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Magnetic fields in galaxy clusters

M. Brüggen⋆

Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, D-21029 Hamburg, Germany

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While it is established that galaxy clusters host magnetic fields of the order of a few μG, both, their origin as well as their role in the intracluster medium (ICM) remain unclear. I will review the observational evidence for magnetic fields in galaxy clusters and present various lines of research that study the effects of magnetic fields in the ICM. Magnetic fields affect the way in which galaxies interact with the ICM, they may render the ICM buoyantly unstable in the presence of anisotropic thermal conduction, and they affect the thermal structure of the gas in cluster cores. Finally, opportunities for future research in this field, in particular in light of new radio telescopes is highlighted.

1 Introduction

Like most astrophysical objects, galaxy clusters are permeated by magnetic fields. The strongest evidence for the presence of cluster magnetic fields comes from radio observations. Magnetic fields are inferred from the synchrotron emission of cluster-wide diffuse sources, so-called radio halos, or from inverse Compton hard X-ray emission (e.g. Fusco-Femiano et al. 2004; Rephaeli et al. 2006). The magnetic fields in clusters can also be determined via the Faraday effect that rotates the plane of polarisation by an angle that is proportional to the square of the wavelength, the electron density, and the strength of the field along the line-of-sight (e.g. Bonafede et al. 2010). The sources' intrinsic polarization need not be known, as the effect can be observed as a characteristic wavelength-dependent rotation measure (RM) signature. Magnetic fields can be studied with background and embedded radio sources as well as with RM-synthesis (Brentjens & de Bruyn 2005). Finally, magnetic fields have been inferred from the sharpness of temperature discontinuities at cold fronts in clusters (ZuHone et al. 2013).

The magnetic fields have strengths of the order of 1 μG and coherence scales of the order of 10 kpc (e.g. Bonafede et al. 2010; Carilli & Taylor 2002; Enßlin & Vogt 2003; Laing et al. 2008); see Fig. 1. In cool cores of clusters even higher fields of 10–40 μG have been found (e.g., Enßlin & Vogt 2003). Moreover, different methods give somewhat discrepant estimates for the field strengths. The magnetic field strengths obtained by RM studies are systematically higher than the values derived from radio halo data and from inverse-Compton X-ray studies. Simulations are needed to investigate the systematic errors of various techniques to infer magnetic fields.

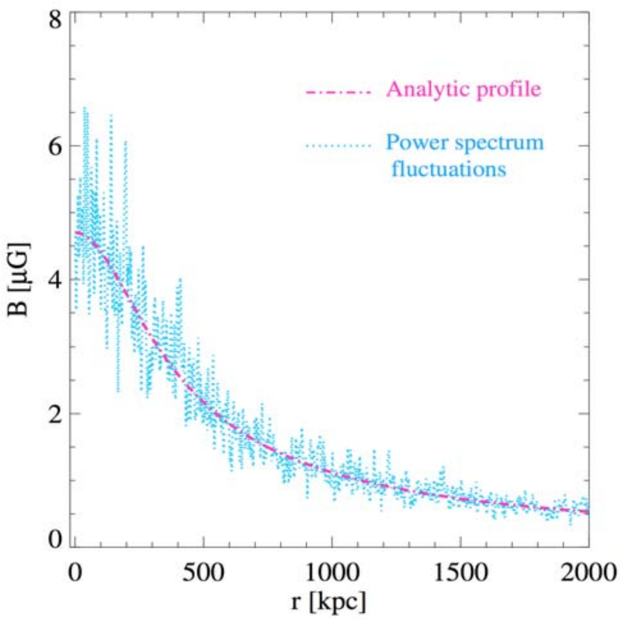

Fig. 1 Profile of the best-fit magnetic field model for the Coma cluster of galaxies. The magenta line shows an the analytic profile, while the blue line refers to a slice extracted from the simulated magnetic field numerical model. From Bonafede et al. (2010).

