The Magnetic Field in Galaxies, Galaxy Clusters, and the InterGalactic Space

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ABSTRACT

Magnetic fields of debated origin appear to permeate the Universe on all large scales. There is mounting evidence that supernovae produce not only roughly spherical ejecta and winds, but also highly relativistic jets of ordinary matter. These jets, which travel long distances, slow down by accelerating the matter encountered on their path to cosmic-ray energies. We show that, if the turbulent motions induced by the winds and the cosmic rays generate magnetic fields in rough energy equipartition, the predicted magnetic-field strengths coincide with the ones observed not only in galaxies ($5\,\mu$G in the Milky Way) but also in galaxy clusters ($6\,\mu$G in Coma). The prediction for the intergalactic (or inter-cluster) field is 50 nG.

1. Introduction

The average magnetic field (MF) of the interstellar medium (ISM) of our Galaxy ($B_{\mathrm{MW}} \sim 5\,\mu$G) corresponds to an energy density of ~ 0.5 eV cm^{-3}, in good agreement with the energy density of cosmic rays (CRs). This provides a strong hint of a common origin and of energy equipartition (see, e.g. Longair 1992), though other theories of the origin of galactic fields — e.g. by dynamo amplification of primordial seed fields— have been proposed (Parker 1992). The origin of intergalactic MFs, both within and without galaxy clusters, is also undecided. Here we discuss how all of these MFs could have a common origin, and be in equipartition with the corresponding local energy densities of CRs.

Radio observations of clusters indicate that the *intra*-cluster medium (ICM) between the galaxies is permeated by intense MFs (e.g. Kronberg 2004). Nearby clusters are seen

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to have a "radio halo" with a distribution similar to that of the cluster gas, observed in X-rays. These halos are produced by synchrotron emission from CR electrons spiralling in the cluster's MF, while the X-rays are electron bremsstrahlung. Measurements of the Faraday rotation of linearly polarized radio emission traversing the cluster's medium, in combination with X-ray data, support the existence of cluster MFs of a few μG (Kim et al. 1989, 1990; Taylor & Perley 1993; Feretti et al. 1995; Deiss et al. 1997; Eilek 1999; Ensslin et al. 1999; Clarke, Kronberg & Bohringer 2001; Johnston-Hollitt, Hollitt & Ekers 2004). The mapping of the Faraday rotation reveals that the clusters' MFs are turbulent with a Kolmogoroff power spectrum on a variety of scales (Ensslin, 2004; Vogt & Ensslin 2004).

The MF between clusters and isolated galaxies in the *inter*-galactic medium (IGM) is not known. Speculations on its value range from nearly a μG to a pG. Low-level radio emission was detected from the IGM around Coma (Kim et al. 1989; Ensslin et al. 1999) and from the IGM in large-scale filaments of galaxies (Bagchi et al. 2002). The estimated field strengths are of the order of several hundred nG.

Theories of the origin of MFs in the ICM and IGM include cosmic shocks (e.g. Kulsrud et al. 1997; Ryu, Kang & Biermann 1998), ionization fronts (Gnedin et al. 2000) and outflows from primeval galaxies (Kronberg et al. 2004), quasars and/or radio galaxies (Furlanetto & Loeb 2001, Gopal-Krishna & Wiita 2001). Kronberg et al. (2004) have estimated that "giant" extragalactic radio sources, powered by accretion onto massive black holes ($M > 10^8 \, M_\odot$), inject $E_B \sim 10^{60-61}$ ergs of magnetic energy into radio lobes, and have argued that the expansion and diffusion of these Mpc-scale lobes could have magnetized a large fraction of the IGM. Assuming that in the accretion $\sim 1\%$ of M is released in the form of magnetic energy, Kronberg (2004) estimated a mean $B_{\mathrm{IGM}} \sim 40$ nG at redshift $z \sim 2$. This value[1] evolves as $(1 + z)^{-2}$ by cosmic expansion, yielding a two-orders-of-magnitude smaller IGM energy density, and a one-order-of-magnitude smaller B_{IGM} at $z = 0$.

