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X-RAY EMISSION FROM CLUSTERS OF GALAXIES CONTAINING CLASSICAL DOUBLE RADIO SOURCES

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ABSTRACT

We report X-ray observations of three Abell galaxy clusters, each containing an undeformed classical double radio source. The observations were made with the *Einstein Observatory* in the wavelength range 2.8–83 Å with 2′ resolution. We derive upper limits to the X-ray emission from two of the three clusters, Abell 643 and Abell 1562. These lead to insignificant thermal densities and thus to insignificant ram pressures at the locations of the radio galaxies 0816+526 and 1234+414 (which are 520 kpc and 715 kpc, respectively, from their cluster centers). This result may account for the lack of deformation in their radio shapes. The X-ray emission of the third cluster, Abell 1763, has been mapped, showing the center and extent of its thermal gas. The classical double radio galaxy 1133+412 is near the center of the X-ray emitting region. The thermal pressure of the gas associated with the extended X-ray source can withstand the pressure of the relativistic particles and magnetic fields in the radio components. The apparently small deformation in the double radio source can be accounted for by a small motion of the galaxy relative to the X-ray emitting gas. A limit of at most 1500 km s^{-1} can be placed on the velocity of separation of the radio components from the parent galaxy.

Subject headings: galaxies: clusters of — galaxies: structure — radio sources: galaxies — X-rays: sources

I. INTRODUCTION

Double radio sources found inside clusters of galaxies have a more complex morphological structure than those found outside clusters (e.g., Miley 1980). The more bent, double sources are found in a larger density of galaxies. An extreme example of bending is that of narrow-tailed ("head-tail") galaxies in Abell clusters, reviewed by Vallée (1977) and summarized by Valentijn (1979). Although some X-ray data are available (e.g., Jones *et al.* 1979) on Abell clusters containing deformed double radio sources, there is little published on the combined interpretation of radio and X-ray data in this area. Such a combined interpretation for individual galaxies with deformed radio structure has been made for the cluster Abell 401 (bending of the double structure of 4C 13.17b by ram pressure through a dense X-ray gas; e.g., Burns and Ulmer 1980) and for the cluster Abell 1446 (bending of the double structure of 1159+583 by buoyancy through a dense X-ray gas; e.g., Burns, Owen, and Rudnick 1979). The buoyancy model of 1159+583 is questionable, however, in view of the likeness of that source to the radio structure of 3C 31 and the closeness of a nearby galaxy (e.g., Fig. 2 of Owen and Rudnick 1976), suggestive instead of an orbital bending of a type proposed earlier by Blandford and Icke (1978).

Most elliptical galaxies with colinear classical double morphologies are outside clusters of galaxies or on their outskirts (i.e., >3 Mpc from the cluster center). A few are very close to cluster centers (e.g., Ulrich 1978). Those radio galaxies between 100 kpc and 3 Mpc from cluster centers usually have deformed, albeit basically double, radio structures as mentioned earlier. Burns, Owen, and Rudnick (1978) observed at radio wavelengths some exceptional elliptical galaxies in these intermediate cluster locations that nevertheless have a classical double radio structure. Burns *et al.* interpreted these systems with the use of multiple-explosion models or beam models which continuously supply relativistic

