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High resolution radio and X-ray observations of A115

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Summary. High resolution radio and X-ray observations are presented for the cluster of galaxies Abell 115, which is known in the literature for being characterized by a double X-ray structure and a multiple optical structure. The brightest galaxy of the cluster is associated with the radio source 3C28, which shows a very unusual radio morphology in the high resolution map presented here. A tail-type radio source is also found at $\approx 4'$ from 3C28, in NE direction.

A resolved X-ray structure is detected around 3C28 and is interpreted to originate from a hot gas which is likely to be accreting onto the galaxy. The complex radio structure of 3C28 is understood by invoking a combination of external ram pressure plus buoyancy effects of light radio plasmoids.

Key words: galaxies: radio – clusters of galaxies – X-rays: generals

1. Introduction

The cluster of galaxies A115 (D = 6, R = 3, BM-Type = III) is one of the most distant clusters ($z = 0.1971$) for which a considerable number of redshifts are available in the literature and for which a study of the system dynamics has been attempted (Noonan, 1981; Beers et al., 1983). The latter authors have measured redshifts for 29 galaxies in the region, 19 of which are cluster members, and mapped the galaxy distribution finding three major clumps of galaxies (A, B, and C in Fig. 4a of their paper).

Clumps A and B correspond in detail to the peaks of the X-ray surface brightness distribution map obtained by Forman et al. (1981) from an analysis of data taken with the Imaging Proportional Counter (IPC) on board the Einstein Observatory. No X-ray emission has been found associated with the third clump. The double X-ray surface brightness distribution of A115 and its possibly multiply but at least double optical structure suggests that the cluster represents a possible intermediate stage of dynamical evolution before the final merging of the subclusters in a relaxed Coma-type cluster.

The brightest galaxy of the cluster, which lies in condensation A, is identified with the strong radio source 3C28. Maps of this source at 2.7 and 5 GHz are presented by Riley and Pooley (1975) and Macklin (1983). The morphology of the source in the latter observations is of the bent double type (Simon, 1978), with no emission coincident with the optical galaxy and a very steep spectral index in the radio lobes ($\alpha_{2.7\,\mathrm{GHz}}^{5\,\mathrm{GHz}} \gtrsim 1.5$; $S_\nu \propto \nu^{-\alpha}$).

In the present paper high resolution radio and X-ray data of this region of sky are presented.

Radio data at 1.4 GHz were obtained with both the Westerbork Synthesis Radio Telescope (WSRT) and the Very Large Array (VLA), with the following goals in mind: a) to search for radio sources of interesting structure identified with cluster galaxies and to detect a possible low brightness structure associated with 3C28, b) to map at high resolution the details and structure of this radio source.

X-ray observations were performed with the High Resolution Imager (HRI) on board the Einstein Observatory to investigate the possible presence of discrete X-ray sources embedded in the diffuse emission detected by the IPC. Since the HRI angular resolution nicely matches the resolution obtained with the VLA, it is possible to compare on the same scale the radio and X-ray structures.

The values $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0$ are used throughout this paper. At the distance of A115, 1″ corresponds to 2.26 kpc.

2. Radio observations

A 12^{h} synthesis centered on 3C28 was obtained with the WSRT at 1.4 GHz in November 1982. Details of the telescope are given by Högbom and Brouw (1974). The observation was performed in the standard mode, with baselines ranging from 72 to 2736 m. The half power width of the resulting synthesized beam is 12″ × 27″ (p.a. 90°, FWHM). The Clean and Restore technique (Högbom, 1974; Clark, 1980) was applied to remove sidelobe and grating lobe effects from the two dimensional map, 1° × 2° in size, obtained by Fourier inversion. In the final map the 3 rms noise level, including dynamic range effects, is 3 mJy/beam area.

The isocontour map of the surroundings of 3C28 is shown in Fig. 1. 3C28 looks like a classical double, with the optical galaxy lying between the two components; no low brightness feature is detected around the radio source.

In the field, a possible tail-type source is located at about 4′ N–E of 3C28. The candidate for the optical identification of this source is a cluster galaxy (No. 2 in Fig. 1 of Beers et al., 1983). A red object of $m_v \approx 19$, also present in the region of the radio emission, was spectroscopically measured by John Huchra (private communication) and was found to be a K star.

