Simulating large-scale structure formation with magnetic fields

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Abstract. In the past, different works based on numerical simulations have been presented to explain magnetic fields (MFs) in the large scale structure and within galaxy clusters. In this review, I will summarize the main findings obtained by different authors and - even if many details are still unclear - I will try to construct a consistent picture of our interpretation of large-scale magnetic fields based on numerical effort. I will also sketch how this is related to our understanding of radio emission and summarize some arguments where our theoretical understanding has to be improved to match the observations.

Key words: cosmology: large-scale structure – cosmology: theory – magnetohydrodynamics (MHD)

1. Introduction

There are several different approaches to study the build-up of MFs in the intergalactic medium. Many papers consider MHD simulations of cloud-wind interaction (see Gregori et al. 2000 and references therein) or are simulating the rise of relic radio bubbles (see Jones & De Young 2005, Reynolds et al. 2005 and references herein). Such work is usually focused more on the relevance of the local MFs within these processes, whereas in this review I will concentrate more on the discussion of MHD simulations which aim at understanding the build-up of the cluster MF and its possible origin. So far, firm evidence for the presence of extended MFs has been found only in galaxy clusters. For recent reviews see Carilli & Taylor (2002) and Govoni & Feretti (2004). Recently there are observational claims of a detection of substantial MFs also within the large scale structure (LSS), see contribution by Kronberg. The origin of the MF in galaxy clusters is still under debate. The variety of possible contributors ranges from primordial fields, battery and dynamo fields over all classes of astrophysical objects which contribute with their ejecta. The later possibility is supported by the observation of the metal enrichment of the intracluster medium (ICM), which has to be originated as ejecta of astrophysical objects. In addition, the MFs produced by all these contributors will be compressed and amplified by the process of structure formation. The exact amount of this amplification and the resulting MF filling factor will depend on place and time at which the contributor is thought to be most efficient.

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2. Possible origins of MFs within the LSS

In the following I will describe the three main classes of models for the origin of cosmological MF within the LSS.

In the first one, MFs are assumed to be produced ‘locally’ at relatively low redshifts ($z \sim 2 - 3$) by galactic (e.g. Völk & Atoyan 2000) or AGN ejecta (e.g. Furlanetto & Loeb 2001). One of the main arguments in favor of this model is that the high metallicity observed in the ICM suggests a significant enrichment driven by galactic winds or AGNs in the past. Winds and jets should carry MFs together with the processed matter. While it has been shown that winds from ordinary galaxies give rise to MFs which are far weaker than those observed in galaxy clusters, MFs produced by the ejecta of starburst galaxies can be as large as $0.1 \mu G$. Clearly, this class of models predicts that MFs are mainly concentrated in galaxy clusters. Note that, if the magnetic pollution happens early enough (around $z \sim 3$), these fields will not only be amplified by the adiabatic compression of the proto-cluster region, but also by shear flows, turbulent motions, and merging events during the formation of galaxy clusters.

In the second class of models, the MF seeds are assumed to be produced at higher redshifts, before galaxy clusters form gravitationally bound systems. Although the strength of the seed field is expected to be considerably smaller than in the previous scenario, the adiabatic compression of the gas and the shear flows driven by the accretion of structures can give rise to a considerable amplification of the MFs. Several mechanisms have been proposed to explain the origin of MF seeds at high redshift. Some of them are similar to those discussed above, differing only in the time at which the mag-
suggests that they may have a cosmological origin. In general, early universe. Indeed, the ubiquity of MFs in the universe allows them to magnetize a large fraction of the volume. Alternative models invoke processes that took place in the early universe. Indeed, the ubiquity of MFs in the universe suggests that they may have a cosmological origin. In general, all ‘high-z’ models predict MF seeds filling the entire volume of the universe. However, the assumed coherence length of the field crucially depends on the details of the models. While scenarios based on phase transitions give rise to coherence lengths which are so small that the corresponding fields have probably been dissipated, MFs generated at neutrino or photon decoupling have much higher chances to survive until the present time. Another (speculative) possibility is that the seed field was produced during inflation. In this case, the coherence length can be as large as the Hubble radius. See Grasso & Rubinstein (2001) for a recent review.

