INTRACLUSTER MAGNETIC FIELDS FROM X-RAY AND RADIO MEASUREMENTS

R. SCHLICKEISER[1], Y. REPHAELI[2]
[1] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 5300 Bonn 1, FRG*
[2] *School of Physics and Astronomy, Tel Aviv University, 69978 Tel Aviv, Israel*

ABSTRACT. The combination of the observed diffuse radio and hard X-ray emission from clusters of galaxies is used to estimate lower limits on the intracluster magnetic field strength or upper limits on the energy density of the cosmic infrared background radiation.

1. Magnetic field estimates in clusters of galaxies

The determination of the magnetic field strength in clusters of galaxies is vital to our understanding of the physics of hot gas in clusters because it (1) provides additional pressure, (2) couples cosmic ray particles to the intracluster gas, (3) is a seed field for dynamo action in cluster galaxies, (4) constrains the heat conductivity in cooling flows, (5) influences the star formation process in cooling flows.

An upper limit to the magnetic field strength in clusters of galaxies is provided by the virial theorem (Chandrasekhar, 1961, p. 583). For the existence of a stable equilibrium it is necessary that the total magnetic energy of a system does not exceed its negative potential energy, yielding

$$\left[\langle B^2\rangle_{av}\right]^{1/2} < M\, R^{-2}\, [6\, q\, G]^{1/2}$$

$$= 1.2\ 10^{-5}\ \mathrm{G}\ (M/8\ 10^{14}\ M_0)\ (R/3\ \mathrm{Mpc})^{-2}\ (q/1)^{1/2} \qquad (1)$$

for parameters typical for the Coma cluster.

A lower limit to the magnetic field strength is obtained by combining measurements of the diffuse radio and hard X-ray fluxes. Radio emission is most likely synchrotron radiation from a population of relativistic electrons which traverse the intracluster magnetic field. By inverse Compton scattering the target photons of the cosmic microwave background radiation (temperature T_0 = 2.7 K, energy density w_B = 0.25 eV cm^{-3}) and additional (e.g. infrared) radiation fields (temperature T_i, energy density w_i) the same relativistic electrons produce hard X-rays. Since intracluster soft X-ray emission is predominantly thermal, evidence for inverse Compton scattered X-rays should be looked for mainly in the

R. Beck et al. (eds.), Galactic and Intergalactic Magnetic Fields, 487–491.

hard X-ray band, at energies 40 keV and higher (Rephaeli, 1979, 1988). Recently, HEAO-1 A4 data of six Abell clusters have been analyzed (Rephaeli et al., 1987; Rephaeli and Gruber, 1988). There is strong evidence of diffuse radio emission from these clusters, so hard X-ray emission should be detected at some flux level. But due to the insufficient sensitivity of the A4 detectors, we have only upper limits on this emission.

The diffuse radio emission from clusters of galaxies is derived by measuring the total (point source and diffuse) emission with the 100-m Effelsberg radio telescope and subtracting the point source contribution by using Very Large Array observations. For the clusters A1656 (Coma) and A1367 as well as A2319 this has been done by Schlickeiser et al. (1987) and Sievers (1988), respectively. Table 1 summarizes the available best radio and hard X-ray data for six Abell clusters.

We can use the HEAO-1 upper limits to set a lower limit on the magnetic field strength as follows. Consider a relativistic electron distribution (γ: Lorentz factor)

$$N(\gamma) = N_0\, \gamma^{-p} \;\; cm^{-3}, \qquad \gamma > \gamma_{min} \tag{2}$$

in a spherical (radius R) homogeneous source at distance d with the uniform large-scale random magnetic field B and the radiation fields (w_B, T_0) and (w_i, T_i). The synchrotron, I_R, and inverse Compton, I_x, fluxes are

$$I_R(\nu) = (R^3/3d^2)\; \sigma_T^{1/2}\; m_e c\; A(p)\; N_0\; \nu_0 (\nu/\nu_0)^{(1-p)/2} \; Jy \tag{3}$$