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TABLE 1

EINSTEIN DATA AND RELATED CONDITIONS

Parameter	Abell 643	Abell 1562	Abell 1763
	A. Instrumental Data		
Field center: R.A.	$08^h16^m02\overset{s}{.}0$	$12^h32^m05\overset{s}{.}0$	$13^h33^m10\overset{s}{.}0$
Decl.	+52°41′55″	+41°26′05″	+41°15′20″
Observing data................	1979 Oct 4	1979 Dec 8	1979 Dec 8
Net integration time	$01^h19^m04^s$	$01^h19^m40^s$	$01^h16^m34^s$
	B. Observational Data		
X-ray peak emission: R.A.	N.A.	N.A.	$13^h33^m08\overset{s}{.}1\pm2\overset{s}{.}7$[a]
Decl.	N.A.	N.A.	+41°15′09″.8±30″[a]
Optical cluster center:			
R.A.[b]	$08^h15^m48^s\pm12^s$	$12^h31^m48^s\pm12^s$	$13^h33^m12^s\pm12^s$
Decl.[b]	+52°40′±2′	+41°27′±2′	+41°14′±2′
Radio galaxy centroid:			
R.A.[c]	$08^h16^m02\overset{s}{.}0\pm0\overset{s}{.}3$	$12^h32^m05\overset{s}{.}0\pm0\overset{s}{.}3$	$13^h33^m09\overset{s}{.}6\pm0\overset{s}{.}2$
Decl.[c]	+52°41′55″±5″	+41°26′05″±5″	+41°15′23″±2″
	C. Physical Data		
Thermal matter density:			
Centroid of gas	$\leq5\times10^{-4}$ cm^{-3}	$\leq7\times10^{-4}$ cm^{-3}	3.6×10^{-3} cm^{-3}
Radio galaxy[d]	$\leq2\times10^{-4}$ cm^{-3}	$\leq1\times10^{-4}$ cm^{-3}	3.6×10^{-3} cm^{-3}
Thermal pressure:			
Radio galaxy	$\leq2\times10^{-12}$ dyne cm^{-2}	$\leq5\times10^{-13}$ dyne cm^{-2}	3×10^{-11} dyne cm^{-2}
Ram pressure:			
Radio galaxy	$\leq2\times10^{-12}\Psi^2$ dyne cm^{-2}	$\leq7\times10^{-13}\Psi^2$ dyne cm^{-2}	$\leq3\times10^{-11}\Psi^2$ dyne cm^{-2}
Relativistic electron pressure:[e]			
Northern radio lobe........	4×10^{-10} dyne cm^{-2}	2×10^{-10} dyne cm^{-2}	7×10^{-11} dyne cm^{-2}
Southern radio lobe	3×10^{-10} dyne cm^{-2}	1×10^{-10} dyne cm^{-2}	7×10^{-11} dyne cm^{-2}

[a] From this paper.
[b] From Sastry and Rood 1971.
[c] From Burns, Owen, and Rudnick 1978; Rudnick and Owen 1977.
[d] The thermal density is taken as decreasing as in the King model.
[e] From this paper; *B* values for A643 and A1562 are taken from Burns, Owen, and Rudnick 1978, or computed here for A1763 from data in Rudnick and Owen 1977 with angular sizes of lobes of 2″×9″ (8 kpc×8 kpc×35 kpc).

particles to the radio reservoirs, and predicted low (less than a few times 10^{-4} cm^{-3}) thermal densities surrounding them.

We report X-ray observations of three Abell clusters apparently containing classical double radio sources at a mean offset of 520 kpc from their optical centroids. The observations were made (a) to test the predictions of low thermal densities around the radio galaxies 0816+526 and 1234+414 made by Burns, Owen, and Rudnick (1978) and (b) to investigate the environment of another such galaxy, 1333+412. We use $H_0=50$ km s^{-1} Mpc^{-1} and $q_0=0.5$ throughout this paper.

II. THE X-RAY OBSERVATIONS

The observations were made with the Imaging Proportional Counter (IPC) of the *Einstein Observatory* (Giacconi *et al.* 1979). The IPC operates in the photon energy range 0.15–4.5 keV (2.8–83 Å). Its field of view is 75′ by 75′, while its angular resolution is a function of photon energy range (99″ for 0.5–4.5 keV; 184″ for 0.15–0.5 keV), giving an effective resolution of 2′ weighted over the combined energy ranges. Other data pertinent to the observations are given in Table 1A. Each field center was chosen at or near the position of the radio galaxy; the centroid of the galaxy distribution was well within the field of view in every case (Table 1B).

No emission was detected from Abell 643 or Abell 1562 (the cluster fields containing 0816+526 and 1234+414) to limits of L_X less than 10^{43} and 2×10^{43} ergs s^{-1}, respectively (integrating from 0.5 to 4.5 keV, assuming a typical cluster thermal spectrum at 6×10^7 K [5 keV]). Abell 1763 was detected with L_X equal to 10^{45} ergs s^{-1} (computed with the same assumptions).