The third scenario assumes that the MF seeds were produced by the so-called Biermann battery effect (Kulsrud et al. 1997, Ryu, Kang & Biermann 1998). The idea here is that merger shocks related to the hierarchical structure formation process give rise to small thermionic electric currents which, in turn, may generate MFs. The battery process has the attractive feature of being independent of unknown physics at high redshift. Its drawback is that, due to the large conductivity of the IGM, it can give rise to at most very tiny MFs, of order $10^{-21}$ G. One therefore needs to invoke a subsequent turbulent dynamo to boost the field strength to the observed level. Such a turbulent amplification, however, cannot be simulated numerically yet, making it quite difficult to predict how it would proceed in a realistic environment. It is clear that such a process could indeed explain the significantly higher MF observed in the starburst galaxy halo compared to what is expected from the MFs observed within galactic disks. When applied to a cluster core environment, the KH timescale turns out to be $10^7$ years, making it an interesting process for further amplifying weak MFs.

In recent high-resolution smoothed particle hydrodynamic (SPH) simulations of galaxy clusters within a cosmological environment, using a novel scheme to treat artificial viscosity within the Gadget2 code (Springel 2005), Dolag et al. (2005) demonstrated how such shear flows, which are quite common in the process of cosmic structure formation, drive fluid instabilities and increase the turbulence level within the ICM to a significant level (see Fig. 2). It was also shown that the artificial viscosity used in standard SPH simulations might significantly suppress such fluid instabilities. In earlier work, extensive MHD simulations of single merging events performed using the Eulerian code ZEUS...
In particular they found that first, the field becomes quite filamentary as a result of stretching and compression caused by shocks and bulk flows during infall, but only a minimal amplification occurs. Second, field amplification is more rapid, particularly in localized regions, as the bulk flow is replaced by turbulent motions (e.g., eddies), see Fig. 3. The total MF energy is found to increase by nearly a factor of three with respect to a non-merging cluster. In localized regions (associated with high vorticity), the magnetic energy can increase by a factor of 20 or more. A power spectrum analysis of the magnetic energy showed that the amplification is largely confined to scales comparable to or smaller than the cluster cores: this indicates that the core dimensions define the injection scale. It is worth to notice that, due to the lack of resolution, the previous results can be considered a lower limit on the total amplification. Furthermore, it is quite likely that a galaxy cluster undergoes more than one such an event during its formation process, and that also the accretion of smaller haloes injects turbulent motions within the ICM: consequently the MF amplification within galaxy clusters will be even higher.

**Fig. 3.** The evolution of (logarithm of) gas density (left column), gas temperature (central column), and (logarithm of) magnetic pressure (right column) in two-dimensional slices taken through the cluster core in the plane of the merger. Each row refers to different epochs: $t = 0$ (i.e. the time of core coincidence), $t = 1.3$, $t = 3.4$, and $t = 5.0$ Gyrs, from top to down. Each panel is $3.75 \times 3.75$ Mpc. Taken from Roettiger et al. (1999).

**Fig. 4.** In the left panel we show the simulated A3667 X-ray surface brightness and radio data. Contours represent the X-ray surface brightness. The grayscale represents the synthetic radio emission at 1.4 GHz. The image is $3.15 \times 3.85$ Mpc. Dashed and dotted lines refer to the location of the radio spectral index ($\alpha_{14.0}$) profiles displayed in the right panel. Taken from Roettiger et al. (1999).

A detailed discussion of the amplification of MF in a cluster environment, using various simulations of driven turbulence, can be found in Subramanian, Shukurov & Haugen (2005), where it is shown that reasonable strength and length scales for galaxy clusters can be obtained by turbulent processes.