We estimate the magnetic field at the front of radio relics by assuming minimum energy densities in the relics (e.g., Govoni et al. 2004) and using the same procedure as described in van Weeren et al. (2009). The so-called "revised" equipartition magnetic field strength (Beck & Krause 2005) is found to be 9.2 μG at more than 1 Mpc from the cluster centre. Both the polarization and equipartition results indicate a relatively high magnetic field strength. These relatively high values have also been found for other relics by Finoguenov et al. (2010); van Weeren et al. (2010) us-

⋆ Corresponding author: mbrueggen@hs.uni-hamburg.de

ing limits on the IC X-ray emission or modeling the relic's brightness profile.

However, the origin of cluster magnetic fields remains unclear. It has been suggested that they are primordial (Gnedin et al. 2000); i.e., a seed field that has formed prior to recombination is subsequently amplified by compression and turbulence. Alternatively, it has been proposed that the magnetic field was of protogalactic origin (Kulsrud et al. 1997) or that it had been produced by a cluster dynamo (Bonafede et al. 2011; Roettiger & Flores 2000), cosmic rays at shocks (Beresnyak et al. 2009) or turbulence (Iapichino & Brüggen 2012; Ryu et al. 2008). Finally, some recent work has explored how outflows from galaxies (Donnert et al. 2009) or active galactic nuclei could have contributed to the magnetisation of the intracluster medium (ICM) (Xu et al. 2010).

While the magnetic field pressure is most likely not dynamically important in galaxy clusters, magnetic fields can affect the ICM by modifying microphysical transport processes. The ICM is a dilute plasma in which the mean free path between particle collisions can be much larger than the ion gyroradius. Under such conditions the gas is predicted to be convectively unstable in the presence of anisotropic thermal conduction which conducts heat preferentially along magnetic field lines. This effect could have significant consequences for the temperature and metal profiles in clusters, the level of turbulence, as well as the scaling relations in groups and clusters of galaxies. While gravitational collapse mainly determines the large-scale properties of clusters, the smaller scales are strongly affected by non-thermal pressure. Non-thermal pressure includes turbulent pressure and pressure exerted by cosmic rays. It also includes magnetic pressure, for which we must understand the magnetic field strength and topology, and how magnetic fields drive instabilities in the ICM. Measuring the secondary CMB anisotropy in order to determine cosmological parameters is one of the goals of large-scale Sunyaev-Zel'dovich (SZ) surveys using ACT and the South Pole Telescope (Kosowsky 2003; Ruhl et al. 2004). These surveys measure the thermal SZ effect, which is sensitive to the integral of the thermal pressure of the ICM, and combining hydrostatic equilibrium arguments with the observed SZ signal can be used to determine cluster mass. However, non-thermal pressure support will decrease the cluster mass found assuming hydrostatic equilibrium.

Indeed, there is a some disagreement between the SZ and WMAP 7 measurements of σ_8 (Komatsu et al. 2011; Lueker et al. 2010), which can be remedied if the predicted SZ power is roughly halved (Shaw et al. 2010, and references therein). Gopal & Roychowdhury (2010) show that the strength and topology of cluster magnetic fields change the ICM density profiles and thus impact the SZ power. In particular, they find that a radial cluster magnetic field with a strength of $\sim 3\,\mu$G will increase the central SZ decrement by 25 % in a 10^{14} $\mathrm{M}_\odot$ cluster. Other magnetic field configurations will have different effects on cluster gas profiles, and therefore on the SZ signal. Also, they find that radial fields of tens of μG may bring the SZ σ_8 into agreement with the WMAP 5 result (Gopal & Roychowdhury 2010; Komatsu et al. 2009).

