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Author(s): Stirling A. Colgate, Los Alamos National Lab

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Acceleration in Astrophysics

Stirling A. Colgate, MS B275, LANL, Los Alamos, NM87545
colgate@eagle.lanl.gov 11/28/93

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Abstract

The origin of cosmic rays and applicable laboratory experiments are discussed. Some of the problems of shock acceleration for the production of cosmic rays are discussed in the context of astrophysical conditions. These are 1) The presumed unique explanation of the power law spectrum is shown instead to be a universal property of all lossy accelerators; 2) The extraordinary isotropy of cosmic rays and the limited diffusion distances implied by supernova induced shock acceleration requires a more frequent and space-filling source than supernovae; 3) The near perfect adiabaticity of strong hydromagnetic turbulence necessary for reflecting the accelerated particles each doubling in energy roughly 10^5 to 10^6 scatterings with negligible energy loss seems most unlikely; 4) The evidence for acceleration due to quasi-parallel heliosphere shocks is weak. There is small evidence for the expected strong hydromagnetic turbulence, and instead, only a small number of particles accelerate after only a few shock traversals ~~are observed~~; 5) The acceleration of electrons in the same collisionless shock that accelerates ions is difficult to reconcile with the theoretical picture of strong hydromagnetic turbulence that reflects the ions. The hydromagnetic turbulence will appear adiabatic to the electrons at their much higher Larmor frequency and so the electrons should not be scattered incoherently as they must be for acceleration. Therefore the electrons must be accelerated by a different mechanism. This is unsatisfactory, because wherever electrons are accelerated these sites, observed in radio emission, may accelerate ions more favorably. Because of these difficulties, an alternate explanation has been given where reconnection of twisted magnetic fields (from condensation, accretion, and conservation of angular momentum) accelerates particles along field lines. The acceleration is coherent provided the reconnection is coherent, in which case the total flux, as for example of collimated radio sources, predicts single charge accelerated energies much greater than observed. The same acceleration process should occur during the formation of stars associated with the T-tauri phase and bi-polar outflows. Because of the ubiquitous nature of matter condensations in the universe, the acceleration is inherently isotropic and space-filling in nature.

Four laboratory experiments are suggested that would form the basis of a substantiated science of plasma processes of acceleration. These include an α - ω dynamo using liquid sodium, a one-ended plasma pinch that simulates the formation of collimated radio sources or bi-polar out-flows, reconnection in a tokamak which simulates acceleration by coherent reconnection, and finally a collisionless shock experiment to simulate shock acceleration.

1) Introduction

Cosmic Rays are the extremum of non-thermal phenomena within the galaxy as well as within the universe. The present upper energy limit of the most energetic event, observed at the Fly's Eye corresponds to 4×10^{20} eV or $\Gamma = 4 \times 10^{11}$. When one compares this to the 3 degree cosmic background radiation, the ratio becomes 1.6×10^{24} , an awesome departure from thermal equilibrium. There are only a few proposed mechanisms

of acceleration by which this extraordinary departure from equilibrium can likely arise Among these are:

- 1) The stochastic processes, the Fermi mechanism, where a single particle can scatter elastically and randomly off of individual, more massive units of matter The units of matter may be either magnetized moving galactic or metagalactic clouds or hydromagnetic waves induced by magnetized collisionless shocks.
- 2) The hydrodynamic relativistic shock acceleration that occurs when a strong shock in a supernova propagates in the decreasing density gradient of the envelope of a star during the supernova explosion.
- 3) The coherent acceleration of particles by electric fields parallel to the local magnetic field as for example occurs in reconnection or by hydromagnetic waves that coherently accelerate particles along field lines.

