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IMAGING THE RADIO HALO IN THE ABELL 2256 CLUSTER OF GALAXIES

K.-T. KIM
Department of Astronomy and Space Science, Chungnam National University, Daejeon, 305-764, Korea
E-mail: ktkim@nsastro3.chungnam.ac.kr
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ABSTRACT

Diffuse radio emission in Abell 2256 was detected above 3 σ with DRAO observations at 1420 MHz. The halo size is $\sim$13′×10′ ($\sim 1h_{50}^{-1}$ Mpc) in full extent and is elongated along a position angle of about 112°. The total flux density contained in the halo is 30±10 mJy at 1420 MHz and its spectral index is −2.04±0.04, showing no evidence for steepening up to 1420 MHz. Using the size estimate, yields a more reliable equipartition magnetic field strength which is $0.34(1+k)^{2/7}$ μG. In addition, five new radio sources are identified.

Key words : galaxies : clustering – galaxies : intergalactic medium – galaxies : X-rays – magnetic fields – radio sources : galaxies

I. INTRODUCTION

Abell 2256 is a Coma-like cluster of galaxies which exhibits strong emission at all wavelengths, and thus encompasses many of the modern problems in astrophysics. Existence of a steep spectrum radio source in Abell 2256 was first noted by Costain et al. (1972) who measured $\alpha = -1.9$ between 22.25 and 81.5 MHz. Since then it has been an attraction to both theoretical and observational investigators in relation to the inverse Compton origin of X-ray emission. In the inverse Compton model a large volume of the cluster is filled with relativistic electrons having a steep power-law energy distribution; the lower-energy electrons produce X-rays by inverse Compton scattering on the 3K background radiation, while higher-energy electrons produce an extended diffuse steep-spectrum radio source (radio halo) by synchrotron radiation in an extensive weak intracluster magnetic field. Rephaeli & Gruber (1988), however, were not successful in detecting nonthermal X-ray emission from A2256 between 13-175 keV, yielding a lower limit of the intracluster magnetic field of 0.15 microgauss in strength.

The first synthesis radio map of Abell 2256 was made by Bridle & Fomalont (1976). This observation revealed two diffuse emission regions which altogether extend nearly 1 Mpc with an unusually high number of head-tail sources. This was later confirmed with high resolution observations to contain at least five head-tails (Valentijn 1981; O'Dea & Owen 1985). A barely visible radio halo was presented on their 610 MHz map (WSRT) and with further observations (Bridle et al. 1979), they suggested with corroborating evidence that a radio halo of about 10′ in size exists near the cluster center. However, all the details remained veiled due to lack of adequate sensitivity to extended emission in the aperature synthesis observations.

In this paper, we present an image of the halo emission with the data collected by DRAO synthesis telescope observed at 1420 MHz. The organization of this paper is the following. In Section II, the observations and data reduction are presented. Physical properties of the radio halo are studied in Section III, followed by discussion in Section IV. Throughout this paper the redshift of A2256 is taken to be 0.0601 (Struble & Rood 1987), and $H_0 = 50$ Mpc km^{-1}s^{-1} ($\equiv h_{50}$) and $q = 0$ are used.

II. RADIO OBSERVATIONS AND DATA REDUCTION

Continuum radio observations were made at both 1420 and 408 MHz using the synthesis telescope at the Dominion Radio Astrophysical Observatory (DRAO).[1] At the time of these observations, the DRAO synthesis telescope (Roger et al. 1973; Veidt et al. 1985) consisted of four 9-m paraboloidal antennas providing east-west interferometer spacings of 13 to 600-m. Due to the small diameter of the antennas, information on broad emission structures as large as 53 arcmin in diameter is well represented. Observations were made in 1990 January-June with a field center at RA 17^h 06^m 18.0^s DEC +78° 41′ 57″ (epoch 1950.0 throughout this work), the position of the strongest source in A2256 and only a few arcmin offset from the cluster center. The observations were tied to the flux density scale of Baars et al. (1977) by assuming flux densities of 48.0 and 54.0 Jy for 3C147 and 3C295 at 408 MHz and 22.9 Jy for 3C147 at 1420 MHz. The theoretical r.m.s. sensitivities of the observations at 1420 and 408 MHz are 0.35 and 3.3 mJy/beam respectively.

