A POWERFUL RADIO HALO IN THE HOTTEST KNOWN CLUSTER OF GALAXIES 1E 0657 − 56

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ABSTRACT

We report the detection of a diffuse radio halo source in the hottest known cluster of galaxies 1E 0657 − 56 (RX J0658 − 5557). The radio halo has a morphology similar to the X-ray emission from the hot intracluster medium. The presence of a luminous radio halo in such a hot cluster is further evidence for a steep correlation between the radio halo power and the X-ray temperature. We favor models for the origin of radio halo sources involving a direct connection between the X-ray emitting thermal particles and the radio emitting relativistic particles.

Subject headings: cosmic microwave background —
galaxies: clusters: individual (1E 0657 − 56, RX J0658 − 5557) —
tabulated medium — radio continuum: general — techniques: interferometric —
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1. INTRODUCTION

Diffuse cluster radio sources are found in a few X-ray luminous clusters of galaxies. They are extended (~ 1 Mpc), have low surface brightnesses, and exhibit steep spectra ($\alpha \leq -1$, $S \propto v^{-\alpha}$). They cannot be identified with any one individual galaxy but are associated with the cluster as a whole. Diffuse cluster radio sources are generally separated into two classes: halos and relics. Halos are centered on the X-ray emission (e.g., Coma C is a prototype radio halo source; Giovannini et al. 1993), whereas relics are peripheral and exhibit stronger polarization than halos (e.g., A3667 has a large relic; Röttgering et al. 1997). In this paper, we will concentrate on halo sources.

Until recently, systematic surveys for radio halo sources found few examples, with the total number of known halos being ~ 5 (Feretti & Giovannini 1996). They are thus considered to be rare, and owing to their small number remain a poorly understood class of radio sources even though the first example, Coma C, was discovered over 20 years ago. The spectra suggest that halo radio emission arises predominantly by the synchrotron process. However, the formation of radio halos remains a puzzle: why do they occur in some clusters and not in others, and what is the origin of the magnetic field and relativistic particles?

A number of models have been proposed to explain the formation of radio halos (e.g., Jaffe 1977; Dennison 1980; Roland 1981). Most of these early models suggest that ultrarelativistic electrons originate either as relativistic electrons from cluster radio sources reaccelerated by in situ Fermi processes or turbulent galactic wakes, or as secondary electrons produced by the interaction between relativistic protons (again from cluster radio galaxies) and thermal protons. However, the energetics involved are problematic and the models could not always fit the observations (e.g., see review by Böhringer 1995). Harris, Kapahi, & Ekers (1980) first suggested that radio halos are formed in cluster mergers where the merging process creates the shocks and turbulence necessary for the magnetic field amplification and high-energy particle acceleration. More recently, Tribble (1993) showed that the energetics involved in a merger are more than enough to power a radio halo. The halos thus produced are expected to be transient since the relativistic electrons lose energy on time scales of $\sim 10^8$ yr and the time interval between mergers is of order $\sim 10^9$ yr. This argument was used to explain why radio halos are rare.

In this paper, we will describe the properties of the radio halo found in one of the hottest known clusters 1E 0657 − 56 and suggest a new model for the origin of cluster halos based on the radio and X-ray properties of all 10 confirmed halos. Section 2 describes the multiwavelength properties of cluster 1E 0657 − 56; § 3 describes the radio observations; § 4 discusses the radio properties of the halo found in 1E 0657 − 56; and § 5 discusses the origin of radio halos. Throughout the paper we will use $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$ and $\Lambda_0 = 0$.

2. THE CLUSTER 1E 0657 − 56

The cluster 1E 0657 − 56 was originally found in the Einstein slew survey (Tucker, Tananbaum, & Remillard 1995), and subsequent optical observations confirmed it to be a rich cluster at $z \sim 0.296$ with a velocity dispersion of $1213^{+352}_{-491}$ km s$^{-1}$ (Tucker et al. 1998). It has high X-ray luminosity and was shown to be one of the hottest known clusters by Tucker et al. (1998).

2.1. X-Ray Properties

The cluster was observed for 25 ks by ASCA in 1996 May and with the ROSAT High-Resolution Imager (HRI) in
1995 for 58 ks (Tucker et al. 1998). Tucker et al. (1998) analyzed the ASCA Gas Scintillation Imaging Spectrometers (GIS) and Solid-state Imaging Spectrometers (SIS) data and found the cluster to have a best-fit temperature of $kT_X \sim 17.4 \pm 2.5$ keV and a bolometric luminosity of $L_{bol} \sim (1.4 \pm 0.3) \times 10^{46}$ ergs s$^{-1}$. However, Yaqoob (1999) challenged these results by reanalyzing the ASCA GIS/SIS data and arrived at a temperature of $\sim 11$–$12$ keV, abundance $A \sim 0.2$ solar, and a neutral hydrogen absorption column density $N_H \sim 15 \times 10^{20}$ cm$^{-2}$, much higher than the Galactic value. Yaqoob found that the only way to reproduce the high-temperature deduced by Tucker et al. (1998) was to fix the neutral hydrogen column density to the Galactic value and concluded that fixing the absorption column density in such a way leads to an artificially high temperature.