III. PHYSICAL CONDITIONS IN THE X-RAY SOURCES

We infer thermal electron densities from the observed values of L_X using

$$L_X = 4.92\times 10^{-27} T^{1/2} \times \left[\exp(-E_1/kT) - \exp(-E_2/kT)\right] \times g n_0^2 a_c^3 \text{ ergs s}^{-1},$$

where T is the temperature, E_1 and E_2 are the photon energy limits, g is the average Gaunt factor, a_c is the core radius, and n_0 is the central density in the King approximation for the density profile:

$$n(r) = n_0\left[1+(r/a_c)^2\right]^{-1.5}.$$

We assume $g=1.2$ and also take $a_c=400$ kpc (a typical value for cluster X-ray sources; e.g., Jones *et al.* 1979; Kriss *et al.* 1980) for the undetected clusters, such as those studied here, and $a_c=515$ kpc (the observed value) for Abell 1763. A deviation from these a_c values by a factor of 4 *either way* would lead to a possible decrease or increase in the density by a factor of 10 or so for a mean galaxy offset of about 500 kpc from the gas centroid. Also, a typical deviation from a mean temperature by a factor up to 10 will be minimized by the square root factor in the L_X equation used to determine the density.

The thermal pressure is obtained from

$$p_{\text{th}} = n(r)kT = 1\times 10^{-12}\left(\frac{n(r)}{10^{-4}\text{ cm}^{-3}}\right)\left(\frac{kT}{6\text{ keV}}\right) \text{ dyne cm}^{-2},$$

while the ram pressure on a radio structure moving at velocity v_g relative to the cluster gas is

$$p_{\text{ram}} = n(r) m_{\text{H}} v_g^2 = 1\times 10^{-12}\left(\frac{n(r)}{10^{-4}\text{ cm}^{-3}}\right) \times \left(\frac{v_g}{10^3\text{ km s}^{-1}}\right)^2 \text{ dyne cm}^{-2},$$

where m_{H} is the proton mass. Since little is known about the total velocities of the galaxies in these three clusters, we take $v_g=1000\Psi$ km s^{-1}, where $\Psi\approx 1$. The pressures in the radio emitting reservoirs of the sources have been estimated from the equipartition parameters given for the radio components by Burns, Owen, and Rudnick (1978) and by Rudnick and Owen (1977). Table 1C summarizes our estimates of the thermal, ram, and internal pressures for each source.

IV. ABELL 643 AND ABELL 1562

The redshift of 0816+526 is unknown, but that of its cluster (Abell 643) is 0.138 (from m_{10}). The galaxy is much fainter than the brightest cluster member (Rudnick and Owen 1977), so its association with Abell 643 is still uncertain (Burns, Rudnick, and Owen 1978; Burns and Christiansen 1980). The redshift of 1234+414 is 0.19 (J. O. Burns, private communication of a measurement by R. White), within errors of 0.17 estimated for Abell 1562 from m_{10}. It is clear from Table 1C that there is too little thermal gas in Abell 643 or Abell 1562 to confine equipartition pressures in 0816+526 or 1234+414 by static pressure, or by ram pressure if v_g is less than 1000 km s^{-1} for these sources, even for the case of a moderately large deviation by a factor of 4 *either way* from the mean core radius a_c used for this type of cluster.

The relative absence of thermal gas in these clusters is consistent with their low richnesses ($R=0$ for Abell 643, 1 for Abell 1562), given the cluster richness-luminosity relation deduced by Jones and Forman (1978).

V. ABELL 1763

Abell 1763 is in richness class 3 and is indeed detected here (parameters in Table 1B). The radio galaxy 1333+412 is its brightest member and the cluster redshift from m_{10} is 0.1870 (Pilkington 1964). Figure 1 shows the distribution of the X-ray intensity over Abell 1763 observed with the IPC in the energy range 0.15–4.5 keV. The centroid of this distribution coincides with that of the radio source to within the errors (Table 1B). The parameters deduced in Table 1C show that the undeformed shape of the radio source 1333+412 can be explained if its velocity relative to the thermal gas is $v_g<1500$ km s^{-1}. A velocity in this range is plausible if the near coincidence between the position of the radio galaxy and the centroid of the X-ray emission is taken to imply that the galaxy is close to the center of the gravitational potential well in Abell 1763. The thermal pressure of the distributed gas in Abell 1763 is amply sufficient to confine the equipartition pressure in the radio components of 1333+412 (Table 1C).

