Available online at www.sciencedirect.com
SCIENCE DIRECT
C. R. Physique 5 (2004) 431–440
COMPTES RENDUS PHYSIQUE

Ultimate energy particles in the Universe/Particules d'énergies ultimes dans l'Univers

Acceleration mechanisms 2: force-free reconnection

Stirling A. Colgate, Hui Li

MS 227, Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545, USA

Available online 5 May 2004

Presented by Pierre Encrenaz

Abstract

We suggest an unconventional view of the origin of most cosmic rays (CRs) in the universe. We propose that nearly every accelerated CR was part of the parallel current that maintains all force-free (f-f) magnetic fields. Charged particles are accelerated by the electric field $E_\parallel$ produced by reconnection parallel to the magnetic field **B**. The inferred total energy in extragalactic cosmic rays is $\sim 10^{60}$ ergs per galaxy spacing volume, provided that the assumed acceleration mechanisms do not preferentially only accelerate ultra high energy cosmic rays (UHECRs). This total energy is quite large, about 10^5 times the parent galactic CR or magnetic energy. We argue that the formation energy of supermassive black holes (SMBHs) at galaxy centers, $\sim 10^{62}$ ergs, becomes the only feasible source. We propose an efficient dynamo process which converts gravitational free energy into magnetic energy in an accretion disk around a SMBH. Aided by Keplerian winding, this dynamo converts a poloidal seed field into f-f fields, which are transported into the general intergalactic medium (IGM) eventually. This magnetic energy must also have been efficiently converted into particle energies, as evidenced by the radiation from energetic particles. In this view CRs of the IGM are the result of the continuing dissipation, in a Hubble time, of this free energy, by acceleration in situ within the f-f fields confined within the super-galactic walls and filaments of large scale structures. In addition, UHECRs are diffusively lost to the galactic voids at time scales below the GZK attenuation time, $\sim 10^8$ years. Similarly, within the galaxy we expect that the winding by the disk rotation of the galaxy, by the rotation energy of magnetized neutron stars, and by the Keplerian winding of star formation disks are efficient sources of f-f magnetic field energy and hence the sources of galactic CR acceleration. ***To cite this article: S.A. Colgate, H. Li, C. R. Physique 5 (2004).***

Résumé

Mécanismes d'accélération 2 : reconnexion de champs sans force. Nous proposons une vision non conventionnelle de l'origine de la plupart des rayons cosmiques dans l'univers. Notre idée est que pratiquement tout rayon cosmique ayant subi une accélération est issu du courant parallèle qui entretient tout champ magnétique sans force (force-free, f-f). Les particules chargées sont accélérées par le champ électrique $E_\parallel$ produit par la reconnexion parallèle au champ magnétique **B**. L'énergie totale qui en résulte pour les rayons cosmiques extra-galactiques est $\sim 10^{60}$ ergs par volume moyen extra-galactique correspondant à une galaxie. Cette énergie totale est assez importante. Elle est environ 10^5 fois plus élevée que l'énergie transportée par les rayons cosmiques ou l'énergie magnétique dans la galaxie mère. Nous proposons comme seule source crédible d'énergie celle de formation de trous noirs super-massifs, $\sim 10^{62}$ ergs, au centre de galaxies. Nous présentons un mécanisme de dynamo efficace qui transforme l'énergie libre gravitationnelle en énergie magnétique dans le disque d'accrétion d'un trou noir. Grâce à l'enroulement keplerien, cette dynamo transforme un champ-germe poloidal en champs f-f (sans force), qui en fin de compte sont transportés vers le milieu inter-galactique. Cette énergie magnétique doit également être convertie en énergie cinétique avec un bon rendement, comme tendrait à le prouver le rayonnement émis par les particules énergétiques. Vus sous cet angle, les rayons cosmiques des milieux inter-galactiques résultent de la dissipation continue de cette énergie libre dans le temps de Hubble. Cette énergie sert à leur accélération *in situ* par les champs f-f confinés aux parois super-galactiques et aux filaments des structures à grande échelle. De plus, les rayons cosmiques d'énergies extrêmes disparaissent par diffusion à des échelles de temps inférieures à celles de l'atténuation par le mécanisme GZK, à savoir $\sim 10^8$ années. De même, nous pensons

E-mail addresses: colgate@lanl.gov (S.A. Colgate), hli@lanl.gov (H. Li).

1631-0705/$ – see front matter © 2004 Académie des sciences. Published by Elsevier SAS. All rights reserved.
doi:10.1016/j.crhy.2004.04.002

que l'accélération des rayons cosmiques galactiques peut être due à des mécanismes puissants tels que l'enroulement du champ par l'énergie de rotation du disque galactique ou des étoiles à neutrons magnétisées, ou l'enroulement keplerien des disques de formation stellaires. ***Pour citer cet article : S.A. Colgate, H. Li, C. R. Physique 5 (2004).***

Keywords: UHE cosmic rays; Acceleration mechanisms; Force-free reconnection

Mots-clés : Rayons cosmiques d'énergies extrêmes ; Mécanismes d'accélération ; Reconnexion de champs sans force

1. Introduction

In this view of the origin of CRs, the source of the necessary free energy and the form that it takes, force-free magnetic fields, is the organizational principle in determining the mechanism of CR acceleration. Here not only the CR acceleration mechanism is different from traditional views, but also the implied and necessary strength and origin of the magnetic fields in the general IGM. There are literally hundreds of topics and issues to be addressed, both on the positive and the negative side of this view. We will address a few of these here, but recognize that attempting to reverse the conclusions of so many people over so many years is well beyond this single article. However, we emphasize again that the available free energy for CR acceleration is the organizing principle of this view of CR origin.

There are three primary issues:

(i) The likely total energy of extragalactic CRs (including radio lobes) compared to the likely sources of this energy.
(ii) The astrophysical circumstances for the generation of this energy as f-f magnetic field energy within the galaxy and within the meta galaxy.
(iii) The scaling in time and space of $E_\parallel$ reconnection acceleration leading to the CR spectrum and energy upper limit.