Moreover, magnetic fields in the intra-cluster medium and in the inter-stellar gas affect the way galaxies evolve in clusters. The ram-pressure experienced by galaxies in clusters may deplete their interstellar medium severely disrupting star formation the galaxies. However, ram-pressure may also trigger episodes of star formation at the leading edges of galaxies or in the stripped tail. Finally, ram-pressure stripping may also enrich the ICM with metals from the ISM and is thus relevant to the cluster elemental abundance discrepancy, i.e. the observed excess of metals in the ICM of rich cluster compared to the expectation from the stellar population. This is a poorly understood process which we are only beginning to simulate now. In the following I will highlight work that addresses the effect of magnetic fields on the interaction between galaxies and the ICM (Sect. 2) and the stability of the ICM (Sect. 3).

2 Interaction between galaxies and the magnetised ICM

Galaxies in clusters are moving through the intracluster gas and are thus experiencing a headwind. The ram pressure exerted by this headwind has important consequences for the galaxies because the pressure can remove some of the interstellar medium from the gravitational potential of the galaxy. As a result, the building material for new stars is depleted and the evolution of the stellar population is seriously affected. This manifests itself in H I deficient and redder galaxies in clusters (see Boselli & Gavazzi 2006). The stripped material is seen as tails in H I, Hα, or X-ray emission in the wake of galaxies. In return, the ICM gets enriched in the gas that is stripped off the galaxies. However, the interaction between galaxies and their environment can be significantly altered by the presence of magnetic fields, both in the galaxy and in the ICM. For example, magnetic fields in the ICM will get "draped" around the galaxies as they move through the ICM and this draping has been suspected of reducing the amount of ram-pressure stripping (Dursi & Pfrommer 2008; Lyutikov 2006; Pfrommer & Dursi 2010). As the magnetic field lines bunch up at the bow of the galaxy, the magnetic fields get amplified up to the point where the magnetic pressure becomes of the same order of magnitude as the ram-pressure and they can thus shield the galaxy from the disruptive flow. But the galaxy is also rotating and the ISM is thus shearing against the ambient medium leading to potential instabilities. Moreover, the magnetised interstellar medium is subject to star formation and outflows which will also affect the dynamics of the gas.

Modelling these effects requires simulations that attempt to model all these effects. Recently, the first attempts in this direction have been made. Tonnesen & Bryan (2012) look at star formation in ram-pressure stripped tail and

Ruszkowski et al. (2012) have studied the effects of ambient magnetic fields on the efficiency of stripping and on the morphology of the tails. While still fairly simplified owing to the substantial computational resources required, these magnetohydrodynamical simulations make a number of interesting points: Most obvious are the changes to the morphology of the stripped tails. The presence of ambient magnetic fields has a strong impact on the morphology of the tail. While the MHD case shows long (>100 kpc) filamentary structures in the tail, in the purely hydrodynamical case the tail is very clumpy on scales of a few kpc. In the filaments of the ram-pressure stripped tail the magnetic pressure support dominates and is aligned with the filaments. This may prevent thermal conduction between filaments and the ambient, hot ICM and could be relevant to the question whether stars can form in ram-pressure stripped gas. The filamentary structure is more in line with observations of ram-pressure stripped tails, for example, it can explain the existence of bifurcated tails (see Fig. 2) as they have been observed in the galaxy ESO 137-001.

Moreover, it has been found that the build-up of the inhomogeneous magnetic field causes pressures that undo the protective effect of the draping layer and allow the gas to stream out of the galaxy. The presence of uniform magnetic fields in the ICM leads to larger amounts of gas stripping than in the absence of magnetic fields. A disk galaxy shears against the ambient ICM and the magnetic field will not be able to suppress the onset of instabilities. As a result, the ordered horizontal fields are transformed into vertical filamentary fields that vary on scales of <1 kpc. This may be an artifact of the set-up and the convergence of these simulations is still under scrutiny demonstrating that clearly more work is needed. However, these simulations are all missing magnetic fields in the interstellar medium of the stripped galaxy, and therefore are missing the added pressure support from these fields in the stripped gas. Also, they do not include important plasma physics processes that would act on a ram-pressure stripped tail, such as anisotropic heat conduction and Braginskii viscosity. These kinds of simulations are still in its infancy and are essentially wind-tunnel experiments of idealised galaxies. Advances in algorithms and computational power are going to change this in the next years.