Concerning the ICM, it was suggested that the jets formed by accretion onto massive black holes in clusters provide the heat source in the so-called "cooling flow" (CF) clusters (e.g. McNamara et al. 2000). But Kronberg et al. (2004) have also found that the radio lobes of the powerful radio galaxies at the centre of rich clusters contain a magnetic energy of only $E_B \sim 10^{58-59}$ erg. Assuming equipartition between the kinetic energy output and the magnetic energy, the energy supply from such objects is insufficient to power the X-ray emission from bright CF clusters over a Hubble time ($\sim 10^{62}$ erg for bright CF clusters).

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[1]If the ratio of the mass of the central massive black hole and the luminosity of the Galaxy ($\sim 1.5 \times 10^{-4} \, M_\odot/L_\odot$) is universal, the luminosity density of the local universe ($\sim 1.2 \times 10^8 \, L_\odot \, \mathrm{Mpc}^{-3}$) implies a black hole mass density of $\rho_{\mathrm{BH}}(z = 0) \sim 1.8 \times 10^4 \, M_\odot \, \mathrm{Mpc}^{-3}$, and $\rho_{\mathrm{BH}}(z = 2) \sim 1.5 \times 10^5 \, M_\odot \, \mathrm{Mpc}^{-3}$ at the "quasar epoch", consistent with $\rho_{\mathrm{BH}}(z = 2) \sim 2.2 \times 10^5 \, M_\odot \, \mathrm{Mpc}^{-3}$, adopted by Kronberg (2004).

Moreover, some CF clusters contain neither powerful radio galaxies nor active galactic nuclei. Contrariwise, Colafrancesco, Dar & De Rújula (2004) have shown that the required heat supply in CF clusters can be provided by the energy deposited in the ICM by jets and CRs emitted from the cluster galaxies[2], and that the equipartition of energy between the ionized gas, the MF and the CRs can explain the origin of MFs of several μG.

In this letter we argue that the outflow of jets, CRs and winds from SN explosions in star formation regions, where most SNe take place, magnetize the ISM in galaxies, the ICM in galaxy clusters and the IGM outside galaxy clusters. Our main assumption is that of a rough equipartition between the energy of the SN jets and winds and the energy of the accompanying CRs. The predicted strengths of the MF in the ISM and ICM are consistent with those observed. In large structures, the predicted magnetic energy density is roughly proportional to the luminosity density, with a mean MF of several μG in the ICM of rich galaxy clusters and ~ 50 nG in the IGM.

2. Galactic CRs, magnetic fields and supernova explosions

As a result of the steep energy spectrum of galactic CRs, the bulk of the CR energy is carried by nuclei with an average energy of a few GeV. The most accurate measurements of their flux, dI/dE, near Earth and during solar minimum (minimum solar modulation) are those of AMS (Alcaraz et al. 2000a,b) and BESS (Haino et al. 2004). Their measurements yield a local CR energy density[3]:

$$\rho_E[\text{CR}] = \frac{4\,\pi}{c}\,\int \frac{dI}{dE}\,E\,dE \approx 0.5\,\text{eV}\,\text{cm}^{-3}. \tag{1}$$

If the energy densities of galactic CRs and MFs are in equipartition,

$$B_{\text{MW}}^2/(8\,\pi) \approx \rho_E[\text{CR}], \tag{2}$$

and $B_{\text{MW}} \sim 5\,\mu$G, in good agreement with observations, as is well known (Longair 1992).

There is evidence from gamma-ray bursts (e.g. Dar & De Rújula 2004, Dar 2004a), from SN1987A (Nisenson & Papaliolios 1999), and from the morphology of young supernova

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[2]For the CRs to be the heating agent of the cluster gas, the CR luminosity of a Galaxy must be a few times its "classic" estimate (Colafrancesco et al. 2004). For the related interpretation of the Gamma Background Radiation to succeed, the jets must travel a few kpc or more (Dar & De Rújula 2001). Both requirements are predictions of the "Cannonball" model of high-energy astrophysics (e.g. De Rújula 2004a,b).

[3]At energies below ~ 1 GeV, dI/dE is affected by Earth and Sun's effects. The uncertainties on the energy-weighed integral of Eq. (1) are much smaller.

