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The Magnetic Field in A3667

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The magnetic field strength of galaxy clusters may be estimated in several different ways, such as statistical measurements of extragalactic Faraday rotation, use of Inverse Compton emission, estimates from diffuse synchrotron emission and Kelvin-Helmholtz stability arguments along sharp, cold gas fronts. At present A3667 is unique in that it allows the field to be estimated using each of these techniques. I will present a summary of the field estimates for each technique and discuss these results, which are found to be consistent, within the errors, and suggest a central magnetic field of 1–2 μG, tangled on sizes of roughly 100 kpc. This characteristic field has then been enhanced in both the region of the central cold front and at the locations of the putative shock induced Mpc-scaled radio emission observed on the cluster periphery.

1. Introduction

Magnetic fields are assumed to be pervasive throughout the Universe on all scales, from the fields surrounding planets right up to fields in the intracluster and intergalactic media. In recent years the role of magnetic fields in both galactic and extragalactic regimes has gained increased attention across many astrophysical disciplines. For example, the magnetic field is a key factor in studies of large-scale structure formation, galaxy and star formation, and cosmic ray generation. Cosmic magnetic fields, on all scales, have been studied since the late seventies with varying degrees of success. While it is clear that magnetic field research has progressed considerably in this time, the mostly indirect measurement techniques have meant that it has been difficult to address many basic issues. Questions as to how strong magnetic fields are, how uniform they are, what the seeding and amplification mechanisms are, and, most importantly, what their contribution is to the energy density of the intergalactic medium, remain topics of animated debate.

The presence of magnetic fields in galaxy clusters is revealed by both statistical Faraday rotation studies and the presence of diffuse synchrotron emission associated with the intracluster medium (ICM). In addition, estimates of the intracluster field strength can be made using Inverse Compton scattering and Kelvin-Helmholtz stability arguments for cold fronts in the cluster X-ray gas. The ACO cluster A3667 is at present unique in that it allows magnetic field estimates to be made using all available techniques. I will discuss this particular cluster and its magnetic field as derived by various arguments.

2. The ACO Cluster A3667

The ACO Cluster, A3667 (Abell et al. 1989), is arguably the most interesting and consequently most studied cluster in the southern sky. However, the physical picture of the cluster is constantly evolving as more multi-wavelength data is obtained and it seems that many basic questions about the dynamical history of A3667 remain unanswered.

A3667 is a rich, X-ray luminous, southern galaxy cluster which has the distinction of being one of only a handful of galaxy clusters to have a cold gas front at the center and the only cluster yet seen with two diffuse radio emission regions. It is relatively close, having a redshift of 0.0555 and has a high velocity dispersion, σ= 1102 km s^{-1} (Johnston-Hollitt et al. 2003a). The Abell richness class is 2 and the Bautz-Morgan type is I–II (Abell et al. 1989), indicating the presence of many galaxies in this region. *ROSAT* observations revealed a high X-ray luminosity with $L_x = 8.74 \times 10^{44}\ h_0^2$ ergs s^{-1} in the 0.4–2.4 keV range (Ebeling et al. 1996), making it one of the brightest X-ray sources in the southern sky. Furthermore, the X-ray isophotes are distorted in the direction of the reported bimodal optical distribution and observations from the *Einstein* satellite are reported as showing clear evidence of substructure (Sodré et al. 1992). Observations of the temperature of the X-ray gas with *ASCA* by Markevitch et al. (1999) showed the central part of the cluster to be cool and the X-ray surface brightness profile along the elongation axis suggests a shocked region is present. Recent *Chandra* observations confirmed this interpretation revealing the central part of the cluster to contain a cold gas front moving through the warm intracluster medium (Vikhlinin et al. 2001).

