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Radio jets and diffuse X-ray emission around the peculiar galaxy pair ESO 295-IG022

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Abstract. We report Australia Telescope Compact Array (ATCA) radio-continuum and ROSAT PSPC X-ray observations of the region surrounding the peculiar galaxy pair ESO 295-IG022, lying at the centre of the poor cluster Abell S0102. We identify a radio galaxy coincident with the galaxy pair, with bipolar, bent radio jets appearing centred on the southern galaxy, and extending both to the south, for about 95″(≈100 kpc at the distance of ESO 295-IG022), and to the north, for ≈80″, encompassing the northern galaxy. We discuss also the idea of an additional single jet structure from the northern galaxy contributing to the emission. We estimate lower limit jet velocities of at least 1000 $\mathrm{km\,s^{-1}}$, and a relative proper velocity for the southern galaxy through the cluster of ∼200 $\mathrm{km\,s^{-1}}$. Diffuse ($kT = 2.2$ keV) X-ray emission consistent with group or poor cluster emission is seen centred on the southern galaxy surrounding the galaxy pair and the associated radio jets. Structure within the radio jets and the X-ray emission is very suggestive of there being some channeling of the radio emission with the surrounding intragroup medium. Another bipolar jet radio galaxy, discovered close by, is likely to be a background object, the optical counterpart having a magnitude $m > 22$.

Key words. galaxies: clusters: individual: Abell S0102 – galaxies: individual: ESO 295-IG022 – galaxies: interactions – galaxies: jets – radio continuum: galaxies – X-rays: galaxies

1. Introduction

Radio galaxies in clusters and groups are an important probe of the intracluster medium (ICM), as the jets can be confined and bent by the dense medium, and the non-thermal synchrotron radio emission provides complementary data to the (mainly thermal) X-ray emission.

The galaxy cluster Abell S0102 (Abell et al. 1989) (also known as EDCC 494; Lumsden et al. 1992), at a redshift of $z = 0.054824$ (Bica et al. 1991), is a poor cluster from Abell's supplementary catalogue. The ESO 295-IG022 galaxy pair (Bica et al. 1991), classified as a merging galaxy system (Lumsden et al. 1992) and members of the APM Bright Galaxy Catalogue (Loveday 1996), lie at the cluster centre. Cappi et al. (1998) showed that the southeastern part of Abell S0102 is in fact a separate cluster (Cl 0053-37) at a more distant redshift ($z = 0.165$), and is therefore not physically connected with the rest of Abell S0102. Lumsden et al. (1992) estimated that Abell S0102 has some 15+ members within a radius of ∼20′, and recently, Ratcliffe et al. (1998), in their "Durham/UKST Galaxy Redshift Survey", gave optical details of some 78 Abell S0102 cluster members.

Although the cluster was covered by the NVSS radio-continuum survey, the low resolution (40″) meant that the radio structures were not resolved clearly. This galaxy cluster however, lies some 18′ northeast of the nearby Sculptor group galaxy NGC 300, and radio observations of NGC 300 with the Australia Telescope Compact Array (ATCA) and X-ray observations with the ROSAT PSPC, also covered the area of this cluster, lying within the primary beam of the ATCA $\lambda = 20$ cm wavelength and within the ROSAT PSPC field. Here, we present these new ATCA and ROSAT PSPC results. In Sect. 2, we describe the radio, X-ray and optical observations and data analysis. The results of this analysis are presented and discussed in Sect. 3. Finally, in Sect. 4, we present our conclusions.