(SN) remnants (e.g. Hwang et al. 2004) that in addition to quasi-spherical ejecta, SNe produce highly relativistic and narrowly collimated jets, which carry an average kinetic energy $E_K[\text{Jet}] \sim 2 \times 10^{51}$ erg, similar to the kinetic energy of the spherical ejecta. The jets slow down by collisions with the interstellar matter (ISM) along their path. The intercepted ISM is thereby accelerated to CR energies, carrying away almost entirely the original energy of the jets. This simple theory of CRs agrees very well with the observed CR spectra and CR composition at all energies (Dar 2004b; De Rújula 2004a,b). The fast winds also transport CRs and magnetic fields within galaxies and out of them. We assume equipartition in the sense that, of the total energy ($\sim 2\, E_K[\text{Jet}]$) of winds and jets, 1/2 ends up in CRs.

Can the bulk of the galactic CRs be accelerated by SNe in the stated way? If SNe produce the observed flux of galactic CRs, the galactic CR luminosity must satisfy:

$$L_{\text{CR}}[\text{MW}] \approx \frac{4\,\pi\, V_{\text{CR}}[\text{MW}]}{c} \int \frac{dI}{dE} \frac{E}{\tau(E)}\, dE \approx R_{\text{SN}}[\text{MW}]\, E_K[\text{Jet}] \approx 1.3 \times 10^{42}\,\text{erg}\,\text{s}^{-1}. \quad (3)$$

where $V_{\text{CR}}[\text{MW}]$ is the confinement volume of low-energy CRs in the Galaxy, $\tau(E)$ is their mean confinement time, and $R_{\text{SN}}[\text{MW}]$ is the present Galactic SN rate. In the numerical result we have used the estimate $R_{\text{SN}}[\text{MW}] \approx 1/50\ \text{y}^{-1}$, obtained from the rate and spatial distribution of historical SNe and the measured galactic extinction, and the quoted value of $E_K[\text{Jet}]$. This SN rate is also consistent with the value measured in the local universe[4].

By fitting the diffuse gamma-ray emission of the Galaxy, as measured by EGRET (Sreekumar et al. 1998), to the CR production rate of γ-rays in a "leaky box" model of the galactic CR halo, Strong et al. (2004) obtained $V_{\text{CR}}[\text{MW}] \approx 2.1 \times 10^{68}$ cm^3 (the volume of a cylinder with 30 kpc diameter and 10 kpc height). Using the observed CR spectrum and $\tau(E) \sim 2 \times 10^7\, (E/\text{GeV})^{-0.5 \pm 0.15}$ y (inferred from the relative abundance of unstable isotopes in CRs), we obtain for the mean injection rate of CR energy per unit volume in the Milky Way $\dot{\rho}_E[\text{CR}] \approx 1.8 \times 10^{-19}$ erg cm^{-3} y^{-1}, and consequently $L_{\text{CR}}[\text{MW}] \sim 1.2 \times 10^{42}$ erg s^{-1}. This number agrees with the RHS of Eq. (3).

From the above we conclude that SN explosions seem to be the source of the bulk of the CR and MF energies in the ISM of ordinary galaxies.

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[4] The SN rate is 2.8 y^{-1} (Van den Bergh & Tammann, 1991) in a "fiducial sample" of 342 galaxies within the Virgo circle (whose total B-band luminosity is $1.35\, h^{-2} \times 10^{12}\, L_\odot^B$). For $h = 0.65$ (H_0 in units of 100 km Mpc^{-1} s^{-1}) and the galactic luminosity $L_{\text{MW}} \sim 2.4 \times 10^{10}\, L_\odot$, we also obtain $R_{\text{SN}}[\text{MW}] \approx 1/50\ \text{y}^{-1}$.

3. The magnetic field in the ICM of galaxy clusters

Let $R(z)$ be the rate of SN events in a galaxy such as ours, at redshift z, or look-back time t. For a standard cosmology with $\Omega = \Omega_M + \Omega_\Lambda = 1$, $dt/dz = [\Omega_M (1+z)^3 + \Omega_\Lambda]^{1/2}/[H_0 (1+z)]$, where $\Omega_M \approx 0.27$, $\Omega_\Lambda \approx 0.73$ and $H_0 \approx 65$ km Mpc^{-1} s^{-1}. The SN rate is proportional to the star formation rate $R_{\rm SF}(z)$, so that $R(z) = R(0) R_{\rm SF}(z)/R_{\rm SF}(0)$. The observations (see, e.g. Lilly et al. 1995; Madau et al. 1996, Steidel et al. 1999; Schiminovich et al. 2004) are: $R(z) \sim R(0) (1+z)^\alpha$ with $\alpha \approx 2.5 \pm 0.5$ for $z \leq 1$ and $R(z) \approx R(1) ([1+z]/2)^{0\pm0.5}$ for $1 \leq z \leq 5$, a redshift beyond which the relative volume is small. If the star formation history in a galaxy cluster (GC) is not very different from that in the Milky Way or the rest of the universe, the cluster's SN rate is simply weighed by the ratio of luminosities: $R_{\rm GC}(z) \approx (L_{\rm GC}/L_{\rm MW}) R(z)$. For reasonable MF coherence lengths, low-energy CRs do not diffuse out of a rich cluster during a Hubble time, and the total CR energy in their ICM is:

$$E_{\rm CR}(z_o) = \frac{2}{3} E_K[\text{Jet}] \frac{R_{\rm SN}[\text{GC}]}{H_0} \int_{z_o}^\infty \frac{R_{\rm SF}(z)}{R_{\rm SF}(0)} \frac{dz}{(1+z)\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}, \qquad (4)$$

if the cluster decouples from the Hubble expansion at a relatively early time. The factor 2 reflects the equality of energies of jetted and "spherical" ejecta; the factor 1/3 the energy equipartition between CRs, MFs, and the *dense*[5] ICM plasma.

For $z_o = 0$, the integral in Eq. (4) is $\approx 2.6 \pm 1.3$, implying a CR energy density:

$$\rho_{\rm ECR}[\text{ICM}] \sim \frac{L_{\rm GC}}{L_{\rm MW}} \frac{R_{\rm SN}[\text{MW}] E_K[\text{Jet}]}{H_0 V_{\rm GC}} \sim (0.22 \pm 0.11) \left(\frac{L_{\rm GC}}{10^{12} L_\odot}\right) \left(\frac{\text{Mpc}}{R_{\rm GC}}\right)^3 \text{eV cm}^{-3}. \quad (5)$$

If the CRs from SN explosions magnetize the ICM in the same way that they magnetize the ISM, the MF in the ICM has the same energy density as the CRs: $B_{\rm ICM}^2/(8\pi) \sim \rho_{\rm ECR}$. This prediction is in good agreement with observations. For instance, the observed luminosity of Coma within a radius of 1 Mpc is $L_{\rm Coma} \approx 3 \times 10^{12} L_\odot$ (Fusco Femiano & Hughes 1994), implying a CR energy density, $\rho_E[\text{CR}] \sim (0.67 \pm 0.33)$ eV cm^{-3}, and $B_{\rm Coma} \approx 5.1 \pm 1.2 \,\mu$G, in agreement with the observed $\sim 6 \,\mu$G (e.g. Clarke et al. 2001).

4. Intergalactic cosmic rays and magnetic fields

Let $R_{\rm SN}(z = 0) \approx 10^{-4}$ Mpc^{-3} y^{-1} be the current local SN rate per comoving unit volume (the observed SN rate per unit luminosity within the Virgo circle, multiplied by

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[5]CR-induced hadronic and electromagnetic showers are efficient in transferring energy to the dense ICM plasma, but not to the thin ISM or IGM (Colafrancesco et al. 2004).

$\rho_L \approx 1.2 \times 10^8 \, L_\odot \, \mathrm{Mpc}^{-3}$, the mean luminosity density in the local universe). In a steady state, the injection rate of CRs into the IGM by a galaxy is equal to its CR production rate. Consequently, SN explosions in galaxies, at a cosmic time $t(z)$, inject energy into the IGM at a rate $\sim 2 \, E_K[\mathrm{Jet}] \, R_{\mathrm{SN}}(z)$. Let dN_{SN}/dE be the CR spectrum produced by a single SN. Its energy dependence is that of $(dI/dE)/\tau(E)$, with dI/dE the observed CR spectrum, and $\tau(E)$ the CR the residence time. In equipartition, its normalization is $\int (dN_{\mathrm{SN}}/dE) \, E \, dE = E_K[\mathrm{Jet}]$. The CR spectral density in the IGM at redshift z_o, is given by:

$$\frac{dn}{dE}(z_o) = \frac{R_{\mathrm{SN}}(0)}{H_0} \int_{z_o}^{\infty} \frac{dz}{\sqrt{\Omega_M \, (1+z)^3 + \Omega_\Lambda}} \, \frac{R_{\mathrm{SF}}(z)}{R_{\mathrm{SF}}(0)} \, \frac{dN_{\mathrm{SN}}}{dE'}\bigg|_{E'=(1+z)\,E} . \tag{6}$$