### 4. The quest for radio relics

By extending such merger simulations to reproduce the observed X-ray properties of A3667 and adding a model for in situ re-acceleration of relativistic particles, Roettiger, Burns & Stone (1999) were able to reproduce the main features of the extended peripheral radio emission (the so-called radio relics) observed in A3667. In their models they injected relativistic electrons with a power-law spectrum, where the power-law index $\gamma = 3/(\gamma - 1) + 1$ is related to the gas compression rate $r$ at the shock. They also relate the age of the radio plasma $t_s$ to the distance $d = \kappa v_s t_s$, using a weak-field/high-diffusion limit $\kappa = 1$. Having effective shock velocities $v_s \approx 700 - 1000$ km/s and aging the synchrotron spectrum using the formalism by Myers & Spangler (1985) they have been able to reproduce the observed distribution of spectral index for a MF of $\approx 0.6\mu$G at the position of the radio relic, see Fig. 4. Since such configurations seem to be quite common in galaxy clusters, naturally the question arises, why not all clusters show such a peripheral radio emission. One possible explanation is that such shock structures are relatively short lived compared to the merger event itself. Also, it is necessary to have the presence of a large-scale MF. It could further be that only massive clusters can provide enough MF and strong enough merger events to trigger such a peripheral emission.

To overcome this problem, Enßlin & Brüggen (2002) proposed that such radio relics could be made by pre-existing fossil radio plasma illuminated via shock waves initiated by merger events. In their work they evolved the electron spectrum for the tracer particles, representing the fossil ra-
5. Shocks in cosmological simulations

Cosmological shocks, mainly the accretion shocks on cosmological objects like galaxy clusters and filaments, are much more frequent than the ones produced by individual merger events. They also can produce MFs by the so-called Biermann battery effect (Kulsrud et al. 1997; Ryu et al. 1998) on which a subsequent turbulent may operate (see section 2).

In such a scenario, the MF is strongly correlated with the large-scale structure (see Fig. 7). This means that in such a case, the MF within the filamentary structure could be even slightly higher than its equipartition value without violating the (weak) upper limits of rotation measure of quasars, as pointed out by Ryu et al. (1998). It is worth to point out that the arguments for the turbulent dynamo action, which could amplify the battery seed fields up to μG level, as presented in Kulsrud et al. (1997), refer explicitly to regions about to collapse into galaxies. It has still to be proven that such arguments hold within proto-clusters or even cosmological structures, like sheets and filaments. In general, the time evolution of the MF as predicted by these simulations saturates around $z \approx 3$ (Kulsrud et al. 1997) and leads to a relatively uniform MF strength on scales of tens of Mpc within the LSS around galaxy clusters (see Fig. 7). Note that so far there is no comparison of synthetic rotation measurements obtained by the MFs predicted by up-scaling the battery fields, with observations on scales of galaxy clusters. This might be partially motivated by the lack of resolution in simulated clusters.

In addition these shocks act as place for acceleration of cosmic rays (CR) which then will be accreted into the LSS, specially within galaxy clusters. Using the COSMOR code, Miniati et al. (2001) followed primary ions and electrons (injected and accelerated by diffuse cosmic shocks) and secondary electrons and positrons (produced in p-p inelastic collisions of CR ions with thermal ICM nuclei) within a cosmological simulation. Under the assumption that the MF produced by the battery effect reflects a fair representation of the true distribution of relative MF strengths within the LSS, they were able to predict the central radio emission (radio halos) - mainly produced by secondary CRs - as well as the peripheral radio emission (radio relics) - mainly produced by primary CRs - in a self-consistent treatment (see Fig. 9): the resulting morphology, polarization and spectral index match the observed properties. However, one has to notice that the extrapolation of these simulations (on group scale) to...
the observed data (i.e. on massive cluster scale) might not be straightforward (see Fig. 13). It is further worth to notice that even with a proton injection ratio $R_{\text{inj}}$ of $10^{-2}$ (which is derived from observations, see Tab. 5 in Miniati et al. 2001), the predicted luminosities for the primary emission is still significantly higher than for the secondary one (see Fig. 13), which seems not to be confirmed by the observations. Although the results for the secondary model are in agreement with previous work on massive galaxy clusters (Dolag & Enßlin 2000), we notice that generally in the secondary model radio haloes are predicted for every cluster, which is in contradiction to the observations (see Fig. 13).