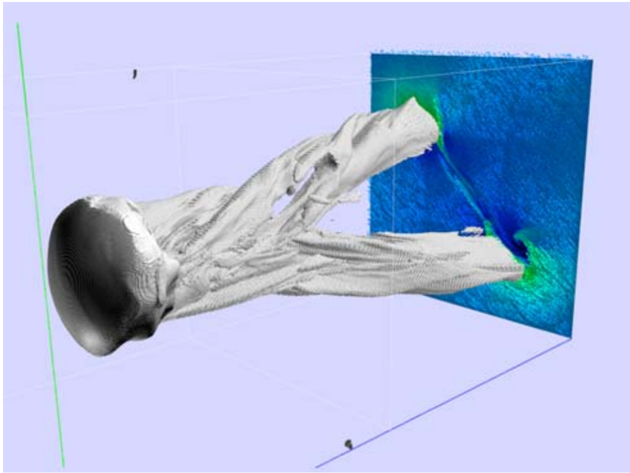

Fig. 2 Visualisation of the magnetic field topology around a ram-pressure stripped galaxy. A clear double tail in the wake of the galaxy is observed. For more details of the simulations, see Ruszkowski et al. (2012).

3 Stability of the intracluster medium to three-letter instabilities

One should note that the ICM is only weakly collisional. The particle mean free path $\lambda_{\rm mfp}$ is up to a thousand times smaller than the thermal-pressure scale height, but still 10^{11}–10^{13} times larger than the ion gyroradius (e.g. Schekochihin & Cowley 2007, and references therein). As a result, transport properties of the ICM are strongly anisotropic and governed by the direction of the magnetic field, even if the intra-cluster magnetic field is relatively weak (~ 0.1–$10\ \mu$G, which constitutes only ~ 0.01–$1\,\%$ of the thermal energy.

Magnetic fields suppress thermal conduction in the direction perpendicular to the magnetic field. However, even in the case of highly tangled magnetic fields, the effective thermal conduction can be a substantial fraction the Spitzer conductivity (Narayan & Medvedev 2001). The anisotropy due to magnetic fields leads to new phenomena with potentially important consequences for the ICM.

It has been demonstrated, both, analytically (Balbus 2000) and numerically (McCourt et al. 2011; Parrish & Stone 2005; Parrish et al. 2008) that such plasma must be unstable in the presence of weak magnetic fields and anisotropic thermal conduction in case the temperature is increasing in the direction of gravity as found in cluster outskirts (magneto-thermal instability, MTI). When magnetic fields are partially aligned with the temperature gradient, the heat flow from the hotter to cooler regions along the field lines causes them to become more buoyant. For an illustration see Fig. 3. This causes the magnetic field to become more aligned with the temperature gradient and leads to instability (even if the gas is expected to be stable according to the Schwarzschild criterion; i.e., even if the entropy increases with radius). This causes the magnetic field to become more aligned with the temperature gradient and leads to the instability and preferentially radial magnetic fields.

In addition in can be shown that the gas is also unstable when the temperature decreases in the direction of gravity by an instability that has been named heat-flux buoyancy (HBI) instability (Parrish & Quataert 2008; Quataert 2008). The saturated state of the HBI corresponds to the magnetic fields oriented in the direction perpendicular to gravity. Such field configurations lead to magnetic fields that wrap around the cool cores and that suppress the thermal conduction from the hotter cluster periphery to their cool centres.

