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RADIO-CONTINUUM JETS AROUND THE PECULIAR GALAXY PAIR ESO 295-IG022

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SUMMARY: We report new radio-continuum observations with the Australia Telescope Compact Array (ATCA) of the region surrounding the peculiar galaxy pair ESO 295-IG022 at the centre of the poor cluster Abell S0102. We observed this cluster at wavelengths of λ=20/13 and 6/3 cm with the ATCA 6 km array. With these configurations, we achieved a resolution of $\sim 2''$ at 3 cm which is sufficient to resolve the jet-like structure of $\sim 3'$ length detected at 20 cm. From our new high resolution images at 6 and 3 cm we confirm the presence of a double jet structure, most likely originating from the northern galaxy (ESO 295-IG022-N), bent and twisted towards the south. We found the spectral index of the jet to be very steep (α=–1.32). No point source was detected that could be associated with the core of ESO 295-IG022-N. On the other hand, ESO 295-IG022-S does not show any jet structure, but does show a point radio source. This source has variable flux and spectral index, and appears to be superposed on the line-of-sight of the jets (seen at 20-cm) originating from the northern galaxy ESO 295-IG022-N. Finally, regions of very high and somewhat well ordered polarisation were detected at the level of 70%.

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

1. INTRODUCTION

Merging and interacting galaxies are often found in galaxy clusters. Such interactions and mergers provide a valuable insight into the evolution of both the cluster and the embedded galaxies, thus underpinning the most current theories of cluster and galaxy formation and evolution. As an example, it is now well established that radio jets interact with the intracluster medium (ICM) providing energy to the ICM. It is shown by Rafferty et al. (2006) and Bîrzan et al. (2007) that the synchrotron ages of the radio jet lobes are generally less than the X-ray ages of the cluster cavities; suggesting that the cavities are being pumped by the energy supplied by the jet. In their study, they compared the size of the cavities (determined from X-ray data) with the size of the lobes (found on radio maps) and concluded that the lower radio frequencies maps are a better tool (than the higher frequency maps) to study the several hundred million year history of active clusters.

A prime example of a complex, merging and interacting system of galaxies within a cluster has been discovered by Read et al. (2001). They reported a prominent (bipolar) radio source with jets embedded in the poor 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). The ESO 295-IG022 galaxy pair also coincides with Abell S0102 and was classified as a merging galaxy system by Bica et al. (1991).

Read et al. (2001) suggested two possible scenarios for the appearance of radio-continuum jet/s. One is a "single galaxy" model with two jets coming out of either ESO 295-IG022-S or ESO 295-IG022-N and with the other galaxy seen superimposed on the jet structure. For this scenario they suggest the southern galaxy (ESO 295-IG022-S) as the "origin" of the bipolar radio jets which extend south about $95''$ (≈ 100 kpc at the distance of ESO 295-IG022), and to the north about $\approx 80''$. The northern termination is positional coincidence with the northern galaxy ESO 295-IG022-N.

The alternatively scenario suggested by Read et al. (2001) is that the emission emanates from the northern galaxy ESO 295-IG022-N and that there is a positional coincidence with a similar jet structure associated with ESO 295-IG022-S. This second, and less likely scenario, requires the northern and southern galaxies to produce their own substantive jets. In this two jet model, Read et al. (2001) estimate projected lengths of up to 100 kpc, with velocities of at least 1000 km s^{-1}, and explain the bending of the jets as being due to ESO 295-IG022-S moving through the ICM at ~ 190 km s^{-1}.

The ROSAT PSPC observations of Read et al. (2001) indicate relatively cool diffuse X-ray emission from Abell S0102 consistent with group or poor cluster emission. This emission, when compared with the radio jets, is suggestive of channeling effects taking place that might create the so-called cavities where jets are able to punch holes in the ICM and displace the X-ray emitting gas, as is seen in other galaxy groups/clusters such as Hydra A (Wise et al. 2007), Abell 2204 (Sanders et al. 2009) or Abell 1446 (Douglass et al. 2008).

