Cosmic Magnetic Fields in Large Scale Filaments and Sheets

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Abstract. We consider the possibility that cosmic magnetic field, instead of being uniformly distributed, is strongly correlated with the large scale structure of the universe. Then, the observed rotational measure of extragalactic radio sources would be caused mostly by the clumpy magnetic field in cosmological filaments/sheets rather than by a uniform magnetic field, which was often assumed in previous studies. As a model for the inhomogeneity of the cosmological magnetic field, we adopt a cosmological hydrodynamic simulation, where the field is passively included, and can approximately represent the real field distribution with an arbitrary normalization for the field strength. Then, we derive an upper limit of the magnetic field strength by comparing the observed limit of rotational measure with the rotational measure expected from the magnetic field geometry in the simulated model universe. The resulting upper limit to the magnetic field in filaments and sheets is $\bar{B}_{fs} \lesssim 1\mu$G which is $\sim 10^3$ times higher than the previously quoted values. This value is close to, but larger than, the equipartition magnetic field strength in filaments and sheets. The amplification mechanism of the magnetic field to the above strength is uncertain. The implications of such a strength of the cosmic magnetic field are discussed.

Key words: cosmology: large scale structure of universe - magnetic fields

1. Introduction

The strength and morphology of the intergalactic magnetic fields remain largely unknown, because it is intrin-

sically difficult to observe them (for recent reviews, see Kronberg 1994; Beck et al. 1996; Zweibel & Heiles 1997). While the magnetic fields inside typical galaxies are observed to be of order of $3 - 10\mu$G, recent observations indicate that the magnetic fields of the similar strength are also common in core regions of rich clusters (for a recent discussion see Enßlin *et al.* 1997). On the other hand, the upper limit for a large-scale field strength placed by the observed rotation measure (RM) of quasars is about $B_{IGM} \lesssim 10^{-9}L_{\rm rev,Mpc}^{-1/2}$G (Kronberg 1994). Here, $L_{\rm rev,Mpc}$ is the reversal scale of the magnetic fields in units of Mpc in comoving coordinates. It was assumed the fields are uniform in direction within the reversal scale and varied as a comoving passive field in the expansion of the universe. The above value is close to the limit placed by the observed anisotropy in the cosmic microwave background radiation is $B_{IGM} < 6.8 \times 10^{-9}(\Omega_o h^2)^{1/2}$G (Barrow, Ferreira & Silk 1997). Here, a uniform magnetic field was assumed. h is H_o in unit of 100 km/s/Mpc.

According to a recent popular view based on both observational and theoretical cosmology, the dominant nonlinear structure in the universe is a web-like network of filaments (*e.g.,* Bond, Kofman & Pogosyan 1996; Shectman *et al.* 1996). At a lower density contrast, however, bubbly walls whose intersections are in fact filaments are the dominant structures. Such large scale structures form via gravitational instability, and then turbulent motions inside the structures as well as streaming motions along the structures necessarily exist (*e.g.,* Kang *et al.* 1994). Hence, magnetic fields in the early universe, if existed, should have been modified and amplified by those flow motions (*e.g.,* Kulsrud & Anderson 1992; Kulsrud *et al.* 1997). As a result, we expect that *the "geometry" of cosmic magnetic field, which means the spatial distribution of the field strength and its orientation, should be correlated with the large-scale nonlinear structures of the universe.* In other

words, the field strength increases with the matter density and its orientation tends to align with the sheets and filaments, while its random component is associated with the local turbulent motions. The magnetic fields should be strong along the walls of cosmic bubbles, even stronger along the filamentary superclusters, and the strongest inside the clusters of the galaxies, while they are very weak inside the voids.

Based on the proposition that the large scale magnetic field is correlated with the large scale structure of the universe, we consider a way to estimate the field strength which relies on the observational data.

The cosmic magnetic field together with free electrons in the intergalactic medium (IGM) induces the Faraday rotation in polarized radio waves from extra-galactic sources. The observational RM data of quasars show a systematic growth of RM with redshift, z, and limit RM to ~ 5 rad m^{-2} or less at $z = 2.5$ (Kronberg & Simard-Normandin 1976; Kronberg 1994 and references therein). Adopting a model for the distribution of the large scale magnetic field, these data can be used to constrain the strength of the magnetic field. For example, the upper limit estimated by Kronberg (1994) was based on a model in which the field is uniform within the reversal scale, the orientation is random, and there are $N = l_s/L_{rev}$ reversals along the line of sight to a source l_s Mpc away from us.