However, by far the most dramatic features of A3667 are the two symmetrically located regions of diffuse radio emission, first detected in a 843 MHz image taken with the Molonglo Observatory Synthesis Telescope, MOST (Röttgering et al. 1997), and then confirmed and studied in detail at 1.4 and 2.4 GHz with the Australia Telescope Compact Array, ATCA (Johnston-Hollitt 2003, see Figure 2). The combination of all the observed features has been interpreted as evidence that the cluster is observed in a post merger state (Röttgering et al. 1997; Roettiger et al. 1999; Markevitch et al. 1999; Vikhlinin et al. 2001). A new study of the optical galaxy population has shown that the velocity distribution is well modeled by a Gaussian and that there is little evidence of substructure in the velocity distribution suggesting that the putative merger axis must be entirely within the plane

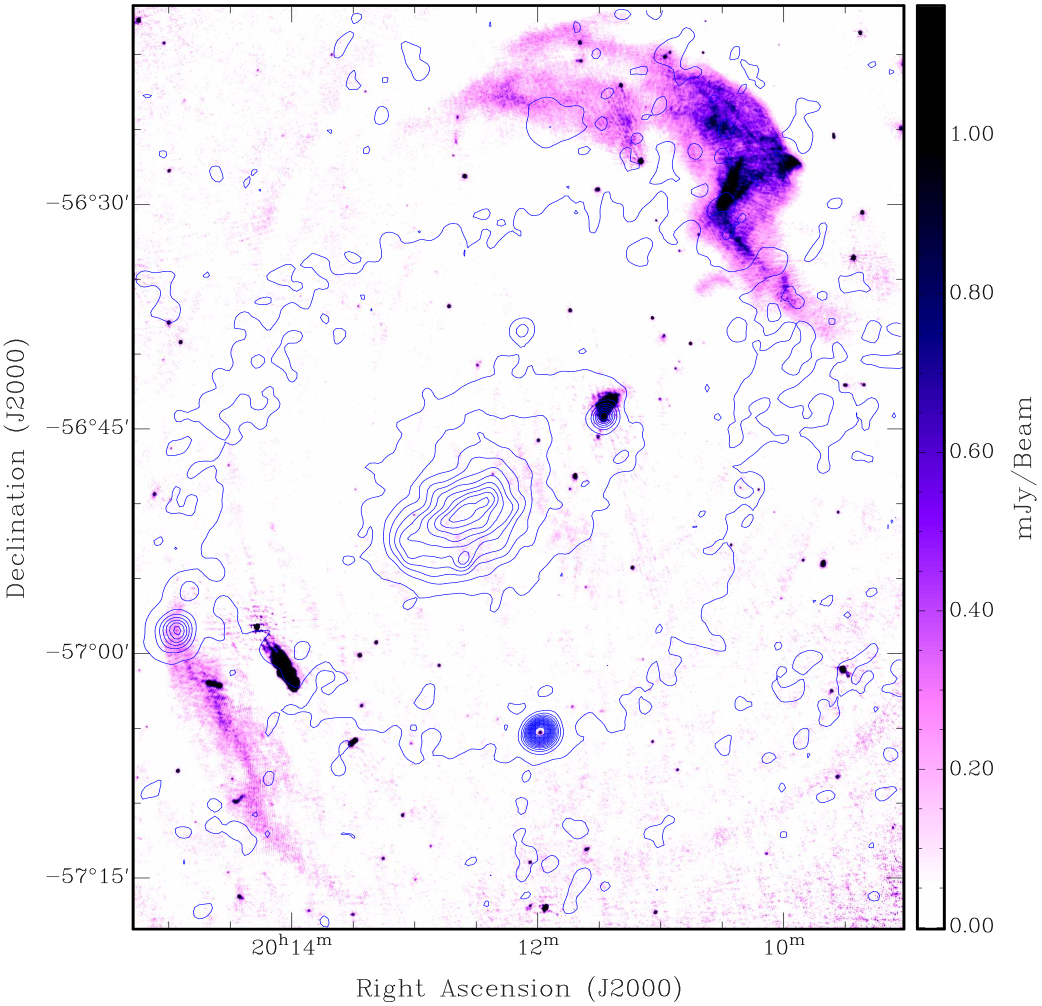

FIG. 1.— 1.4 GHz ATCA data for A3667 shown at 6 arcsecond resolution and overlaid with contours from the *ROSAT* PSPC observation (Johnston-Hollitt 2003). The radio sensitivity is 0.09 mJy per beam. X-ray contours are given at 2.25, 7.25, 12.25, 17.25, 22.25, 27.25, 32.25, 37.25, 42.25, 47.25 and 52.25 times the background.

of the sky (Johnston-Hollitt et al. 2003a).