Since then, some ROSAT Position-Sensitive Proportion- al Counter (PSPC) data have become publicly available. Since it is known that ASCA SIS data below 1 keV suffer from inaccurate calibration, we reestimate the cluster temperature by fitting to the combined ASCA GIS and ROSAT PSPC data. The GIS and PSPC data complement each other: the GIS is more sensitive to the cluster temperature, while the PSPC is more sensitive to the soft X-ray absorption.

We followed the standard ASCA procedure for screening the GIS2 and GIS3 data as set out in The ABC guide to ASCA data reduction. The spectra were extracted from a circular region of radius 7.25 centered on the cluster, after the subtraction of a local background, extracted from the same frame in areas with no obvious emission. The spectra were regrouped to a minimum of 50 counts per bin. The XSPEC package$^2$ (Arnaud 1996) was used to fit the GIS spectra between 0.8 and 10 keV by a Raymond-Smith spectrum (Raymond & Smith 1977), with fractional solar relative abundances from the table of Feldman (1992) and photoelectric absorption (Morris & McCammon 1983). Temperature, abundance $A$, absorption (parameterized by $N_{H}$), and the normalization were taken as free parameters. The best fit was $kT_X \sim 15.6 \pm 0.2$ keV, $N_H \sim (2.2 \pm 0.3) \times 10^{20}$ cm$^{-2}$, and $A \sim 0.49 \pm 0.27$ with a reduced $\chi^2 \sim 1.03$ d.o.f. The errors correspond to 90% confidence limit. It is clear that $N_H$ is poorly constrained by the GIS data alone, as expected from the absence of low-energy data.

We retrieved from the ROSAT archive a 4.7 ks exposure PSPC event file observed in 1997 February. A spectrum of the X-ray emission from the cluster gas was extracted from an annulus between radii of 8$\rlap{\sim}$–10$\rlap{\sim}$ centered on the cluster. Only the spectrum within the energy range between 0.1 and 2.0 keV was used for model fitting.

A combined fit of a Raymond-Smith spectrum to the GIS and PSPC spectra gave the best fit as follows: $kT_X = 14.5^{+1.0}_{-0.9}$ keV, $N_H = (4.2^{+0.5}_{-0.5}) \times 10^{20}$ cm$^{-2}$, $A = 0.33 \pm 0.16$ (see Fig. 1) with a reduced $\chi^2 \sim 1.03$ d.o.f. A direct radio-astronomical measure of the Galactic neutral hydrogen column density toward 1E 0657$-$56 gives $N_H \sim 5.8 \times 10^{20}$ cm$^{-2}$ (E. M. Arnal 1999, private communication; Arnal et al. 2000);Dickey & Lockman (1990) gives a value of $6.6 \times 10^{20}$ cm$^{-2}$. Recently, we have obtained a high-resolution (16$\rlap{\prime}$ beam) measurement of the Galactic neutral hydrogen column density toward 1E 0657$-$56 using the Parkes telescope, giving a $N_H \sim 4.6 \times 10^{20}$ cm$^{-2}$ (C. Brüns 1999, private communication) which is very close to the X-ray fitted value. Thus, it appears that the temperature is lower than that estimated in Tucker et al. (1998), although 1E 0657$-$56 is still one of the hottest known clusters. On the other hand, our best-fit temperature is higher than that deduced by Yaqoob (1999), and our best-fit $N_H$ is much closer to the Galactic value than that given by Yaqoob. The difference is unlikely to be caused by different background subtraction techniques, since Yaqoob tried a wide range of background subtraction methods and found that the systematic differences between the various techniques are less than the statistical errors. We tested our result by fixing the $N_H$ and abundance $A$ at the values given by Yaqoob and found a best fit $kT_X \sim 11.3 \pm 1.0$ keV, consistent with his result but with a high reduced $\chi^2$ of 1.56 per d.o.f. Figure 2 shows that Yaqoob’s fit (to the ASCA data alone) is inconsistent with the PSPC data which extend to lower energies ($\sim 0.1$ keV) than the SIS ($\sim 0.5$ keV) and are therefore more sensitive to soft X-ray absorption.

The HRI image of the cluster shows two clearly separated clumps (see Fig. 5). Andreani et al. (1999) analyzed the spatial distribution of the X-ray emission using the HRI data and found that the X-ray surface brightness can be fitted with two spherically symmetric $\beta$ models (Cavaliere & Fusco-Femiano 1976) with gas density distributions given by

$$n_g(\theta) = n_{g,0}\left[1 + \left(\frac{\theta}{\theta_c}\right)^{2}\right]^{-3\beta/2},$$

where $\beta = 0.7$, 0.49, $\theta_c = 1.23, 0.26$ and $n_{g,0} = 0.0063, 0.015$ cm$^{-3}$ for the eastern and western clumps, respectively.

2.2. Sunyaev-Zel'dovich Effect

The Sunyaev-Zel’dovich (SZ) effect is the distortion of the blackbody spectrum of the cosmic microwave background (CMB) due to inverse Compton scattering of CMB photons.