2. Observations and data analysis

2.1. Radio-continuum data

The Abell S0102 region was observed as part of the NGC 300 ATCA observations with a baseline of 6 km at 1384 MHz ($\lambda = 20$ cm) and 2496 MHz ($\lambda = 13$ cm), with corresponding angular resolutions of 6″ and 4″. More information regarding these observations can be found in

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Table 1. Radio-continuum integrated flux densities (S) and lengths (L) of the two radio galaxies within Abell S0102

ATCA Radio Name	L (″)	$S_{20\ \rm cm}$ (mJy)	$S_{13\ \rm cm}$ (mJy)	$S_{6\ \rm cm}$ (mJy)
J0055.7-3724 (core)	–	47.0	63.9	32.6
J0055.7-3724 (N jet)	80	103.0	–	–
J0055.7-3724 (S jet)	95	36.7	–	–
J0056.0-3723 (all)	45	17.6	–	–

Filipović et al. (in preparation). These observations were quite far down the primary beam pattern of the ATCA, and so some primary beam correction has been applied using the standard techniques in the MIRIAD software package (Sault & Killeen 1999) with the parameters of the ATCA primary beam.

Additional archival 4800 MHz ($\lambda = 6$ cm) ATCA data, centred on ESO 295-IG022, was also used, though only of $\sim$20 min duration and of fairly low sensitivity. This data was used only to determine the main feature's core flux and position.

1384 MHz ($\lambda = 20$ cm) primary beam corrected radio contours of these data are shown in Fig. 1, overlaid on a Digital Sky Survey (red) image. Two bipolar jet radio sources are seen, one (J0055.7-3724: core at α(J2000) = $00^{\rm h}55^{\rm m}46.58^{\rm s}$, δ(J2000) = $-37°24'27.7''$) coincident with the southern galaxy (ESO 295-IG022-S), the other (J0056.0-3723: core at α(J2000) = $00^{\rm h}56^{\rm m}00.21^{\rm s}$, δ(J2000) = $-37°23'47.6''$) having a very faint optical counterpart (positions are from the 1384 MHz observations). The frequency-dependent integrated flux densities (S) and, where applicable, lengths (L) of J0055.7-3724's core and two jet features, and of the entirety of J0056.0-3723 are given in Table 1. As the 13 and 6 cm data are of lower signal-to-noise ratio than the 20 cm data, these corresponding fluxes for the low surface brightness northern and southern jets (and of J0056.0-3723) have been omitted. The 13 cm J0055.7-3724 core flux value is also rather uncertain due to the beam correction applied.

The J0055.7-3724 20 cm integrated flux density was determined as the sum of the flux density in a box around ESO 295-IG022-S and the two jet features. The flux density of the central radio core coincident with ESO 295-IG022-S was determined using the two-dimensional elliptical Gaussian fitting algorithm within the MIRIAD software package. Similarly, flux densities of the ESO 295-IG022-S core at 13 and 6 cm were determined once the images were smoothed to the same resolution as the 20 cm data, i.e. to 6″. Our derived integrated flux at 20 cm for the ESO 295-IG022 source agrees well with the flux from the VLA NVSS.

2.2. X-ray data

The field surrounding NGC 300 was observed with the ROSAT PSPC (see Trümper 1982) twice; for 9324 s in November 1991, and for 36 693 s in May 1992. Each dataset was cleaned of both very high and very low accepted event rates and master veto rates. Source detection and position determination were performed over the full field of view with the EXSAS local detect, map detect, and maximum likelihood algorithms (Zimmermann et al. 1994). The two eventsets were then shifted with respect to the prominent bright star in the field, HD 5403, correcting for the proper motion of the star (Perryman et al. 1997) at the epoch of the ROSAT observations. The two cleaned and position-corrected datasets were then merged together, and the source detection procedures were re-ran yielding 79 sources. Though many sources were found within NGC 300 (detailed in a forthcoming paper, Read & Pietsch, in preparation), much interesting X-ray structure was seen surrounding the interacting galaxy pair ESO 295-IG022, and we concentrate here solely on this emission.