In the present paper, we re-derive the upper limit by taking a new model in which the intergalactic magnetic field is mostly confined within filaments and sheets but very weak inside voids, rather than the simple model of uniform field. Of course the field would be strongest inside clusters, but their contribution is usually excluded in the observed RM. If we take only the geometric consideration that the field distribution along the lines of sight to radio sources has a small filling factor, high only inside filaments and sheets but low inside voids, then it is obvious that the expected magnetic field strength in filaments and sheets should be higher than the value derived from the uniform field model. But this geometric model is too simple, since the electron distribution as well as the field direction are uncertain. Here, we take a more practical approach by adopting numerical data in a simulated universe which includes a magnetic field, which is evolved during the large scale structure formation. With the magnetic field distribution, specific to this simulation model, we argue that the magnetic field strength in filaments and sheets is limited to $\bar{B}_{fs} \lesssim 1 \ \mu$G. We should emphasize that *this limit should be approximately valid regardless of details of any model for the origin of the large scale magnetic field, provided that it is correlated with the large scale structure of the universe.*

In the next section, we describe the model simulation and the resulting magnetic field geometry. In §3, we explain the procedure to calculate the upper limit of the magnetic field strength in filaments and sheets constrained by the observed RM. In the final section, we discuss the implications of the possible existence of $\sim 1 \ \mu$G or less magnetic field in filaments and sheets.

2. Model Simulation

In this section we describe one particular simulation of the origin and growth of magnetic fields, but will retain at the end only the geometry and the *relative* strength of the magnetic fields across the cosmological structures. It is this structure for which we require a realistic simulation to probe the universe for its Rotation Measure across a large number of simulated paths.

The generation of the large scale magnetic field by the Biermann battery mechanism (L. Biermann 1950) and its subsequent evolution has been followed by solving the equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{c \nabla p_e \times \nabla n_e}{n_e^2 e} \qquad (1)$$

along with the cosmological hydrodynamic equations. Here, p_e is the electron pressure and n_e is the electron number density. The simulation has been done with a version of the cosmological hydrodynamic code which extends the one described in Ryu *et al.* (1993) by incorporating the above equation "passively". That is, the Lorenz force term in the momentum equation has been ignored. Alternatively, the equation for the magnetic field could have been incorporated by solving the full MHD equations. Then the code would have been more diffusive.

A standard cold dark matter (CDM) model universe with total $\Omega = 1$ has been simulated in a periodic box with $(32h^{-1}{\rm Mpc})^3$ volume using 128^3 cells and 64^3 particles from $z_i = 20$ to $z_f = 0$. The values of other parameters used are $\Omega_b = 0.06$, $h = 1/2$, and $\sigma_8 = 1.05$. A more detailed description of the simulation can be found in in Kulsrud *et al.* (1997).

In the simulations which include the evolution of baryonic matter as well as that of dark matter, accretion shocks form in the infalling flows towards the growing nonlinear structures such as sheets, filaments and clusters (*e.g.,* Kang *et al.* 1994; Ryu & Kang 1997b). We note that some evidence has been found in radio relic sources, that these accretion shocks have actually been detected (Enßlin *et al.* 1998). The properties of the shocks depend upon the power spectrum of the initial perturbations on a given scale as well as the background expansion in a given cosmological model. These shocks are the sites of the generation of weak seed field by the battery mechanism represented by the last term in the right hand side of Eq. (1). The evolution of the strength of the seed field generated was plotted in Figure 1 of Kulsrud *et al.* (1997). It grows monotonically to the mass averaged value of order 10^{-21}G by $z \sim 2 - 3$, and then levels off without further increase. The saturation is believed to be due to the finite numerical resistivity inherent in the numerical

scheme used to solve Eq. (1). At the saturation, the magnetic energy is much smaller (by $\sim 10^{30}$) than the kinetic energy. So the dynamical influence of magnetic field into flow motion can be ignored, and neglecting the Lorenz force in the momentum equation is justified.

To illustrate the general characteristics of the field geometry in relation to the matter distribution and flow velocity, a two-dimensional cut of the simulated box is presented in Figure 1. The plot shows a region of $32h^{-1} \times 20h^{-1} (\mathrm{Mpc})^2$ with a thickness of $0.25h^{-1}\mathrm{Mpc}$ at $z = 0$. The three panels display baryonic density contours, velocity vectors, and magnetic field vectors.