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1. http://heasarc.gsfc.nasa.gov/docs/asca/abc/abc.html.
2. http://legacy.gsfc.nasa.gov/docs/xanadu/xspec/xspecu_manual.html.
by free electrons in a plasma such as an intracluster medium (Sunyaev & Zel’dovich 1972). The cluster 1E 0657—56 was selected as a candidate for the detection of the SZ effect in the 1994–1995 Swedish ESO Submillimeter Telescope (SEST) campaign (Andreani et al. 1999). The SEST observations show a $\sim 4 \sigma$ detection of the SZ effect at 1.2 mm ($\sim 150$ GHz) and a $\sim 3 \sigma$ detection at 2 mm ($\sim 250$ GHz) (Andreani et al. 1999). By combining the SEST results at 2 mm with the X-ray surface brightness and temperature results (assuming an isothermal $kT_{x} \sim 17$ keV), Andreani et al. (1999) deduced a Hubble constant of $H_{0} = 53^{+38}_{-28}$ km s$^{-1}$ Mpc$^{-1}$.

Shortly after the SEST observations, we obtained data to confirm the SEST detection of the SZ effect. The primary flux calibrator PKS B1934—638 was observed at least once a day and the phase calibrator PKS B0742—56 was observed every $\sim 20$ minutes. The data were calibrated with the MIRIAD package$^{3}$ (Sault, Teuben, & Wright 1995).

A radio halo source was clearly detected in maps with resolution $\sim 60''$ in all frequencies (see Fig. 3). A high-resolution 1.3 GHz image of the cluster field is shown in Figure 4a, where we see the halo source at the cluster center, a possible relic source to the east, and a number of tailed sources on the periphery.

3. RADIO OBSERVATIONS

3.1. ATCA Data

The ATCA has five 22 m antennas on a 3 km east-west rail-track and a sixth antenna 3 km from the western end of the track, giving baselines up to 6 km. Simultaneous observations were made in two frequency bands each of bandwidth 128 MHz divided into 32 frequency channels. The cluster 1E 0657—56 was observed at 1.3, 2.4, 4.9, 5.9, and 8.8 GHz in several antenna configurations, so that similar UV coverage was obtained at all frequencies. Table 1 gives a summary of all the radio observations. The primary flux calibrator PKS B1934—638 was observed at least once a day and the phase calibrator PKS B0742—56 was observed every $\sim 20$ minutes. The data were calibrated with the MIRIAD package.$^{3}$

A radio halo source was clearly detected in maps with resolution $\sim 60''$ in all frequencies (see Fig. 3). A high-resolution 1.3 GHz image of the cluster field is shown in Figure 4a, where we see the halo source at the cluster center, a possible relic source to the east, and a number of tailed sources on the periphery.

3.2. MOST Data

The Molonglo Observatory Synthesis Telescope (MOST) is an east-west synthesis array comprising two collinear cylindrical paraboloids each 11.6 m wide by 778 m long, separated by a 15 m gap (Mills 1981; Robertson 1991). The telescope operates at 843 MHz, with a detection bandwidth of 3.25 MHz, and forms a comb of 64 real-time fan beams spaced by 22', which are interlaced to a spacing of 11''. The synthesized beam-width is $43'' \times 43''$ csc $|\delta|$ FWHM (R.A. x decl.). The observations of 1E 0657—56 were made as part of the Sydney University Molonglo Sky Survey (SUMSS, Bock, Large, & Sadler 1999), in which the pointing of the beam set was time shared among seven adjoining positions to give a field size of $164'' \times 164''$ csc $|\delta|$. The

TABLE 1

| Date       | Frequency (MHz) | Configuration | Center (J2000)   | $t_{\text{obs}}$ (hr) |
|------------|-----------------|---------------|------------------|---------------------|
| 1996 Dec    | 8768:8896       | 210           | 06 58 32.7, —55 57 19 | 56.6                |
|            | 4800:4928       | 210           | 06 58 32.7, —55 57 19 | 11.2                |
|            | 5824:5952       | 210           | 06 58 32.7, —55 57 19 | 11.4                |
| 1997 May    | 1344:2240       | 6B            | 06 58 32.7, —55 57 19 | 11.2                |
| 1997 Jun    | 1344:2240       | 750A          | 06 58 32.7, —55 57 19 | 10.0                |
| 1998 Jul    | 1344:2496       | 750E          | 06 58 32.7, —55 57 19 | 10.8                |
|            | 8768:4800       | 750E          | 06 58 32.7, —55 57 19 | 9.7                 |
| 1998 Jan    | 843             | MOST          | 07 00 00.0, —56 35 24 | 12.0                |