The present CR energy density of the IGM implied by equipartition and Eq. (6) is:

$$\rho_{\mathrm{ECR}}[\mathrm{IGM}] = \int \frac{dn}{dE} \, E \, dE \approx (0.76 \pm 0.38) \times 10^{-4} \, \mathrm{eV \, cm}^{-3}. \tag{7}$$

If the galactic winds and CRs from SN explosions magnetize the IGM in the same way that they magnetize the ISM, then, under the assumption of equipartition, the magnetic field in the IGM has the same energy density as the CRs: $B_{\mathrm{IGM}}^2/(8\,\pi) = \rho_{\mathrm{ECR}}[\mathrm{IGM}]$. Hence the average strength of magnetic fields in the IGM is predicted to be $B_{\mathrm{IGM}} \sim 50 \pm 12$ nG. The estimated field in the outskirts of Coma (several hundred nG; see Kim et al. 1989; Ensslin et al. 1999) is intermediate between our expectations for the ICM and the IGM.

5. Conclusions

There is evidence that long-duration gamma ray bursts are produced by relativistic jets ejected in core-collapse SN explosions, as long advocated in the "Cannonball" (CB) model (Dar & De Rújula 2004; Dar 2004a and references therein). The jets, along their long paths (much larger than a galaxy's size), transfer essentially all of their energy to the local medium, which is accelerated to CR energies (Dar 2004; De Rújula 2004, Dar & De Rújula in preparation). The generation of CRs and the subsequent MFs along the jet's path is fast: it occurs at nearly the speed of light. It is known from "first-principle" simulations that a relativistic plasma (in our case, the CRs) impinging on a medium at rest generates turbulence and MFs efficiently and very rapidly (Frederiksen et al. 2004). The transport of CRs and MFs by SN winds, even at a modest few thousand km s^{-1} reaches —in a Hubble time— distances larger than the mean separation between galaxies. This justifies our implicit assumption that, in equipartition with CRs, sufficiently uniform MFs are generated in a time much shorter than Hubble's time.

In equilibrium, the CRs escaping a galaxy —or being generated by jets beyond the galaxy's confines— have the same spectrum: the CR "source spectrum": the observed spectrum deprived of the galactic confinement-time effect, as in Eq. (3). We have assumed equipartition between CR and MF energies in the low-density ISM and IGM, and between the energies of CRs, MFs and the dense plasma of the hot central regions of the ICM. On this basis, we obtained $B_{\mathrm{MW}} \sim 5\,\mu\mathrm{G}$ for the mean magnetic field in the Galaxy, and a very similar value for B_{Coma}, the mean magnetic field in the ICM within 1 Mpc from the centre of the Coma cluster (or similarly rich clusters), in agreement with the observations. The prediction for the IGM is $B_{\mathrm{IGM}} \sim 50$ nG. The observations in the outskirts of Coma are between our predictions for the ICM and the IGM, but not enough is known about the propagation of CRs in the IGM to claim that this is a success.

Our theory of large-scale MFs also explains in a very simple fashion the properties of CRs (Dar 2004; De Rújula 2004). It individuates the heat-source in "cooling flow" clusters and predicts the temperature profile of the intra-cluster gas (Colafrancesco et al. 2004). It predicts an extragalactic γ-ray background radiation with a spectral index ~ -2.1, dominated by inverse Compton scattering (ICS) of the microwave background radiation by CR electrons in the galactic halo and in the IGM. A similar radiation from the halo of Andromeda may be observable by GLAST (Dar & De Rújula 2001). The theory entails a γ-ray emission from the ICM of clusters of galaxies, due to ICS of CR electrons and π^0 production and decay (with spectral indices ~ -2.1 and ~ -2.2, respectively) in the collisions of CR nuclei with the ICM (Dar & De Rújula 2001). These radiations are also at a level detectable by GLAST.

Although other accelerators —such as flaring stars, stellar winds, SN remnants, pulsars, microquasars, and massive black holes in active galactic nuclei— contribute to the production of non-solar CRs, supernova explosions seem to be the dominant source of CRs, as speculated long ago (Baade & Zwicky 1934). Not only can the SN outflows accelerate the bulk of the high energy CRs, but they can also magnetize the entire universe at the observed level.

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