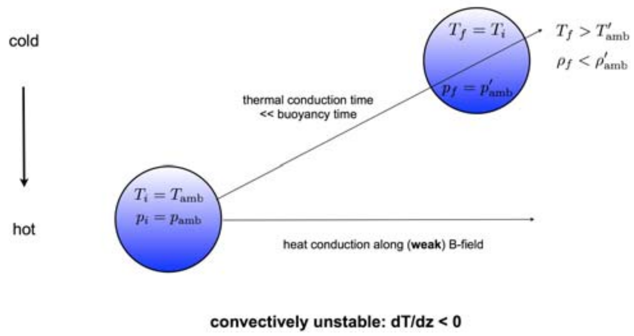

Fig. 3 Illustration of the physical origin for the magneto-thermal instability (MTI). In the situation sketched, gravity as well as the temperature gradient point downwards. For simplicity, we assume a purely horizontal magnetic field that has no dynamic effect. Its only effect is that heat is conducted solely along magnetic field lines. If a blob of plasma is displaced upwards in a fashion that thermal conduction operates faster than buoyancy forces, the temperature of the blob is kept constant. However, because of the hydrostatic stratification of the medium the density becomes less than the ambient density, causing buoyancy to push the blob even further up. An instability ensues causing the magnetic field to become more vertical.

As a result, the effective cooling rate in the core is increased. However, the exact topology of the magnetic fields depends on whether externally imposed turbulence is present. Such turbulence may have its origins in outbursts from active galactic nuclei, galaxy motions and structure formation. This has been recently investigated by Ruszkowski et al. (2011) and Parrish et al. (2010) who showed that there exists a critical level of turbulence above which the field can be randomized and the conductive heating to the core restored. Although this analysis was performed for the HBI, similar arguments apply to the MTI. A similar instability occurs when energy is transported anisotropically via cosmic rays (Sharma et al. 2009).

Finally, Balbus & Reynolds (2010) discovered a related set of overstabilities that operate in those configurations that are stable to the HBI and MTI. They predict that configurations which tend to result from the non-linear evolution of the HBI have g-modes that are driven overstable by radiative loses. On the other hand, configurations which tend to result from the non-linear evolution of the MTI have g-modes that are driven overstable by the conductive heat flux. The effects of these overstabilities for the ICM plasma thermodynamics and the properties of magnetic field are yet to be understood.

The main results from recent work are that (i) in cluster outskirts, the magnetic field is preferentially radial, (ii) this radial field is caused mainly by the accretion of matter and only to a lesser extent by the MTI, and (iii) radiative cooling in combination with anisotropic conduction can lead to higher amplification of magnetic fields than cooling only (Ruszkowski et al. 2011).

4 Conclusions

This is a very brief review in which I singled out some recent results that challenge the wide-held view that magnetic fields do not have a significant impact in clusters of galaxies.

In particular, it has been shown that (i) thermal conduction in the magnetised ICM can affect hydrodynamic stability even though it is still unclear whether this has a dramatic effect in real cluster, (ii) magnetic fields have a significant effect on ram-pressure stripping; they change the morphology of the tails of stripped gas and instabilities undo the protective effect of the draping layer.

While this work is promising there are a number of caveats that I have not even begun to discuss. For example, in cluster outskirts, the MHD approximations begin to break down, and effects such as the electron-proton equilibration time or ohmic dissipation have not been studied. In the future this field will receive a lot of attention.

Polarisation can be used to probe the magnetic field geometry in the ICM (Bogdanović et al. 2009). The capabilities to map out the magnetic field through radio observations is going to be greatly improved with the Low Frequency Array (LOFAR), the Expanded Very Large Array (EVLA) and Square Kilometer Array (SKA), which will provide the sensitivity to study a sufficient number of background and embedded sources to detect the RM patterns with high spatial resolution. Bogdanović et al. (2009) have evaluated the effects of various mechanisms on the Faraday RM in a cool core cluster, as detectable by the EVLA and SKA. They compare a scenario in which conduction-driven MHD instabilities dominate the dynamics of the ICM, to a one in which the magnetic field topology is governed by turbulent motions. Employing polar shapelets, they analyse the resulting RM maps and classify the morphologies. Within the bounds of their simple models they find that future spectro-polarimetric measurements will have sufficient sensitivity to detect magneto-conductive instabilities from purely turbulent motions using relatively short exposures with the SKA.