3. Diffuse Radio Emission in A3667

The diffuse radio source to the northwest of A3667 is not a recent discovery. It has been observed with increasing frequency since the early 60s when it was first included as one of the brightest sources in the MSH catalog (Mills et al. 1961) with a flux density of 81 Jy at 85.5 MHz being reported. Even the complex shape and low surface brightness have been known for the last 30 years. Ekers (1969) attempted to model the source using limited data from the two element ANRAO interferometer but found the brightness distribution too complex. Shortly after, it was imaged at 408 MHz with MOST by Schilizzi et al. (1975) who commented on the unusual twisted shape and low surface brightness. Goss et al. (1982) improved upon the resolution of Schilizzi et al. (1975) by observing the source at 1415 MHz with the Fleurs Synthesis Telescope. They reported a total flux density of 1.5 ± 0.2 Jy for the source and argued that as this was in good agreement with the result of Ekers (1969) who observed 1.9 Jy, that there was little or no flux missing for the source despite their low sensitivity to large-scale structure. It was not until the source was mosaiced with the ATCA by Röttgering et al. (1997) that a clear picture of the extent of the source was obtained, revealing that all previous observations were missing part of the source structure. Röttgering et al. (1997) improved the flux density estimate further, giving a lower limit of 2.4 ± 0.2 Jy at 1.4 GHz and 1.4 Jy at 2.4 GHz. Also in Röttgering et al. (1997), though not directly discussed in the paper, was a second diffuse source to the southeast of the cluster. This source was seen in a new 843 MHz image taken with the Molonglo Synthesis Telescope. Both sources were shown to border the edge of the X-ray emission as observed with *ROSAT*. Recently the entire cluster was re-observed at 1.4 and 2.4 GHz and the Northern part also at 4.8 GHz (Johnston-Hollitt 2003), revealing filamentary structure in the diffuse radio emission and further increasing the northern source size and flux density to 3.7 ± 0.3 Jy at 1.4 GHz. In comparison, the southern source was found to