We can see accretion shocks around the high density structures of clusters, filaments, and sheets in the density contours. The locations of the shocks can be seen more clearly in the velocity vector plot where accretion motions stop suddenly. In the highest density regions of clusters, flow motion is turbulent. Also we can see the streaming flow motion along the structures, that is, the accretion motion towards clusters in filaments and the accretion motion towards filaments in sheets. On the top of the streaming motion, we expect some amount of turbulent motion which is induced by the cooling, gravitational, and nonlinear thin shell instabilities in filaments and sheets (Vishniac 1994; Anninos, Norman & Anninos 1995; Valinia *et al.* 1997). So the magnetic field in filaments and sheets could have been stretched by the streaming motion as well as amplified by the turbulent motion. As a result, the amplified magnetic field in filaments and sheets is expected to be aligned with the structures, as shown in Figure 1.

Here, we propose that *the geometry of the magnetic field in the simulated universe, with an arbitrary normalization for the field strength, represents the geometry of the real magnetic field correlated with the large scale structure of the universe.* Thus we take from the simulation only the geometry of the field distribution and its relative strength across the spatial distribution.

3. Upper Limit on the Magnetic Field in Filaments and Sheets

We have calculated the expected RMs induced by the magnetic field in filaments and sheets in the simulated universe and compared them with the observed upper limit of RM of distant quasars.

Due to the field reversal of randomly oriented magnetic field along lines of sight, the RMs from sources at a given redshift have a Gaussian distribution centered at zero and its standard deviation gives a statistical measure for the field strength. The standard deviation of the distribution of the RMs from quasars at $z \sim 2.5$ is RM $\lesssim 5$ rad m^{-2} (Kronberg 1994).

The RM which measures the amount of the rotation is given by

$$\mathrm{RM} \equiv \frac{\psi}{\lambda^2} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^{l_s} n_e B_\parallel \frac{\lambda(l)^2}{\lambda} dl \tag{2}$$

where ψ is the rotated angle, $\lambda(l)$ is the wavelength of the polarized wave along the propagating path, l, λ is the observed wavelength, and $B_\parallel$ is the magnetic field component along l (*e.g.,* Shu 1991). The RM for a source at a given redshift z can be calculated numerically by the following line integral

$$\mathrm{RM}\left(\frac{\mathrm{rad}}{\mathrm{m}^2}\right) = 8.1 \times 10^5 \int_0^{l_s} \tilde{n}_e B_\parallel dl = 9.2 \chi h^2 \int_0^{l_s} \Omega_b B_\parallel dl \tag{3}$$

where l is the comoving length in the unit of Mpc, $B_\parallel$ is the proper magnetic field in $\mu\mathrm{G}$, $\tilde{n}_e$ is the comoving electron number density in cm^{-3}, Ω_b is the baryonic density as a fraction of the critical density, and χ is the ionization fraction. The integration length l is related to the redshift by the following equation

$$dl = -\frac{c}{H_o}(1 + z)^{-1}(1 + \Omega_o z)^{-1/2} dz. \tag{4}$$

In the calculation, we have assumed the gas inside filaments and sheets is fully ionized (*i.e.,* $\chi = 1$). The simulated *distributions* of the gas and magnetic field at $z = 0$, 0.5, 1, and 2 have been used, and they have been interpolated in between to integrate the above equation up to $z = 2.5$.

For the relative growth of the field strength for $2.5 \geq z \geq 0$, however, we need to adopt a model, since the numerical simulation could not follow the growth of magnetic field in detail due to numerical resistivity. Again, the normalization of the field strength is arbitrary. Considering that theoretical studies on dynamo processes on large scales do not yet provide a unambiguous model, we assume for simplicity that the magnetic field has reached an "equipartition" with the energy in turbulence. Then its energy should be proportional to the kinetic energy which is, in turn, proportional to the gravitational potential energy. Then, the self-similar solution for an $\Omega = 1$ universe gives