2. Total energy in extragalactic and galactic CRs

2.1. CR spectra and implied energies

There are two circumstances where the evidence for extragalactic cosmic rays appears to be beyond doubt, UHECRs and giant radio lobes. The first is because the particle energy is great enough, beyond the 'ankle', or $E \gtrsim 10^{18}$ eV, that confinement by the magnetic fields of the Galaxy is unlikely. Here the spectral index of UHECRs returns to nearly the same slope as at lower energies, below the 'knee' at $E \lesssim 10^{15}$ eV. A likely explanation of the change in slopes, $\sigma = -2.7$, -3.0, and -2.6, for the energy regions $E \lesssim 10^{15}$, 10^{15} eV $\lesssim E \leqslant 10^{18}$ eV, and $E \gtrsim 10^{18}$ eV, is that at lower energies, protons escape from the galaxy at $E \lesssim 10^{15}$ eV, nuclei with progressively higher rigidity A/Z escape at 10^{15} eV $\lesssim E \lesssim 10^{18}$ eV up to iron at $E \simeq 10^{18}$ eV, and extragalactic protons above this energy. The expected enrichment in the interval 10^{15} eV $\lesssim E \lesssim 10^{18}$ eV has been observed [1]. This spectrum is shown in Fig. 1 with various extrapolated slopes superimposed from $E \lesssim 10^{18}$ eV down to the proton rest energy m_pc^2. Normalizing at 10^{19} eV and extrapolating the spectrum back to $E = m_pc^2$ using a slope of $\sigma = -2.0$ gives a minimal estimate of the total energy in extragalactic CRs. The result is that the local specific energy content in the extragalactic component in the meta galaxy, $\varepsilon_{\rm mg}$, is $\varepsilon_{\rm mg} \simeq 2 \times 10^{-19}$ erg/cm^3, as compared to $\varepsilon_{\rm gal} \simeq 10^{-12}$ erg/cm^3 for the energy content of the galactic cosmic ray spectrum. Since the ratio of the two volumes is ~ 4 Mpc^3/300 kpc^3 $\sim 10^7$, both total CR energies, inside and outside the galaxy, would be about equal. However, a spectrum as flat as $\sigma = -2.0$ is quite optimistic for any stochastic acceleration process. It implies that the total energy in accelerated particles per logarithmic interval in energy is a constant so that the integral or total energy diverges with the upper energy limit. The back reaction from such an efficient acceleration mechanism would necessarily alter the source of the energy leading to a self limiting spectrum. Values of $\sigma = 0$ describe a modern research accelerator where losses during acceleration are near zero and the spectrum is a delta function in energy. An astrophysically reasonable spectrum corresponds to $\sigma \lesssim -2.0$. Acceleration to such high energies has confounded astrophysicists for nearly a century. The slope, $\sigma \simeq -2.7$, is constant over 6 energy decades, for CRs of energy $E \lesssim 10^{15}$ eV within the galaxy, and nearly constant for extragalactic CRs over 2 energy decades with slope $\sigma \simeq -2.6$ for $E \gtrsim 3 \times 10^{17}$ eV. The constant slopes of roughly the same value strongly imply a single scale independent mechanism, so that for extragalactic CRs we expect the slope $\sigma \simeq -2.6$ to extend as a constant to low energy in the same way as in the galaxy. The small difference in slopes is likely explained by the small (over 6 decades) additional nuclear scattering spallation loss, $\sim 50\%$ in 10^7 years within the galaxy.