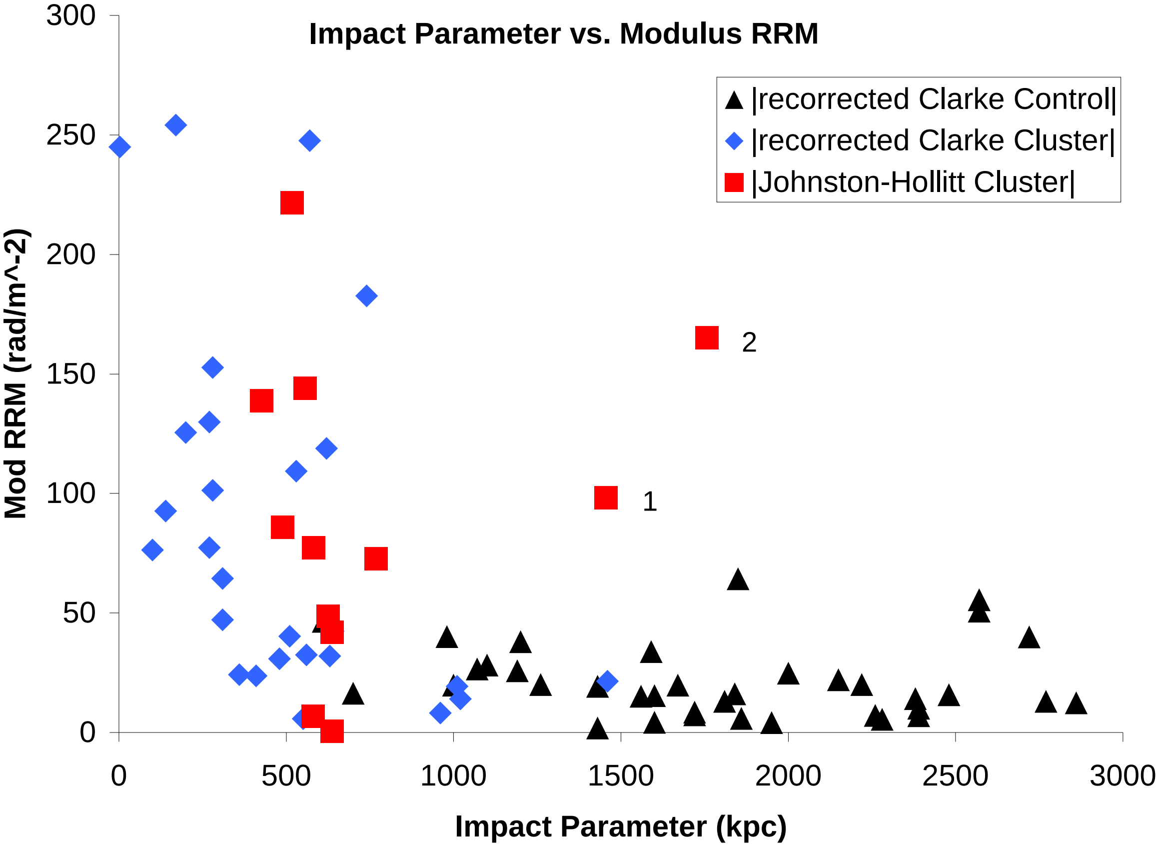

Fig. 2.— Impact Parameter versus Residual Modulus Rotation Measure. The blue diamonds correspond to sources viewed in projection through a sample of 24 northern clusters, whereas the black triangles correspond to the non-cluster control RMs. Both samples were originally obtained by Clarke (2000) but have been corrected for the Galactic contribution using an interpolated all-sky RM map (Johnston-Hollitt et al. 2002). The red squares represent RMs measured in project through a sample of 6 southern galaxy clusters (Johnston-Hollitt et al. 2003b). The labeled points correspond to sources seen in projection through a region of diffuse synchrotron emission in A3667 (see Figure 3).

have a flux density of 0.30 ± 0.02 Jy at 1.4 GHz. Figure 1 shows the most sensitive, high resolution image of A3667 yet taken overlaid with contours from the *ROSAT* PSPC data (Johnston-Hollitt 2003). In addition, marginal evidence from low resolution imaging was presented for a central cluster halo with a flux density of 33 ± 6 mJy at 1.4 GHz. If this detection is confirmed then A3667 will be the first object seen with a central halo and two Mpc-scale diffuse emission regions. At the time of writing new data was being obtained to verify the presence of the halo.

4. **Magnetic Field Estimates**

In Johnston-Hollitt et al. (2003b) a statistical search for an enhancement of the rotation measures, RMs, observed towards the center of southern non-cooling flow clusters was conducted. Data obtained in this study for six southern galaxy clusters, including A3667, were compared to that taken for 24 northern clusters by Clarke (2000).

First the RMs of the Southern sample were corrected for the contribution from the Galactic rotation measure, G_{RM}. This was done by using an interpolated all-sky rotation measure map generated from published RM catalogs (Johnston-Hollitt et al. 2002). The map is an estimate of the Milky Way's contribution to the RM sky. The Galactic contribution was subtracted from the measured RM to give a residual RM (RRM), which represents a combination of the cluster RM and the intrinsic source RM. Clarke (2000) also corrected for the Galactic contribution via examining published RMs in a 15 degree radius about each cluster. In order to directly compare the two datasets, the RRMs from the Clarke (2000) sample were recalculated using the interpolated map. In most cases this made a 5–10% difference in the RRM values. The two samples were then plotted together showing distance from the cluster center (the so-called impact parameter) versus |RRM|. This plot is shown in Figure 2. The plot shows a restricted impact parameter range of 0 to 3000 kpc. The RRM of the southern cluster sample presented here agrees well with the northern sample of Clarke and both cluster samples drop to the level of the non-cluster control (which has a mean modulus value of 10 rad m^{-2}) at around 800 kpc from the cluster core. The two labeled points are both from A3667 and are background sources to the northern diffuse radio emission region (Röttgering et al. 1997; Johnston-Hollitt 2003). These two points are significantly above the RM level suggested by the other data. They are further beyond the region of X-ray emission in A3667 and should fall at a background level. The fact that they do not strongly suggests that these RMs are probing the magnetic field of the diffuse radio emission.