Our aim was to use Australia Telescope Compact Array (ATCA) high-resolution radio-continuum observations to resolve the jet structure of this Abell cluster, and to better determine the relationship between the optical galaxies and radio-continuum/X-ray (anti)correlation. In this paper, we present new ATCA radio results of this cluster area at 6 and 3 cm. In Section 2, we describe our radio-continuum observations and data analysis. The results of this analysis are given in Section 3. Finally, we summarise our findings in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

The Abell S0102 region was initially observed as a part of the ATCA observations of the NGC 300 area (ATCA project C828) at wavelengths of 20 and 13 cm (ν=1384 and 2496 MHz) with a 6A array giving angular resolutions of $6''$ and $4''$ (see Figs. 1 and 2). More information regarding these observations can be found in Payne et al. (2004). As the Abell S0102 positions are well down the primary beam pattern of the ATCA, we have applied a primary beam correction using the standard techniques in the MIRIAD software package (Sault and Killeen 2010).

We again observed Abell S0102 with the ATCA on October 9, 2000 (ATCA project C913), with an array configuration 6A, at wavelengths of 6 and 3 cm (ν=4800 and 8640 MHz). These observations were undertaken in the so-called full synthesis mode and total $\sim$10.5 hours of integration over a 12 hour period. Source 1934-638 was used for primary calibration and source 0048-427 was used for secondary calibration. The MIRIAD (Sault and Killeen 2010) and KARMA (Gooch 2006) software packages were used for data reduction and analysis.

The 6 cm image (Figs. 2 and 3) has a resolution of $4''\times3''$ at position angle 2° and the r.m.s noise is estimated to be 0.1 mJy/beam. Similarly, the 3 cm image was constructed with a resolution of $2.2''\times1.6''$ and r.m.s noise of 0.1 mJy/beam (Fig. 4).

Additional archival λ = 6 cm ATCA data from December 13, 1991 (ATCA project C133), centred on ESO 295-IG022 were found. These observations are only $\sim$20 minutes of fairly low sensitivity observations, and were only to determine the ESO 295-IG022-S flux and position. Finally, we note recent (January 17, 2010), Burnett et al. (2010) ATCA CABB observations with some significant calibration problems, from which they managed to extract integrated flux densities for the main feature of ESO 295-IG022-S. We report their results in our Table 1 (also see Fig. 5c).

Two prominent radio features are seen at 13 and 6 cm – the "core/s" and "jet/s". The radio point source (J005546-372427: at RA(J2000)=$00^h55^m46.58^s$, DEC(J2000)=–37°24′27.7″) is coincident with the southern galaxy (ESO 295-IG022-S). The "jet" – named J005547-372320 (at RA(J2000)=$00^h55^m47.31^s$, DEC(J2000)=–37°23′20.6″) appears to be associated with the optical counterpart ESO 295-IG022-N (positions from the 6 cm observations).

The frequency-dependent integrated flux densities (S) of J005547-372320 and J005546-372427 features are given in Table 1 and shown in Fig. 5. We point out that we do not detect the jets at 3 cm because of the very steep radio spectrum of the jets, however, this steep spectral index ($\alpha = -1.32 \pm 0.14$; see Fig. 5a) may be the result of the missing flux of the short spacings at the higher radio-continuum frequencies (6 and 3 cm).

The integrated flux density of J005547-372320 was determined as the sum of the flux density in a box around ESO 295-IG022-N and that of the two twisted jet features. The integrated flux density of the central point-like radio source coincident with ESO 295-IG022-S was determined using the two-dimensional elliptical Gaussian fitting algorithm within the MIRIAD software package. The spectral index distribution of this object is shown in Figs. 5b and 5c. We emphasise that the integrated flux at 20 cm of the ESO 295-IG022 source in our February 28, 2000 observations agrees well with the flux density from the VLA NVSS and that reported by Read et al. (2001). We estimate the integrated flux density errors for all our images to be less than 10%.