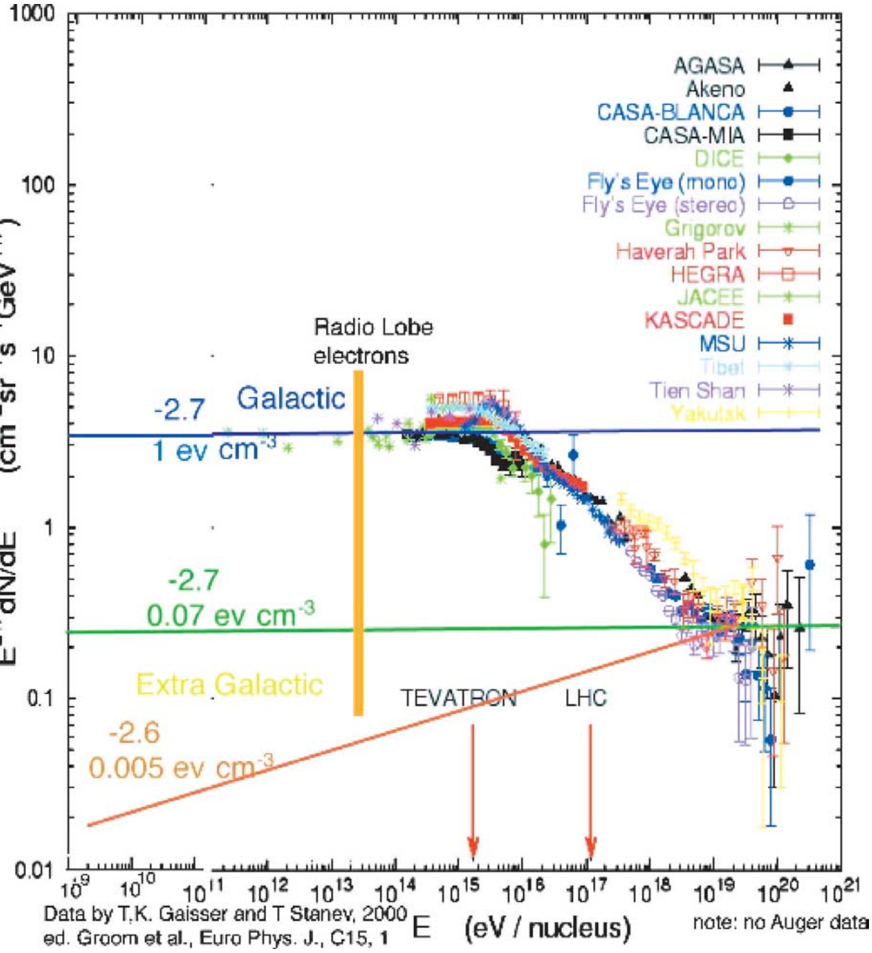

Fig. 1. The many measurements of high energy cosmic rays as compiled by Gaisser and Stanev [2]. The data are plotted as $E^{2.7}\,\mathrm{d}N/\mathrm{d}E$ versus energy E and thus with the slope $\sigma = -2.7$ removed. The change in slope to $\sigma \simeq -3.0$ in the energy interval 10^{15} eV $\lesssim E \lesssim 10^{18}$ eV is evident between the 'knee' and the 'ankle'. This change in slope is interpreted as a transition from galactic confinement to extragalactic CRs. The width of the transition region is interpreted as progressive loss of nuclei of progressively higher rigidity A/Z, with the highest being iron nuclei. Particles above 10^{18} eV are interpreted as extragalactic UHECRs, primarily protons. Several lines are drawn at different slopes tangent to the UHECR spectrum and extrapolated back in energy to $E = m_p c^2$ where the maximum in total CR energy resides. The slope $\sigma \simeq -2.7$ is the galactic slope and results in an energy density of extragalactic CRs of $\sim 7\%$ of the galactic value. The slope for CRs in the IGM for the same acceleration mechanism should be slightly flatter because of the lack of nuclear spallation. Spallation attenuates galactic CRs by a factor $\simeq 1/2$ over 6 decades in energy and so we estimate that without spallation $\sigma \simeq -2.6$. This results in an extragalactic CR energy density of $\simeq 0.005$ times the one in galactic CRs.

With this assumption in Fig. 1 we have drawn extrapolated spectra backwards at various slopes from the measured values at high energy. First we note that at the 'ankle' at $E \simeq 10^{18}$ eV where the galactic magnetic field confinement should cease to modify the spectrum, defining CRs in the meta galaxy, the ratio of energy densities becomes $\varepsilon_{\mathrm{mg}}/\varepsilon_{\mathrm{gal}} \simeq 1/30$. This value is comfortably close to what we would expect if galactic and extragalactic CRs reach equipartition in energy with what we believe are the magnetic energies within and external to the galaxy. We will discuss the origin and evidence for the extragalactic fields later in more detail.

2.2. Radio lobes

A second indicator of extragalactic CRs is extragalactic radio lobes. Giant radio lobes are a strong signature of extra galactic in-situ particle acceleration. Since radio lobes are detected by their radio emission and since strong polarized correlated emission is observed over distances of up to Mpc, only synchrotron emission by relativistic electrons in a magnetic field makes a sensible explanation. However, it has been known since Burbidge [3], that a minimum in the total energy required to create the radio lobe emission, wave length, luminosity, and dimension, occurs for specific values of magnetic field, electron number and electron energy. These total energies as reported for up to 70 such giant radio lobes in [4] are immense, up to 10% of the SMBH rest mass energy. In that analysis the minimum energy is calculated assuming that the electrons are accompanied during acceleration by a hundred times more protons at a given energy, just as observed in the Galaxy. If one chooses not to accelerate the protons, the minimum energy is reduced by a factor $\simeq 10$. We conclude that the extragalactic CRs require so much energy, that only the free energy of black hole formation is a feasible source and that furthermore the radio lobes are a signature of this energy and acceleration mechanism. Finally this picture of immense high energy electron fluxes within radio lobes has recently been confirmed by Chandra observations of x-rays from high Lorentz factor, $\Gamma \sim 10^3$, electrons Compton scattering cosmic background photons [5].

2.3. Our basic model

The magnetic field within the Galaxy is well recognized to be $B_{\rm gal} \simeq 5$ μG, but we will claim in this paper an equally unconventional large magnetic field in the meta galaxy, $B_{\rm mgal} \simeq 1$ μG. We will discuss further this estimated large value of the magnetic field in the meta galaxy later, but here note that this ratio of magnetic energy densities is consistent with the expected infall pressures, presumably a confinement pressure, of the IGM accreting onto the galaxy and the infall pressure from the matter in the voids accreting onto the galaxy walls or filaments. At this accretion rate the masses of both the galaxy and filaments increase by $\sim 50\%$ in a Hubble time. The extragalactic field of $B_{\rm mgal} \simeq 1$ μG is also consistent with the inferred radio lobe magnetic fluxes derived from minimum energy derivations, rotation measure limits, and the theoretical magnetic flux production from the SMBH accretion disk dynamo. When we slightly increase the extra galactic index to $\sigma = -2.6$ from the value $\sigma = -2.7$ within the galaxy, the total energy density in extragalactic CRs is then reduced to $\varepsilon_{\rm mgal}/\varepsilon_{\rm gal} \simeq 1/300$. This is sufficient such that the total energy in extragalactic CRs per galaxy spacing volume of ~ 4 Mpc^3 becomes $(1/300) \times 10^{62}$ ergs or $(1/300) \times 10^8 M_\odot c^2$, where $10^8 M_\odot c^2$ is the energy available in the accretion disks that form the SMBHs. Thus the extragalactic CRs local to the wall or filament may be replenished ~ 100 times in a Hubble time. This replenishment time, $\sim 10^8$ years, is close to the estimated loss time by random walk using a semi-coherent intergalactic field of a galactic spacing (GS) distance, $d_{\rm GS} \simeq 2$ Mpc and a filament thickness of $R_{\rm filament} \simeq 5 d_{\rm GS}$, or 5 galaxies thick, or 10 Mpc. The random walk distance to escape the filament becomes $R^2_{\rm filament}/d_{\rm GS} \simeq 30$ Mpc. This leads to a typical loss time of the CRs to the voids of $\tau_{\rm loss} \simeq R^2_{\rm filament}/(c d_{\rm GS}) \simeq 10^8$ years. This loss or replenishment time ensures that roughly half of the UHECRs that are subject to the GZK loss will have been lost to the voids before detection at Earth provided the total energy available for continuing acceleration during a Hubble time is $\sim 10^{62}$ ergs. This loss time is also the maximum likely, upper limiting acceleration time since the f-f fields are primarily confined to the filaments. The likely upper energy limit of $E_\parallel$ acceleration for a particle that remains in a reconnection flux tube for the entire time will be $E_{\rm max} \simeq B \mu \tau_{\rm loss} c = 3 \times 10^{22}$ eV where $\mu = 300$, the conversion from gauss to volts at velocity c. This limit excludes any possible reconnection current filamentation that may locally increase the acceleration field $E_\parallel$, but the Larmor radius within the filament and dependence upon its size and geometry in a μG field may limit the maximum energy to an order of magnitude less, $\sim 3 \times 10^{21}$ eV. In this picture there are no local sources, just a space-filling acceleration and a possible bias in flux opposite to the direction of the nearest void.