The first LOFAR data on galaxy clusters is also in the process of being published. de Gasperin et al. (2012) have presented the first observations made with LOFAR of the central portion of the Virgo cluster at frequencies down to 20 MHz. They used these observations together with archival data to perform a spectral analysis in the wide frequency range 30 MHz–10 GHz. This data has been used to make maps of the magnetic field in the centre of the Virgo cluster. In the next years LOFAR is going to survey the Northern sky to unprecedented depth at low frequencies. This is expected to lead to discoveries of hundreds of diffuse radio sources in clusters.

Cassano et al. (2012) showed that the planned EMU + WODAN surveys at 1.4 GHz have the potential to detect up to about 200 new radio halos, increasing their number by almost one order of magnitude (see Fig. 4). Moreover, they predict a larger number of radio halos in the

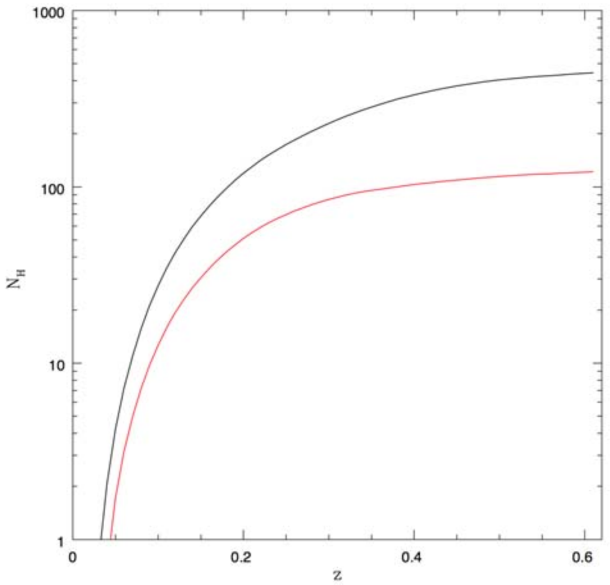

Fig. 4 Integral number of radio halos as a function of redshift in the WODAN (red line) and LOFAR (black line) surveys. From Cassano et al. (2012).

LOFAR survey due to the high LOFAR sensitivity, but also due to the existence of halos with very steep spectrum that become visible at lower frequencies (these estimates are a bit higher than those by Sutter & Ricker (2012)).

The particular advantage of LOFAR regarding such observations is its big field of view, combined with good sensitivity. This enables us to study nearby clusters with one or two pointings, while detecting already tens of polarised radio sources. Finally, RM synthesis will take advantage of the broad λ^2 coverage that is possible with LOFAR.