with $\nu_0 = 2.8 \cdot 10^6$ (B/1G) Hz and

$$A(p) = \pi\; 3^{(p+1)/2}\; 2^{-7/2}\; (p + 7/3)\; (p+1)^{-1}\; \Gamma[(p+5)/4]\; \Gamma[(3p-1)/12]$$
$$\Gamma[(3p+7)/12] \;/\; \Gamma[(p+7)/4] \tag{4}$$

and

$$I_x(\varepsilon) = (R^3/3d^2)\; (3/4\pi)\; \sigma_T (\hbar c)^{-2}\; F(p)\; N_0\; (\varepsilon/kT_0)^{(1-p)/2}$$
$$[1 + (w_i/w_B)\; (T_i/T_0)^{(p-3)/2}] \tag{5}$$

with

$$F(p) = 2^{p+3}\; (p^2+4p+11)\; (p+1)^{-1}\; (p+3)^{-2}\; (p+5)^{-1}$$
$$\Gamma[(p+5)/2]\; \zeta[(p+5)/2] \tag{6}$$

From the ratio $I_x(\varepsilon)/I_R(\nu) < L$ we can deduce with eqs. (3) and (5) that

$$B > B_{min} = c_1(p)\; L^{-2/(1+p)}\; T_0^{(p+5)/(p+1)}$$
$$[1 + (w_i/w_B)\; (T_i/T_0)^{(p-3)/2}]^{2/(1+p)} \tag{7}$$

For a discussion on the relation of the "synchrotron-inverse Compton-volume-averaged" magnetic field strength to the local mean and RMS magnetic field value we refer the reader to the work of Cowsik and Mitteldorf (1974) and Rockstroh and Webber (1978).

Table 1. Radio and hard X-ray data, estimate of B_{min} and $W_{e,max}$ for $w_i = 0$

Cluster	z	Radio flux[a] (Jy)	Radio radius	Ref.	2σ upper limit on flux at 30 keV (Jy)	Ref.	B_{min}[b] (G)	$W_{e,max}$[b] (erg/cm³)
A 401	0.075	$2.0 \cdot 10^{11}$ $\nu^{-1.4}$	15'	1	$3.8 \cdot 10^{-7}$	6	$4.0 \cdot 10^{-8}$	$2.0 \cdot 10^{-13}$
A1367	0.0213	$(7.4 \pm 1.5) \cdot 10^{6}$ $\nu^{-0.86 \pm 0.12}$	16'	2	$4.2 \cdot 10^{-7}$	7	$5.6 \cdot 10^{-8}$	$7.7 \cdot 10^{-13}$
A1656 (Coma)	0.0235	$(1.7 \pm 0.5) \cdot 10^{12}$ $\nu^{-1.42 \pm 0.06}$	20'	3	$4.8 \cdot 10^{-7}$	7	$1.1 \cdot 10^{-7}$	$2.6 \cdot 10^{-13}$
A2255	0.080	$1.7 \cdot 10^{14}$ $\nu^{-1.7}$	4'	4	$2.4 \cdot 10^{-7}$	6	$1.2 \cdot 10^{-7}$	$7.0 \cdot 10^{-12}$
A2256	0.060	$6.5 \cdot 10^{14}$ $\nu^{-1.8}$	5'	5	$1.0 \cdot 10^{-7}$	6	$1.5 \cdot 10^{-7}$	$3.0 \cdot 10^{-12}$
A2319	0.0529	$(5.7 \pm 0.9) \cdot 10^{12}$ $\nu^{-1.46 \pm 0.15}$	10'	2	$4.4 \cdot 10^{-7}$	7	$1.1 \cdot 10^{-7}$	$1.0 \cdot 10^{-12}$

Notes: *a)* ν in Hz
b) from Rephaeli et al. (1987), Rephaeli and Gruber (1988)