Note: — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
Fig. 3.—Low-resolution radio images overlaid on gray scale PSPC hard-band (0.5–2.0 keV) image smoothed with a 50″ Gaussian: (a) MOST contour image at 843 MHz smoothed to a beam size of 60″, the beam shown is the original beam before smoothing; (b–e) ATCA contour images with a 60″ beam at 1.3, 2.4, 4.9, 5.9, and 8.8 GHz, respectively; only the shortest spacings (< 3600″) are used. Contour levels are (-3, 3, 6, 12, 24, 48, 96, 192, 384) × σ, where rms noise are σ ~ 1100, 51, 110, 56, 65, 56 μJy beam⁻¹ for frequencies of 0.8, 1.3, 2.4, 4.9, 5.9, and 8.8 GHz, respectively.
FIG. 3.—Continued
Fig. 3.—Continued
Fig. 4.—(a) A 1.3 GHz ATCA image toward 1E 0657−56 at a resolution of 6.5 × 5.9, using all the data (uniform weighting). The noise level in the image is 44 \(\mu\)Jy beam\(^{-1}\). (b) A 1.3 GHz image using only the long baseline data (>5000\(\lambda\)) with only the CLEAN components within the marked region “1” restored (beam size 6\(\arcmin\)). The unresolved sources are marked by a circle and the two extended sources (A and C) are marked by the small areas that were used to integrate their total flux. The sources are marked by letters and the three regions marked from “1” to “3” correspond to regions used for total flux estimates.
background noise in this 12 hr image was 1.1 mJy rms and the reduction followed the standard survey pipeline. For comparison with the ATCA images, the MOST image in Figure 3a was convolved out to a 60° circular beam.

4. A RADIO HALO IN 1E 0657 – 56

4.1. Subtraction of Discrete Sources

In order to obtain a high-quality image of the diffuse radio halo and estimate its total integrated flux density, it is necessary to separate the emission from discrete sources embedded in the halo.

One way of estimating the flux density of discrete sources is to make a high-resolution image using only the long baseline data (>5000λ) that are unlikely to contain any signal from the diffuse halo emission. This image, which has a synthesized beam FWHM ~ 6°, is then deconvolved using the CLEAN algorithm. Figure 4 shows the image made from all the 1.3 GHz data and the image from the long-baseline data with only sources within the halo region restored. The clean components of discrete sources embedded in the halo are then subtracted from the visibility (or UV) data set. These sources, marked in Figure 4b, are unresolved with the exception of two sources (A, C) which were slightly extended. The flux densities of these discrete sources at various frequencies are listed in Table 2. A radio image of the halo at 1.3 GHz, with these embedded discrete sources subtracted, is shown in Figures 5a and 5b.

4.2. Halo Total Flux Density

Estimation of the total flux density of a diffuse source is rather difficult, even after solving the problems of separating discrete sources from the diffuse emission (§ 4.1). The difficulty is twofold: first, we need to define the angular size of the emission, which depends on the noise level in the image; and second, we need to know if we have sampled a large enough angular scale (i.e., short enough baselines) to include all the flux density. In the following paragraphs we describe two independent methods of estimating the integrated flux density as a function of the area of integration.

First, we make a low-resolution image (~ 60° beam) using the UV data set that has the discrete sources already subtracted, but taking only the short-baseline data (<3600λ). This ensures that the data used for the estimation of the halo flux density are independent of the long-baseline data used for the subtraction of discrete sources. The integrated flux density of the halo estimated from such an image is plotted as a function of the area of integration in Figure 6 (open circles). While the low-resolution of the image ensures relatively high brightness sensitivity, the area of integration is limited because of blending with extended sources near the halo, a problem made worse by the large beam size (see Fig. 4a).

We now examine an alternative method of estimating the total halo flux density which also serves as a check on the method above. We integrate the signal within increasing regions of the halo on the high-resolution image (Fig. 4a) which uses all the data and has not undergone source subtraction. The flux densities of the sources embedded in these regions are estimated from the image in Figure 4b (see Table 2) and subtracted from the integrated flux density, giving the open triangles shown in Figure 6. By careful exclusion of extended sources in or near the halo, the halo can be integrated over a larger area. In the first method (Fig. 6, open circles) the largest area of integration corresponds to region “1” marked in Figure 4b. The largest area used in the second method (open triangles) corresponds to the full extent of the X-ray emission less the regions of other extended sources. The smallest region in Figure 6 corresponds to region “2” in Figure 4b.

Figure 6 shows that the two methods agree and that the halo emission extends over a region at least 3.5 Mpc² in area with a total flux density of 78 ± 5 mJy at 1.3 GHz, which corresponds to a rest frame 1.4 GHz power of (4.3 ± 0.3) × 10⁻²⁵ W Hz⁻¹. This power is likely to be a lower limit since there are negative contours around the halo in the 1.3 GHz image (Fig. 3b), which we interpret as evidence of missing short spacings. Further ATCA observations in the 210 m configuration are needed to study better the outer parts of the halo. With a power $P_{1.4} \sim 4.3 \times 10^{-25}$ W Hz⁻¹, and a largest linear extent ~2 Mpc, the radio halo source in 1E 0657 – 56 is the strongest and largest known.

4.3. Correction for the SZ Effect

As mentioned in § 2.2, this cluster shows a relatively strong SZ effect which produces a decrement at centimeter wavelengths and is also cluster-wide and diffuse. It is thus difficult to separate the SZ effect from the halo emission using the radio data alone. However, the SZ effect is strong enough at 4.9, 5.9, and 8.8 GHz to cause a significant underestimate of the radio halo flux density and an apparent steepening of the spectrum.