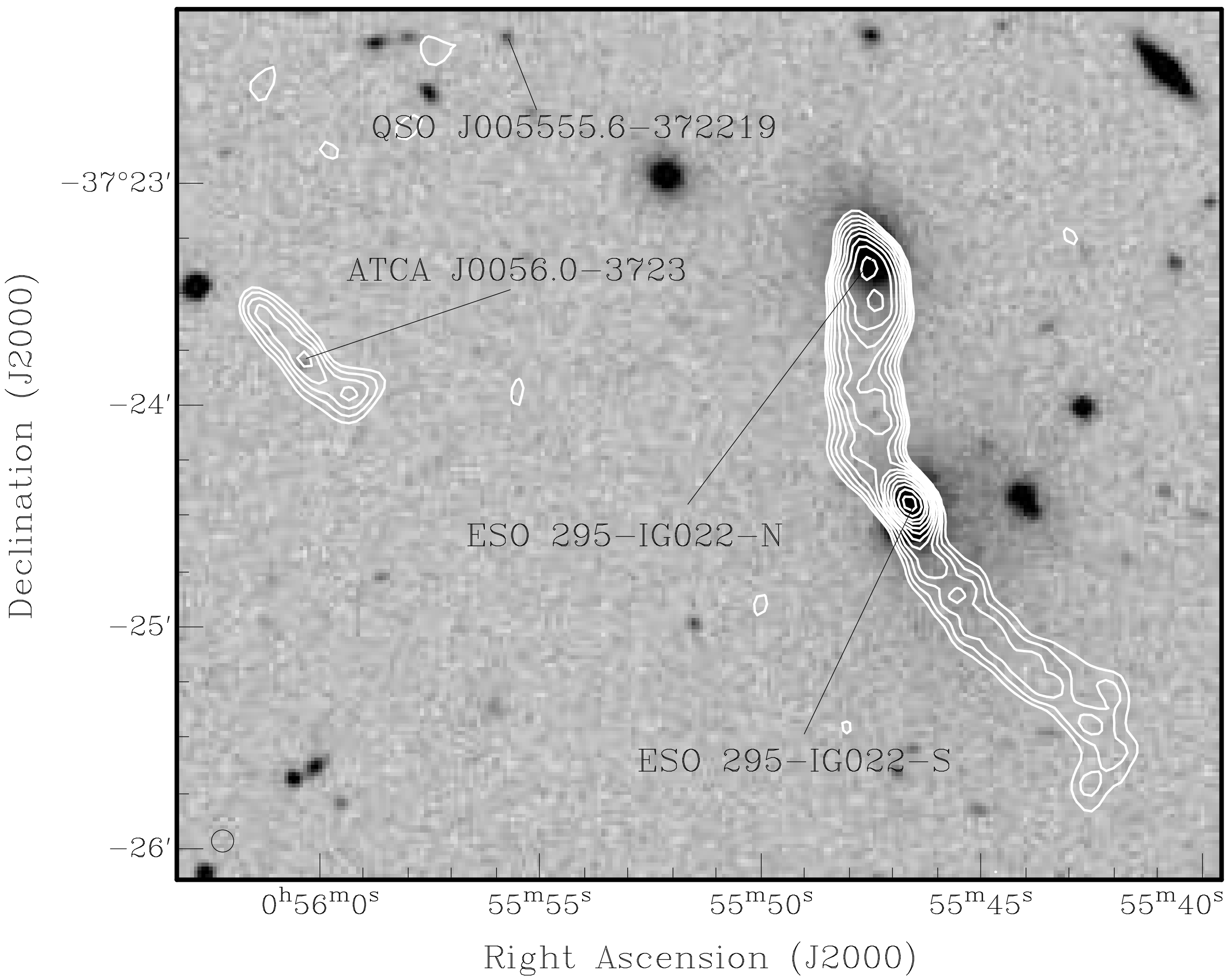

Fig. 1. *Digital Sky Survey (red) image of the Abell S0102 cluster central region overlaid with primary beam corrected 20 cm ATCA radio-continuum contours. The synthesised beam of the ATCA observation is 6″ × 6″ (see circle, lower left corner) with r.m.s. noise (1σ) of 0.06 mJy. Contours increase by factors of* $\sqrt{2}$ *from 0.5 mJy/beam. This picture is adapted from Read et al. (2001).*

Table 1. Radio-continuum integrated flux densities (S) of the two radio features within Abell S0102. Our new spectral index (α) estimates are based on two observing sessions from 2000 while Burnett et al. (2010) is also shown in Column 8.