References:
1 Roland et al. (1981)
2 Sievers (1988)
3 Schlickeiser et al. (1987)
4 Harris et al. (1980)
5 Bridle et al. (1979)
6 Rephaeli and Gruber (1988)
7 Rephaeli et al. (1987)

2. Results

2.1 No additional radiation fields $w_i = 0$

If all other radiation fields besides the microwave background are negligibly small ($w_i \simeq 0$) eq. (7) readily yields a lower limit for the magnetic field strength B_{min}, which then can be used in eq. (3) together with the angular size ($\propto R/d$) and the distance of the cluster (from the redshift) to infer an upper limit on the number density of relativistic electrons $N_0 < N_{max}$. Integrating eq. (2) then yields an upper limit on the energy density of relativistic electrons

$$W_e < W_{e_{max}} = \frac{N_{max}\, m_e\, c^2}{p-2}\; \gamma_{min}^{2-p} \qquad (8)$$

with

$$\gamma_{min} = 10^3 \left(\frac{n}{10^{-2}\ cm^{-3}}\right)^{1/2} \left[1 + 0.1 \left(\frac{B}{\mu G}\right)^2\right]^{-1/2} \qquad (9)$$

being fixed by the equality of Coulomb and radiation losses of the relativistic electrons in the cluster, and only weakly dependent on the cluster electron gas density n. Table 1 summarizes the resulting estimates after Rephaeli et al. (1987) and Rephaeli and Gruber (1988).

It is interesting to note the dependence $B_{min} \propto L^{-2/(1+p)}$ in eq. (7) which in case of A2319 yields $B_{min} \propto L^{-0.41}$. A factor 10 improvement on the value of L by more sensitive X-ray observations, would raise the value of B_{min} by a factor of 2.5.

2.2 Additional radiation fields $w_i > 0$

The presence of additional radiation fields in clusters as e.g. infrared photons would raise the estimate of B_{min} by the factor in the square brackets in equation (7) which for p = 3.92 as characteristic for A2319 is shown in Figure 1 as a function of the ratio (w_i/w_B) for various values of T_i. This first demonstrates that $B_{min}(w_i=0)$ is a true lower limit.

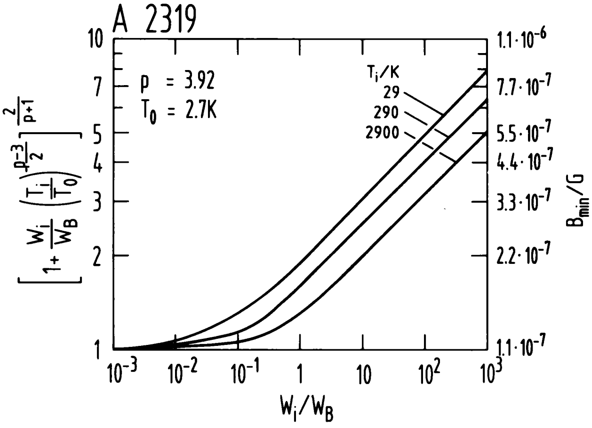

Figure 1. Inverse Compton correction factor accounting for the presence of additional photon gases as a function of the energy density ratio (w_i/w_B) for various values of T_i in case of cluster A2319.

On the other hand, relation (7) can also be used to derive an upper limit for additional radiation fields w_i, if the magnetic field strength B can be inferred by some other observational method as e.g. the Faraday rotation studies by Kim and Kronberg (1989) and Vallèe et al. (1987). In case of the cosmic infrared background radiation this has been recently emphasized by Rephaeli and Schlickeiser (1988). For a magnetic field strength estimate $B = 2\cdot10^7$ G in case of A2319 (Vallée et al., 1987) one finds from Figure 1 the upper limits

$$w_i/w_B \leq \begin{cases} 5.6 & \text{for } T_i = 3000\text{ K } (\lambda_m = 1\ \mu m) \\ 1.8 & \text{for } T_i = 300\text{ K } (\lambda_m = 10\ \mu m) \\ 0.7 & \text{for } T_i = 30\text{ K } (\lambda_m = 100\ \mu m) \end{cases} \qquad (10)$$

References

Bridle, A.H., Fomalont, E.B., Miley, G.K. and Valentijn, E.A. (1979) Astron. Astrophys. **80**, 201.