To obtain a reliable radio spectrum for the halo, we need to correct for the SZ effect at each frequency. We simulate the SZ effect at 4.9 to 8.8 GHz, using the X-ray data and the

| TABLE 2 |

| SOURCE | PEAK POSITION (J2000) | $S_{1344}$ | $S_{2350}$ | $S_{4864}$ | $S_{8832}$ |
|--------|----------------------|-----------|-----------|-----------|-----------|
| A      | 06 58 37.9, –55 57 25 | 19.1 ± 1  | 11.8 ± 0.6 | 6.3 ± 0.3 | 3.3 ± 0.2 |
| B      | 06 58 34.1, –55 57 54 | 0.5 ± 0.05| <0.3      | <0.3      | <0.4      |
| C      | 06 58 42.2, –55 58 37 | 37 ± 2    | 21 ± 2    | 8.4 ± 0.5 | 3.2 ± 0.5 |
| D      | 06 58 23.4, –55 56 41 | 1.1 ± 0.06| 0.4 ± 0.07| <0.3      | <0.4      |
| E      | 06 58 27.2, –55 56 08 | 0.4 ± 0.05| <0.3      | <0.3      | <0.4      |
| F      | 06 58 24.3, –55 55 13 | 0.6 ± 0.05| 0.4 ± 0.07| <0.3      | <0.4      |
| G      | 06 58 19.3, –55 58 43 | 0.8 ± 0.05| 0.4 ± 0.07| <0.3      | <0.4      |
| H      | 06 58 16.6, –55 58 23 | 0.4 ± 0.05| <0.3      | <0.3      | <0.4      |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The upper limits in flux densities are 3σ, but the errors quoted are 1σ.
SEST detection at 2 mm. Andreani et al. (1999) found that the SZ effect detected at 2 mm was consistent with a model of the X-ray surface brightness expressed by two $\beta$ models (corresponding to the two X-ray clumps) assuming an isothermal gas temperature of $\sim 17$ keV, if $H_0 \sim 50$ km s$^{-1}$ Mpc$^{-1}$. For consistency with the SEST results, we use this gas temperature only for these calculations; in the rest of the paper, we use the newly derived gas temperature given in §2.1. Since the SEST results provide no structure information for the gas, we have to use the X-ray derived gas parameters, i.e., $n_{e,0}, \theta_0, \beta$ from Andreani et al. (1999; or see §2.1), to simulate an SZ effect image at each frequency. This simulated SZ effect image is then weighted by the primary beam of the ATCA, Fourier transformed, and subtracted from the UV data set at that frequency. The image obtained from the resulting UV data set contains only the radio emission from the halo and can be analyzed as in §4.2 to get the halo flux densities. Figure 7 shows the halo flux density in a specific region at various frequencies before and after the correction for the SZ effect, indicating a substantial difference at high frequencies.

4.4. Radio Spectrum

To obtain the spectral index of the halo, we took data from the inner UV-plane (baselines $<3600\lambda$) for each available frequency. The observations were planned such that roughly the same region in the UV-plane was sampled at the various frequencies. The data were tapered such that the synthesized beam FWHM was $\sim 60^\prime$ at each frequency. The images are shown in Figure 3. To form a spectrum, the same area of integration was used at each frequency and methods in §§4.1 and 4.2 were used to correct for small-angular-size
radio sources and the SZ effect. The areas were selected to include only regions of obvious emission at all frequencies. The radio spectrum between 1.3 and 8.8 GHz for region "2" marked in Figure 4b is shown in Figure 7 (dots). Determination of the spectral index from region "2" is complicated since it includes three point sources (B, D, and E) and an extended source (A; see Fig. 4b). The three point sources are detected only in the 1.3 GHz image. We can obtain the flux density of the extended source (A) from images like that of Figure 4b at each frequency and subtract them from the total integrated flux. The resulting spectral index of region "2" is $\sim -1.2$ between 1.3 and 4.9 GHz, and $\sim -1.3$ between 2.4 and 8.8 GHz, indicating no significant steepening of the spectral index between 1.3 and 8.8 GHz.

We use the data from MOST to extend the spectrum to lower frequencies. The MOST images were produced by a real-time FFT and are thus fixed in resolution, excluding the possibility of subtracting the discrete sources embedded in the halo. We can only form a spectrum for the central part (region "3") of the halo that is devoid of discrete sources. The ATCA data at various frequencies were tapered such that the final resolution would match the MOST resolution of $51'' \times 43''$ (P.A. = 0'). The spectrum of region "3" is shown by the triangles in Figure 7. The spectrum can be fitted with a power law with a spectral index of $-1.4 \pm 0.1$ using a least squares fit. In comparison, the average spectral index for the larger region (region "2") is $\sim -1.3 \pm 0.1$. There is no evidence of any steepening of the spectral index in the outer regions compared with the central region (unlike what is observed in the Coma cluster; Giovannini et al. 1993). The areas of the regions "3" and "2" marked in Figure 4b are 0.14 and 0.78 Mpc$^2$, respectively.