In this picture CRs are accelerated by the same mechanism inside the Galaxy as well as in extragalactic space, namely by space-filling reconnection of f-f fields; these CRs are closely isotropic, mostly not attenuated by cosmic background photons, they diffuse in an equipartition field both inside and outside the galaxy, where the flux and fields are consistent with long time mass accretion rate estimates. Furthermore, extragalactic CRs are consistent with an energy source of SMBH accretion disks, and galactic CRs are related to similar sources within the Galaxy. We therefore discuss next the basis of f-f fields in the astrophysical environment and the more limited possibilities of magnetic field energy generation from the free energy of SMBH formation.

3. Force-free fields in astrophysics

The ansatz of this paper is that once an accretion disk has been ‘seeded’ with magnetic flux of sufficient magnitude, then subsequent accretion will wind up this poloidal flux into a force-free field, a combination of both toroidal and poloidal components, whose total energy is that of the gravitational energy released in accretion. The seed flux is produced by the dynamo action occurring either in the SMBH accretion disk, or in stars [6]. The physics of the $\alpha - \omega$ dynamo is beyond the subject of this paper [7], but without such a dynamo, it is most unlikely that primordial effects such as the Biermann battery or early phase transitions can supply the seed field necessary to transfer the angular momentum of accretion to tension in the magnetic field. The energy contribution of the dynamo is small just as the exciter field of any commercial electric generator is a

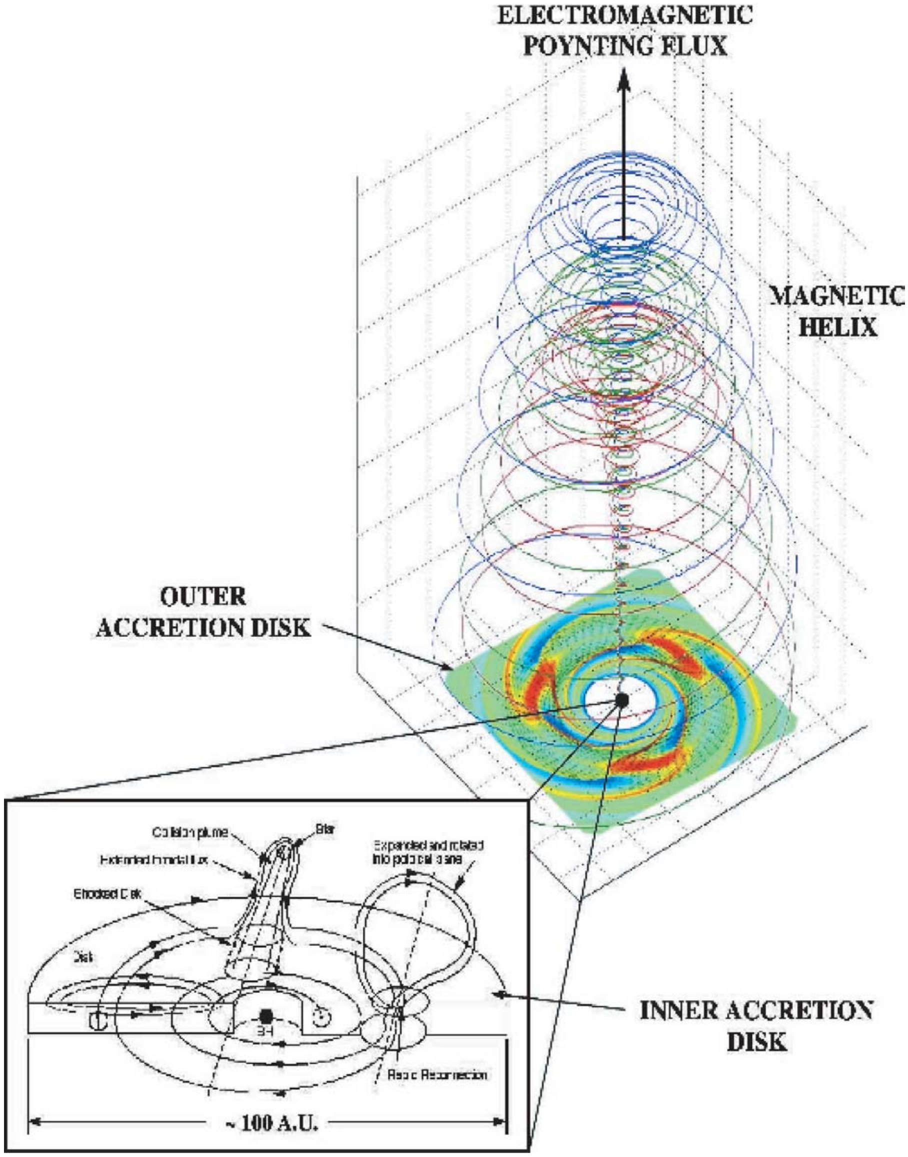

Fig. 2. A concept of the formation of massive back holes in galaxies. A galaxy forms as a 'flat rotation curve' disk, with mass proportional to radius. At some radius in this mass distribution the column density becomes great enough, $\Sigma_{\rm crit} \simeq 100\ {\rm g\,cm^{-3}}$ such that the Rossby vortex instability is excited, shown as the co-rotating vortices in the disk. The resulting transport of angular momentum allows the interior mass to collapse forming the black hole. This simple criterion predicts the mass and mass-velocity correlation of massive black holes. An $\alpha - \omega$ dynamo forms within this disk because of the differential rotation and the helicity injected by star collisions with the disk. The dynamo, with near infinite gain in $n_t \simeq 10^{12}$ revolutions in $\sim 10^8$ years, provides the (small) poloidal flux out of which the helix is formed by the differential winding of the foot prints. This helix is force-free because the field lines are primarily axial and azimuthal and so matter, tied to the field lines, falls back to the disk in the strong gravity. The helix extends a distance of $D \simeq n_t 2\pi r_g \simeq 60$ Mpc. Reconnection leads to radio lobes at smaller distances.

trivial fraction of the power produced, but without an exciter field no power is produced. The subsequent flow of power by the winding of the poloidal field within a conducting medium, external to an accretion disk, a Poynting flux, produces the helical f-f field that we associate with the 'jet' of SMBHs [8] or a jet identified with star formation [9]. Fig. 2 shows a composite of how such an accretion disk, dynamo, and f-f helix are formed. The f-f magnetic helix is a minimum energy configuration where the major magnetic stress is maintained by the tension in the field itself. The f-f helix is then self illuminating by the electrons accelerated by reconnection and appears as a jet in shape only. The relativistic velocities are then a combination of the velocity of relativistic synchrotron emitting electrons and the phase velocity of the reconnection instabilities.