$$\bar{B} \propto (1 + z)^{\frac{2(2n\epsilon - 1)}{n\epsilon}}, \tag{5}$$

where $n = 1$ is for sheets, 2 for filaments, and 3 for clusters (Fillmore & Goldreich 1984). Here, ϵ is the parameter which characterizes the initial perturbation of the self-similar solution and has $0 < \epsilon \leq 1$. Hence, for filaments and sheets, we expect
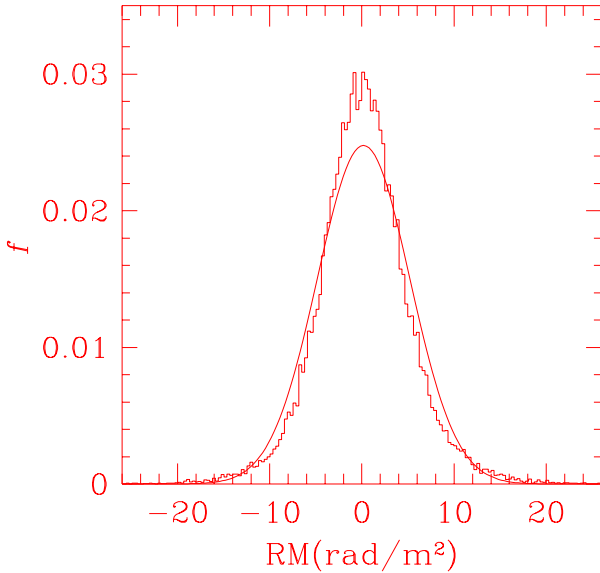
$$\bar{B}_{fs} \propto (1 + z)^q \tag{6}$$

with $0 \lesssim q \lesssim 1.5$. However, we have also considered the model in which the magnetic field grows as time passes
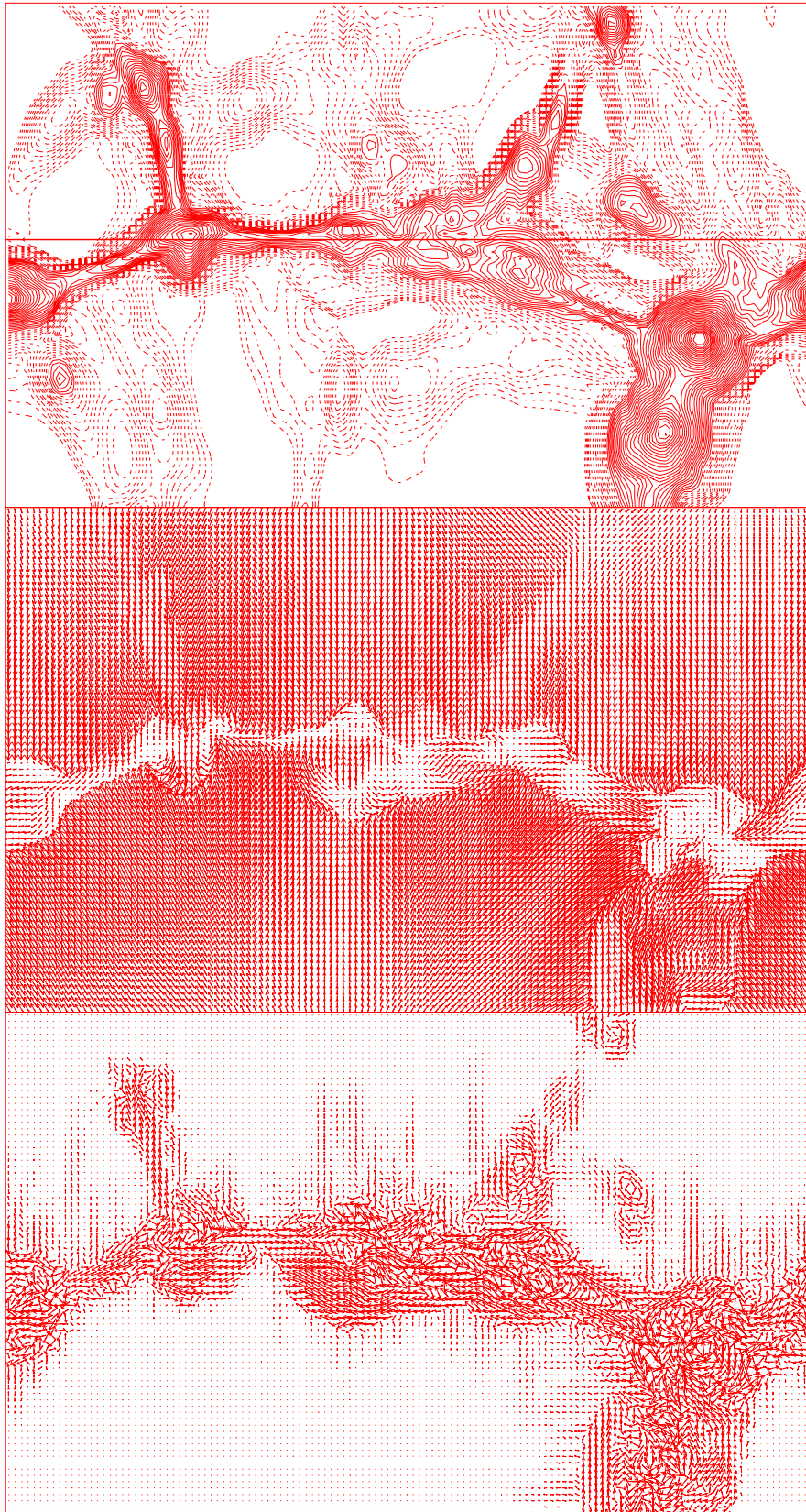
Fig. 1. Two-dimensional cut of the simulated universe at $z = 0$. The plot shows a region of $32h^{-1} \times 20h^{-1}\mathrm{Mpc}^2$ with a thickness of $0.25h^{-1}\mathrm{Mpc}$, although the simulation was done in a box of $(32h^{-1}\mathrm{Mpc})^3$ volume. The first panel shows baryonic density contours, the second panel shows velocity vectors, and the third panel shows magnetic field vectors. In the first panel, the solid lines contour the regions of $\rho_b \geq \bar{\rho}_b$ and the dotted lines contour those of $10^{-1.2}\bar{\rho}_b \leq \rho_b < \bar{\rho}_b$. In the third panel, the vector length is proportional to the log of magnetic field strength.