The VLA observation at 1.4 GHz (50 MHz bandwidth) was made in September 1982, with the array in the standard "B" configuration (see Thompson et al., 1980 for a description of the

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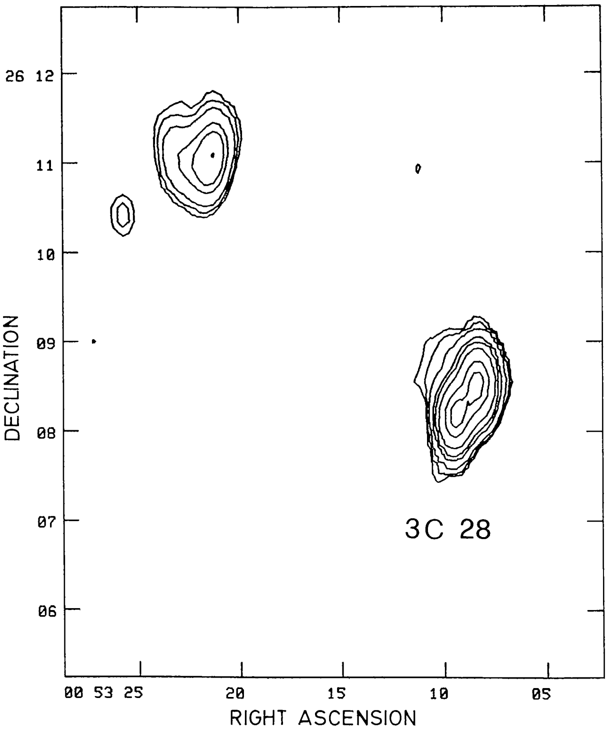

Fig. 1. Isocontour map of the surrounding of 3C28, obtained with the WSRT at 1.4 GHz. Contours are 3, 5, 10, 30, 50, 100, 250, 400 mJy/beam area. The radio source N–W of 3C28 is a tail-type source, probably identified with a cluster galaxy (see Sect. 2)

instrument). The observation lasted 28 minutes and was centered on 3C28. The final map, obtained with the same procedure adopted for the WSRT data, has a resolution of 3″.5 (FWHM) and a 3 rms noise level of 1.5 mJy/beam area.

Due to the large bandwidth attenuation in regions far away from the field center, only the radio source 3C28 could be mapped. Figure 2 shows this source: the two components detected by the WSRT are resolved by the VLA beam in a complex structure. No radio emission coincident with the optical galaxy is detected at a level of 3 mJy/beam area. The total flux density measured with the WSRT and the VLA are in agreement, within 10%, confirming the absence of a low brightness extended feature. A summary of the radio data is given in Table 1.

The spectrum of the source between 178 MHz and 5 GHz is fairly straight, with a spectral index ≈1.2 (Pacholczyk, 1978).

3. X-ray observations

As part of a guest investigation program with the Einstein Observatory, an X-ray exposure 8232 s long of A115 was obtained in February 1981, using the HRI (see Giacconi et al., 1979, for a description of the instrument) with a resolution of 3″ (FWHM). The 24′ × 24′ field of view centered at RA = $00^h53^m06^s$ and DEC = 26°09′00″ (1950.0), completely overlaps the region of sky of the IPC image where the double X-ray source was found (Forman et al., 1981). An extended source, centered on the optical counterpart of 3C28 and lying in the northern IPC component of A115, has been detected by the HRI. Evidence of diffuse emission consistent with the IPC detection, and associated with the whole cluster, is

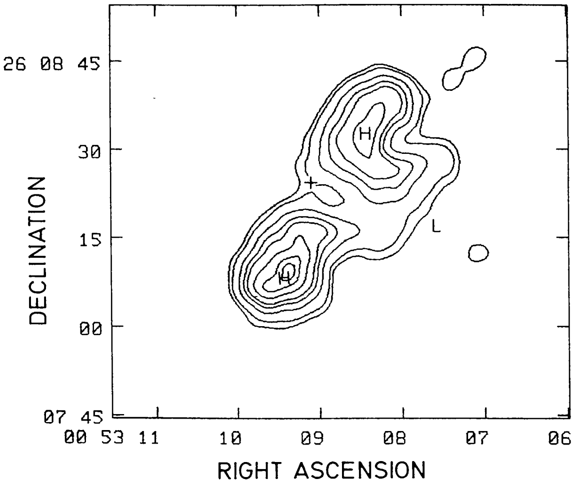

Fig. 2. Isocontour map of 3C28, obtained with the VLA at 1.4 GHz. The cross marks the optical galaxy. High brightness regions and low brightness tails are marked as H and L, respectively. Contours are 1.5, 3, 10, 20, 30, 50, 70, 80 mJy/beam area

also found. Table 2 summarizes the relevant X-ray data and related physical parameters.