6. **Cosmological MHD simulations**

Using GrapeMSPH (Dolag, Bartelmann & Lesch 1999) and assuming that a small initial magnetic seed field exists before structure formation (see section 2), the first self-consistent simulations which follow the MF amplification during the formation of galaxy clusters with cosmological environment have been performed (Dolag et al. 1999, Dolag, Bartelmann & Lesch 2002). These runs were able to demonstrate that the contribution to the amplification of MFs by shear flows (and by its induced turbulence) is significant (see Fig. 10). Therefore for the first time a consistent picture of the MF in galaxy clusters could be constructed: the amplification predicted by the simulations was capable to link the predicted strength of the seed MFs (see section 2 and references therein) at high redshift ($z \approx 3$ and higher) to the today observed MF strength in galaxy clusters. Furthermore the simulations predicted that the final structure of the MF in galaxy cluster reflects the process of structure formation, and no memory on the initial MF configuration survives: this relaxes the constraints on models for seed MFs. In general such models predict a MF profile similar to the density profile. Thereby the predicted rotation measure (RM) profile agrees with the observed one (see Fig. 11). Dolag et al. (2001) found a quasi linear correlation between two observables, namely the X-ray surface brightness and the RM r.m.s.

This result is now confirmed to hold over several orders of magnitude in a collection of observational data existing in the literature (see Fig. 12). Extending Gadget2 to follow the full set of ideal MHD equations, Dolag et al. (2004, 2005) performed several realizations of a cosmological volume confirming the previous findings even at much higher resolution. Recently, Brüggen et al. (2005) performed a simulation of the formation of a single galaxy cluster in a cosmological framework, using a passive MHD solver implemented into FLASH. Thereby they nicely confirmed all previous results based on the SPH codes, using their adaptive mesh refinement (AMR) simulation code (see Fig. 5).

Another interesting quantity to look at is the slope $\alpha$ of the MF power spectrum ($\propto k^{-\alpha}$, with $k$ being the wave vector). Within galaxy clusters $\alpha$ is predicted by the SPH simulations (Dolag et al. 2002, Rordorf, Grasso & Dolag 2004) to be slightly lower, but still very close to $11/3$, which is the expected value for a Kolmogorov-like spectrum (in 3D). The AMR simulation by Brüggen et al. (2005) nearly perfectly matches the Kolmogorov slope. Fig. 13 shows a collection of predicted and observed slopes for the MF spectrum. Note that this can only be a crude comparison, due to the limitations in both observations and simulations. But in general the range of slopes predicted by the simulations seems to be consistent with the slopes inferred from observations of real clusters. It is worth to notice that the numerical results suggest that the spread of the slopes might reflect the dynamical stage of the system, indicated by the inlay, showing the two mass accretion histories. Here the smoothly accreting clusters show the smallest slope (indicating the lack of large-scale power). On the contrary, the clusters having a quite violent history, with several major mergers indicated by the small arrows, show a very steep spectra. Two of them happened in the last 3 Gyrs, thereby inducing an excess of power on large scales.

Further support for strong MF amplification during the process of structure formation comes from the application of the Zel’dovich approximation to follow the MHD equations.

**Fig. 7.** A two-dimensional cut through a cosmological box simulated by Miniati et al. (2001), and following the evolution of battery fields. Shown is (the logarithm of) the up-scaled MF strength in Gauss taken at $z = 0$. Taken from Enßlin, Miniati & Enßlin (2004).