Data reduction was performed using the standard DRAO software package. Weighting of the observations was chosen to give synthesized beams of 1.06′ × 0.90′

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[1] The DRAO Synthesis Telescope is operated as a national facility by the National Research Council of Canada.

at 1420 MHz and 3.77′ × 3.14′ at 408 MHz. This corresponds to a 20% UV taper at the maximum spacing. In both maps the sampling was at least 2.0 points per synthesized half-power beamwidth in the direction of both RA and Dec, requiring map sizes of 512×512 pixels. To avoid aliasing of grating rings into the inner quarter of the map from the FFT process, a 1024×1024 map was made for 1420 MHz. Subsequent CLEANing of the maps used the routine developed by Steer et al. (1984) for the inner quarter of the map area, giving CLEANed regions 256 and 445 arcmin square at 1420 and 408 MHz respectively.

The dynamic range of the 1420 MHz map reached about 700, which is practically the best obtainable without applying self-calibration. In the case of 408 MHz, due to interference, the dynamic range was limited to about 250 and sources weaker than 20 mJy/beam were not measured on the CLEAN map. A total of 375 sources were detected above 5σ within the -10 db attenuation level of the primary beam. For 1420 MHz, the RMS noise on the CLEAN map is 0.4 mJy/beam. The flux densities of sources were determined using an elliptical Gaussian fitting routine, yeilding a total of 216 sources within the -10 db attenuation level of the primary beam. Radio properties of 15 galaxies measured at 1420 MHz are given in Table 2. Five new optical identifications are included.

Low spacing data from Stockert 25-m observations (Reich 1982; Reich & Reich 1986) were added into the 1420 MHz data but did not change the map, hence no large scale emission is missing. At full resolution, the radio halo appears barely above the noise level of the map. However, after convolving to a circular beam of FWHM 2′ of the map where all of small diameter sources were removed, the overall features of the radio halo appear well above the 3 σ level. The convolved DRAO map is shown in Figure 2. No systematic slope in rms noise is noticeable on the map around the halo.

The size of the halo is estimated to be 13′×10′ ($\sim 1 h_{50}^{-1}$ Mpc) in full extent and it is elongated along a position angle of about 112°. The total flux density contained in the region is 30±10 mJy at 1420 MHz. No attempt was made to measure halo emission at 408 MHz.

III. PHYSICAL PROPERTIES OF THE RADIO HALO

Combining all existing observations, the halo appears to have a steep spectrum which is $\alpha = -2.04 \pm 0.04$ (see Figure 3). Here $S_\nu \propto \nu^\alpha$ where S_ν is the flux density at frequency ν. This value is not significantly different, within the error, from the earlier estimate $\alpha = -1.9 \pm 0.2$ between 22.25 to 81.5 MHz by Costain et al. (1972). It is worth pointing out that the halo spectrum does not show any sign of steepening up to 1420 MHz. Given the size, equipartition parameters become more reliable. Using the spectral index, the equipartition magnetic field strength of the halo is about $0.34(1+k)^{2/7}$ μG, which becomes 1.3 μG if $k = 100$ is used. Here k is the proton/electron energy density. This estimate is consistent with the lower limit set by nondetection of nonthermal X-ray emission (Rephaeli & Gruber 1988). Along with two other extended sources, related parameters of the halo are summarized in Table 1. Optical identifications made to date in A2256 are listed in Table 2, including five new identifications.

