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EVIDENCE FROM GRAVITATIONAL LENSING FOR A NONTHERMAL PRESSURE SUPPORT IN THE CLUSTER OF GALAXIES ABELL 2218

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ABSTRACT

The central mass distribution of clusters of galaxies can be inferred from gravitationally lensed arcs with known redshifts. For the cluster Abell 2218, this method yields a core mass which is larger by a factor of 2.5 ± 0.5 than the value deduced from X-ray observations, under the assumptions that the gas is supported by thermal pressure and that the cluster is spherical. We examine various potential causes for this discrepancy and show that a nonthermal pressure support is a plausible explanation. Such a pressure can be provided by strong turbulence and equipartition magnetic fields (~ 50 μG) that are tangled on small scales in the cluster core. The turbulent and magnetic pressures do not affect the measured Sunyaev-Zel'dovich effect. Comparable intracluster magnetic fields (~ 10–100 μG) have already been detected by Faraday rotation in other clusters. If generic, a small-scale equipartition magnetic field should affect the structure of cooling flows and must be included in X-ray determinations of cluster masses.

Subject headings: dark matter — galaxies: clusters of — gravitational lensing — magnetic fields

1. INTRODUCTION

The central mass distribution in clusters of galaxies can be inferred unambiguously from gravitational lensed arcs with known redshifts (Grossman & Narayan 1989). Surprisingly, this method yields a core radius which is smaller by a factor of a few than the value deduced from X-ray observations (e.g., Jones & Forman 1984; Edge & Stewart 1991) under the standard assumptions of thermal hydrostatic equilibrium and spherical symmetry. This discrepancy was highlighted recently by Miralda-Escudé & Babul (1994, hereafter MB94). Possible explanations of the discrepancy involve different violations of the standard assumptions, such as deviations from sphericity or nonthermal contributions to the gas pressure. In this *Letter* we show that the plausible explanation to the above discrepancy in Abell 2218 is the existence of turbulence and equipartition magnetic fields in the cluster core.

Strong magnetic fields were detected in many clusters of galaxies through Faraday rotation of radio sources (Kim et al. 1990; Kim, Tribble, & Kronberg 1991; Taylor & Perley 1993). The detected fields have a typical magnitude of a few microgauss and a coherence length of 10–100 kpc. Although significant, these fields are still an order of magnitude smaller than the equipartition values needed to make them dynamically important for the support of the cluster gas. However, the Faraday rotation method is limited from probing fields that are tangled on small spatial scales, because field reversals along the line of sight cancel out in the observed rotation measure. The possibility therefore remains that somewhat stronger magnetic fields, tangled on small scales ($\lesssim 10$ kpc), make a significant contribution to the pressure support of the cluster gas. Indeed, tangled magnetic fields with magnitudes as high as ~ 10–100 μG were found in several clusters. In the Hydra A cluster, Taylor & Perley (1993) found a magnetic field ~ 6 μG on a scale ~ 100 kpc, and a tangled field ~ 30 μG on smaller scales. In A1795, Ge & Owen (1993) observed rotation measures exceeding 3000 rad m^{-2}, which translate to a field greater than 20 μG. Similar results were obtained by Dreher, Carilli, & Perley (1987) for Cygnus A, and by Perley & Taylor (1991) for 3C 295. Such fields should result in a discrepancy between the thermal pressure of the gas and the depth of the cluster potential well. In this work we argue that this discrepancy was in fact detected through gravitational lensing in A2218. The outline of this *Letter* is as follows. In § 2 we present a method to derive the mass of the cluster core from the X-ray observation (cf. Fabricant, Rybicki, & Gorenstein 1984) and independently from gravitationally lensed arcs. In § 3 we apply our approach to A2218 and show that these two mass estimates differ by a factor of 2.5 ± 0.5. We argue that the discrepancy can naturally result from strong turbulence and equipartition magnetic fields in the cluster core. In § 4 we summarize our results and discuss some future empirical tests.