4.5. Polarization

The ATCA measures all components of linear polarization, and takes account of the polarization leakage terms in the calibration of the data by the MIRIAD package.
Polarized emission was not detected for the radio halo source. We obtain an upper limit for linearly polarized emission at 1.3 GHz of 20%, 6.5%, and 1.4% at resolutions of 10'', 20'', and 60'' (corresponding to linear sizes of 55, 110, and 327 kpc), respectively. The upper limit was calculated as \((Q^2 + U^2)^{1/2}/I\), where \(I\) was the Stokes \(I\) peak halo flux density and \(Q\) and \(U\) were the 3 \(\sigma\) of the Stokes \(Q\) and \(U\) maps, respectively. The polarization upper limits obtained at higher frequencies were poorer, because of the steepness of the halo spectral index and consequent decrease in signal-to-noise of the data. So far polarization has not been detected in any halo source.

4.6. Pressure and Energy

The total energy density, or pressure, is minimum when the energy density of the relativistic particles is close to the energy density of the magnetic field (Burbidge 1958). There is no strong physical justification for the particle and field energies to be in equipartition, but it has been conjectured that they may be close to equipartition (Longair 1997). If we make this assumption, then we can calculate the minimum pressure of radiating electrons and magnetic fields in the halo source and compare it to the thermal pressure from the X-ray gas. We estimate the minimum pressure by following the procedure set out in Pacholczyk (1970), assuming a constant spectral index of \(\sim -1.3\) between the cutoff frequencies of 10 MHz and 100 GHz, an emission volume filling factor \(\phi\) of 1 and a ratio \(k\) between the energy in relativistic protons and electrons of 1. The minimum pressure of the radio plasma is a factor \(\sim 10^4\) smaller than the thermal pressure. Since \(P_{\text{min}} \propto \phi^{-4/7}(1 + k)^{4/7}\), we need \(k > 10^6\) for \(P_{\text{min}}\) to match the thermal pressure which seems unlikely. Similar results have been found in other radio halos (e.g., Feretti et al. 1997a, 1997b). Since the radio plasma interpen-
The total energy of the thermal plasma is \( \sim 10^{63} \) ergs, and the energy in the relativistic plasma is \( \sim 10^{60} \) ergs under conditions of equipartition.

4.7. Morphological Structure

The radio halo is similar in extent and overall appearance to the cluster X-ray emission (see Fig. 5a). While Figure 5a shows that the radio emission is enhanced at the main peak of the X-ray emission, Figure 5b shows that the radio emission is also enhanced at the densest part of the optical galaxy distribution. On the whole, the radio emission follows that of the optical galaxy distribution more closely than the X-ray emission. This was also found in the Coma cluster (Kim et al. 1990). We will discuss this point further in § 5.3.

The main concentration of galaxies is displaced from the dominant (eastern) peak of the X-ray emission (see Fig. 5c). Both the X-ray gas and the galaxy distribution suggest that the cluster is undergoing a merging process. Since the X-ray clumps are well separated, the merger appears to be in a relatively early stage. Since galaxies are more or less collisionless, but gas is collisional, a merger between two sub-clusters tends to allow the galaxies to stream past one another, while the gas tends to coalesce quickly. Figure 5c shows that the galaxy clumps in 1E 0657−56 are further apart than the gas clumps, indicating that the galaxies have crossed each other at least once. The projected merging axis appears to be close to the RA-direction. Shocks produced during the merger are a plausible source for the energy of the relativistic electrons responsible for the radio halo emission.

5. The Origin of Radio Halos

5.1. Are Radio Halos Intrinsically Rare?

A number of surveys have been conducted to search for radio halos. The earliest were conducted at Green Bank at 610 MHz (Jaffe & Rudnick 1979), at meter wavelengths 50–120 MHz (Cane et al. 1981), and at Arecibo at 430 MHz (Hanisch 1982), but yielded few examples. Most of the surveys selected either nearby Abell clusters (Hanisch 1982), or clusters with known X-ray emission or radio sources. More recently, Lacy et al. (1993) imaged a sample of radio sources from the 8C 38 MHz survey (within of the North Ecliptic cap) using the Cambridge Low Frequency Synthesis Telescope at 151 MHz but did not find any new halo sources.

Recent X-ray selected surveys of halos as well as observations aimed at detecting the SZ effect have found many more halo candidates suggesting that halos may not be as rare as they were once thought to be.

Moffet & Birkinshaw (1989) first suggested that there may be a correlation between the presence of an SZ effect and a radio halo source, since the only three clusters A2218, A665, and CL 0016 + 16 which had an SZ effect detected at the time also had extended diffuse radio emission. One of the strongest radio halos was found in A2163 in an attempt to detect the SZ effect (Herbig & Birkinshaw 1994). Among the seven clusters observed at the ATCA for the SZ effect, two show clear evidence of a radio halo (A2163, 1E 0657−56), while another three show faint extended emission which may be either the result of the blending of discrete radio sources or a faint halo (Liang 1995). It is perhaps not surprising that searches for the SZ effect have been

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**Fig. 6**—Integrated diffuse halo flux density vs. the area of integration. The open circles are integrated flux densities from an image made with a source-subtracted UV data set and smoothed to 60″ resolution using only the short baseline (\(< 3600\)″) data. The triangles are integrated flux densities from a high-resolution image shown in Fig. 4 but with the embedded sources obtained from Fig. 4b subtracted afterward. The error bars are 1σ errors.