Table 1. Physical parameters*of three diffuse sources

PARAMETER (1)	HALO (2)	G (3)	H (4)
Flux Density (mJy)$^+$	46±9	240±12	218±10
Spectral Index	-2.04 ± 0.04	-0.75 ± 0.12	-0.79 ± 0.11
Size (kpc)	1250×960	160×80	380×160
Luminosity (erg/s)	8.2×10^{41}	2.4×10^{41}	2.2×10^{41}
$P_{1.4}$ (Watt/Hz)	3.8×10^{23}	3.1×10^{24}	2.8×10^{24}
U_{eq} (erg)	1.7×10^{62}	1.6×10^{60}	4.1×10^{60}
P_{eq} (dyne cm^{-2})	3.5×10^{-13}	5.5×10^{-12}	1.5×10^{-12}
N_e^{++} (particles)	2.0×10^{60}	3.5×10^{59}	6.1×10^{59}
H_{eq} (μG)	1.3	4.8	2.6

Note: * Equipartition values for $k = 100$, where k is the proton/electron energy density. $P_{1.4}$, U_{eq}, P_{eq} are radio power at 1.4 GHz, equipartition energy density and pressure, respectively. Redshift of the cluster is 0.0601 taken from Struble & Rood (1987) which gives the luminosity distance and angular scale 371 Mpc and 96 kpc arcmin for $H_0 = 50$ km/s/Mpc and $q = 0.0$, respectively. $^+$ Flux density at 1 GHz. $^{++}$ Total number of relativistic electrons in the source. H_{eq} is the equipartition value of mangetic field. Radio data for source G and H are from Bridle et al. (1979).

The halo as well as the two diffuse components can be sufficiently confined by thermal pressure exerted by X-ray emitting cluster gas. Using the gas parameters from both Einstein (Fabricant et al. 1989) and ROSAT (Briel et al. 1991), the number density at radius of 10′ becomes 3.4×10^{-4} cm^{-3} and these exert thermal pressure of the amount 3.8×10^{-12} dyne cm^{-2}, which is one order of magntude larger than that of the radio halo. This condition of course helps support longer lifetime against adiabatic losses.

Table 2. Optical identifications

No (1)	RA(1950) (2)	ΔRA (3)	DEC(1950) (4)	ΔDEC (5)	$S_{1.4}$ (6)	Δ $S_{1.4}$ (7)	$P_{1.4}$ (8)	α_s δ_s (9)	m$_r$ (10)	cz (11)	(12)	Note (13)
29	17 01 02.65	.48	78 33 59.1	1.6	4.3	0.5	0.72	02.1 54	14.77	17844	40	*
30	17 01 29.75	.84	78 29 22.2	4.6	2.1	0.5	0.35	28.7 40	15.18	15613	48	*
44	17 03 46.05	.35	78 45 54.6	1.7	7.8	1.0	1.30	42.9 30	15.89	17325	39	I
36	17 03 50.14	.17	78 34 15.7	1.1	11.7	0.5	1.96	10.9 49	16.32	17421	52	*
47	17 04 04.2	.2	78 47 34.1	0.4	6.5	1.1	1.09	02.4 43	15.29	16038	100	J
63	17 05 12.0	.3	78 50 10.0	0.6	5.2	1.0	0.87	11.6 06	15.96	19752	40	K
71	17 05 52		78 40 40		62	4	10.4	51.1 51	16.16	16545	35	B
75	17 06 00		78 44 00		39	3	6.52	02.4 27	16.31	15901	39	C(i)
79	17 06 18		78 41 57		157	10	26.2	18.5 46	14.00	17584	100	A
98	17 07 38.46	.07	78 42 22.2	0.2	11.0	1.2	1.84	38.9 19	14.76	19276	100	D
113	17 08 30.6	.2	78 55 06.6	0.4	4.4	1.0	0.74	31.0 03	15.98	19637	39	E
122	17 09 47.0	.3	78 44 54.8	0.6	11.0	2.0	1.84	49.2 51	15.60	16865	46	F(iii)
131	17 11 22.80	.62	78 33 55.0	3.4	3.8	0.6	0.64	25.9 43	15.40	18734	34	*
135	17 11 55.48	.92	78 49 56.3	9.3	3.9	1.2	0.65	57.0 50	15.46	11924	41	*
138	17 12 23.68	.28	78 45 16.5	1.6	11.4	0.9	1.86	18.0 48	16.39	17956	77	M

(1) List numbers of galaxies in Fabricant et al. (1989). (2),(3),(4),(5) Right Ascension and its error (in second) and Declination and error (arcsec). (6),(7) Flux density at 1.4 GHz and its error (mJy). (8) $P_1.4$ is the radio power at 1.4 GHz in units of 10^{23} W/Hz. (9) α_s and δ_s are the second and arcsec part of the corresponding optical position. (10) Apparent magnitude in red. (11),(12) Redshift (km s^{-1}) and its error. (13) Source names and identifications by Bridle & Fomalont (1976). * New identification.