The recently reprocessed HRI data give a positional accuracy of ≈4″ (90% confidence circle radius). The X-ray coordinates agree, within the experimental errors, with the accurate optical position of the galaxy (Beers et al., 1983). Analysis of the X-ray image, including gaussian smoothing and maximum entropy deconvolution methods, reveals that the extent of this source is ≈35″ × 25″ in RA and DEC, respectively. No point-like source has been found at the center of the emission; an upper limit for its possible contribution to the total flux has been estimated ≲15%.

Figure 3 shows the isointensity contour map obtained by smoothing the raw data binned in 2″ × 2″ cells with a 10″ FWHM gaussian. The background level is 0.07 counts per cell. Contours correspond to 0.11, 0.15, 0.19, 0.23, 0.25, 0.28, 0.31 counts over the

Table 1. Radio data

Optical position	$00^h53^m09^s.1$	26°08′24″
Radio peak position	A: $00^h53^m08^s.47$	26°08′32″
(from VLA)	B: $00^h53^m09^s.38$	26°08′09″
Flux densities	A: 0.61 Jy	
	B: 0.64 Jy	
Total flux density (from WSRT)	1.39 Jy	
Largest angular size	38″	

Table 2. X-ray data

Peak position	$00^h53^m09^s.18$	26°08′21″.7
Net counts[a]	60 ± 9	
F_x[b]	$(1.00 \pm 0.15)\,10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$	
L_x	$5\,10^{43}\,\mathrm{erg\,s^{-1}}$	

[a] In a 25″ radius circle
[b] Assuming thermal bremsstrahlung with $kT = 6$ keV

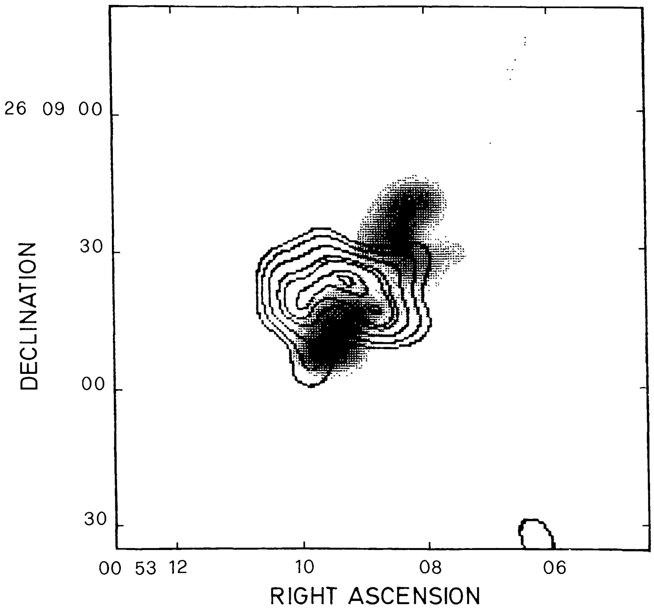

Fig. 3. X-ray isocontour map of 3C28, obtained with the HRI on board Einstein Observatory, overimposed onto a grey scale map of the radio emission. The X-ray background level is 0.07 counts per cell (2″ × 2″). Contours correspond to 0.11, 0.15, 0.19, 0.23, 0.25, 0.28, 0.31 counts over the background

background. The integrated flux of the source was computed in the $0.5 \div 4.5$ keV band by deriving the number of net counts from a circle of 25″ radius centered on the source position and assuming a photoelectric cutoff due only to our galaxy ($N_H = 6.1\,10^{20}\,\mathrm{cm}^{-2}$, Heiles, 1975). Assuming a thermal bremsstrahlung spectrum with temperature $kT = 6$ keV we find that the flux in the same energy band is $F_x = (1.00 \pm 0.15)\,10^{-12}$ erg cm^{-2} s^{-1}, corresponding to the X-ray luminosity $L_x = 5\,10^{43}$ erg s^{-1}. The use of different thermal spectra with kT's from 2 keV to 10 keV changes the fluxes by a factor of $\pm 30\%$ at most.