The number density of the current carriers n_e necessary to carry the current $J_\|$ is trivially small compared to the surrounding IGM, and so the mass carried by such a jet is also trivially small. The ratio of energy in relativistic current carriers to magnetic energy density at distances $\sim 3r_g$ from the SMBH, where $r_g = MG/c^2$ is the gravitational radius, is $\beta = n_e m_e c^2/(B^2/8\pi) \sim 10^{-15}$, and thus trivially small. Such a f-f field jet is then a self illuminated (in x-rays, optical, and radio) f-f field configuration. It is illuminated in synchrotron radiation by electrons accelerated the same as in the radio lobes. A similar jet is formed in star formation or by the winding of flux by either neutron stars, as we believe in the Crab nebula or by the galaxy itself (not yet observed but predicted). In any case the jet subsequently morphologically transforms by tearing mode reconnection into the radio lobes and finally into a galactic and inter galactic space-filling f-f magnetic flux and therefore a source of free energy. It is the continuing reconnection of this space-filling f-f magnetic flux that we associate with the production of a near equipartition flux of galactic and extragalactic CRs. Because of the general lack of familiarity with f-f fields in astrophysics, we give a laboratory example of the physical steps necessary to produce such fields and point out the analogy with accretion disks. We conclude this section with a description of the evolution of this flux within cosmic structure calculations.

3.1. A laboratory example of the generation of force free fields

The magnetic field inside a current carrying coil is orthogonal to the boundary current and the force of the field on the coil winding is $\mathbf{J} \times \mathbf{B} = \mathbf{B^2}/\mathbf{8}\pi$, which we will call a 'force-bounded' magnetic field. In particular $\mathbf{J} \cdot \mathbf{B} \simeq \mathbf{0}$ everywhere except possibly the coil current leads. If now two conducting metal disks are located at either end of the coil and are threaded by the predominantly axial field, the field will penetrate the conducting metal disks in a finite time and the field will return to its original primarily axial configuration. If now the disks are rotated relative to each other, an electric field will develop with both radial and axial components, but nothing further will happen because the medium between them, air, is an insulator. If now the air is replaced by a conducting fluid medium, e.g., plasma or liquid metal and provided the conductivity, disk rotation velocity, and dimension are great enough, i.e., the magnetic Reynolds number, $R_\mathrm{m} = vL/\eta \gg 1$ (v, L, and η are the fluid velocity, length scale, and conductivity, respectively), a current I_z will flow both plus and minus axially at the inner and outer radius. The axial currents are connected to radial currents, I_r within the disks. The axial current will produce an azimuthal field, bounded by the plus and minus axial currents as well as by the plus and minus radial currents within the disk. The vector sum of the axial and azimuthal fields $\mathbf{B_z} + \mathbf{B}_\phi$ changes the topology of the field from initially axial to helical. Furthermore the radial current in the disks produce a torque $r \cdot \mathbf{J}_r \times \mathbf{B_z}$ at radius r which, multiplied with the winding of the disks, performs the work that increases the magnetic energy. In addition this field will exert a radial force on the conducting fluid depending upon its confinement, a 'pinch'. The same plasma configuration, a 'stabilized pinch' is produced in the laboratory by replacing the rotation of the disks by a voltage (capacitors) between the disks and a low pressure plasma between them. The resulting current between the disks (electrodes) produces the current of the resulting helical, f-f fields. If the pressure of the conducting plasma is small or some of the incompressible liquid metal can escape either because of instabilities or through the disk wall, then the fluid cannot exert a force on the field due to the induced azimuthal field or original axial field. The resulting configuration is called a force-free field where without force, $\mathbf{J} \times \mathbf{B} = \mathbf{0}$ and therefore $\mathbf{J} = \lambda\mathbf{B}$. In general, when the minimum energy state is reached of such a f-f field, subject to various boundary conditions of flux and helicity conservation, the field strength decreases with radius $B \propto 1/r$ so that a much weaker outer boundary field exists which must be supported at some conducting boundary with a weak $\mathbf{J} \times \mathbf{B} = \nabla(\mathbf{B^2}/\mathbf{8}\pi) = \nabla\mathbf{P}$ force. This boundary pressure in the astrophysical case is the pressure of the IGM or interstellar medium. However, the main point is that the differential rotation of the disks has added free energy to the field by the work done by twisting the field, equivalently supplied by the capacitor in laboratory plasma experiments, thereby increasing both components of the field, $(B_z^2 + B_\phi^2)/8\pi$. Furthermore, the major fraction of the field pressure is supported by the tension in the field itself and so is called force-free. This energy can be accessed by allowing the disks to unwind due to the torque of the tension in the field, an electric motor, or more likely because of reconnection dissipated by $\mathbf{E} \cdot \mathbf{J}$ or $\eta\mathbf{J^2}$.

3.2. Formation of astrophysical force-free fields and their distribution

In astrophysics the winding of accretion disks forming near every compact object plays the role of the conducting disks. The original angular momentum of matter, both baryonic and dark, is formed randomly by the three body interactions in the first non-linear gravitational collapse starting from initial small perturbations [10]. The specific angular momentum is large, $\sim 10^7$ times greater than the limiting specific angular momentum of, say, the SMBH of every galaxy. Subsequently a mass selection, $M_\mathrm{SMBH} \simeq 10^{-3} M_\mathrm{gal}$, and an angular momentum transport process, the Rossby vortex mechanism [11], are invoked to explain how such an accretion disk could form [12]. A similar angular momentum is formed in pre-stellar structure formation from molecular cloud cores in star formation, but here the ratio of the specific angular momentum of the core to the limiting specific angular momentum of the star is less, ~ 300. Regardless, once an accretion disk is initiated, half the gravitational energy of forming the collapsed object must be released in the transport of angular momentum of the matter accreted to the condensed object. By far the largest free energy is released in forming the SMBH, $10^8 M_\odot c^2 = 10^{62}$ ergs versus $10^{11} M_\odot \varepsilon_{\rm stars} = 10^{59}$ ergs where $\varepsilon_{\rm stars} \simeq 10^{15}$ ergs/g, the specific binding energy of the average star, in forming all of the stars of the galaxy and a similar energy in forming the galaxy itself. Hence we concentrate on the SMBH case where we see a direct mechanism for converting this free energy into f-f magnetic field energy.