**Fig. 8.** Slice through the centre of the simulated box, hosting a massive galaxy cluster. The simulation, made using the AMR code FLASH, follows the evolution of a weak magnetic seed field. Shown is the logarithm of the MF strength in Gauss, as measured at $z = 0.5$. Taken from Brüggen et al. (2005).
during the gravitational collapse (Bruni, Maartens & Tsagas 2003; King & Coles 2005). Such works showed super-adiabatic amplification due to the anisotropy of the collapse of the LSS within the cold dark matter paradigm.

A novel aspect of including MF pressure into LSS simulation - even if in a simplified way - is investigated in an ongoing project (see the contribution by Gazzola), which aims at identifying the point for which such non thermal pressure support starts to significantly modify the structure formation.

7. Conclusive remarks

It seems that within the last years a probably consistent picture of MFs arises from numerical works and observations. Supported by simulations of individual events/environments like shear flows, shock/bubble interactions or turbulence/merging events, a super-adiabatic amplification of MF is predicted. It is worth to notice that this common finding is obtained by using a variety of different codes, based on different numerical schemes. Further support for such super-adiabatic amplifications comes from analytical estimates of anisotropic collapse making use of the Zel’dovich approximation. When applied in fully consistent cosmological simulations, various observational aspects are reproduced (see Figs. 11 and 12) and the resulting MF amplification reaches a level sufficient to link models predicting seed MFs at high redshift with the MFs observed in galaxy clusters today. It is important to mention that all simulations show that this effect increases when the resolution is improved, and therefore all the numbers have to be taken as lower limits of possible amplification.

Note that on the other hand there are significant differences for the predictions of the MF structures coming from different models of seed MFs. In particular there are main differences between the up-scaled, cosmological battery fields (Miniati et al. 2001; Sigl et al. 2003) and the MF predicted from high-resolution simulations of galaxy clusters using either AMR (Brüggen et al. 2005) or SPH (Dolag et al. 1999, 2002, 2003). In the latter case it is possible to follow the amplification of seed fields within the turbulent ICM in more detail. A good visual impression can be obtained by comparing the regions filled with high MFs shown in Figs. 7 and 8.

Fig. 9. Synchrotron power at 1.4 GHz from secondary electrons (left panel) and primary electrons (right panel). Note that the values for the luminosities for primary electrons should be scaled with the electron to proton injection ratio $R_{e/p}$. Taken from Miniati et al. (2001).

Fig. 10. The MF strength as a function of baryonic overdensity. The long-dashed line shows the expectation for a purely adiabatic evolution, the solid line gives the mean field strength at a given overdensity within a cosmological simulation (Dolag et al. 2005). While the latter is close to the adiabatic value in underdense regions, there is a significant inductive amplification in clusters due to shear flows and turbulence, subject however to saturation in the cluster cores. At any given density, a large fraction of particles remains close to the adiabatic expectation, as shown by the dotted line, which gives the median of the distribution at each density.
timescale reaching the observed $\mu$G level. However it is still unclear how such very small scale fields can be ordered on large (up to hundreds of kpc) scales as observed.

Concerning Radio haloes and relics the picture is only partially consistent (for a more detailed discussion of primary and secondary models see Brunetti 2004 and references therein). Radio relics seem to be most likely related to strong shocks produced by major merging events and therefore produced by direct re-acceleration of CRs, the so-called primary models. Although some of the observed features like morphology, polarization and position with respect to the cluster centre can be reasonably well reproduced, there might be still some puzzles to solve. On one hand, direct acceleration of CRs in shocks seems to overestimate the abundance and maybe the luminosity of radio relics; on the other hand simulations which illuminate fossil radio plasma can produce reasonable relics only starting from a small range of parameter settings. A similar situation arises for modelling the central radio emission of galaxy clusters by secondary processes showing radio emission contain higher MFs than the ones without observable extended, diffuse radio emission. On the contrary, the cluster A2142 has a MF strength similar to the Coma cluster (see Fig. 12), but the upper limit on its radio emission is at least two orders of magnitude below the value expected from the correlation (see Fig. 13). Note that both clusters are merging systems characterized by the presence of two central cD galaxies. This indicates that there should be further processes involved or additional conditions to fulfill to produce radio emission. It is worth to notice that recent models, based on turbulent acceleration, seem to overcome this problem (see Kuo, Hwang & Ip 2003; Brunetti & Blasi 2005 and references therein). Note that there is also no indication from observations that clusters showing radio emission contain higher MFs than the ones without observable extended, diffuse radio emission. On the contrary, the cluster A2142 has a MF strength similar to the Coma cluster (see Fig. 12). The other problems is that the dynamical machinery of such structures for which the MF might dominate the evolution, is a real challenge within LSS simulations. However, we expect that - if succeeding in overcoming these limitations - the dynamical impact of the MF on regions like the cooling flows at the centres of galaxy clusters will be significant and will contribute to solve these outstanding puzzles.