Analysis of HRI data for the region overlapping the two subclusters detected in the IPC reveals the presence of weak diffuse emission (≈ 8 net counts/arcmin^2) consistent with the measurements of Forman et al. (1981). In the area of the northern subcluster, the diffuse emission present in the HRI is of the order of $(3.0 \pm 0.6)\,10^{-12}$ erg cm^{-2} s^{-1}, computed assuming the same thermal spectrum with $kT = 6$ keV. Thus the source centered on 3C28 accounts for about 30% of the emission from this subcluster. This determination confirms the estimate made by Beers et al. (1983). However, the distinction between the diffuse emission of the subcluster and the component associated with 3C28 should be taken with caution, since the two components must be in pressure equilibrium and, therefore, the surface brightness of one component must smoothly blend into that of the other.

4. Discussion

High resolution radio observations of 3C28 reveal an unusual structure associated with this source. The two components, located on both sides of the optical galaxy, show low brightness tails in the western direction. There is some misalignment of the radio components with respect to the galaxy position, still in the western direction. The structure extends over a linear size of about 85 kpc. The scale of the X-ray emission detected by the HRI is of the order of 70 kpc. The luminosity of the radio source, obtained by integrating from 10 MHz to 10 GHz, is $6\,10^{42}$ erg s^{-1}.

From the radio data we have derived a value of equipartition magnetic field and minimum energy density, in both the high brightness regions (H in Fig. 2) and the low brightness tails (L in Fig. 2), assuming a depth of the source along the line of sight of 30 kpc, the same energy for protons and electrons and a filling factor equal to unity. Table 3 gives these parameters and the values of the density required by an external gas with temperature of 6 keV, to thermally confine the radio plasmoids.

The X-ray source detected with the HRI is centered on the galaxy associated with 3C28. It is resolved and has a surface brightness distribution quite different from the radio structure.

Since the radio and X-ray emitting regions are disjoint, it is quite unlikely that X-rays are produced by inverse Compton scattering between microwave background photons and relativistic electrons emitting at radio wavelengths. This consideration allows us to put a lower limit of $9\,10^{-7}$ G on the value of the magnetic field in the radio source (Harris and Grindlay, 1979). This limit is substantially lower than the equipartition value.

The X-ray emission centered on 3C28 is likely to be thermal bremsstrahlung emission from a hot gas. Assuming $kT = 6$ keV and a core radius for the X-ray emitting region of 35 kpc (obtained by fitting the X-ray distribution with a King model, Lea et al., 1973), we derived a central gas density of 0.047 cm^{-3}. Such a density is considerably higher than that estimated by Forman et al. (1981) from IPC data for the entire cluster. Our data give a mass within a core radius of $10^{11}\,M_\odot$ and a cooling time of $5\,10^8$ yr ($\approx 0.05\,H_0^{-1}$). Therefore radiative cooling around 3C28 is very important. A comparison of the derived parameters L_x, M_{gas}, n_{gas}, t_{cool} of this source with those of other cluster radio galaxies (Burns et al., 1981) indicates that it is characterized by a high X-ray luminosity, a very high gas density and a short cooling time; these properties are not surprising if we remember that 3C28 is the dominant galaxy of a richness 3 Abell cluster.

Table 3. Physical parameters

	H	L
Equipartition magn. field	$2.1\,10^{-5}$	$7.8\,10^{-6}$ Gauss
Minimum energy density	$4.2\,10^{-11}$	$5.7\,10^{-12}$ erg cm^{-3}
External density needed for thermal confinement	$7.2\,10^{-4}$	$9.8\,10^{-5}$ cm^{-3}

The radio components are strongly confined by the surrounding X-ray emitting gas, which has a density about an order of magnitude greater than required (see Table 3). External confinement counteracts adiabatic losses and enhances the lifetime of the radio source, which loses energy mainly by synchrotron emission. The absence of a strong nuclear source and the steep spectral index of the components indicate that little or no activity is present in the core and radiation losses are dominant. The source is old, injection of fresh relativistic particles in the tails should have stopped $\approx 2\,10^7$ yr ago (derived from spectral considerations following Pacholczyk, 1970). To allow the diffusion of electrons from the nucleus to the outer parts of the radio source, within such a time scale, a quite reasonable travel speed of $1000\,\mathrm{km\,s^{-1}}$ is required.