(Welter, Perry, & Kronberg 1984). So, we have explored the cases of $-1.5 \leq q \leq 1.5$. This large range of the parameter q explored here should encompass many models for the origin of magnetic fields in the cosmos (See, *e.g.*, the discussions in L. Biermann 1950; Parker 1958; Rees 1987; Beck *et al.* 1996; P. Biermann 1997; Kronberg & Lesch 1997).

With the above prescription for the evolution of magnetic field in filaments and sheets, we have integrated Eq. (3) up to $z = 2.5$ along 3×10^4 randomly chosen paths. Figure 2 shows the distribution of the expected RMs for the model with $q = 0$. The magnetic field is normalized so that the standard deviation of the Gaussian fit (the solid line) to the expected RMs matches the observational upper limit of RM $= 5$ rad m^{-2}. With this normalization for the field strength, the upper limits in the rms of magnetic field in filaments and sheets can be calculated for several models. They are given in Table 1 for the several values of q, and they are $\sim 1~\mu$G for $h = 1/2$.

Table 1. Upper Limits on the Magnetic Field Strength in Filaments and Sheets

q [a]	$\bar{B}_{z=0;fs}(\mu\mathrm{G})h_{0.5}^2$ [b]
1.5	0.27
1	0.42
0.5	0.63
0	0.89
−0.5	1.15
−1	1.39
−1.5	1.58

[a] The exponent in the temporal evolution of magnetic field in filaments and sheets, $\bar{B}_{z=0;fs} \propto (1+z)^q$.

[b] The rms of magnetic field in filaments and sheets at the present epoch ($z = 0$) in units of μG for $h = 1/2$.
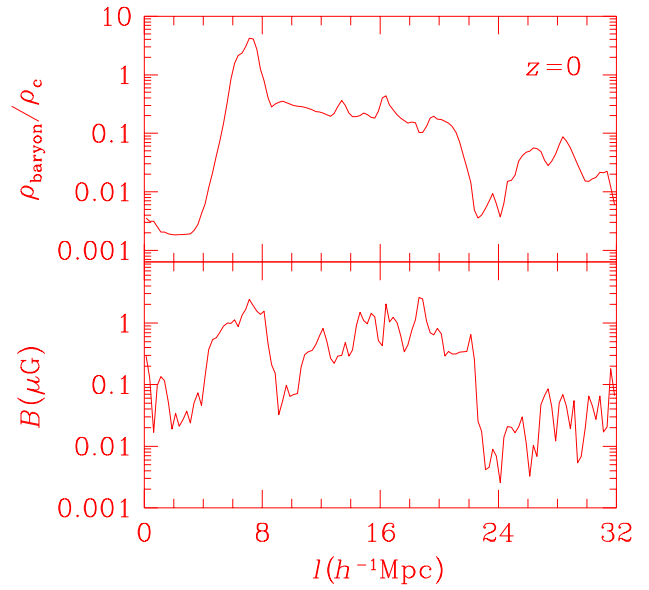
Fig. 3. Distributions of baryonic density and magnetic field strength at $z = 0$ along the line drawn in the first panel of Figure 1, when the exponent in its temporal evolution is, q, zero. The density is given in units of the critical density, while the magnetic field is given in units of μG for $h = 1/2$.