IV. DISCUSSION AND CONCLUSIONS

From Bridle et al. (1979), an intriguing point is that Sources G and H (see Figure 1) are in morphology and polarization character more likely to be relics of radio-tails. Assuming this is so, their sizes suggest that a strong radio episode was occured over a period of about $5\times10^8 v_g^{-1}$ yrs, where v_g is the velocity dispersion of the cluster galaxies in units of 10^3 km s^{-1}. If the source was not strong enough, as for example the average radio power of the five head-tails (A, B, C, D, and I; see Valentijn 1981 and O'Dea & Owen 1985), it would require nearly 10^{10} yrs to produce G+H, during which time the host galaxy would travel about 10 Mpc (100′), leaving the relic tail too weak and too elongated. To match the morphology, the radio power required is about 10 times stronger than the average of the above head-tails, which corresponds to a particle supply rate on the order of 10^{51} e/yr. Hence the source which was responsible for the hypothetical wide-angle tail was likely to maintain a radio power over about $5\times10^8 v_g^{-1}$ yrs.

How long ago did this source stop being a "head" of the WAT? (Here WAT stands for a Wide Angle Tailed radio source.) The spectra and high degree of polarization favour these as relatively young objects. Suppose G and H are not located near the cluster center and have a smaller chance for reaccelerations. They would be lost rather quickly on a time scale of 10^8 yrs, which is the half life time $t_{1/2}$ of the particles against synchrotron and inverse Compton losses in G and H where magnetic field strengths are about one microgauss. In this case their spectra or even their existence favour relatively young ages. If, on the other hand, these are indeed located near the center, frequent encounter with galaxies would soon lead to substantial depolarization. The fact, however, that they maintain a high degree of polarization suggests low deformation in them, also implying young ages. An analogy is found in 1253+275 which is very elongated; its magnetic field is aligned along the source, and shows a high degree of polarization (20 – 30%; Giovannini et al. 1985). These radio properties lead former investigators (Andernach et al. 1984; Hanisch et al. 1985) to suggest that 1253+275 is likely to be a 'relic' of a powerful double-lobe radio source whose radio characteristics are comparable to 3C31 or 3C465 (Miley & van der Laan 1973) and whose radio activity has ceased some 10^8 yrs ago.

Interestingly enough, the electron content of the halo is nearly the same as the sum of those contained in source G and H (see Table 1), within the errors of course. Although the origin of the relativistic electrons responsible for the radio halo continues to be a problem, the morphology and the steep spectrum of the halo seem to indicate that this is an old object whose life time has been prolonged due both to sufficient thermal confinement via X-ray emitting gases and to particle reaccelarations. As proposed in Giovannini et al. (1993) and as early as in 1978 by Harris & Miley, if a relic of a strong head-tail were the progenitor of a halo, the time scale needed to relax the relic to an amorphorous state can be expressed by the time required for the volume that the relic source occupied to be swept up by galaxies. This is a diffusion time scale, $\tau_D \approx 10^9 v_g^{-1}(r_g/5\ \mathrm{kpc})^{-2}(N_g/50)^{-2}$ yrs, for a relic left within a core radius. Here r_g and N_g are an effective galaxy radius and number of galaxies within a core radius of a rich cluster, respectively.

