.31	0.15	144 ± 8	239 ± 9	70 ± 8	114 ± 7
0.00	-15.32	0.04	123 ± 7	239 ± 7	69 ± 7	123 ± 7
2.25	-15.26	0.13	132 ± 7	238 ± 8	68 ± 7	117 ± 8
4.50	-15.30	0.15	134 ± 8	239 ± 9	68 ± 8	118 ± 8



Figure 8. AM 2229–735 DD log[N II] λ 6583/H α versus log[S II](λ 6716 + λ 6730)/H α . The blue circles and black squares correspond to NED01 and NED02 regions, respectively. The green lines correspond to the separation between narrow-line AGNs and H II galaxies proposed by Pérez-Montero et al. (2013), while the magenta lines the one proposed Coziol et al. (1999).

Analysis for these objects was done by Pastoriza et al. (1999), who found the same result for NED01. They classified NED02 as having a composite spectrum, i.e. the ionizing sources being AGN and massive stars. Pastoriza et al. (1999) used the Veilleux & Osterbrock (1987) classification criteria, and used integrated spectrum of the nuclear region, leading them to a different conclusion for the ionizing mechanism of NED02. Accordingly, in Fig. 8, all measured regions of NED02 are near to the limit between star-forming region and AGN.

The line ratios in the diagrams in Fig. 9 were used to separate objects with distinct ionization sources, following the criteria of Kewley et al. (2001) and Ho et al. (1997). They showed that Seyferts and low-ionization narrow emission-line regions (LINERs) form clearly separated branches on the standard optical DD, such as the ones used in this paper. We can see all points of NED01 and NED02 occupy the star-forming objects site in these diagrams. However, NED02 regions are located near to the separation limit.

Fig. 10 shows the corresponding total abundances as derived from the calibrations cited above. The oxygen content of the NED01 and



Figure 9. DD log[O III] λ 5007/H β versus log[N II] λ 6583/H α and log[S II](λ 6716 + λ 6730)/H α . The blue full lines correspond to the empirical separation between narrow-line AGNs and H II galaxies, after Kewley et al. (2001). The black dashed lines show the model uncertainty of 0.1 dex in both planes. The green dot–dashed lines, determined by Ho, Filippenko & Sargent (1997), determines an area where LINERs and transition objects. Symbols as in Fig. 8.



Figure 10. Spacial distribution of oxygen abundances, computed using different indicators as labelled, for NED01 (dashed lines) and NED02 (solid lines).

NED02 apertures are very similar, leading to a total oxygen abundance of $12 + \log (O/H) \approx 8.5$. About the same oxygen abundance value was derived by Brosch et al. (2007) for the PRG AM 1934-563 and for VGS31b by Spavone & Iodice (2013). The slight metallicity difference between the oxygen distribution in NED01 and NED02 by using the N2 indicator is not visible using O3N2. This difference is probably real because it is also seen in N/O, which at this metallicity depends directly on the metallicity Z, but it is still not clear because all values are consistent within the errors. In both NED01 and NED02, the empirical parameters used point towards a chemical homogeneity in the regions observed. Pérez-Montero & Contini (2009) showed that parameters involving high-excitation oxygen lines (O23; Pagel et al. 1979) and sulphur (S23; Díaz & Pérez-Montero 2000) are affected by aperture effects in knot A of the galaxy IIZw71, while N2 (Denicoló, Terlevich & Terlevich 2000), which involves low-excitation nitrogen lines, yields more homogeneous values than the parameters cited above.

Since we are dealing with photoionized regions, we could use the ionization parameter U defined as $U = Q_{ion}/4\pi R_{in}^2 nc$, where Q_{ion} is the number of hydrogen ionizing photons emitted per second by the ionizing source, R_{in} is the distance from the ionization source to the inner surface of the ionized gas cloud (in cm), *n* is the particle density (in cm⁻³) and *c* is the speed of light.

We computed $\log U$ by means of

$$\log U = -1.66(\pm 0.06) \log([S_{\rm II}]/{\rm H}\alpha) - 4.13(\pm 0.07), \tag{4}$$

taken from Dors et al. (2011), and compared it with the oxygen abundance via N2 for the regions of each galaxies. Fig. 11 shows the resulting plot. Regions with larger abundances have lower ionization parameter than the less metallic ones. Bresolin, Kennicutt & Garnett (1999) found that the effective temperature of the ionizing stars in star-forming regions with high metallicity are somewhat lower than the ones (see also Dors & Copetti 2003). However, this cannot be the case for our objects, since it should imply that NED02 should be redder then NED01 and the opposite is found (see Fig. 3 and Table 5).