ATCA Radio Name	Other Name	Obs. Date	$S_{20\,\mathrm{cm}}$ (mJy)	$S_{13\,\mathrm{cm}}$ (mJy)	$S_{6\,\mathrm{cm}}$ (mJy)	$S_{3\,\mathrm{cm}}$ (mJy)	$\alpha \pm \Delta\alpha$	Reference
J005547-372320	ESO 295-IG022-N	28/02/2000	80.0	42.5		–	-1.32 ± 0.14	Read et al. (2001)
J005547-372320	ESO 295-IG022-N	09/10/2000			15.5	–		This paper
J005546-372427	ESO 295-IG022-S	13/12/1991			32.6			Read et al. (2001)
J005546-372427	ESO 295-IG022-S	28/02/2000	47.0	63.9			-0.11 ± 0.14	Read et al. (2001)
J005546-372427	ESO 295-IG022-S	09/10/2000			48.6	41.1		This paper
J005546-372427	ESO 295-IG022-S	17/01/2010	18.2		74.0	67.0	$+0.78 \pm 0.31$	Burnett et al. (2010)

3. RESULTS AND DISCUSSION

In comparing our various radio-continuum images with optical Digital Sky Survey 2 (DSS2) images (Figs. 1, 2, 3 and 4), we see some striking features in and around the central Abell S0102 cluster galaxy pair, ESO 295-IG022. From the higher resolution image at 13 and 6 cm (Figs. 2 and 3), the southern peak appears quite compact and NOT a knot in the jet. The compact nature of this source is supported by our 2000 observations of ESO 295-IG022-S that give a flat spectrum of $\alpha = -0.11 \pm 0.14$ (Fig. 5b). This spectral index is, however, significantly different from $\alpha = +0.78 \pm 0.31$ found in 2010 by Burnett et al. (2010) (Fig. 5c) and we note that the flux density values for Burnett et al. (2010) are higher than ours by a factor of ∼1.6 at the higher frequencies (6 and 3 cm) but substantively lower than that of Read et al. (2000) by a factor of ∼0.4 at the lower (20 cm) frequency. We are, therefore, assuming that the source is both of flat spectrum and variable, and interpret the inconsistencies of flux density as a consequence of either variability (over two decades) or the loss of flux due to the missing spacings in the data set/s.

As pointed by Read et al. (2001), the galaxy ESO 295-IG022-S has a complex optical morphology with two nuclei ≈ 6″ (i.e. 6.5 kpc) apart. This may be a merging pair or a NGC 5128 type object seen at great distance. The bright and compact northernmost radio knot at 3 cm (RA(J2000)=$00^h55^m46.57^s$, DEC(J2000)=$-37°24'27.5''$) lies within ∼ 1″ of the northern component of ESO 295-IG022-S (Fig. 4) and, given the positional errors of both the optical and radio data (both ≈1″), it seems sensible to interpret the point radio source as coincident with ESO 295-IG022-S and emanating from the AGN core of the northern component of that galaxy.

The scenario put forward by Read et al (2000), that ESO 295-IG022-S is the origin of the observed (20 cm) jets, is therefore unlikely. We do not find the jet structure asymmetric as the northern jet is much brighter than the southern. Combining this with the compact and potentially variable nature of the radio source and its identification with a component of ESO 295-IG022-S. We argue that the jet structure most likely originates from ESO 295-IG022-N and not from ESO 295-IG022-S as suggested by Read et al (2000). This is therefore probably a rare, but not too unlikely random line of sight coincidence.

The 6 cm twin jet of the northern source (Fig. 3) is nicely coincident with an optical object which is an extended and elliptical galaxy. We point out the lack of a point radio source which could be associated directly with ESO 295-IG022-N but see the