**Fig. 7**—Radio spectra from 0.843 GHz to 8.8 GHz of the cluster halo in 1E 0657−56. The spectrum of the central region (region 3 in Fig. 4b) is marked by triangles. For the larger region (region 2 in Fig. 4b) the spectrum is marked by circles. The filled data points have been corrected for the SZ effect. The uncorrected flux are represented as open symbols. The error bars are 1σ errors. The straight lines are the best least square fits to a power law spectrum.
good at finding halo sources: the SZ effect is also cluster-
wide, thus diffuse and extended like the halo sources. Any
observation designed to search for the SZ effect will opti-
mize the brightness sensitivity and thus favor the detection
of halos. If, in addition, there is a physical mechanism that
associates hot, luminous, X-ray emitting atmospheres and
radio halos, searches for SZ effects which target such clus-
ters would be expected to find radio halos frequently.

Giovannini et al. (1999a), in their correlation of NVSS
images with the catalog of X-ray Brightest Abell Clusters
(XBAC; Ebeling et al. 1996), found 13 candidates for diffuse
radio halos. They noticed a significant increase in the per-
centage of diffuse radio sources in high-luminosity clusters
compared with low-luminosity clusters: 27%–44% in clusters
with \( L_x > 10^{45} \) erg s\(^{-1}\) as compared with 6%–9% for
\( L_x < 10^{45} \) erg s\(^{-1}\).

We conclude that radio halos are not intrinsically rare
and appeared to be rare from the results of early surveys
partly because of the difficulty of detecting such low surface
brightness objects and partly because of the selection criteria.

5.2. The Link between Thermal and Relativistic Electrons

While Giovannini et al. (1999a) found more halos in high
than in low X-ray luminosity clusters, they did not find a
connection between their radio power and the cluster X-ray
luminosity. Here we plot the rest frame 1.4 GHz radio
power \( (P_{1.4}) \) against the cluster X-ray luminosity \( (L_x) \) for
only well-confirmed radio halos (not relic sources) using the
best radio data available for each halo. Figure 8 shows that
there is a correlation between radio and X-ray luminosities
for \( L_x \) > \( 10^{44} \) ergs s\(^{-1}\) clusters contrary to Gio-
vannini et al. (1999a) where they plotted all candidate halos
using the radio power obtained from the NVSS for each halo.
Instead of plotting radio power against X-ray luminos-
itity, we examine the relationship between halo radio
power and cluster X-ray temperature. Figure 9 shows the
1.4 GHz integrated radio power of cluster halos plotted
against the cluster temperature, demonstrating a steep
correlation (Liang 1999; Colafrancesco 1999). Since only
well-confirmed radio halos are plotted, the sample of clus-
ters shown is by no means complete. The apparent rareness
of halos can be explained by the steepness of the relation-
ship shown in Figure 9: only clusters with a high X-ray
temperature at moderate redshifts are easily detectable. The
surface brightness of halos decreases with increasing red-
shift at least as fast as \((1 + z)^2\) when taking account of the
K-correction, thus the halo surface brightness rapidly
diminishes with increasing redshift. On the other hand,
halos at low redshift are also difficult to detect since they
tend to be resolved out in simple interferometric maps (or
single dish observations without a large beam throw).

In the three well-imaged cluster halos (Coma, A2163, and
1E 0657 – 56), the extent and shape of the radio halo follows
closely that of the cluster X-ray emission (Fig. 5; Deiss et al.
1997; Herbig & Birkinshaw 2000, in preparation). Both the
correlation shown in Figures 8 and 9 and the similarities
between the radio and X-ray morphology indicate a direct
connection between the thermal particles and the rela-
tivistic electrons responsible for the radio emission.

5.3. Formation of Radio Halos

We favor a model for radio halos where thermal electrons
in the ICM provide the seed particles for acceleration to the
ultrarelativistic energies necessary for synchrotron radi-
gyrofrequency. In the low-amplitude limit the waves are \( \perp \) to the magnetic field, and is the relativistic electron components of the wavenumber and particle velocity parallel to the magnetic field to be \( \perp \). However, in a high-density environment, \( \gamma_{\text{min}} \) is close to one and thermal electrons can be accelerated by Alfvén waves. The environments of radio galaxies, including clusters, were considered to be of low density since the magnetic field strength \( B \) was thought to be a few \( \mu G \), which means the density threshold is higher than the densities of most clusters.

Recent hard X-ray results from BeppoSAX and Rossi-RXTE for Coma and other clusters have shown the magnetic field to be \( B \approx 0.2 \mu G \) if the excess hard X-ray emission is due to inverse Compton scattering of relativistic electrons by the CMB (e.g., Fusco-Femiano et al. 1999; Rephaeli et al. 1999; Valinia et al. 1999). Thus, the density threshold is now \( \approx 8 \times 10^{-6} \eta^{-1} \text{cm}^{-3} \), which makes most parts of clusters high-density environments. For example, in the centers of clusters where \( n_e \approx 10^{-3} \), the minimum energy required is just a few keV, and in the outer parts of a cluster where \( n_e \approx 10^{-4} \) the minimum energy is still just a few tens of keV. Electrons with energies of a few tens of keV are readily available in intracluster plasma of hot clusters. Therefore, it is possible to accelerate thermal electrons in clusters through resonance with Alfvén waves. Further, Dogiel (1999) has shown that it is possible to produce a substantial suprathermal tail in the electron energy distribution through second-order Fermi acceleration in cluster environments, so that additional seed electrons are naturally present in clusters without involving injection from radio galaxies.