There is a big challenge for the next generation of cosmological MHD simulations. Simulations are quite close to having the resolution necessary to properly describe the MF components down to the observed scales, but on the other hand this means to resolve galaxies inside the simulations as well. Note that following the dynamics of such structures for which the MF might dominate the evolution, is a real challenge within LSS simulations. However, we expect that - if succeeding in overcoming these limitations - the dynamical impact of the MF on regions like the cooling flows at the centres of galaxy clusters will be significant and will contribute to solve these outstanding puzzles.

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REFERENCES

Fig. 13. Total power of radio halos observed at 1.4 MHz vs. cluster temperature. We plot data from [Liang et al. 2000], which were partially re-observed by Feretti (2005, in preparation) together with data from [Govoni et al. 2001; Bacchi et al. 2003; Venturi et al. 2003]. Some additional upper limits are collected with the help of F. Govoni. We applied a secondary hadronic model as described in Dolag & Enßlin (2000) to calculate the radio emission from the simulated galaxy clusters. We also added the predictions for the emission from primary (upper) and secondary (lower) electrons taken from [Miniati et al. 2001]. Note that the values for the luminosities for primary electrons should be scaled with the electron to proton injection ratio $R_{e/p}$.

discussions and comments. Special thanks also to F. Govoni who helped a lot in preparing many of the observation-related figures.

References

Bacchi M., Feretti L., Giovannini G., Govoni F.: 2003, A&A 400, 465
Birk G. T., Wiechen H., Otto A.: 1999, ApJ 518, 177
Brüggen M., Ruszkowski M., Simionescu A., Hoeft M., Dalla Vecchia C.: 2005, ApJ 631, L21
Brunetti G.: 2004, Journal of Korean Astronomical Society 37, 493
Brunetti G., Blasi P.: 2005 MNRAS 363, 1173
Bruni M., Maartens R., Tsagas C. G.: 2003, MNRAS 338, 785
Carilli C. L., Taylor G. B.: 2002, ARA&A 40, 319
Cassano R., Brunetti G.: 2005, MNRAS 357, 1313
Clarke T. E., Kronberg P. P., Böhringer H.: 2001, ApJ 547, L111
Dolag K., Bartelmann M., Lesch H.: 1999, A&A 348, 351
Dolag K., Bartelmann M., Lesch H.: 2002, A&A 387, 383
Dolag K., Enßlin T.A.: 2000, A&A 362, 151
Dolag K., Grasso D., Springel V., Tkachev I.: 2004, Journal of Experimental and Theoretical Physics Letters 79, 583
Dolag K., Grasso D., Springel V., Tkachev I.: 2005, Journal of Cosmology and Astro-Particle Physics 1, 9
Dolag K., Schindler S., Govoni F., Feretti L.: 2001, A&A 378, 777
Dolag K., Vazza F., Brunetti G., Tormen G.: 2005, MNRAS 364, 753
Enßlin T.A., Brüggen M.: 2002, MNRAS 331, 1011
Enßlin T.A., Gopal-Krishna: 2001, in: Laing R.A., Blundell K.M. (eds.) Particles and Fields in Radio Galaxies, ASP Conf. Ser. 250, p. 454