2. EMPIRICAL RELATION BETWEEN THE LENSING MASS AND X-RAY DATA

The standard description of the hot gas in clusters of galaxies assumes hydrostatic support by thermal pressure and spherical symmetry. To consider deviations from these standard assumptions, we express the total gas pressure as the sum of thermal and nonthermal components $p = p_t + p_{nt}$, and assume an ellipsoidal geometry for the cluster gas. An elongation of the cluster along the line of sight is the most conceivable selection bias in both the X-ray and lensing observations. The thermal pressure of the gas at a temperature T is given by $p_t = \rho_g kT/\mu m_p$, where ρ_g is its mass density, k is the Boltzmann constant, m_p is the proton mass, and $\mu \approx 0.6$ is its mean atomic weight. The nonthermal pressure may contain three separate parts (which are comparable in magnitude for the interstellar medium of the Galaxy), namely, magnetic pressure p_B, turbulent pressure p_{turb}, and cosmic-ray pressure p_{ray}. A magnetic field that is tangled on scales small compared with the cluster core radius (~ 100 kpc) yields a diagonal magnetic stress tensor with a pressure[1] $p_B = \langle |\boldsymbol{B}|^2 \rangle / 8\pi$. Turbulent motions and bulk velocities add $p_{\rm turb} = \frac{1}{3}\langle \rho_g v^2 \rangle$, while cosmic rays confined by the magnetic field provide their own kinetic pressure $p_{\rm ray} \lesssim p_B$.

The hydrostatic equilibrium equation is

$$\frac{1}{\rho_g} \nabla p = -\nabla \Phi , \tag{1}$$

where Φ is the gravitational potential of the cluster. Since gravitational lensing probes mainly the cluster core, we assume for simplicity that

$$p_{\rm nt} = \alpha p_t , \quad \alpha = {\rm constant} , \tag{2}$$

and that the gas is isothermal. Equations (1) and (2) yield $\rho_g \propto \exp\,[-\mu m_p \Phi/(1+\alpha)kT]$. The total mass density of the cluster can then be inferred from Poisson's equation,

$$\rho_{\rm tot} = \frac{1}{4\pi G} \nabla^2 \Phi = \frac{(1+\alpha)kT}{4\pi G \mu m_p} \nabla^2 \ln \rho_g^{-1} , \tag{3}$$

if the gas density distribution is known from X-ray observations.

The X-ray surface brightness of the cluster gas is obtained by a line integral of its bremsstrahlung emissivity, $I \propto \int \rho_g^2\, dz$, where we use cylindrical (r, z) coordinates around the line of sight. Typically, the observed X-ray brightness contours are close to circular. We therefore assume axial symmetry around the line of sight and adopt the simplest model to describe deviations of clusters from sphericity. In particular, the gas density is assumed to be a function of the ellipsoidal coordinate $m^2 = r^2/r_c^2 + z^2/z_c^2$, where (r_c, z_c) is the ellipsoidal core size. Note that for a spherical gas distribution, $m = R/R_c$ is the radial coordinate and $R_c = r_c = z_c$ is the core radius. With $\rho_g = \rho_g(m)$ we can use Abell's equation (e.g., Binney & Tremaine 1987, pp. 101, 651) to invert the emissivity I and ρ_g:

$$\rho_g^2 \propto \int_{mr_c}^{\infty} \left(-\frac{dI}{dr}\right) \frac{dr}{(r^2/r_c^2 - m^2)^{1/2}} . \tag{4}$$