As, unfortunately, this area of the sky was partially obscured by the ROSAT PSPC entrance window support structure, a careful exposure correction had to be performed. Exposure maps were calculated in seven different standard ROSAT energy bands. These were combined with cleaned images in the same seven bands, and then smoothed with Gaussians on energy-dependent spatial scales (using a smoothing σ of from 66″ [low energy] to 33″ [hard energy]). The resultant cleaned, exposure-corrected and smoothed images were combined into broad (0.1−2.4 keV), soft (0.1−0.4 keV), hard (0.5−2.0 keV), hard 1 (0.5−0.9 keV) and hard 2 (0.9−2.0 keV) band images. Figure 2 shows the resultant hard-band (0.5−2.0 keV) image as grey scale, overlaid with the 1384 MHz J0055.7-3724 radio contours of Fig. 1. The X-ray emission is seen to surround the J0055.7-3724 radio feature and, though no obvious central peak to the emission is evident, bright clumps are seen, notably in between the two ESO 295-IG022 galaxies, and both to the northwest of the southern jet and to the east of the southern jet "foot". Note that the three ROSAT HRI observations of NGC 300 were not used, as the sensitivity at the Abell S0102 position (at the very edge of the FOV) was severely reduced.

2.3. Optical data

In the Digital Sky Survey 2 (DSS2) optical red image of the field surrounding ESO 295-IG022 (Fig. 1), we can see that the southern galaxy is *itself* interacting, optical filaments being visible to the west, enveloping a nearby companion. This can be seen far more clearly in Fig. 3, where in addition, two nuclei are seen within ESO 295-IG022-S itself. Looking into the lower-quality DSS1 data, taken 14 years earlier, we see that the situation appears identical, indicating that we have a true double nucleus system, and not some transient bright source such as a supernova. Surrounding ESO 295-IG022, we see several other fainter optical galaxies, probable members of Abell S0102.