The apparent displacement of the centroid of the X-ray emitting gas from the *optical* centroid of the galaxy distribution in Abell 1763 may be due to the high value of the Bautz-Morgan type of the cluster (BM III; Leir and van den Bergh 1977). Since BM III clusters do not contain dominant galaxies, it may be more difficult to estimate the positions of their optical centroids than in the case of clusters with lower BM types. In such clusters the X-ray centroid may give a more reliable estimate of the center of the gravitational potential.

An unresolved X-ray source appears in Figure 1 at $\alpha(1950)=13^{\text{h}}32^{\text{m}}05^{\text{s}}.6\pm 0^{\text{s}}.8$; $\delta(1950)=+41°37'35''.5\pm 8''$. A search of the Palomar Sky Atlas prints near this

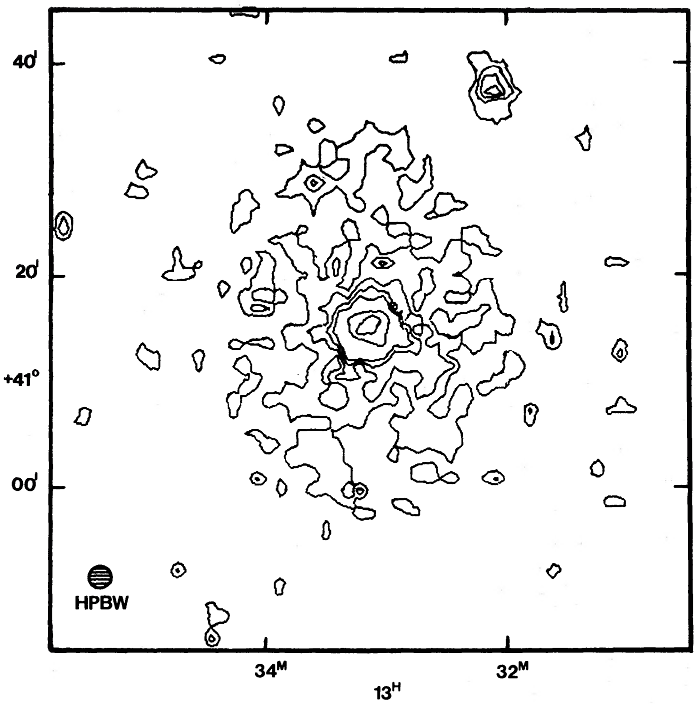

FIG. 1.—The X-ray brightness distribution over Abell 1763 with an angular resolution of 2′, as observed with the IPC telescope of the *Einstein Observatory* and integrated from 2.8 Å (4.5 keV) to 83 Å (0.15 keV). One arcminute corresponds approximately to 232 kpc ($H_0=50$ km s^{-1} Mpc^{-1}). The HPBW is shown in the bottom left corner. Contour values are drawn at 11%, 16%, 22%, 27%, 55%, and 82% of the peak flux density value of 0.20 μJy per beam area at a wavelength of 6 Å. Most of the large-scale X-ray emission is due to a background over which two sources are seen: (i) the cluster X-ray emission proper, extending radially out to about 6′ from the center (position of the peak intensity), and (ii) an unresolved X-ray source (see text) at $13^h32^m05^s.6$; $+41°37'35''.5$.

TABLE 2

GROSS PROPERTIES OF ABELL 1763

A. Observations	
X-ray angular size (FWHM)	2′.5±0′.3 (deconvolved from HPBW)
X-ray flux density at 12.4 Å (1 keV)	1.2 μJy (whole gas)
at 6.2 Å (2 keV)	0.7 μJy (whole gas)
at 4.1 Å (3 keV)	0.5 μJy (whole gas)
Optical Abell richness	3
Optical Bautz-Morgan type	III
B. Physical Data[a]	
Cluster distance..............................	1120 Mpc
X-ray luminosity (0.5–4.5 keV)	1.2×10^{45} ergs s^{-1}
X-ray core radius (King model)	515 kpc
X-ray size (FWHM)	580 kpc
Gas temperature[b]	6×10^7 K (5 keV)
Central thermal gas density (King model) ...	3.6×10^{-3} cm^{-3}
	3.4×10^{-3} cm^{-3} (after removal of a point core of 10% of total lum.)
	2.5×10^{-3} cm^{-3} (after removal of point core of 50% of total lum.)
Core gaseous mass (King model)	2×10^{13} $M_\odot$
Cooling time (line+bremsstrahlung)	1×10^{10} yr
Cluster evolutionary stage	Intermediate