Chandrasekhar, S. (1961) Hydrodynamic and Hydromagnetic Stability, Dover Publications, New York.

Cowsik, R. and Mitteldorf, J. (1974) Astrophys. J. **189**, 51.

Harris, D.E., Kapahi, V. and Ekers, R. (1980) Astron. Astrophys. Suppl. **39**, 215.

Kim, K.-T. and Kronberg, P.P. (1989) these proceedings.

Rephaeli, Y. (1979) Astrophys. J. **227**, 364.

Rephaeli, Y. (1988) Comments on Ap. **12**, 265.

Rephaeli, Y. and Gruber, D.E. (1988) Astrophys. J. **333**, 133.

Rephaeli, Y. and Schlickeiser, R. (1988) Astron. Astrophys. **194**, 99.
Rephaeli, Y., Gruber, D.E. and Rothschild, R.E. (1987) Astrophys. J. **320**, 139.
Rockstroh, J.M. and Webber, W.R. (1978) Astrophys. J. **224**, 677.
Roland, J., Sol, H., Pauliny-Toth, I. and Witzel, A. (1981) Astron. Astrophys. **100**, 7.
Schlickeiser, R., Sievers, A. and Thiemann, H. (1987) Astron. Astrophys. **192**, 21.
Sievers, A. (1988) PhD dissertation, University of Bonn
Vallée, J.P., Broten, N.W. and MacLeod, J.M. (1987) Astrophys. Lett. **25**, 181.

BURNS: How does your estimate of the B-field from inverse Compton arguments compare with that from equipartition calculations?

SCHLICKEISER: The equipartition value lies well between my estimate of the lower and upper limit of the magnetic field. In case of Coma I refer you to Figure 11 of Schlickeiser et al. (1987) where $H_{eq} \simeq 2\ \mu G$, $H_{max} = 12\ \mu G$ and $H_{min} = 0.1\ \mu G$.

KIM: In your paper in 1987 you render the spectral steepening, especially at high frequencies, to the in-situ particle reacceleration. Indeed, this explanation is possible, but conventionally the spectral steepening is taken as a sign for ageing of particles. This means that the more energetic particles lose more energy than gained. What kind of particle reacceleration do you think possibly is going on in the intracluster medium?

SCHLICKEISER: In a steady-state case synchrotron ageing steepens your injection spectrum $q \propto E^{-s}$ to $N \propto E^{-(s+1)}$, so you would not get an exponential cutoff. Curved spectra only result from nonstationary calculations which, I think, do not apply to this situation. Particles can be accelerated in-situ by the turbulence and the bow shocks generated by random movement of the cluster galaxies and galactic wakes. I think the experimental evidence, especially at high frequencies, favours the in-situ acceleration model.

SHUKUROV: To what parameter of the magnetic field refer your estimates – the true local field strength, the r.m.s. field, or something else?

SCHLICKEISER: It refers to the volume-integrated magnetic field strength weighted with the spatial distribution of relativistic electrons $\langle N_e\ B^{(p+1)/2}\rangle$. If the spatial distributions of relativistic electrons and B are correlated, this is different from the local field and the r.m.s. field, as has been emphasized earlier by Woltjer and Cowsik and Mitteldorf in the early seventies. In our calculation we also assumed that the field is random on larger scales, i.e. large compared to the Larmor radius of the radiating electrons but small compared to the size of the cluster. That seems to be justified in light of the Faraday rotation measurements (see talk by Kim and Kronberg).