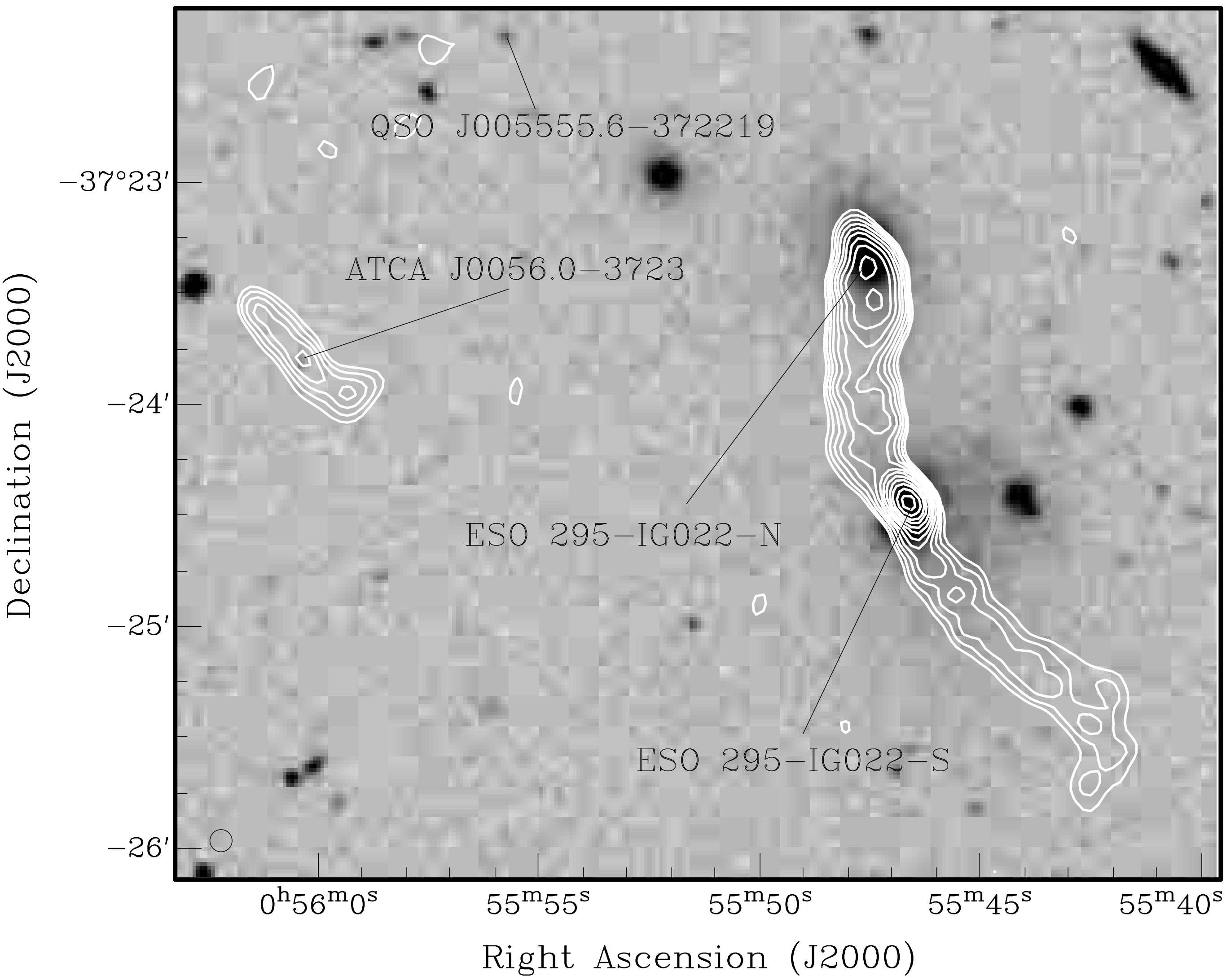

Fig. 1. Digital Sky Survey (red) image of the Abell S0102 cluster central region overlaid with primary beam corrected 1384 MHz ATCA radio-continuum contours. The synthesized beam of the ATCA observation is 6″ × 6″ (see circle, lower left corner) with rms noise (1σ) of 0.06 mJy. Contours increase by factors of $\sqrt{2}$ from 0.5 mJy/beam

3. Discussion

3.1. ATCA J0055.7-3724

In comparing the radio continuum, ROSAT PSPC and optical DSS2 images (Figs. 1 and 2), we see some striking features in and around the central Abell S0102 cluster galaxy pair, ESO 295-IG022. The ESO 295-IG022-S core has a flat or inverted spectrum, but the comparison of the data at the three frequencies (Table 1) indicates that the core is probably variable, so the spectral index is difficult to determine.

The galaxy ESO 295-IG022-S is complex and disturbed with two nuclei, ≈6″ (i.e. 6.5 kpc) apart, and a nearby interacting system around 30″ to the west. The radio core is seen to lie within 1″ of the northernmost ESO 295-IG022-S nucleus. The bright northernmost radio knot (α(J2000) = $00^{\rm h}55^{\rm m}47.53^{\rm s}$, δ(J2000) = −37°23′22.5″) lies some 3−4″ from ESO 295-IG022-N and so, given the positional errors of both the optical and radio data (both ≈1″), it seems sensible to interpret the radio source as a bipolar twin-jet with a core coincident with ESO 295-IG022-S. However, within the jets, several knots of emission are seen, and the northern jet contains almost 3 times as much flux as the southern (see Table 1), hence an alternative interpretation, in that some of the northern radio emission originates as a single jet structure from the northern galaxy, is plausible and will need to be investigated in dedicated, new 6 and 3 cm ATCA observations. Note that we do not have any reliable spectral information from the northern end of the radio jet, as the feature, though seen in the 20 cm data, is barely visible in the 13 and 6 cm data.

The fact that the main "bend" in the radio emission appears to lie some 10″−15″ northeast of the main core, adds some credence to this second "two galaxies" hypothesis (i.e. assuming jets from both ESO 295-IG022 galaxies), as one would expect in the "single galaxy" model (i.e. just a jet solely from ESO 295-IG022-S), to a first