[a] $H_0=50$ km s^{-1} Mpc^{-1}.
[b] *Assumed* value (average of several other Abell clusters).

position showed no object within a radius of 50″ of this position.

Table 2B assembles the deduced physical properties of Abell 1763. The mass of hot gas in the core has been estimated from the relation (Kriss *et al.* 1980):

$$M_c = 0.6 m_{\rm H} \pi a_c^3 n_0 .$$

The cooling time for the gas, including thermal bremsstrahlung (continuum) and line emission, is given by (Fabian, Schwarz, and Forman 1980):

$$t_C = 4\times 10^6 \left\{ \frac{T}{10^7\ \rm K} \right\}^{1.5} \left\{ \frac{n_0}{\rm cm^{-3}} \right\}^{-1} \rm yr.$$

We find that Abell 1763 has an X-ray luminosity, core radius, density, and mass typical of other X-ray clusters. Cooling times of the order of 10^9 years have been found in many other clusters and groups (Schwartz, Schwarz, and Tucker 1980); such times are comparable to the ages of the clusters and groups. Its X-ray structure suggests that its evolutionary stage is intermediate between that of clusters with highly clumped emission around individual galaxies (3 out of 12 clusters studied by Jones *et al.* 1979) and that of more relaxed clusters with smooth and centrally peaked emission centered on a dominant galaxy (6 out of 12 studied by Jones *et al.* 1979).

Radio observations with higher angular resolution than presently available for 1333+412 are required to determine whether its distributions of spectral index, magnetic field, etc., differ significantly from those of classical doubles that are not strongly thermally confined. The integrated properties of the source (Rudnick and Owen 1977), however, do suggest a small overall size (75 kpc) and a steep overall spectral index ($S \sim \nu^{-1.0}$) consistent with confinement and aging of the particles in the presence of significant pressure from the external medium.

We note also that the velocity of $\approx$1500 km s^{-1} at which the ram pressure of the X-ray emitting medium would equal the pressure in the radio components of 1333+412 must also be an *upper limit* to the velocity at which the radio components could be moving away from the parent galaxy (for example, due to the deposition in them of the momentum in a beam or jet generated in the galaxy). This upper limit sets a lower limit of 4×10^7 years for the age of the radio source.

VI. CONCLUSIONS

Einstein IPC observations in the range 0.15–4.5 keV (2.8–83 Å) of three Abell clusters with classical double radio sources have shown that a relative lack of ram pressure on their radio components can account for the undeformed shapes of the radio sources. In Abell 643 and Abell 1562 this lack of ram pressure is due to a lack of a dense medium in the clusters, whereas in Abell 1763 it is probably due to a lack of relative motion between the radio galaxy and the surrounding medium. The source 0816+526 might also be *beyond* Abell 643.

Recent VLA observations of the lobe structure of 0816+526 by Burns and Christiansen (1980) led them to propose that this source has expanded into a dense background gas. While our observations clearly do not lend direct support to this proposal, we note that the lobes could still be interacting with hot gas *provided that this gas was of small angular extent*, so that it could escape detection by our IPC observation. This might be possible if it were a cocoon amassed by the "snowplow" effect of the expanding lobes, or if it were remnants of previous ejecta from the active radio galaxy, as suggested by Burns and Christiansen (1980).

In Abell 1763, the *thermal* pressure of the detected X-ray medium is probably sufficient to confine the equipartition pressure in the radio lobes, and we have set an upper limit of 1500 km s^{-1} to the velocity of separation of the lobes from the galaxy from ram pressure considerations.

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