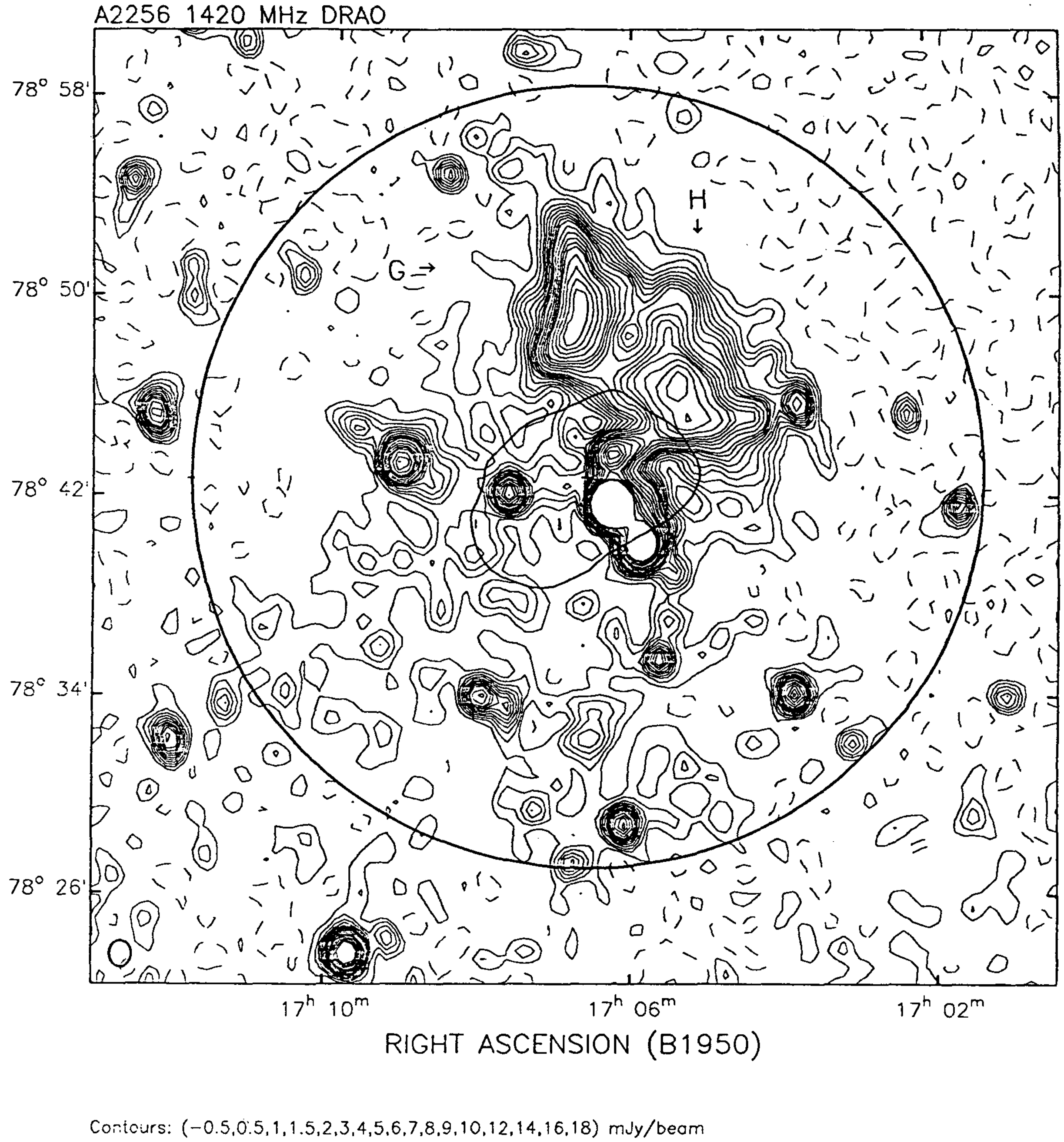

Fig. 1.— Abell 2256 cluster of galaxies was observed with the DRAO synthesis telescope at 1420 MHz. The beam is 1.06′×0.9′ and is shown in the bottom left corner of the map. The noise level at the map center was measued to be 0.4 mJy/beam. The solid circle is drawn (16′ radius) at which radius the galaxy density drops to about 1/20 of the central value (Fabricant et al. 1989; Bahcall 1975). The thick contour shows the half maximum intensity of X-ray emission observed with the Einstein observatory. A cross indicates the optical cluster center. The contour levels are (-0.5, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6, 7, 8, 9, 10, 12, 14, 16, 18) mJy/beam. The halo emission is barely visible at about 2 σ level.