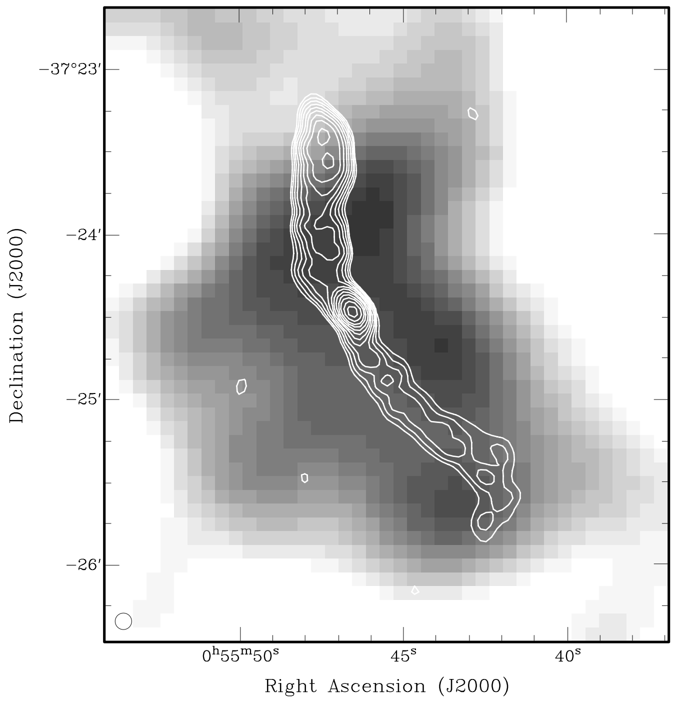

Fig. 2. ESO 295-IG022 in detail: ROSAT hard X-ray band (0.5–2.0 keV) PSPC image overlaid with ATCA primary beam corrected 1384 MHz radio-continuum contours (contour levels same as in Fig. 1)

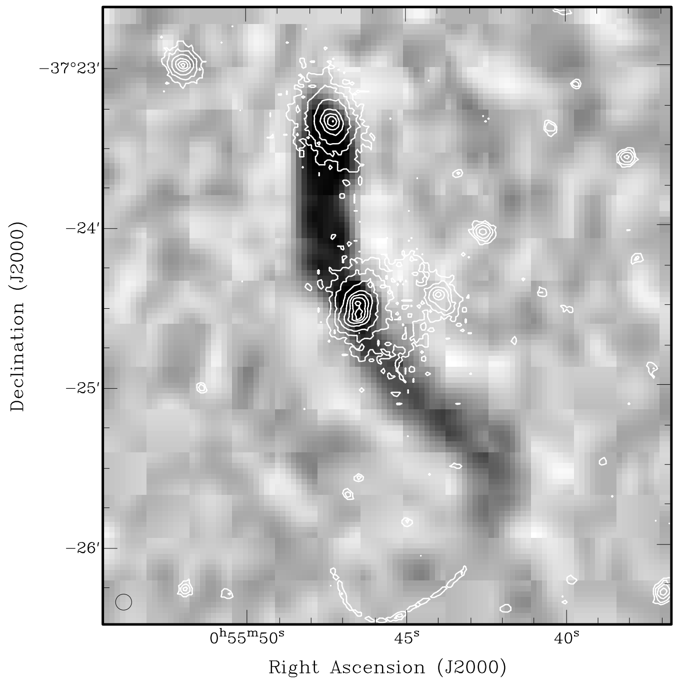

Fig. 3. ESO 295-IG022 in detail: The Fig. 2 (and 1) primary beam corrected ATCA radio-continuum image (this time as grey scale) of ESO 295-IG022, with optical DSS2 (red) contours. The inner contour indicates the merging nuclei of ESO 295-IG022-S

approximation, the bend to occur at the core, as the jet is expelled from both sides and is swept back. However, it is well known (e.g. Owen & Ledlow 1997) that bends occur in the radio features of cluster radio galaxies in a lot of places, not just at the core, and a very similar offset bend to the present case is found in the famous 3C 465 radio galaxy at the centre of the cluster Abell 2634 (Sakelliou & Merrifield 1999). Furthermore, it is known that there are regions of brightening within radio jets associated with shocks and re-acceleration (Hardee 1996), and this could well be the cause of the feature. Interestingly, the X-ray data do show a bright clump of denser emission close to the position of the bend, and so the bend may have been caused by the jet shocking into this denser material. All in all though, there are some arguments for the radio feature not being due solely to a twin-jet structure from ESO 295-IG022-S, but for there being some component of a single jet structure from ESO 295-IG022-N as well. Further investigation is necessary, and is in progress.