Typically, the X-ray surface brightness profile $I(r)$ is well fitted by a functional form (e.g., Birkinshaw & Hughes 1994, hereafter BH94; Bahcall & Lubin 1994 and references therein)

$$I(r) \propto \left(1 + \frac{r^2}{r_c^2}\right)^{1/2 - 3\beta} \frac{z_c}{r_c} , \tag{5}$$

with $\beta = 0.5$–0.9. Equation (4) then yields a gas distribution of the form

$$\rho_g(m) \propto (1 + m^2)^{-3\beta/2} . \tag{6}$$

Gravitational lensing probes the total mass enclosed within a cylinder of a particular radius $r = b$ along the line of sight. To find this mass, we calculate the volume integral,

$$M(b) = \int_V \rho_{\rm tot}\, dV = -\frac{(1+\alpha)kT}{4\pi G \mu m_p} \int_S \nabla \ln \rho_g \cdot dS$$
$$= -\frac{(1+\alpha)kTb}{G\mu m_p} \int_0^{\infty} dz \left.\frac{\partial \ln \rho_g}{\partial r}\right|_{r=b} , \tag{7}$$

where we have substituted equation (3) and have used Gauss's theorem to convert the volume integral to a surface integral on an infinite cylinder. Note that the lensing mass $M(b)$ depends only on the shape of the gas density distribution and not on its absolute normalization. Using equation (6), we finally obtain

$$M(b) = \frac{\pi k T}{G\mu m_p} \frac{3\beta}{2} \frac{b^2}{(b^2 + r_c^2)^{1/2}} (1+\alpha) \frac{z_c}{r_c} . \tag{8}$$

This is our basic result. Observational measurements of T, β, r_c, b, and $M(b)$ can be used to determine the quantity $(1+\alpha)z_c/r_c \equiv \eta$. Values of $\eta \neq 1$ quantify the degree to which the standard assumptions concerning the cluster gas are violated.

Finally, we consider another probe of the thermal state of the cluster gas, namely, the Sunyaev-Zel'dovich (S-Z) effect. This effect involves Thomson scattering of the cosmic background photons by the hot cluster electrons. The frequency shift of a scattered photon results from the second-order Doppler effect in the thermal velocity of the electrons and is therefore proportional to kT. The scattering probability is proportional to the integral of the electron density along the line of sight; thus the net S-Z effect is linear in the electron pressure. The scattering of microwave photons to higher energies leads to a decrease in the Rayleigh-Jeans temperature of the cosmic background radiation $T_{\rm RJ}$, $\Delta T_{\rm RJ}/T_{\rm RJ} \propto -\int p_t\, dz$. Subsonic turbulent velocities provide $v_{\rm turb}^2 \lesssim (kT/m_p)$ and result in an effect that is smaller than the thermal effect of the electrons by the electron-to-proton mass ratio. The existence of magnetic fields and cosmic rays can also be ignored in calculating the S-Z distortion. Thus, for the density profile of equation (6) the distortion is given by

$$\Delta T_{\rm RJ}(r) \propto \left(1 + \frac{r^2}{r_c^2}\right)^{1/2 - 3\beta/2} \frac{z_c}{r_c} , \tag{9}$$

with no reference to the nonthermal pressure. Note that according to equations (5) and (9), the elongation of clusters does not change the radial shapes of either the X-ray surface brightness or the S-Z distortion. It only enhances both effects by the axis ratio factor z_c/r_c.

3. APPLICATION TO A2218

Next we apply the results from § 2 to study A2218, for which there is a wealth of data, including the X-ray surface brightness, the positions and redshifts of gravitationally lensed arcs, the S-Z effect, and the velocity dispersion of the member galaxies. We denote the Hubble constant by $H_0 = 100\ h$ km s^{-1} Mpc^{-1}.

A2218 is a cluster at a redshift $z = 0.175$ (Le Borgne, Pelló, & Sanahuja 1992) with richness class 4, and X-ray luminosity in the 2–10 keV band of 10^{45} ergs s^{-1} (David et al. 1993), a central proton density of $(5.4 \pm 0.5) \times 10^{-3}(h/0.5)^{1/2}(z_c/r_c)^{-1/2}$ cm^{-3} (BH94), and an X-ray temperature of $kT = 6.7^{+0.5}_{-0.4}$ keV (McHardy et al. 1990). At the redshift of the cluster, $1'' \equiv 1.9$ h^{-1} kpc. The optical image of this cluster reveals several gravitationally lensed arcs. One of the arcs is at a redshift of $z_s = 0.702$ with a critical angular radius of $\theta_{\rm crit} = 20\farcs8$ centered at the X-ray peak of the cluster (Pelló et al. 1992; see also MB94). The S-Z effect for A2218 was most recently analyzed by BH94, who improved previous work by McHardy et al. (1990) and derived a Hubble constant of $h = (0.65 \pm 0.25) \times (r_c/z_c)$. The *Einstein* X-ray surface brightness profile was fitted in BH94 using equation (5). The best-fit model has $\beta = 0.65 \pm 0.04$ and an angular core radius of $\theta_c = 60'' \pm 10''$. These values are also in good agreement with recent observation by *ROSAT*