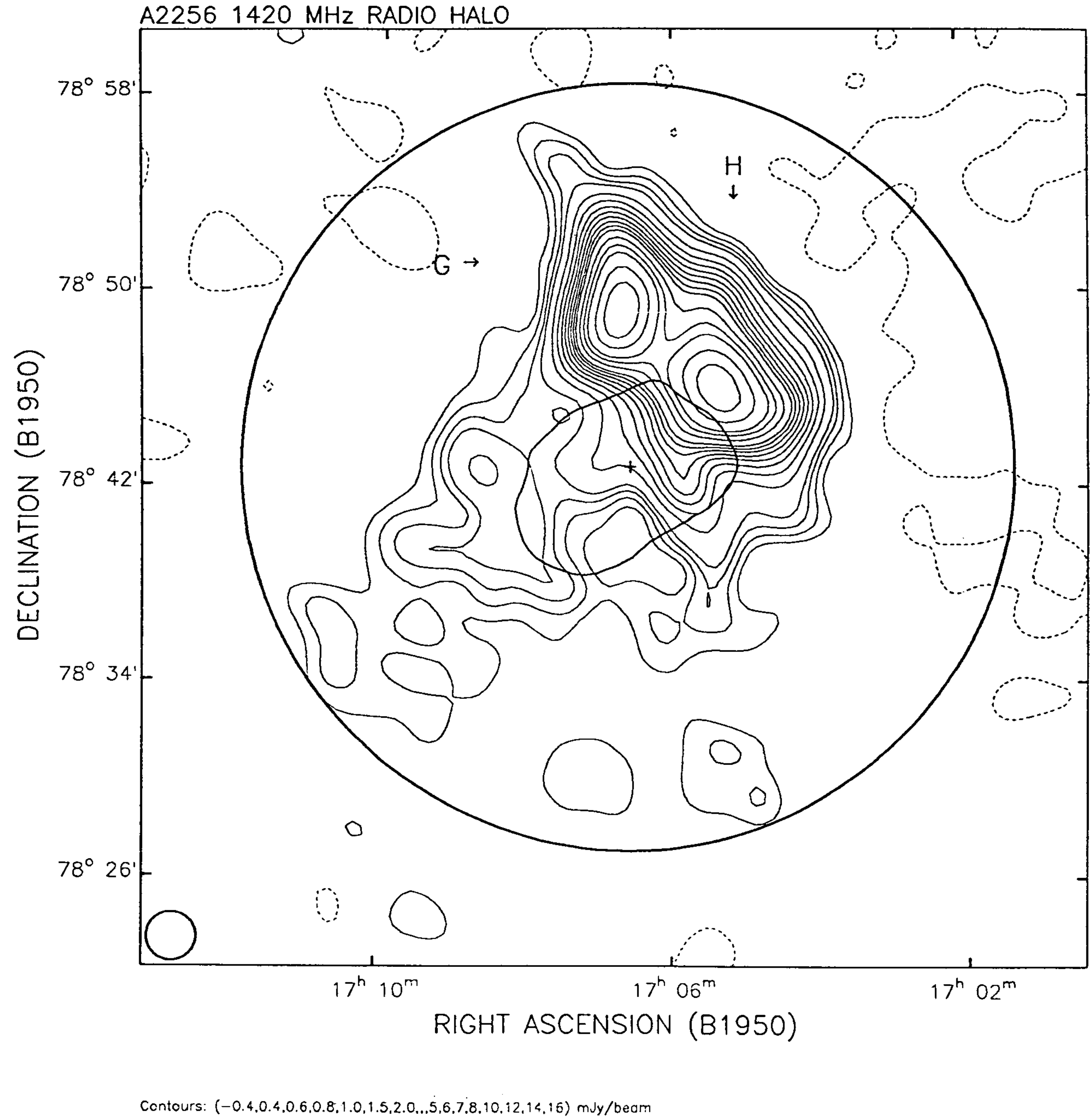

Fig. 2.— Small diameter sources seen in Figure 1 were all removed and this map was convolved to a circular beam of FWHM of 2′ (shown in the lower left corner). The map noise level was reduced to 0.2 mJy/beam and the halo emission is clearly visible above the 3 σ level. The contour levels are (-0.4, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6, 7, 8, 9, 10, 12, 14, 16) mJy/beam. G and H are the extended sources designated by Bridle & Fomalont (1976).