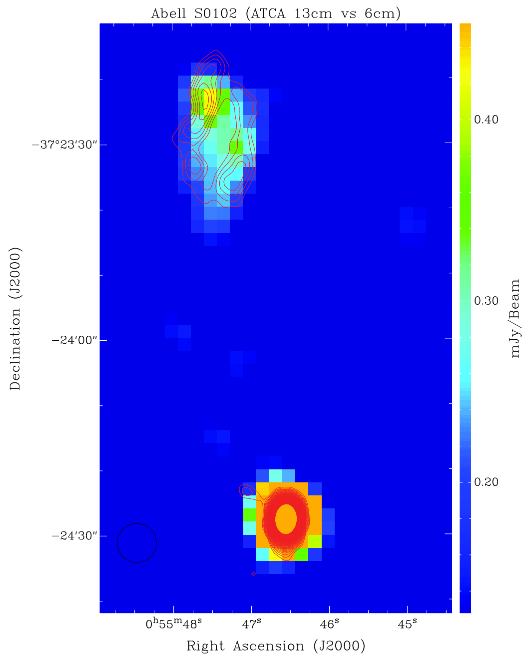

Fig. 2. *ATCA 13-cm image of the Abell S0102 cluster central region overlaid with primary beam corrected 6-cm ATCA radio-continuum contours. The synthesized beam of the ATCA observation is 4″ × 3″ (see circle, lower left corner) with r.m.s. noise (1σ) of 0.1 mJy. Contours increase by factors of 2.5σ from 0.5 mJy/beam.*

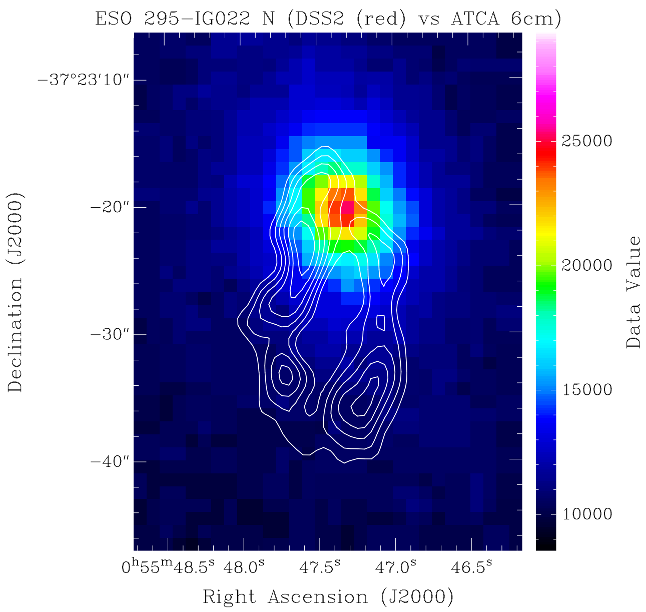

Fig. 3. *Digital Sky Survey (red) image of the ESO 295-IG022-N region overlaid with primary beam corrected 6-cm ATCA radio-continuum contours. Contours are the same as in Fig. 2.*

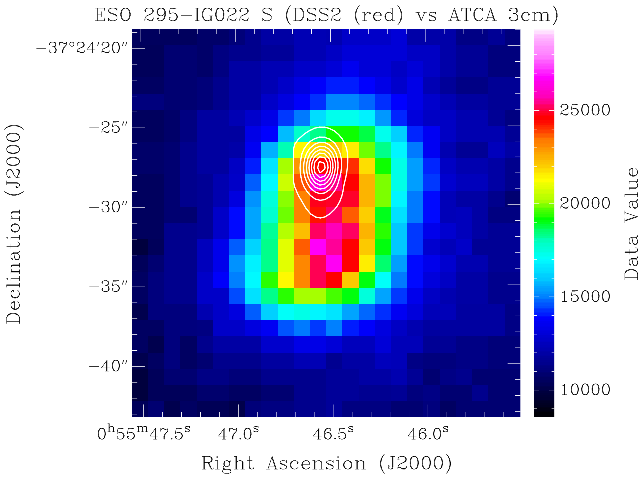

Fig. 4. *Digital Sky Survey (red) image of the ESO 295-IG022-S region overlaid with primary beam corrected 3-cm ATCA radio-continuum contours. The synthesized beam of the ATCA observation is 2.2″ × 1.6″ with r.m.s. noise (1σ) of 0.1 mJy. Contours increase by factors of 50σ from 1.5 mJy/beam.*