Fig. 2 shows the sequence of all three processes leading to the generation of the inter-galactic f-f fields. The pre-collapse from the Lyman-α cloud to the flat rotation curve galaxy is not shown, but a mass selection is made at a critical thickness by the Rossby vortex mechanism leading to a disk of $\sim 10^8 M_\odot$ [12] in which angular momentum is transported by the co-rotating Rossby vortices shown as the disk with vortices [11]. Star-disk collisions produce the helicity to produce an $\alpha - \omega$ dynamo supplying the poloidal seed field. The differential winding of the Keplerian disk flow produces the f-f helix. The f-f helix extends away from the disk a distance determined by winding number, $n_w \simeq 10^8$ years$/(2\pi r_g/c) \simeq 10^{11}$ turns, or ~ 10 Mpc. Reconnection shortens this distance to radio lobe sizes of a Mpc.

3.3. Filling the filaments with magnetic flux

The life time of the radio lobes is roughly the same as the formation time of the SMBH, $\sim 10^8$ years, and so in a Hubble time, $\simeq 100$ times longer, we expect the fields to evolve and fill the IGM quasi uniformly. A simulation of the structure of a local region of the universe with magnetic fields has been made by Ryu, Kang, and Biermann [13] in a $(32h^{-1}\ \text{Mpc})^3$ box, where $h = 0.5$ shown in Fig. 3. Galaxies with typical galaxy spacings are superimposed. In this calculation a primordial magnetic field was assumed and its strength chosen such as to allow the evolution of structure and the support of this structure as typically observed in filaments, (walls) and voids and with a modulation in density of $\sim 20:1$. The variations in the orientation of the fields are due to the instabilities inherent to gravitational structure formation. However, what is more important is the bounding pressure of the filaments which is derived in the calculation from the infall of matter from the voids. This infall is the fundamental instability of structure formation due to gravity and dark matter. The dark matter follows its own gravitational perturbations and continually passes back and forth through itself. The baryons first follow this gravitational perturbation but then cannot pass through themselves, and therefore make shocks and pressure. This pressure is usually assumed to support the filaments from collapse, but cooling should reduce this pressure leading to further collapse of the filaments. Instead, in

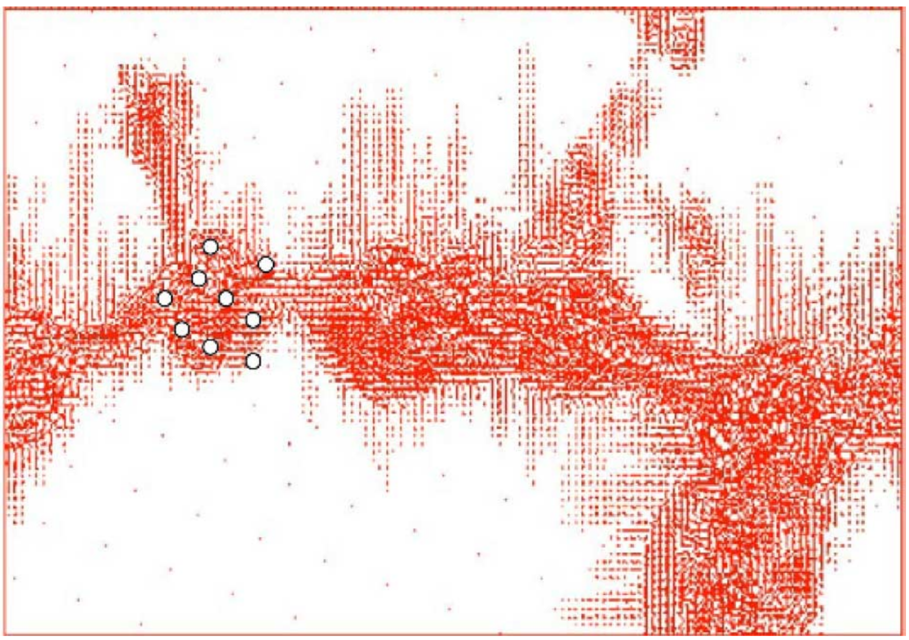

Fig. 3. A two-dimensional cut through a cosmological structure simulation of size $(32h^{-1}\ \text{Mpc})^3$, where $h = 0.5$, by Ryu et al. [13], in which magnetic field was tied to the matter and the structure evolved with magnetic pressure as well as gravity. The final, near-equilibrium state, was one where the magnetic field of ~ 1 µG was confined to the filaments by the in-fall pressure of matter from the voids. In our model of a magnetized universe the magnetic flux, instead of being assumed and adjusted, is instead produced in excess by the winding of the accretion disks and reaches the steady state defined by the in-fall pressure and reconnection. Hence we have superimposed on a local region of a filament, an approximate distribution of symbolic galaxies. CRs will diffuse between galaxies following lines of force until escaping to the voids in $\sim 10^8$ years. This avoids observation of most of the CRs that might have been attenuated by the GZK mechanism.

these calculations the magnetic pressure supports the filaments both against further collapse, but more importantly against the pressure of gas continuing to infall from the voids. It is this infall pressure that confines the magnetic field. They found that the equilibrium magnetic field pressure that retains the necessary density modulation ratio of filament density to void density had to be as large as ~ 1 μG. This is the field shown in Fig. 3. This is very closely the magnetic field strength expected if 10% of the SMBH formation energy, 10^{61} ergs is distributed in a GS box of volume $\simeq 10^{74}$ cm^3. This value of the IGM field is not inconsistent with the background Faraday rotation measures of distant polarized sources, provided one averages field reversals on a scale much smaller, ∼1/10 to 1/100 of GS, uses an electron density of $n_e \sim 10^{-5}$ cm^{-3} and includes the volume ratio of filaments to voids. We expect the synchrotron glow from these distributed, weak fields will outline the structures of the universe when such low frequency arrays as LOFAR are operational. For now, only the radio lobes and their minimum energy indicate consistency with this picture of the magnetic free energy of the universe. With this view of the dominant free energy in the universe in the form of f-f fields, we proceed to an abbreviated theory of reconnection acceleration of CRs.