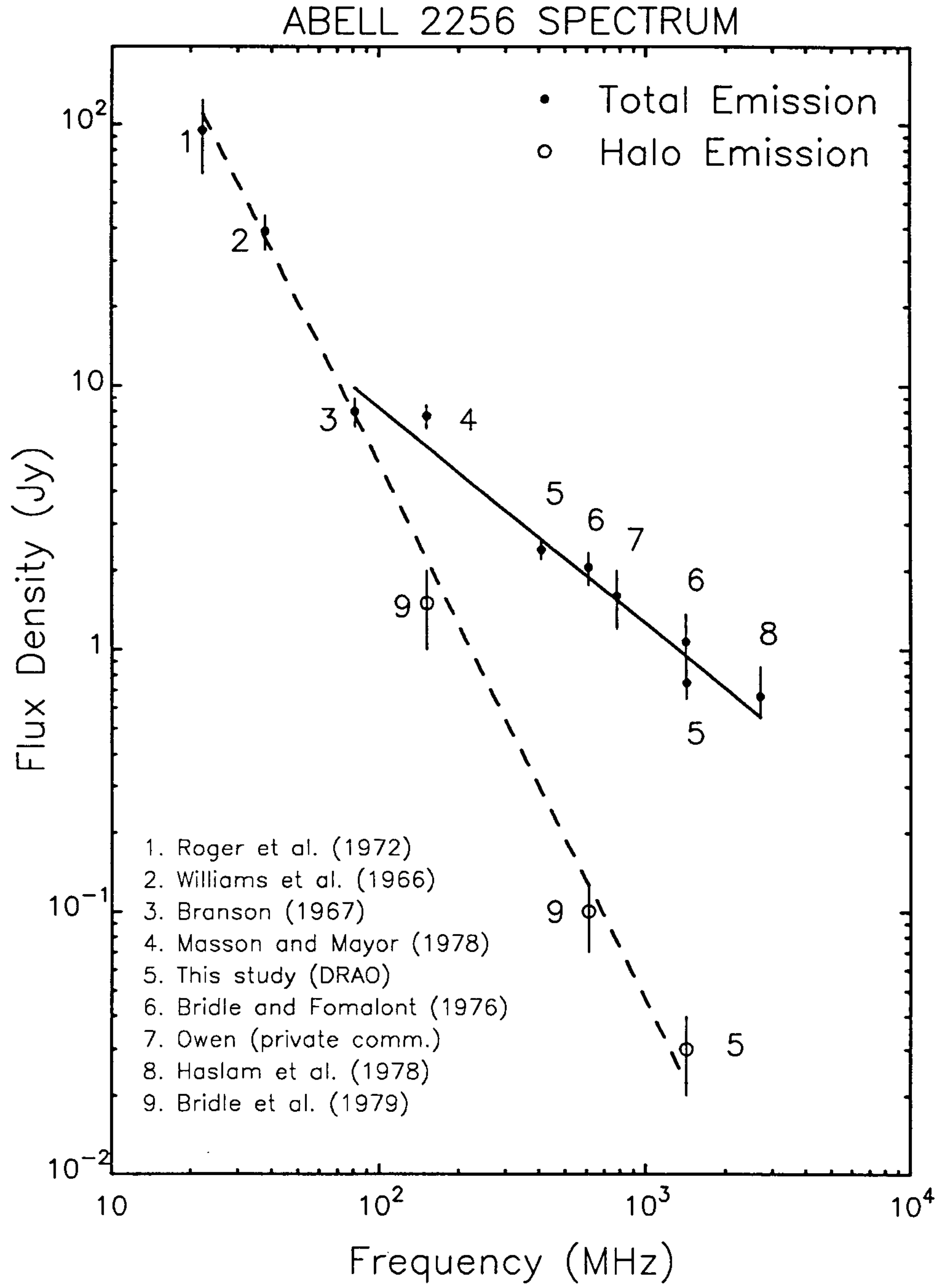

Fig. 3.— Radio spectrum of Abell 2256. The halo flux densities at 150 and 610 MHz (labelled 9) are derived from flux densities for the entire cluster. The 1420 MHz flux density (labelled 5) is a direct measurment.