Fig. 2. Histogram of the fraction of the expected RM along 3×10^4 randomly chosen paths up to $z = 2.5$ in the simulated universe. The solid line represents the Gaussian fit. The exponent in the temporal evolution of the rms of magnetic field in filaments and sheets, q, is assumed to be zero. The magnetic field strength is normalized so that the standard deviation of the Gaussian fit matches the observational upper limit of RM $= 5$ rad m^{-2}.

Figure 3 shows the distributions of gas density and magnetic field strength along the line drawn in the first panel of Figure 1 for the case with $q = 0$. We can see the field strength correlates well with the gas density and ranges $0.2 \lesssim B \lesssim 2\mu$G$h_{0.5}^{-2}$ in the regions of filaments and sheets.

These numbers clearly demonstrate that the essential result is nearly independent of any of the details about the origin of the magnetic field, since for the entire range of values tested in q we obtain to within a factor of a few the same result: The upper limit to the magnetic field in the sheet is of order $\bar{B}_{fs} \lesssim 1\mu$G.

4. Conclusion and Discussion

Our result indicates that, with the present value of the observed limit in RM, the existence of magnetic field of up to $\sim 1~\mu$G in filaments and sheets can not be ruled out, if the cosmic magnetic field is preferentially distributed in these nonlinear structures, rather than uniformly distributed in

the intergalactic space. *We emphasize that this result is independent of the details of how the magnetic field originated.* However, it is not certain if the dynamo processes such as the one considered in Kulsrud *et al.* (1997) can amplify a week seed field to the above field strength.

Interestingly, there is confirmation of such a magnetic field in one case. Kim *et al.* (1989) reported the possible existence of a intercluster magnetic field of $0.3 - 0.6~\mu$G in the plane of the Coma/Abell 1367 supercluster. They reached the result from the observation using high dynamic range synchrotron images at 327 MHz. Clearly, this result should be confirmed in other regions of the sky with the newly available possibilities of low radio frequency interferometry such as with the Giant Meterwave Radio Telescope (GMRT) in India, or the new receiver systems on the Very Large Array (VLA) in the USA.

We may compare the above upper limit with the strength of the magnetic field whose energy is in equipartition with the thermal energy of the gas in filaments and sheets. The equipartition magnetic field strength can be written as

$$B = 0.33h\sqrt{\frac{T}{3 \times 10^6 \text{K}}} \sqrt{\frac{\rho_b}{0.3\rho_c}}~\mu\text{G}. \qquad (7)$$

The fiducial values $T = 3 \times 10^6$K and $\rho_b = 0.3\rho_c$ may considered to be appropriate for filaments (see, Kang *et al.* 1994 and Figure 3). The values appropriate for sheets should be somewhat smaller. So, our upper limit set by RM is close to, but several times larger than, the equipartition magnetic field strength.

Filaments and sheets with the above fiducial temperature and gas density can contribute radiation at X-ray wavelengths to the cosmological background. Using the above values and a typical size of $10h^{-1}$Mpc, the luminosity of filaments and sheets in the soft X-ray band $(0.5-2\,\text{keV})$ is expected to be $\lesssim 3 \times 10^{41}$erg s^{-1}. Actually, Soltan *et al.* (1996) and Miyaji *et al.* (1996) reported the detection of extended X-ray emission from structures of a comparable size and a luminosity of $\approx 2.5 \times 10^{43}$erg s^{-1}, which is correlated to Abell clusters. These observations suggest that the temperature and gas density outside clusters could even be considerably larger than the fiducial values assumed above. In any case, if these observations can be further confirmed, and the equipartition of magnetic field and gas energies is assumed, it would imply the existence of a $\sim 1\mu$G magnetic field on large scales outside galaxy clusters.