twin-jet nature of the jet near ESO 295-IG022-N as a defining feature (this is not seen in the 13 cm image with lower resolution). As radio cores are often much weaker than the jets, the non detection of a core in ESO 295-IG022-N is not too surprising (see Jones et al. 1994; cores typically <1% of jets). Finally, our spectral index estimate for this jet feature is quite steep with $\alpha = -1.32 \pm 0.14$ (Fig. 5a). This steep spectral index may be an explanation for not detecting the jet features in our 3 cm image. However, the steep spectral index is, at least in part, due to the missing flux at higher resolution/frequency. McAdam et al. (1988) reported discovery of radio source PKS 0427-53 interacting with IC 2082 and the cluster medium. The morphology of this radio AGN looks very similar to ESO 295-IG022-S. Even the size of PKS 0427-53 jets of 160 kpc is similar to ESO 295-IG022-S jets estimate of 180 kpc.

The linear polarisation image of Abell S0102 at 6 cm is illustrated in Fig. 6. This linear polarisation image was created using Q and U parameters. Regions of fractional polarisation are quite strong at the southern side of the Abell S0102 cluster with polarisation vectors aligned with the observed jets from ESO 295-IG022-N. We could not determine the Faraday rotation and magnetic field without polarisation measurements at the second wavelength of 3 cm. The mean fractional polarisation at 6 cm was calculated using flux density and polarisation:

$$P = \frac{\sqrt{S_Q^2 + S_U^2}}{S_I} \cdot 100\% \qquad (1)$$

where S_Q, S_U and S_I are integrated intensities for Q, U and I Stokes parameters. Our estimated peak polarisation value is $P \cong 72\% \pm 15\%$ at 6 cm. Along the northern part of the jet there is a pocket of uniform polarisation at approximately 70% (Fig. 6) possibly indicating a varied dynamics along the jet. We speculate that in the mid part of the jet, some twisting of the two bended jets may produce a poorly ordered polarisation as can be seen also in Fig. 6. This strong and ordered polarisation is among the strongest ever observed in a large scale AGN.

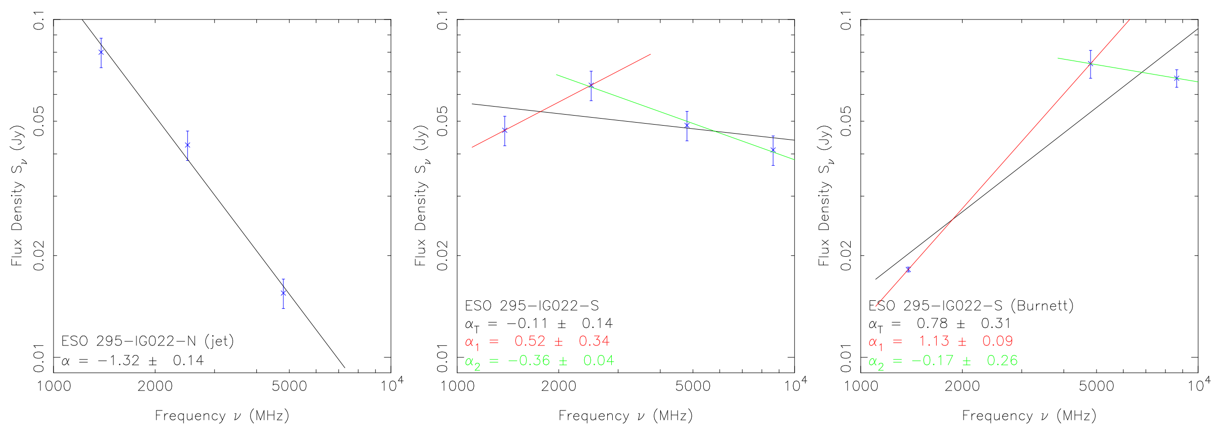

Fig. 5. *Spectral index distribution of the radio features within the Abell S0102. (a) Jet structure associated with ESO 295-IG022-N based on the ATCA 2010 observations (b) ESO 295-IG022-S based on our ATCA 2000 observations (c) ESO 295-IG022-S from Burnett et al. (2010). For (b) and (c) α_T is the fit including all points; α_1 and α_2 are fits using a subset of the points.*