[1] The magnetic pressure we consider contains two components, arising from the magnetic energy density $u_{\rm mag} = (\delta B^2/8\pi)$ and the kinetic energy density $u_{\rm kin} = u_{\rm mag}$ of Alfvén waves (Dewar 1970; McKee & Zweibel 1994). Other modes are Landau-damped (Kulsrud 1994). The magnetic virial theorem (Shu 1992) yields the isotropic wave pressure $p_B = \frac{2}{3}u_{\rm kin} + \frac{1}{3}u_{\rm mag} = \delta B^2/8\pi$. For strong waves $\delta B \sim B$.

(Stewart et al. 1993). We therefore adopt them in the analysis that follows.

The observed arcs primarily constrain the total mass inside the cylinder of the critical radius b. The constraint is relatively insensitive to the mass distribution profile (e.g., Kochanek 1991) and can be expressed as

$$M(b) = \frac{c^2\theta_{\rm crit}^2}{4G}\frac{D_L D_S}{D_{LS}}\,, \quad \theta_{\rm crit} \equiv \frac{b}{D_L}\,, \quad r_c \equiv \theta_c D_L\,, \qquad (10)$$

where D_L, D_S, and D_{LS} are the angular diameter distances to the lens, to the source, and from the lens to the source, respectively (see Kochanek 1992 for the redshift dependence of D on cosmology). For A2218, equation (10) gives $M(b) = 0.32\, h^{-1} \times 10^{14}\, M_\odot$ assuming $\Omega = 1$. This result has a negligible dependence (less than 3%) on the underlying cosmology. Equation (10) assumes an axisymmetric lens geometry. In reality, the contribution from the presence of a central cD galaxy and substructure in A2218, and the ellipticity needed to break the cylindrical symmetry and form arcs instead of rings, lower this mass estimate by $\approx 15\%$ (Miralda-Escudé 1994).

However, from equation (8) we obtain $M(b) = (0.11 \pm 0.02)(kT/6.7\ {\rm keV})\eta\, h^{-1} \times 10^{14}\, M_\odot$. In order for these two mass estimates to be consistent, we find

$$\eta \equiv (1+\alpha)\frac{z_c}{r_c} = 2.5 \pm 0.5\,, \qquad (11)$$

where the error bars are dominated by the uncertainties in the X-ray observations and can be reduced considerably in the future.

The first possible origin for this value of η is that the cluster is prolate. If the contribution of nonthermal pressure is negligible, then the axis ratio for the gas distribution must be $z_c/r_c \approx 2.5$. We then find, using equations (3) and (6), that the total mass distribution has an axis ratio of roughly 6:1 in the cluster core. The axis ratio for the total mass is larger than z_c/r_c because the gas follows the potential, which tends to be smoother than the underlying mass distribution (Binney & Tremaine 1987). Furthermore, the total mass distribution has an unphysical dumbbell shape at large radii for any value of $(z_c/r_c) > \sqrt{3/2}$, as long as the gas distribution is described by equation (6). The above properties of the total mass distribution do not seem plausible. With an axis ratio 6:1, the probability for a perfect alignment of the cluster along the line of sight (as required by the circular X-ray brightness contours) is only a few percent times the relatively small fraction of prolate clusters seen from the side (Jones & Forman 1992). In addition, such a configuration is unstable against bending modes (Merritt & Hernquist 1991). Therefore, a full accounting for the discrepancy by the prolateness of the cluster is unlikely.