4. Reconnection acceleration of CRs

4.1. Dissipation of force-free fields in the laboratory and astrophysics

By way of comparison to shock acceleration, there is a vast literature on the experimental observation and its interpretation of dissipation, reconnection of, and particle acceleration in f-f fields. The organizing physical principle is the maximization of the dissipation rate of the magnetic free energy. The free energy of a f-f magnetic field can be accessed or converted to another form, heat or kinetic energy, only by $\mathbf{E} \cdot \mathbf{J}$. A resistive origin of $E = \eta J$ leads to heat, but the acceleration of relativistic run-away current carriers of say energy $\gamma_{i,e} m_{i,e} c^2$, leads to a kinetic energy density $n_{J,i,e} m_{i,e} \gamma_{i,e} c^2$ where the number density of current carriers is $n_{J,i,e} = J/(ec)$. In order for the current of run-away carriers to exceed the usual or expected much larger slow drift of typical current carrying background plasma, and thereby effectively cause $E_{\|} \sim 0$, some un-identified instability must locally immobilize these background plasma charged particles so that due to current carrier starvation a large $E_{\|}$ is maintained, $E_{\mathrm{accel}} \propto \mathrm{d}J/\mathrm{d}t$. It is reasonable that the greater rigidity of the run-away or accelerated current carriers should circumvent the impedance of such an immobilization instability, but it is puzzling why, as we observe in cosmic rays, that the bulk of the particles energy centers around c^2 or $\gamma \simeq 1$.

In tokamaks, reconnection sometimes leads to 'current interruptions' where all the free energy of the magnetic field is transformed into a run-away beam of relativistic ions or electrons that sometimes 'melts a hole' in the metal vacuum liner. Most often reconnection leads to an interchange of flux surfaces and a consequential loss of confinement of the hot plasma to the cold walls, a multi billion dollar question for fusion. In stabilized pinches or reverse field pinches, more analogous to the above described helical fields and to astrophysical fields where the winding number is large, and so where $B_\phi \simeq B_z$, the flux surface topology becomes tangled and random. An experimental demonstration of these tangled fields is given in the appendix of [14]. We suspect, but cannot prove, that the maximum dissipation rate occurs when the current carriers are accelerated to a velocity, $\sim c$, or $\gamma \sim 1$. The velocity from further acceleration is then bounded, and some optimum rigidity occurs for a given acceleration. High rigidity particles should remain in a reconnecting flux filament the longest, thereby gaining the largest energy from the $E_{\|}$ of reconnection. The momentum of the current carriers, $\gamma m_i c$, then inertially carries the current following the tangled field lines on average to a larger radius and thereby rapidly diffuses the current in radius. This is a very complicated non-linear sequence of energy flow and plasma and field deformations, but it contains the necessary phenomena of acceleration, diffusion and dissipation. It has not yet been simulated.

4.2. Particle acceleration by magnetic reconnection

As mentioned before, radio lobes are clear examples where CRs are being accelerated in a magnetized IGM. To understand particle acceleration by reconnection in lobes, it is instructive to begin in the resistive MHD limit, even though it is probably *not* valid for radio lobes, given their large size and small resistivity – in which case ordinary magnetic field diffusion will not be fast enough to account for the magnetic energy conversion. For example, in a filament of size of ~ 1 kpc, and resistivity of $\eta \sim 10^4$ cm^2/s (using an electron temperature of 10^6 K), the diffusion time will be $\tau_\eta \sim L^2/\eta \sim 9 \times 10^{38}$ sec, much longer than the Hubble time. A very different situation obtains, however, by realizing that as the fluids carry the frozen-in fields and move them around, steep field gradients could be generated; These result in thin sheet-like current structures, and hence greatly reduce the diffusion times. In the Sweet–Parker reconnection picture, in which the current layer width is $\Delta_\eta \sim (\tau_A \eta)^{1/2}$, where $\tau_A \sim L/v_A$, the typical MHD time-scale, and the Alfvén speed $v_A \sim 6.6 \times 10^8 B_{3.10^{-6}}/n_{-6}^{1/2}$ cm/s. Then the rate of energy dissipation is related to the rate of convection of magnetic flux into and out of the reconnection region. This time scale (again in the Sweet–Parker model) is $\tau_{sp} \sim (\tau_A \tau_\eta)^{1/2} \sim 6 \times 10^{25}$ sec, but clearly still much too long to be relevant to radio lobes.

The physical conditions of the lobes are, rather, more consistent with the so-called fast collisionless reconnection scenario, which has recently been studied in the context of hot fusion laboratory plasmas, e.g., tokamaks, and magnetospheric plasmas, e.g., Earth's magnetotail. This is because for radio lobes, the ion skin depth which is understood to be closely related to kinetic effects in reconnection, $d_i = c/\omega_{pi} \sim 2.3 \times 10^{10} n_{-6}^{-1/2}$ cm, is actually larger than the resistive Sweet–Parker layer width,

$$\Delta_\eta \sim 2.1 \times 10^8 \left(\frac{L}{1\ \mathrm{kpc}}\right)^{1/2} \left(\frac{3 \times 10^{-6}\mathrm{G}}{B}\right)^{1/2} \left(\frac{n}{10^{-6}}\right)^{1/4} \left(\frac{\eta}{10^4}\right)^{1/2} \mathrm{cm}. \tag{1}$$

In this limit, reconnection is mediated by the kinetic physics to break the flux frozen-in condition. It has been suggested and shown that the reconnection rate is then independent of the resistivity, e.g., [15]. The exact dependence of the reconnection rate on various parameters, especially d_i, however, is under debate [16–18]. Under a simplified geometry and in two dimensions, the latter two studies suggested that the length of the current layer undergoing reconnection depends on the boundary driving, which is unfortunately very difficult to determine in the radio lobe situation. Another recent study by Li et al. [19] on a fully force-free system using particle-in-cell simulations has shown that collisionless reconnection that is facilitated by the full kinetic physics can indeed proceed at a very fast rate, with flow speeds close to a fraction of the Alfvén speed.