Though we have no real idea as to the orientation of the jets with our line of sight, if we assume them to lie essentially perpendicular to it, then some interesting inferences can be made. Assuming an H_0 of 75 km s^{-1} Mpc^{-1}, the ESO 295-IG022 redshift corresponds to a distance of ≈220 Mpc, leading to jet lengths (or lower limits rather, given the uncertainty in the orientation) of about 85 (North) and 100 (South) kpc.

In order to convert these distances into velocities, some assumed timescale, over which the jets are produced, is necessary. While we agree that there are certainly a few different methods of estimating these sorts of timescales, given the fact that both the radio data and the X-ray data are not of the highest possible quality (both having been obtained serendipitously, and suffering from effects to do with ESO 295-IG022 not being the prime target of the observations), we here use a simple method of estimation. With our upcoming observations, more complex methods for estimating the jet production timescale may be possible (note of course that the velocities calculated here are easily scaled with any other timescale assumed).

Given that the two ESO 295-IG022-S nuclei are so close together, it seems sensible to assume that ESO 295-IG022-S is at a similar interaction stage as mergers such as Arp 220 and NGC 2623 (see Read & Ponman 1998). This interaction stage is thought both observationally and theoretically (e.g. Mihos & Hernquist 1996) to give rise to very violent and efficient compressing and fueling of gas towards the galaxies' centres. This vigorous gas fueling process towards the galaxy centres is thought to last at most 10^8 yr, and assuming, as is commonly believed, the radio structures observed to be due to compact AGN activity (e.g. Urry & Padovani 1995; Laing 1993), here fed with gas via this fueling process, then this interaction and gas-fueling timescale gives rise to jet proper motions of $830-990$ km s^{-1}. The true jet speeds may be far higher due to inclination effects. Also the jet timescale may be somewhat shorter (note that the ESO 295-IG022-S nuclei have not yet completely merged). Note also that the velocity of the end of the jet (which we are here estimating), pushing through the medium, is probably slower than the flow of material within the jet. As we do not have reliable radio spectral index gradients, it is difficult to determine exact particle velocities. For the synchrotron ageing model (Myers & Spangler 1985), velocities of $\sim$1000 km s^{-1} over timescales of 10^8 yr are entirely plausible. It is likely however that re-acceleration does occur, and so synchrotron ageing may not be relevant. Note also that synchrotron lifetimes may not be that reliable (Eilek 1996).

It can be further seen that a circle of radius 140 kpc passes nicely through the radio core and the bright southernmost and northernmost knots, following well the curve of the radio jets. Standard radio jet creation models (e.g. Blandford 1990) predict straight jets. However, as is seen here, they are often bent (see also Owen & Ledlow 1997), and this is usually attributed to the motion of the galaxy through the ICM, resulting in significant ram pressure stripping acting on the jets (Begelman et al. 1984). Assuming ESO 295-IG022-S to move east-southeasterly, one can calculate a proper motion (upper limit) of ESO 295-IG022-S of 190 km s^{-1}, similar to the velocity dispersion of poor clusters and groups. Note that this proper motion is often attributable to the gravitational influence of a companion galaxy. Here, the position of the westerly companion and the interaction-induced optical filaments (Fig. 3) are nicely aligned with the proper motion of ESO 295-IG022-S.