On the one hand, the higher the X-ray luminosity of a cluster, the higher the density of thermal electrons; and on the other hand, the higher the X-ray temperature of a cluster, the higher the fraction of high-energy electrons. These two effects multiply to increase the number of electrons above a threshold energy for efficient acceleration processes.

Both merging activity and the electron temperature may be responsible for the production of radio halos. A possible scenario would be that the initial merging activity provides the energy for accelerating electrons from the suprathermal tail of the energy distribution (where the hotter clusters have more power) to ultrarelativistic energies. Since cluster magnetic field strengths are less than \( 3 \mu G \), the dominant energy loss mechanism for relativistic electrons is inverse Compton scattering of the cosmic microwave background radiation. Thus, the typical lifetime of an electron that emits at 1.4 GHz is \( t_{\text{age}} \approx 8 \times 10^{8} \text{yr} \). If we assume a magnetic field of \( B \approx 0.2 \mu G \), then the lifetime of an electron that emits at 1.4 GHz in 1E 0657 – 56 is \( \approx 10^{7} \text{yr} \). After the shocks have disappeared, radio halos like that of 1E 0657 – 56 may be maintained by in situ electron acceleration in the residual turbulence. In the case of 1E 0657 – 56, we found (Fig. 5) that the radio halo emission is enhanced at the peak of the X-ray emission as well as that of the galaxy distribution. The enhancement of radio emission at the peak of the X-ray emission is naturally explained by our model where we expect the highest density of relativistic electrons at the density peak of the thermal electrons. We
also expect that the galaxies streaming through the hot intracluster gas would maintain local turbulence and hence inject energy into the particles, producing enhanced radio emissions at the galaxy concentrations. Deiss & Just (1996) found through their calculations that it is possible to have turbulent velocities of several hundred kilometers per second, which could considerably enhance the stochastic acceleration rates.

Cooling flow clusters are thought to be relaxed and devoid of merging activity. Most of the clusters shown in Figure 9 are non–cooling flow clusters. This does not imply that mergers are the critical element in radio halo formation, since selection effects act to remove clusters from the sample in Figure 9: cooling flow clusters are more likely to have significant central radio sources than non–cooling flow clusters (e.g., Peres et al. 1998). To our knowledge, no cluster with a strong cooling flow has been observed with sufficient dynamic range and surface brightness sensitivity to test whether or not it follows the $P_{1.4} - kT_X$ trend shown in Figure 9. To illustrate the need for proper observations with high brightness sensitivities, we give as an example, RX J1347–11, a strong cooling flow with the high gas temperature of $\sim 12.5$ keV (Allen & Fabian 1998) which has been observed by the NVSS with no obvious detection. However, the NVSS does not have enough brightness sensitivity to detect, in RX J1347–11, a halo similar to that in 1E 0657–56 because of the large redshift ($z \sim 0.45$) of the cluster (expected signal of $\sim 1.3$ mJy per $45^\circ$ beam) and the high noise levels in the NVSS image ($\sim 0.5$ mJy per $45^\circ$ beam).

6. CONCLUSIONS

We have found a powerful radio halo in the cluster 1E 0657–56. At a rest frame 1.4 GHz radio power of $(4.3 \pm 0.3) \times 10^{25}$ W Hz$^{-1}$, it is one of the most powerful radio halo sources. It has a steep spectral index of $\alpha \sim 0.7$ typical of known halos. The brightness distributions of the radio halo and X-rays from the cluster gas are remarkably similar, suggesting a direct relationship between the ultrarelativistic electrons responsible for the synchrotron emission and the thermal intracluster gas. As further evidence for the radio/X-ray connection, we have found a steep correlation between the radio power of the halo and the X-ray temperature of the intracluster gas ($P_{1.4} - kT_X$) from the 10 confirmed cluster radio halos. We favor an explanation for the origin of radio halo sources, where the high-energy tail of the thermal electron distribution is boosted to ultrarelativistic energies, thus providing a natural link between the halo radio power and X-ray gas temperature. Detailed calculations for such a model will be given in a future paper. Finally, it is important for our understanding of the origin of radio halo sources to establish the robustness of the $P_{1.4} - kT_X$ correlation by observing a temperature selected sample of clusters, and to test the mechanism by searching for halos in clusters with strong cooling flows but high temperature.

In addition, we have reanalyzed the X-ray spectroscopic data using both ASCA GIS and ROSAT PSPC data for 1E 0657–56 and found the best-fit temperature to be $kT_X = 14.5^{+2.0}_{-1.7}$ keV consistent with it being one of the hottest known clusters, as claimed by Tucker et al. (1998). The use of the PSPC data enabled us to determine the soft X-ray absorption to a better accuracy than previous results using ASCA data alone. We found the best-fit neutral hydrogen column density to be consistent with the Galactic value given by radio-astronomical surveys, contrary to the much higher column density claimed by Yaqoob (1999) using ASCA data alone.

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