Fig. 14. Rough comparison of observed index (diamonds) of MF power spectrum [Voigt & Enßlin 2003; Murgia et al. 2004] and the predictions (stars) from simulations [Rordorf et al. 2004; Dolag et al. 2005; Brüggen et al. 2005]. Note that some observations reflect only a weak lower limit. Moreover the displayed data span different environments, length scales and techniques used to constrain the spectral index. Furthermore the spectral index calculated from the simulations may suffer from effects caused by a non constant mean MF strength in the cluster and varying numerical resolution.

Feretti L., Dallacasa D., Giovannini G., Tagliani A.: 1995, A&A 302, 680
Feretti L., Dallacasa D., Govoni F., Giovannini G., Taylor G.B., Klein U.: 1999, A&A 344, 472
Furlanetto S.R., Loeb A.: 2001, ApJ 556, 619
Giaccintucci S., Venturi T., Brunetti G., et al.: 2005, A&A 440, 867
Govoni F., Enßlin T.A., Feretti L., Giovannini G.: 2001, A&A 369, 441
Govoni F., Feretti L.: 2004, International Journal of Modern Physics D 13, 1549
Grasso D., Rubinstein H.R.: 2001, Phys. Rept. 348, 163
Gregori G., Miniati F., Ryu D., Jones T.W.: 2000, ApJ 543, 775
Hoeft M., Brüggen M., Yepes G.: 2004, MNRAS 347, 389
Jones T.W., De Young D.S.: 2005, ApJ 624, 586
Kim K.-T., Kronberg P.P., Tribble P.C.: 1991, ApJ 379, 80
King E.J., Coles P.: 2005, astro-ph/0508370
Kronberg P.P., Lesch H., Hopp U.: 1999, ApJ 511, 56
Kulsrud R.M., Cen R., Ostriker J.P., Ryu D.: 1997, ApJ 480, 481
Kuo P.-H., Hwang C.-Y., Ip W.-H.: 2003, ApJ 594, 732
Liang H., Hunstead R.W., Birkinshaw M., Andreani P.: 2000, ApJ 544, 686
Miniati F.: 2001, Computer Physics Communications 141, 17
Miniati F., Jones T.W., Kang H., Ryu D.: 2001, ApJ 562, 233
Murgia M., Govoni F., Feretti L., Giovannini G., Dallacasa D., Fanti R., Taylor G.B., Dolag K.: 2004, A&A 424, 429
Myers S.T., Spangler S.R.: 1985, ApJ 291, 52
Reynolds C.S., McKernan B., Fabian A.C., Stone J.M., Verner J.C.: 2005, MNRAS 357, 242
Roettiger K., Burns J.O., Stone J.M.: 1999, ApJ 518, 603
Roettiger K., Stone J.M., Burns J.O.: 1999, ApJ 518, 594
Rordorf C., Grasso D., Dolag K.: 2004, Astroparticle Physics 22, 167
Ryu D., Kang H., Biermann P.L.: 1998, A&A 335, 19
Sgîl G., Miniati F., Enßlin T.A.: 2004, PhysRevD 70, 43007
Springel V.: 2005, MNRAS 364, 1105
Springel V., Yoshida N., White S.: 2001, New Astronomy 6, 79
Stone J.M., Norman M.L.: 1992a, ApJS 80, 753
Stone J.M., Norman M.L.: 1992b, ApJS 80, 791
Subramanian K., Shukurov A., Haugen N.E.L.: 2005, MNRAS in press
Völk H.J., Atoyan A.M.: 2000, ApJ 541, 88
Venturi T., Bardelli S., Dallacasa D., Brunetti G., Giacintucci S., Hunstead R.W., Morganti R.: 2003, A&A 402, 913
Vogt C., Enßlin T.A.: 2003, A&A 412, 373