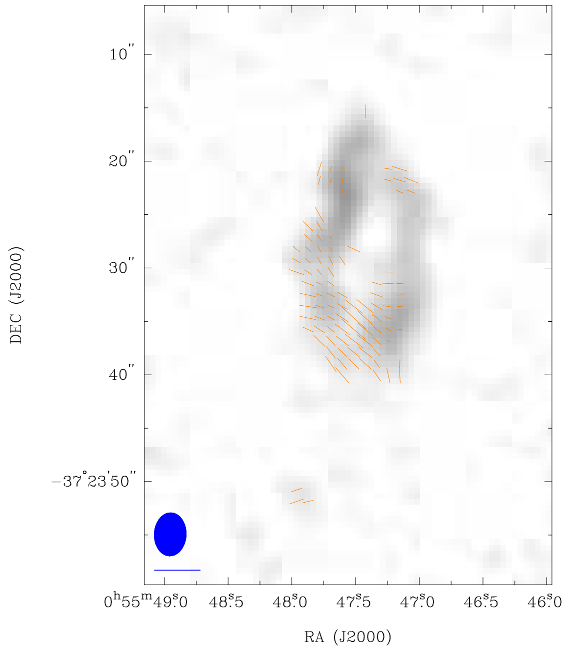

Fig. 6. *ATCA observations of ESO 295-IG022-N at 6 cm (4.8 GHz). The blue circle in the lower left corner represents the synthesised beamwidth of 4″×3″ and the blue line below the circle is a polarisation vector of 100%.*

We note that ESO 295-IG022-N is typical of narrow angle tail radio galaxies which are commonly found in rich Abell clusters. While it looks like the emission is weak, the second tail is now seen well.

4. SUMMARY

We present new high resolution images at various radio-continuum frequencies of the peculiar galaxy pair ESO 295-IG022 at the centre of the poor cluster Abell S0102. The most likely interpretation is that the double jet structure originates from the northern galaxy (ESO 295-IG022-N), which then bends and twists towards the south. We detected strong polarised emission of $\sim$ 70% from the AGN jets. Also, the spectral index of jet filaments is very steep (α=–1.32) indicating the presence of strong magnetic fields. No point source was detected that could be associated with the core of ESO 295-IG022-N.

On the other hand, ESO 295-IG022-S does not show any jet structure, but does have a radio point source with variable flux and spectral index. This appears to be superposed in the line-of-sight of the 20-cm jets, which most likely originate from the northern galaxy ESO 295-IG022-N. We emphasis that the more sensitive and higher resolution radio-continuum observations of this Abell cluster would help to reveal the real nature of this complex system.

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РАДИО-КОНТИНУУМ МЛАЗЕВИ У ОКОЛИНИ НЕОБИЧНОГ ПАРА ГАЛАКСИЈА ESO 295-IG022

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Оригинални научни рад

У овој студији представљамо нове ATCA радио-континуум резултате посматрања региона у окружењу необичног пара галаксија ESO 295-IG022 у центру слабог јата Abell S0102. Посматрања су вршена са 6 км конфигурацијом на таласним дужинама од $\lambda = 20/13$ и $6/3$ цм. Резолуција је $\sim 2''$ на 3 цм што је довољно за разлучивање структуре у облику млаза од $\sim 3'$ дужине оргинално детектоване на 20 цм. Користећи наша нова радио-посматрања потврђујемо постојање два млаза која су настала из северније галаксије (ESO 295-IG022-N). Оба млаза су савијена и увијена према јужној галаксији (ESO 295-IG022-S). Радио спектрални индекс млаза насталог из северне галаксије (ESO 295-IG022-N) је веома стрм ($\alpha = -1.32$) што без обзира на непостојање централног тачкастог објекта потврђује изворност Активног Галактичког Језгра (АГЈ). Са друге стране, (ESO 295-IG022-S) је тачкасти радио објекат те са променљивим флуксом и спектралним индексом указује на центар АГЈ који је пројектован на линију посматрања млазева (виђених на 20 цм) насталих из северне галаксије ESO 295-IG022-N. Детектовали смо правилно организован и веома висок степен поларизације где максимална вредност износи око 70%.