The above scale estimates strongly favor the idea that collisionless reconnection in radio lobes will be Alfvénic, and could play an important role in converting the magnetic energy to particles at a fast rate, given the high Alfvén speeds within radio lobes. This may therefore be the main mechanism of in situ particle acceleration, as demanded by the radio spectral index distributions. More detailed scaling studies, especially the dependence on the system size, need to be done before we can model the role of reconnection in radio lobes in more detail.

For the general IGM, a similar comparison between the resistive layer width and the ion skin depth can be made. The higher density and likely lower magnetic field strength will tend to bring these two scales closer but the key uncertainty will be whether and how thin current sheets can be produced via, say, ideal MHD processes. Many uncertainties remain, such as the global magnetic field configurations in the lobes and the general IGM, how efficiently thin current sheets can be made, etc.

5. The power-law spectrum

The accepted theory of cosmic ray acceleration is shock wave acceleration in the interstellar medium driven by supernova [20–22]. "This acceptance has been largely based upon the good agreement between the 'universal' power-law spectrum predicted by shock acceleration, i.e., the power-law index becomes:

$$\sigma = \frac{\mathrm{d} \ln N}{\mathrm{d} \ln E} \simeq -(2 + \varepsilon),$$

depending only on the Mach number and the observed or inferred particle spectra", see [23] and many papers by Biermann for a more accurate comparison. This belief that a nearly correct power-law spectral index alone is unique is instead, a less restrictive condition than commonly believed. Any accelerator for which a fractional gain in energy, $\mathrm{d} \ln E$, by a few particles is accompanied by a fractional loss, $-\mathrm{d} \ln N$, in the number of the remainder will give a power-law:

$$\mathrm{d}N/N = -\sigma(\mathrm{d}E/E).$$

The fractional loss for a fractional gain in energy is what would be expected for a rigidity dependent loss mechanism where the probability of a relativistic particle being scattered out of an acceleration region is inversely proportional to its energy or rigidity. For values of $\sigma \gtrsim -2.0$, i.e., a smaller fractional loss, the integral energy becomes asymptotically large, and at some energy will truncate or limit the acceleration mechanism, destroying the confinement and hence the accelerating mechanism itself. Hence, it is not likely that at any one time we should see many such accelerators occurring naturally in the Galaxy. On the other hand, accelerators with $\sigma \ll -2.0$ will produce a steep spectrum that, relative to another less steep one, i.e., σ closer to -2, will be lost relative to the less steep mechanisms above some critical energy. Hence it is likely that the spectrum of any observed mechanism should be close to $\sigma = -(2 + \varepsilon)$.

6. Experiments

Laboratory experiments can be performed to simulate both magneto-hydrodynamics as well as the tearing mode reconnection and the associated $E_\parallel$ acceleration of the 'run-away' particles. The spheromak and reverse-field pinch experiments are a step in this direction. Interruptions in tokamaks are already laboratory proof of this acceleration. Experimental proof of an $\alpha - \Omega$ dynamo is similarly needed. We need to perform more laboratory plasma experiments to observe reconnection in the collisionless limit. Without laboratory experiments, as for example shock acceleration, we are still uncertain about the origin of cosmic rays.

Acknowledgements

We are indebted to Philipp Kronberg for extensive knowledge and analysis of radio lobes and to many other colleagues in support of the project of a magnetized universe. This research was performed under the auspices of the Department of Energy. It was supported by the Laboratory Directed Research and Development Program at Los Alamos. S.A.C. and H.L. acknowledge the hospitality of Aspen Center for Physics while part of the research was carried out during the summers of 2001 and 2002.

References

[1] T. Abu-Zayyad, et al., Astrophys. J. 557 (2001) 686.
[2] T.K. Gaisser, T. Stanev, Eur. Phys. J. C 15 (2000) 150.
[3] G.R. Burbidge, Astrophys. J. 124 (1956) 416.
[4] P.P. Kronberg, Q.W. Dufton, H. Li, S.A. Colgate, Astrophys. J. 560 (2001) 178.
[5] D. Harris, New Astronomy 47 (2003) 617.
[6] S.A. Colgate, H. Li, V.I. Pariev, Phys. Plasmas 8 (2001) 2425.
[7] For details see, e.g., A.R. Choudhuri, The Physics of Fluids and Plasmas, Cambridge University Press, Cambridge, 1998.
[8] A.R. Choudhuri, A. Konigl, Astrophys. J. 310 (1986) 96.
[9] H. Li, R.V.E. Lovelace, J.M. Finn, S.A. Colgate, Astrophys. J. 561 (2001) 915.
[10] P.J.E. Peebles, Astrophys. J. 155 (1969) 393.
[11] H. Li, S.A. Colgate, B. Wendroff, R. Liska, Astrophys. J. 551 (2001) 874.
[12] S.A. Colgate, R. Cen, N. Currier, H. Li, M.S. Warren, Astrophys. J. 558 (2003) L7.
[13] D. Ryu, H. Kang, P.L. Biermann, Astron. Astrophys. 335 (1998) 19.
[14] S.A. Colgate, Astrophys. J. 221 (1978) 1068.
[15] M.A. Shay, J.F. Drake, Geophys. Rev. Lett. 25 (1998) 3759.
[16] M.A. Shay, J.F. Drake, B.N. Rogers, Geophys. Rev. Lett. 26 (1999) 2163.
[17] X. Wang, A. Bhattacharjee, Z.W. Ma, Phys. Rev. Lett. 87 (2001) 265003.
[18] R. Fitzpatrick, Phys. Plasmas 10 (2003) 1702.
[19] H. Li, et al., Phys. Plasmas 10 (2003) 2763.
[20] W.I. Axford, E. Leer, K. Skadron, in: 15th ICRC, vol. 11, 1977, p. 132.
[21] A.R. Bell, Mon. Not. Roy. Astron. Astrophys. 182 (1978) 147.
[22] R.D. Blandford, J.P. Ostriker, Astrophys. J. 221 (1988) L29.
[23] R.D. Blandford, D. Eichler, Phys. Rep. 154 (1987) 1.