The presence in the extended radio structure of tails in the western direction indicates that the diffusion of radio plasmoids has been forced westward. From a superposition of the radio and X-rays maps shown in Fig. 3, a tendency for the radio tails to diffuse in the directions of lower X-ray emission is observed. Therefore buoyancy effects (Burns and Balonek, 1982 and references therein) directed outward seem to play an important role in producing the observed radio tails.

The misalignment between radio components and optical galaxy could be due to ram pressure arising from the galaxy motion: in this case the radio structure is consistent with a projected motion of the galaxy in the NE direction, at the velocity of $\approx 600\,\mathrm{km\,s^{-1}}$, which is a bit high for a dominant galaxy. Therefore a combination of buoyant forces and ram pressure effects from slow galaxy motion is invoked.

X-ray emission around cluster dominant galaxies, which are moving at very low speeds at the centre of the cluster gravitational potential well has often been interpreted as bremsstrahlung from an accretion flow of cooling gas onto the galaxy (Fabian and Nulsen, 1977; Canizares et al., 1983; Valentijn and Bijleveld, 1983). In this model a hot isothermal gas in hydrostatic equilibrium (the X-ray source, detected with the IPC) surrounds a cooler component with a strong gradient in gas temperature (decreasing) and density (increasing) toward the nucleus. Because of the strong coincidence between X-ray and radio sources in clusters, it has been suggested that some of the accreting gas could be involved in fueling the engine of the nuclear radio emission. Under these conditions a strong compact radio source is expected to be present, associated with an amorphous radio structure, which derives from the interactions between radio tails and thermal instabilities of the cooling gas (Fabian and Kembahvi, 1981).

The absence in the present case of a compact radio source at the position of the optical galaxy, i.e. in the centre of the X-ray emission, is an argument against the accretion flow model around 3C28. However, knowledge of gas density and temperature profiles, which are not available at present for this distant cluster, are required to support or rule out definitely this model.

An alternative possibility could be that the gas around the galaxy is in hydrostatic equilibrium, trapped by the gravitational force of the galaxy itself. The mass of this gas is high for an elliptical galaxy, but is similar to the mass of gas within a comparable radius around M87 (Fabricant and Gorenstein, 1983). However, a important difficulty is encountered in this interpretation: a low temperature ($kT \approx 0.5\,\mathrm{keV}$) is requested for the gas to be bound to the galaxy; since a much higher temperature is likely to characterize the cluster gas (Forman et al., 1981), it is difficult to maintain hydrostatic equilibrium.

Therefore the cooling flow model seems to be more likely, in spite of the lack of a strong compact radio nucleus; one could argue that the fueling of a radiosource by accreting gas might not be steady (see also Valentijn and Bijleveld, 1983).

The presence around 3C28 of an extended X-ray source which reveals the existence of a hot gas surrounding the optical counterpart, puts this galaxy in a special position with respect to the cluster. No similar radio or X-ray source is in fact detected associated with the brightest galaxy of the southern subcluster. Since galaxy distribution and gas density in the two condensations are similar with no evidence of difficult conditions in the two subclusters, 3C28 could be a D or cD type, where the optical envelope is too weak to be seen.

5. Conclusions

The high resolution radio and X-ray observations of the source 3C28 identified with the brightest member of A115 lead to the following main results:

(i) The radio source presents a peculiar structure characterized by two components with low brightness tails in the western direction and with no nuclear component coincident with the optical galaxy. A slight misalignment is also observed in the western direction of the radio components with respect to the galaxy position.

(ii) The X-ray source detected with the HRI shows a high luminosity, interpreted as due to thermal bremsstrahlung. This laeds to a high central gas density and a short cooling time.

(iii) The radio lobes are strongly confined by the surrounding gas and the overall source structure is likely to be due to buoyancy effects, even if the ram pressure plays a role in the misalignment observed between the radio lobes and the optical galaxy.

(iv) Accretion flow of cooling gas onto the galaxy is likely to occur in 3C28, in spite of the absence of a strong compact radio core. The alternative possibility of gas in hydrostatic equilibrium around the galaxy seems untenable.

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