The ROSAT PSPC hard-band image (Fig. 2) shows much emission enveloping the ESO 295-IG022 galaxy pair. To analyse the cluster/group X-ray emission, a 400$''$ diameter region centred 5$''$ north of the southern galaxy was selected. Comparing the broad-band (unsmoothed) exposure-corrected image with source-subtracted background regions to the northeast and northwest, a broad-band background-subtracted countrate of 0.09 cts/s was estimated. A source spectrum, extracted from the same region was fitted with standard spectral models (power law, thermal bremsstrahlung, blackbody and Raymond & Smith hot plasma models). A best fit (reduced $\chi^2 = 0.69$) was obtained with a low-temperature ($kT = 2.2$ keV) Raymond & Smith hot plasma model, with the metallicity frozen at 0.2 solar. The fitted absorbing column was found to be entirely consistent with the Galactic value in this direction (2.97 10^{20} atoms cm^{-2}; Dickey & Lockman 1990), indicating no intrinsic absorption is present. Combining the results of the spectral fitting with the calculated exposure-corrected countrate and the redshift of Abell S0102, one arrives at an X-ray luminosity (0.1$-$2.4 keV) of 8.6 10^{42} erg s^{-1} for this extended emission. This luminosity, combined with the low temperature and metallicity and the lack of intrinsic absorption, fits very well with the idea that the emission is due to galaxy group/small cluster (as opposed to large cluster) emission, the emission being due to hot gas lying in the potential well of the group, of which ESO 295-IG022-N/S are the prominent members. Note that this idea sits very nicely with the fact that the proper motion of ESO 295-IG022-S calculated earlier is also more similar to that of groups than of large clusters.

The comparison between the radio and X-ray emission (Fig. 2) is very suggestive of the southern jet being confined in the X-ray gas. There is an indication of an X-ray radio anticoincidence around the southern jet, particularly to the northwest near the core and to the east near the southern tip. The jets may be collimated by the surrounding X-ray "cocoon", which maintains the pressure of the ICM in balance with that of the gas within the jet. This would be very suggestive of channeling effects taking place, whereby the violent radio-continuum jets are able to punch holes and displace the X-ray emitting cluster gas, as is seen in the NGC 1275 jet at the centre of the Perseus cluster (Böhringer et al. 1993). Also note how (assuming a "single galaxy" jet model) the northern jet appears to flare and brighten once it reaches the lower density (i.e. less bright) X-ray emitting gas. One might have thought that the radio emission would expand and fade, on losing its confining medium, i.e. once it entered a lower-density region. However it is known (Loken et al. 1994) that a transition even from a dense to a less dense medium can induce instabilities in radio jets, leading to shocks and brightening. Though this may be the case, other possibilities to explain the northern feature include the idea that the northern jet has perhaps run into the northern galaxy, or that, as discussed earlier, there may be significant radio emission from the northern galaxy itself - the "two galaxies" model.

3.2. ATCA J0056.0-3723

Lastly, we move on to the other bipolar twin-jet radio galaxy (ATCA J0056.0-3723; Fig. 1), lying 3$'$ east of ESO 295-IG022-S. We estimate the optical apparent magnitude of the faint coincident source seen in the DSS2 image to be $m > 22$, this based on comparison with the nearby optical quasar QSO J005555.6-372219 with $m = 20.1$ (Veron-Cetty & Veron 1998) (a source is also listed in the SuperCosmos Sky Survey Catalogue within 1$''$ of ATCA J0056-3723 with a magnitude B(J) of 22.65). This optical faintness indicates that the source is likely a distant unrelated background radio galaxy (radio galaxies are giant ellipticals with a small range in absolute magnitude). Finally, it should be stated that, while no X-ray emission was detected from this source, the source is positioned close to the PSPC window support structure, which reduces significantly the X-ray detection efficiency.

4. Summary

The ATCA observations of the peculiar galaxy pair ESO 295-IG022 at the centre of the poor cluster Abell S0102 show what appears to be a bipolar, fairly assymetrical, twin-jet radio galaxy, associated with the southern system ESO 295-IG022-S, itself a galaxy merger. We also discuss the fact that an extra contribution from a one-sided radio jet from the northern galaxy, ESO 295-IG022-N, may exist.

We estimate the jets, with projected lengths of up to 100 kpc, to have velocities of at least 1000 $\mathrm{km\,s^{-1}}$, and can explain the bending of the jets as being due to ESO 295-IG022-S moving through the ICM at $\sim$190 $\mathrm{km\,s^{-1}}$. ROSAT PSPC observations indicate relatively cool diffuse X-ray emission consistent with group or poor cluster emission, and this emission, when compared with the radio jets, is suggestive of channeling effects taking place, i.e. the jets are able to punch holes, and displace the X-ray emitting gas, as is seen in other systems. Another bipolar jet radio galaxy discovered close by is likely to be a background object.

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