The possible existence of strong magnetic field of $1~\mu$G or less in filaments and sheets has many astrophysical implications, some of which we briefly outline in the following:

The large-scale accretion shocks where seed magnetic fields could be generated are probably the biggest shocks in the universe with a typical size $\gtrsim$ a few (1-10) Mpc and very strong with a typical accretion velocity $\gtrsim$ a few 1000 km s^{-1}. The accretion velocity onto the shocks around clusters of a given temperature, or a give mass to radius ratio M_{cl}/R_{cl}, is smaller in a universe with smaller Ω_o, and is given as $v_{acc} \approx 0.9 - 1.1 \times 10^3$ km s$^{-1}[(M_{cl}/R_{cl})/(4 \times 10^{14}\text{M}_\odot/\text{Mpc})]^{1/2}$ in model universes with $0.1 \leq \Omega_o \leq 1$ (Ryu & Kang 1997a). With up to $\sim 1~\mu$G or less magnetic field around them, the large-scale accretion shocks could serve as possible sites for the acceleration of high energy cosmic rays by the first-order Fermi process (Kang, Ryu & Jones 1996; Kang, Rachen & Biermann 1997). Although the shocks around clusters would be the most efficient sites for acceleration, those around filaments and sheets could make a significant contribution as well (Norman, Melrose & Achterberg 1995). With the particle diffusion model in quasi-perpendicular shocks (Jokipii 1987), the observed cosmic ray spectrum near 10^{19}eV could be explained with reasonable parameters if about 10^{-4} of the infalling kinetic energy can be injected into the intergalactic space as the high energy particles (if an E^{-2} spectrum of cosmic rays is assumed; for a slightly steeper spectrum as suggested by radio relic sources, the efficiency is closer to 0.1, Enßlin *et al.* 1998).

The discoveries of several reliable events of high energy cosmic rays at an energy above 10^{20}eV raise questions about their origin and path in the universe (a recent review is P. Biermann 1997), since their interaction with the cosmic microwave background radiation limits the distances to their sources to less than 100 Mpc, perhaps within our Local Supercluster. The Haverah Park and Akeno data indicate that their arrival directions are in some degree correlated with the direction of the Supergalactic plane (Stanev *et al.* 1995; Hayashida *et al.* 1996; Uchihori *et al.* 1996). In Biermann, Kang & Ryu (1996), we noted that if the magnetic field of $\sim 1\mu$G or less exists inside our Local Supercluster and there exist accretion flows infalling toward the supergalactic plane, it is possible that the high energy cosmic rays above the so-called GZK cutoff ($E > 5 \times 10^{19}$ eV) can be confined to the supergalactic plane sheet, an effect analogous to solar wind modulation. In each case a shock front pushes energetic particles upstream as seen from its flow. Obviously, this effect would occur only for a small part of phase space, namely those particles with a sufficiently small initial momentum transverse to the sheet. This would explain naturally the correlation between the arrival direction of the high energy cosmic rays and the supergalactic plane. Also, confinement means that for all the particles captured into the sheets, the dilution with distance d is $1/d$ instead of $1/d^2$, increasing the cosmic ray flux from any source appreciably with respect to the three-dimensional dilution. So we may see sources to much larger distances than expected so far. On the other hand, particles with a larger initial momentum transverse to the sheet would be strongly scattered, obliterating all source information from their arrival direction at Earth.

With the magnetic field in the intergalactic medium, charged particles passing it would not only experience deflection. It would also smear out their arrival direction as well as delay their arrival time. Plaga (1995) suggested that an exhibition of this latter effect would be the delay of the arrival times of γ-rays from a cascade caused by photons from highly time-variable extragalactic sources. However, with strong fields of $\sim 1\ \mu$G or less in filaments and sheets intervening between the sources and us, the expected consequence would be a strong smearing of the sources rather than the delay of arrival times (Kronberg 1995). But, for details, calculations following the propagation of photons and charged particles should be done.

Another interesting exploration is to study the radiation emission arising from filaments and sheets strong magnetic field of $1\ \mu$G or less. We noted that the original estimate of the magnetic field in the plane of the Coma/Abell 1367 supercluster was based on a synchrotron radio continuum measurement (Kim *et al.* 1989). We also noted that the thermal Bremsstrahlung emission in the soft X-ray band may provide an interesting check on the work presented here. Whether these structures can contribute at other wavelengths, such as γ-ray energies, to the cosmological background remains an an unanswered but challenging question at this time.