In Fig. 12, we compared the logarithm of the ionization parameter with oxygen abundance of the regions in NED01 and NED02 with those located in a sample of H π regions in isolated galaxies, taken from the data sample compiled by Dors et al. (2013). We also plot the H π regions located along the disc of the interacting pair



Figure 11. Logarithm of the ionization parameter versus the oxygen abundances computed from equations (4) and (2), respectively. The crosses represent H II regions located in isolated galaxies (data taken from the compilation of Dors et al. 2013). Typical errors (bars not shown) in these estimations are about 0.1 dex. Symbols as in Fig. 8.



Figure 12. Same as Fig. 11, now overplotting H II regions (crosses) located in isolated galaxies, taken from Dors et al. (2013). Circles and squares are NED01 and NED02 regions, respectively. Triangles are data of the interacting pair AM 2306–721 (Krabbe et al. 2008).

AM 2306–721, taken from Krabbe et al. (2008). All U and oxygen abundance values were obtained with the same calibrations, i.e. equations (4) and (2), respectively. We can see that the regions observed in both interacting galaxies present the lowest ionization parameter values for a large range of metallicity. It should be worth investigating if this is a common behaviour among other interacting galaxies. This can be due to H II regions located in interacting galaxies, such as the ones in NED01 and NED02, which have higher electron density than the ones in isolated galaxies Krabbe et al. (2013). Unfortunately, we cannot confirm the hypothesis of a higher electron density in interacting galaxies with our data because we cannot resolve the [S II] lines.

4 CONCLUSION

We report a study based on *BVRI* broad-band imagery and longslit spectroscopy in the wavelength range 4240–8700 Å, of the galaxy pair AM 2229–735 (ESO 048-IG26). It is formed by a disc galaxy, NED01, and a compact perturbed Sb(s)-like galaxy, NED02, showing a tail and counter-tail arc-shaped features. The skyprojected tail is very luminous and seems to connect the galaxies.

The southern region of NED01 is bluer than the northern one, with the blob object 9 being the reddest object in the colour-colour diagrams. The nucleus of NED02 is bluer than the one of NED01 (panels II and III). The whole NED02 appears bluer than NED01, and the object '6' between the galaxies is blue like the NED02 nucleus. The high-pass-filtered R image confirms the evidence of a bar in NED01, plus two structures which suggest that there may be an inner ring ($r \approx 1.6$ kpc).

We obtained a blue absolute magnitude of $M_B = -19.82 \pm 0.2$ for the central 5 arcsec of NED01. The B - R colour index in the galaxy centre is about 0.5 higher than the one of the nucleus companion galaxy.

The line-of-sight nuclear velocities are 17 518 \pm 25 km s⁻¹ for NED01 and 17 326 \pm 27 km s⁻¹ for NED02. NED02 seems to be almost face-on in the line of sight. It presents a U-shaped radial velocity profile, a phenomenon seen in interacting binarydisturbed elliptical galaxies (Borne & Hoessel 1988; Borne et al. 1994; Combes et al. 1995), and in some Sb pairs of peculiar galaxies like RR 24 (Rampazzo et al. 2005). We could interpret this U-shaped profile as a result of an interpenetrating encounter of NED02 into the halo of NED01.

The disturbed kinematics of NED02 and the morphology of the pair suggest that AM 2229-735 may be a case of proto-PRG. N-body simulations presented by Bournaud & Combes (2003) and Reshetnikov et al. (2006) to explore the accretion scenario shows in some stages, after the first perigalacticum, a morphology quite similar to the one seen in AM 2229-735. In this scenario, the polar ring forms out when a donor galaxy is in an almost polar orbit with respect to the accreting host galaxy. After the first perigalacticum, the donor stretches out due to the tidal forces, in a way very similar to what seen in NED02. The tidal tail is then pulled out by the potential well of the host galaxy, wrapping around it, to become a ring. The dynamics of the interaction in AM 2229-735 will be investigated via N-body simulations in a forthcoming paper.

Standard DD proposed by Baldwin et al. (1981), Coziol et al. (1999) and Pérez-Montero et al. (2013), were used to classify the main ionizing source of selected emission-line regions. All measured regions are mainly ionized by massive stars and occupy the star-forming site of those diagrams. Using two empirical methods based on easily observable emission lines, we found oxygen abundances for the H $\scriptstyle\rm II$ regions located at the ring in the range of 12 + log(O/H) = 8.3-8.6 dex. We compared the logarithm of the ionization parameter ($\log U$) with oxygen abundance of the regions in NED01 and NED02 with those located in a sample of H II regions in isolated galaxies (Dors et al. 2013), and also with the H II regions along the disc of the interacting pair AM 2306-721 (Krabbe et al. 2008). The result is that the regions observed in both interacting galaxies present the lowest ionization parameter values for a large range of metallicity. This could be due to H II regions located in interacting galaxies, such as the ones in NED01 and NED02, which probably have higher electron density than the ones in isolated galaxies. It should be worth confirming this behaviour and investigate this frequency among other interacting galaxies.

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