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References

Balbus, S. A. 2000, ApJ, 534, 420
Balbus, S. A., & Reynolds, C. S. 2010, ApJ, 720, L97
Beck, R., & Krause, M. 2005, Astron. Nachr., 326, 414
Beresnyak, A., Jones, T. W., & Lazarian, A. 2009, ApJ, 707, 1541
Bogdanović, T., Reynolds, C. S., Balbus, S. A., & Parrish, I. J. 2009, ApJ, 704, 211
Bonafede, A., Feretti, L., Murgia, M., et al. 2010, A&A, 513, A30
Bonafede, A., Dolag, K., Stasyszyn, F., Murante, G., & Borgani, S. 2011, MNRAS , 418, 2234
Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517
Brentjens, M. A., & de Bruyn, A. G. 2005, A&A, 441, 1217
Brüggen, M., Ruszkowski, M., & Hallman, E. 2005, ApJ, 630, 740
Carilli, C. L., & Taylor, G. B. 2002, ARA&A, 40, 319
Cassano, R., Brunetti, G., Norris, R. P., et al. 2012, A&A, 548, A100
de Gasperin, F., Orrú, E., Murgia, M., et al. 2012, A&A, 547, A56
Donnert, J., Dolag, K., Lesch, H., Mueller, E. 2009, MNRAS, 392, 1008
Dursi, L. J., & Pfrommer, C. 2008, ApJ, 677, 993
Enßlin, T. A., & Vogt, C. 2003, A&A, 401, 835
Fusco-Femiano, R., Orlandini, M., Brunetti, G., et al. 2004, ApJ, 602, L73
Gnedin, N. Y., Ferrara, A., & Zweibel, E. G. 2000, ApJ, 539, 505
Gopal, R., & Roychowdhury, S. 2010, Journal of Cosmology and Astroparticle Physics, 6, 011
Govoni, F., Markevitch, M., Vikhlinin, A., et al. 2004, ApJ, 605, 695
Iapichino, L., & Brüggen, M. 2012, MNRAS, 423, 2781
Komatsu, E., Dunkley, J., Nolta, M. R., et al. 2009, ApJS, 180, 330
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Kosowsky, A. 2003, New Astronomy Review, 47, 939
Kulsrud, R. M., Cen, R., Ostriker, J. P., & Ryu, D. 1997, ApJ, 480, 481
Laing, R. A., Bridle, A. H., Parma, P., & Murgia, M. 2008, MNRAS, 391, 521
Lueker, M., Reichardt, C. L., Schaffer, K. K., et al. 2010, ApJ, 719, 1045
Lyutikov, M. 2006, MNRAS, 373, 73
McCourt, M., Parrish, I. J., Sharma, P., & Quataert, E. 2011, MNRAS, 413, 1295
Narayan, R., & Medvedev, M. V. 2001, ApJ, 562, L129
Parrish, I. J., & Quataert, E. 2008, ApJ, 677, L9
Parrish, I. J., Quataert, E., & Sharma, P. 2010, ApJ, 712, L194
Parrish, I. J., & Stone, J. M. 2005, ApJ, 633, 334
Parrish, I. J., Stone, J. M., & Lemaster, N. 2008, ApJ, 688, 905
Pfrommer, C., & Dursi, J. L. 2010, Nature Physics, 6, 520
Quataert, E. 2008, ApJ , 673, 758
Rephaeli, Y., Gruber, D., & Arieli, Y. 2006, ApJ, 649, 673
Roettiger, K., & Flores, R. 2000, ApJ, 538, 92
Ruhl, J., Ade, P. A. R., Carlstrom, J. E., et al. 2004, Proc. SPIE, 5498, 11
Ryu, D., Kang, H., Cho, J., & Das, S. 2008, Sci, 320, 909
Ruszkowski, M., Lee, D., Brüggen, M., Parrish, I., & Oh, S. P. 2011, ApJ, 740, 81
Ruszkowski, M., Brüggen, M., Lee, D., & Shin, M.-S. 2012, astro-ph/1203.1343
Schekochihin, A. A., & Cowley, S. C. 2007, Turbulence and Magnetic Fields in Astrophysical Plasmas, in Magnetohydrodynamics: Historical Evolution and Trends, ed. S. Molokov, R. Moreau, & H. K. Moffatt (Springer, Dordrecht), 85
Schekochihin, A. A., Cowley, S. C., Rincon, F., & Rosin, M. S. 2010, MNRAS, 405, 291
Sharma, P., Chandran, B. D. G., Quataert, E., & Parrish, I. J. 2009, ApJ, 699, 348
Shaw, L. D., Nagai, D., Bhattacharya, S., & Lau, E. T. 2010, ApJ, 725, 1452
Sutter, P. M., & Ricker, P. M. 2012, ApJ, 759, 92
Tonnesen, S., & Bryan, G. L. 2012, MNRAS, 422, 1609
Xu, H., Li, H., Collins, D. C., Li, S., & Norman, M. L. 2010, ApJ, 725, 2152
ZuHone, J. A., Markevitch, M., Ruszkowski, M., & Lee, D. 2013, ApJ, 762, 69