The alternative explanation involves a nonthermal pressure support of the gas. This explanation is consistent with other observational data. The observed velocity dispersion of galaxies (Le Borgne et al. 1992) 1370^{+160}_{-120} km s^{-1} is larger than $v_t = (kT/\mu m_p)^{1/2} = 1050^{+40}_{-30}$ km s^{-1}. In addition, the most recent determination of the Hubble constant from the S-Z effect in A2218 (BH94) did not yield a value smaller by a factor of 2.5 than the range $0.5 \lesssim h \lesssim 1$, as would be expected according to equation (9) if the gas distribution is elongated along the line of sight rather than being supported by a nonthermal pressure.

In principle, all the potential sources of nonthermal pressure are equally viable in accounting for the mass discrepancy. However, large bulk velocities can be excluded. Supersonic rotational velocities would have flattened the X-ray brightness contours, in conflict with the observed nearly circular shape. Large radial velocities would have relaxed to equilibrium within a dynamical time ($r_c/v_{\rm th} = 10^8\, h^{-1}$ yr). Indeed, the X-ray map of the cluster core does not show large-scale inhomogeneities of the gas. In addition, cooling flow velocities are expected to be highly subsonic at the core radius. The existence of a strong turbulent pressure $p_{\rm turb} \sim p_t$ is likely to be accompanied by equipartition magnetic fields, in analogy with the conditions in the interstellar medium of the Galaxy (cf. Kulsrud & Anderson 1992). We therefore infer that equation (11) implies the existence of dynamically important turbulence and magnetic fields in A2218. For example, $\alpha \approx 2$ may correspond to $p_B \approx p_{\rm turb} \approx p_t$. This amounts to an equipartition magnetic field strength

$$B = 53\ \mu{\rm G}\left(\frac{n_e}{5\times 10^{-3}\ {\rm cm}^{-3}}\right)^{1/2}\left(\frac{kT}{7\ {\rm keV}}\right)^{1/2}\,, \qquad (12)$$

where n_e is the electron density. Previous observations (cf. § 1) of other clusters found evidence for fields that are somewhat weaker or comparable to the equipartition value (1–100 μG). However, even relatively weak fields should eventually approach equipartition values at some radius as they are dragged inward by the cooling flow of the cluster (Soker & Sarazin 1990).

The existence of strong fields results in cyclotron cooling of the cluster electrons. However, since the plasma frequency of the cluster, $f_p = 0.64$ kHz $(n_e/5\times 10^{-3}\ {\rm cm}^{-3})^{1/2}$, is larger than the cyclotron frequency, $f_c = 0.14$ kHz $(B/50\ \mu{\rm G})$, the cyclotron emission is suppressed. The plasma cutoff is effective across the entire region where the field is in equipartition with the thermal pressure of the gas, because the ratio between the above frequencies scales as $\rho^{1/2}/B \propto (p_t/p_B)^{1/2}$. The cyclotron cooling time, greater than 10^{11} yr, is much longer than the bremsstrahlung cooling time in the cluster core, and any residual emission would occur at the unobservable frequency regime of the order of kilohertz. On the other hand, the synchrotron emission by cosmic rays is observable at microwave frequencies. From the fact that the measurement of the S-Z effect (BH94) was not dominated by a synchrotron signal, we conclude that $p_{\rm ray} \ll p_t$. This leaves only magnetic fields and turbulence as viable sources of nonthermal pressure in A2218.

4. CONCLUSIONS

We have shown that the core mass derived from the standard X-ray analysis is smaller than the independent estimate from gravitational lensing by a factor of 2.5 ± 0.5. This conclusion is in agreement with the recent studies by MB94 and Wu (1994), and with a recent study of on the outer part of a cluster by Kaiser et al. (1994). Our result is not sensitive to the underlying cosmology. The main uncertainty is associated with the temperature profile at the cluster core, which was not resolved by early X-ray spectroscopic observations (McHardy et al. 1990). Recent observation by *ROSAT* is consistent with an isothermal cluster (Stewart & Edge 1993). However, note that a lower temperature at the core, as observed in other clusters, only makes the discrepancy larger by lowering the mass estimate from the X-ray observations.