4.1. *Rotation Measure derived Magnetic Field Estimates in A3667*

These points, labeled 1 and 2 on the plot have residual RMs (after galactic correction) of -165.1 ± 4.3 and -98.2 ± 4.3 rad m^{-2} respectively and it should be noted that both sources are background rather than embedded sources. Assuming a uniform but extended Faraday screen the magnetic field required to generate such an RM can be estimated using

$$\langle RM \rangle = 812 B_{||} n_e d \,, \tag{1}$$

where $B_{||}$ is the line of sight magnetic field, n_e is the electron density and d is the path length.

The lines of sight to both sources are beyond the X-ray emitting region of the cluster. Without a high thermal electron component, a large RM here suggests a very high field strength. For the larger RM value, the background source lies behind the very tenuous part of the northern diffuse radio emission region, as shown in Figure 3. Using an electron density of 10^{-4} cm^{-3} (Röttgering et al. 1997) and assuming a spherical geometry of 400 kpc the first point gives $\mathbf{B}_{RM} = 5.1$ μG. Assuming similar dimensions, the second RM value gives $\mathbf{B}_{RM}$ =3.0 μG. Performing a standard equipartition magnetic field calculation in the region of the first source gives $\mathbf{B}_{eq} = 2.5$ μG, assuming a spectral index of 2, or $\mathbf{B}_{eq} = 1.5$ μG assuming a spectral index of 1. For the second source, where the spectral index is known to be roughly 1.3, an equipartition magnetic field of $\mathbf{B}_{eq} = 1.8$ μG is found. Thus, the equipartition field strengths are a factor of two lower than the RM derived field strengths. However, as equipartition field strength calculations require many assumptions, a factor of two difference is not unreasonable.

As it is not possible to untangle the background source's intrinsic RM from that produced along the line of sight it is not possible to say for certain that these RMs are the result of an enhanced field in the region of the diffuse emission. However, statistical examination of a population of over 900 extragalactic RMs from the literature Johnston-Hollitt et al. (2003b) suggests that the probability of encountering a purely intrinsic RM greater than|160| rad m^{-2} at this latitude from the galactic plane is 1.7%, whereas the probability of encountering a value of greater than |95| rad m^{-2} is 2.5%. The combined probability of encountering two such high RM from Faraday rotation purely intrinsic to the probe galaxy at such a close separation is 0.04%. This provides a strong argument that the high RM is due to the cluster magnetic field.

The cluster merger model for A3667 produced by Roettiger et al. (1999) predicts a compression of the magnetic field in the vicinity of the bow shock, but gives its strength to be only 0.6 μG . A field compression would normally not be greater than 3–4 times the original field strength. Using this theory it would be possible to explain these high RMs as an enhancement of standard 1–2 μG magnetic fields observed in other galaxy clusters (Clarke 2000).

Table 1. Magnetic field estimates

Method	Field Estimate (μG)	Location in the cluster
Inverse Compton	≥ 0.4	cluster core
Kelvin-Helmholtz	7–16	along the cold front
Faraday Rotation	1–2	cluster core
Faraday Rotation	3–5	NW radio emission region
Equipartition	1.5–2.5	NW radio emission region

In addition, Kelvin-Helmholtz stability arguments for the cold front observed in the cluster core have already suggested that there is a strong field present in A3667 with values of 7–16 μG being calculated (Vikhlinin et al. 2001). This field, however, will only be localized to the cold front boundary and is expected to be much weaker in the rest of the cluster. In comparison to this a third RM was obtained for the core of the brightest head-tail galaxy seen in the central part of the cluster. This embedded source yielded an RM of -76.7 ± 4.9 rad m^{-2} which is consistent with a field of 1–2 μG in the cluster assuming a tangled cell model with cell sizes of 100 kpc. Position angle measurements of the extended sources were used to determine the cell sizes. Using the head-tail galaxies in the clusters provides sensitivity on scales up to 300 kpc, while the diffuse radio emission provides sensitivity to around 1 Mpc. Preliminary results suggest that the cell size is of the order 50–100 kpc so the RM derived value seems consistent. However, it should be noted that this is only one data point from an embedded source and further data will be required to verify this particular result. In comparison, the volume averaged magnetic field estimate from inverse Compton emission gives a lower limit of 0.41 μG (Fusco-Femiano et al. 2001).