This is comparable to the synchrotron loss time scale $t_{1/2} \approx 2.7\times10^8\gamma_4^{-1}B_\mu^{-1}$ yrs, where γ_4 is the electron's energy in units of 10^4 times the electron rest mass energy (Pacholczyk 1970). Judging by the two time scales, and if indeed the age of the halo is no younger than τ_D, which is most plausible, the spectral index could reflect either aging or rejuvenation especially for electrons of $\gamma_4 > 1$, which are responsible for emission $\geq$ 100 MHz in an intracluster medium of $B_\mu \approx 1$. Aging shows itself with a downward curvature in spectrum above a certain frequency, and this frequency tells us about the nature of particle accelerations ongoing in an intracluster medium. The halo's morphology and its straight spectrum down to 1.4 GHz imply that there should be a reacceleration processes ongoing especially for electrons of $\gamma_4 > 1$.

We may explore the nature of the reacceleration process qualitatively. This process could not be more efficient at lower energies otherwise the halo would only be visible at low frequencies and numerous steep strectrum sources would have been noticieble in clusters in earlier 20 MHz observations (Roger et al. 1986; Viner & Erickson 1975). This efficiency cannot be overly high at higher energies, otherwise steepening of spectral index such as seen in the Coma halo (Schlickeiser et al. 1987) should not be observed. The acceleration process should therefore be negligible at lower energies but increase its efficiency with frequency to some cutoff frequency (e.g. 1 – 2 GHz) at which energy loss rate dominates over the gain. What mechanism supports this behavior? One possibility is Fermi accerelation ($d\epsilon/dt \propto \epsilon$) (Kim 1990): electrons gain energy as they are streaming back and forth along intracluster magnetic fields which are constantly retangled by galaxy motions. Energy equipartition in this case would naturally be set between the magnetic fields and electrons and no energy excess would result at either low or high energies.

Concerning on the origin of a radio halo, Tribble (1993) has noted that all of the clusters which has radio halos are all mergers: Coma, A2256, A2319. As explained in Tribble (1993), and also breifly mentioned in Briel et al. (1991), the merger picture seems to explain most of the radio halo enigmas in A2256, such as the intracluster magnetic field amplification, particle accerlations, X-ray and radic energetics, and the rarity of the radio halos. The rarity is due to $t_m > t_{1/2}$, meaning that the electrons age quick and stay inert long before the rejuvenation via a merging. Here, t_m being the merging time scale which is $t_m \sim 2 - 4\times10^9$ year (Edge, Stewart & Fabian 1992), shorter than the Hubble time.

The cluster merging produces a large scale shocks, which scale could typically extend over 100 kpc or so, comparable to the halo sizes. Thus via this process we expect that the magnetic field on this scale could be amplified, which curvature is large enough to produce ultra energetic particles via the first order Fermi process. At the presence of synchrotron losses, the maximum energy of an electron that can be reached within a merger crossing time is about $\gamma \sim 10^8 u_s/B_\mu^{3/2}$. Here u_s being the shock velocity in units of 2000 km/s. These particles can easily deplete its energy in a short time period down to $\gamma \sim 10^4$, suitable for a radio halo. Therefore, the merger picture can not only produce an intracluster magnetic field on the order of microgauss but also rejuvenate relativistic particles which in turn illuminate the radio halo visible. Further studies with this picture on the strength and structure of intracluster magnetic field would help clarify what is evident in rich clusters of galaxies (Kim et al. 1991).

High resolution observations at moderately low frequencies will be very fruitful in understanding the origin of halos, especially for hypothetical weak halos yet undiscovered at higher frequencies. Continuing observations for nonthermal X-ray emissions from clusters of galaxies, especially in 15-300 keV, will undoubtedly help in understanding the origin of intracluster magnetic fields and even the origin of X-ray emission in the early stage of evolution of clusters of galaxies.

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