The above mass discrepancy can be resolved by relaxing various underlying assumptions of the analysis. In § 3 we argued that the nonthermal pressure provided by turbulence and magnetic fields in equipartition with the thermal energy of the gas can fully account for the above discrepancy in a spherical cluster. This explanation is consistent with other observational data on A2218. Unlike a cluster elongation, the turbulent and magnetic pressures do not influence the S-Z effect, in line with the observations (BH94). The square of the observed velocity dispersion of galaxies (Le Borgne et al. 1992) is larger than $kT/\mu m_p$ by a factor of $1.7^{+0.4}_{-0.3}$, a value that may also reflect the different bias and virialization history of the galaxies relative to the gas in the cluster.

Magnetic fields greater than or of the order of microgauss were detected by Faraday rotation in many other clusters (cf. § 1). The tangled magnetic field we predict for A2218 is comparable in amplitude to the strong fields already detected in some of these clusters. Although the average rotation measure (RM) of such a tangled field is close to zero, the dispersion in the rotation measure should be large,

$$\langle \mathrm{RM}^2 \rangle^{1/2} = 2140(n_e/5 \times 10^{-3})(B/50\ \mu\mathrm{G}) \times (l/10\ \mathrm{kpc})(N/10)^{1/2}\ \mathrm{rad\ m^{-2}}\ ,$$

where N is the number of cells of size l and field strength B along the line of sight. Aside from the existence of such strong magnetic fields, our model predicts a considerable "β-discrepancy" (cf. Bahcall & Lubin 1994) for A2218. The radial distributions of the gas and the galaxies should not be consistent with their relative velocity dispersions, because of the nonthermal support of the gas.

Although galaxy-driven turbulence cannot readily produce the observed microgauss magnetic field (De Young 1992), there are a variety of field-generating mechanisms operating in the cores of clusters (Taylor & Perley 1993). A natural source for the needed fields is dynamo amplification of seed galactic fields (Ruzmaikin, Sokoloff, & Shukurov 1989; Kulsrud & Anderson 1992) due to the strong turbulence and shearing present during the collapse and virialization stages of the cluster. In particular, for an $\Omega = 1$ universe the accretion of clumps of matter by the cluster continues at all times (Richstone, Loeb, & Turner 1992) and can persistently excite turbulence in it. The amplified magnetic field can be further compressed by the cooling flow of the cluster (Soker & Sarazin 1990), which may also be turbulent (Fabian 1990). In analogy with the interstellar gas, the amplification process would saturate at equipartition with the turbulent pressure. Since the magnetic diffusion time across a scale l is very long, $\sim 10^{34}$ yr $\times$ $(l/\mathrm{kpc})^2$, the field would be frozen in the cluster plasma but may change its topology by reconnection. Even as field lines tend to straighten up, a considerable component of the magnetic pressure could still remain in the form of strong Alfvén waves that suffer relatively weak damping in a fully ionized plasma (McKee & Zweibel 1994).

If future observations show that turbulence and magnetic fields are dynamically important not only in the inner parts but also in the outer parts of rich clusters, this would have a variety of interesting implications. First, it would increase the cluster mass-to-light ratio by a factor of a few and shift the estimate of Ω from the range 0.2–0.3 (e.g., White et al. 1993) to about unity. The baryonic mass fraction of clusters would consistently decrease to values $\lesssim 0.1$. Both changes would make the cluster data agree with the predictions of inflation and standard nucleosynthesis. Second, an increase in the high-mass tail of the cluster mass function would affect the comparison between observational data and popular cosmological models (Bahcall & Cen 1993). Finally, this would raise the possibility that magnetic fields have a nonnegligible influence on structure formation in the universe.

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