These issues will be discussed elsewhere.

5. acknowledgments

References

Anninos, W. Y., Norman, M. L. & Anninos, P., 1995, ApJ, 450, 1
Barrow, J. D., Ferreira, P. G. & Silk, J., 1997, Phys. Rev. Letters, 78, 3610
Beck, R., Brandenburg, A., Moss, D., Shukurov, A., & Sokoloff, D., 1996, Ann. Rev. Astron. & Astroph., 34, 155
Biermann, L., 1950, Z. Naturforsch, 5a, 65
Biermann, P. L., 1997, Journal of Physics G, 23, 1
Biermann, P. L., Kang, H. & Ryu, D., 1996, In Proc. ICRR Symposium on Extremely High Energy Cosmic Rays, Tokyo, ed. M. Nagano, p. 79
Bond, R. R., Kofman, L. & Pogosyan, D., 1996, Nature, 380, 603
Enßlin, T., Biermann, P. L., Kronberg, P. P., Wu, X.-P., 1997, ApJ, 477, 560

Enßlin, T.A., Biermann, P.L., U. Klein, S. Kohle, 1998, A&A, in press (astro-ph/9712293)
Fillmore, J. A. & Goldreich, P., 1984, ApJ, 281, 1
Hayashida, N. *et al.* , 1996, Phys. Rev. Letters, 77, 1000
Jokipii, J. R., 1987, ApJ, 313, 842
Kang, H., Cen, R., Ostriker, J. P. & Ryu, D., 1994, ApJ, 428, 1
Kang, H., Rachen, J. P. & Biermann, P. L., 1997, MNRAS, 286, 257
Kang, H., Ryu, D. & Jones, T. W., 1996, ApJ, 456, 422
Kim, K.-T., Kronberg, P. P., Giovannini, G. & Venturi, T., 1989, Nature, 341, 720
Kronberg, P. P., 1994, Rep. Prog. Phys. 57, 325
Kronberg, P. P., 1995, Nature, 404, 430
Kronberg, P. P. & Lesch, H., 1997, In The Physics of the Galactic Halos, Proc. 156 WE Heraeus Seminar, ed. H. Lesch *et al.*
Kronberg, P. P. & Simard-Normandin, M., 1976, Nature, 263, 653
Kulsrud, R. M. & Anderson, S. W., 1992, ApJ, 396, 606
Kulsrud, R. M., Cen, R., Ostriker, J. P. & Ryu, D., 1997, ApJ, 480, 481
Miyaji, T., Hasinger, G., Egger, R., Trümper, J., & Freyberg, M.J., 1996, A&A, 312, 1
Norman, C. A., Melrose, D. B. & Achterberg, A., 1995, ApJ, 454, 60
Parker, E. N., 1958, ApJ, 128, 664
Plaga, R., 1995, Nature, 374, 430
Rees, M. J., 1987, QJRAS, 28, 197
Ryu, D. & Kang, H., 1997a, MNRAS, 284, 416
Ryu, D. & Kang, H., 1997b, In Proc. of The 18th Texas Symposium on Relativistic Astrophysics, ed. A. Olinto, J. Frieman & D. Schramm
Ryu, D., Ostriker, J. P., Kang, H. & Cen R., 1993, ApJ, 414, 1
Shectman, S. A., Landy, S. D., Oemler, A., Tucker D. L., Lin, H., Kirshner, R. P. & Schechter, P. L., 1996, ApJ, 470, 172
Shu, F. H., 1991, The Physics of Astrophysics (Volume1): Radiation, (Mill Valley: University Science Books)
Soltan, A. M., Hasinger, G., Egger, R., Snowden, S., & Trümper, J., 1996, A&A, 305, 17
Stanev, T., Biermann P. L., Lloyd-Evans, J., Rachen, J. P., & Watson, A. A., 1995, Phys. Rev. Letters, 75, 3056
Uchihori, Y. *et al.* , 1996, In Proc. "Extremely High Energy Cosmic Rays", Ed. M. Nagano, University of Tokyo meeting, p. 50
Valinia, A., Shapiro, P. R., Martel, H. & Vishniac, E. T., 1997, ApJ, 479, 46
Vishniac, E. T., 1994, ApJ, 428, 186
Zweibel, E. G. & Heiles, C., 1997, Nature, 385, 131
Welter, G. L., Perry, J. J. & Kronberg, P. P., 1984, ApJ, 279, 19