Thus we have a set of magnetic field estimates for various regions of the cluster. These estimates are summarized in Table 1. It seems that the current data are consistent with a 1–2 μG central field, tangled on scales of 100 kpc, which has been compressed in both the region of the cold front and through shock compression at the location of at least the northern diffuse emission region to a value of 3–5 μG.

5. **Conclusion**

Magnetic field estimates have been calculated for A3667 from several different techniques. The results of each estimation, perhaps with the exception of inverse Compton scattering which is known to have large uncertainties, are consistent within the errors. Further, these results point to a typical 1–2 μG field, tangled on scales of roughly 100 kpc pervading the cluster's central region. This field has been further enhanced in the region of the observed central cold front to a level of 7–16 μG Vikhlinin et al. (2001) and to around 3–5 μG in the region of the Mpc-scaled diffuse emission in the northern part of the cluster. As the diffuse emission is currently thought to

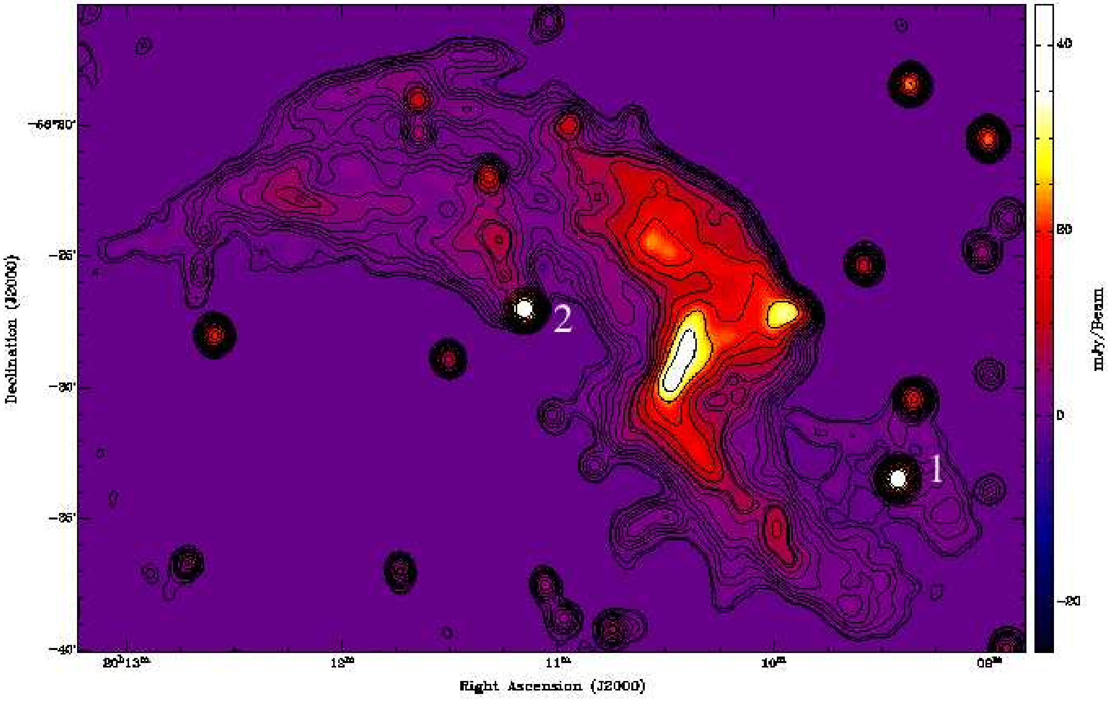

FIG. 3.— Locations of extragalactic objects used to probe the magnetic field in the region of the diffuse radio emission via Faraday rotation measures. The northern radio emission is shown at 1.4 GHz in low resolution (43 × 40 arcseconds) with contours at 0.027, 0.038, 0.054, 0.076, 0.11, 0.15, 0.21, 0.30, 0.42, 0.59, 0.83, 1.2, 1.7, 2.4 and 3.4 mJy beam^{-1}, and the two sources with high RMs are labeled as source 1 and 2.

be the result of a cluster merger it is likely that the central field would be compressed and elevated by a factor of 3–4. Thus, the measurement of a compressed field of 3–5 μG in the region of the diffuse emission is consistent with the merger scenario.

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