The most generally accepted mechanism is the collisionless shock (here after CS) in galactic and intergalactic space. The reason for this wide acceptance is the almost universal intuitive acceptance of a power-law (in energy) producing mechanism that occurs because of diffusion.. The tacit assumption that in general a power law is unlikely is false and instead occurs naturally in many circumstances as we shall discuss. Since there are many unresolved questions even insuperable difficulties to applying the CS mechanism universally to cosmic ray acceleration, there is a strong motive to consider all other possibilities and how we can possibility resolve this major and dramatic phenomena. Towards this end, the CS mechanism and its limitations will be reviewed in Section II leading to why additional mechanism are needed. The remaining two mechanisms will then be discussed in Sections III and IV. The second mechanism, the relativistic hydrodynamic shock ejection of supernova envelopes will be rejected for nearly the same reasons as the rejection of the CS mechanism, leaving only the coherent magnetic reconnection mechanism as the likely universal explanation of cosmic rays. In order to help resolve this difficult question, five laboratory experiments will be suggested in Section V to help substantiate physical modeling. No conclusion is possible except for the usual one that more research is needed.

II) Power Laws, Isotropy and Collisionless Shock Acceleration

Power-law Spectrum

The accepted theory of cosmic ray acceleration is shock wave acceleration in the ISM driven by supernova (Axford, Leer, and Skadron, 1977; Bell, 1978; Blanford and Ostriker, 1988). "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:

$$s=(d \ln N)/(d \ln E) \sim -(2+\epsilon)$$

depending only on the Mach number and the observed or inferred particle spectra." (see Blanford and Eichler, 1987 for a review, and many papers by P. 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, $(d \ln E)$, by a few particles is accompanied by a significantly larger fractional loss, $-(d \ln N)$, in number of the remainder will give a power-law:

$$dN/N = -s(dE/E) .$$

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 $s < \sim 2$, i.e. a smaller fractional loss, the integral energy becomes asymptotically large, $\int_0^E NdE \approx E^{s-2}$ 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 $s \gg 2$ will produce a steep spectrum that, relative to another less steep one, i.e. s closer to 2, will not be observed relative to the less steep one above some critical energy at which the two mechanisms give the same flux. Hence it is likely that the spectrum of any observed mechanism should be close to $s=2+\epsilon$. The conclusion of this argument is that a power law distribution of energy or rigidity versus number is expected for any natural acceleration mechanism that results in a significant departure of the distribution from thermal equilibrium.

If a power law producing mechanism, and even the correct value of the power law exponent, is then not such a singular signature of uniqueness, what then is inconsistent about the CS mechanisms as the primary or universal explanation of cosmic rays that might encourage us to look more widely for another explanation?

Why do we need a new Theory of the Origin of Cosmic Rays?

- 1) The spectral argument for shock acceleration is not compelling.
- 2) The observed isotropy requires a space-filling mechanism, or if supernova shocks are the sources, that the diffusion mean-free path after acceleration must be very long, > 1 kpc, in order that the spatial fluctuations due to a small number of contributing supernova be averaged out and furthermore that the surrounding "leaky box" be extraordinarily isotropic.
- 3) The plasma physics of the required scattering mechanism is uncertain in that 10^5 to 10^6 scatterings per particle must occur from strong, self-excited hydromagnetic waves per doubling in energy and yet with negligible damping. Furthermore, at the same time, the hydromagnetic turbulence must be "strong" in order that a particle be scattered with a mean free path not too many Larmor orbits in dimension.
- 4) The evidence for acceleration due to quasi-parallel heliosphere shocks is weak, in some cases with small or no evidence for the expected strong hydromagnetic turbulence, and where acceleration is demonstrated, with only a few shock traversals by the accelerate particles implied.
- 5) The acceleration of electrons in the same collisionless shock that accelerates ions is difficult to reconcile with the theoretical picture of hydromagnetic turbulence self-excited by the anisotropic streaming energetic accelerated ions. This hydromagnetic turbulence will appear adiabatic to the electrons at their much higher Larmor frequency and so the electrons should not be scattered incoherently as they must be for acceleration. Therefore the electrons must be accelerated by a different mechanism. This is unsatisfactory, because wherever electrons are accelerated these sites, observed in radio emission, may accelerate ions more favorably.

Isotropy

The shocks in the ISM that would produce the bulk of the cosmic rays up to an energy of $\sim 10^{14}$ eV (Lagage and Caesarsky) are presumably derived from supernovae. The energy of the supernova explosion, $\sim 10^{51}$ ergs produces a shock of sufficient strength out to a radius of roughly 100 pc or the thickness of the Galaxy. Any mechanism for accelerating cosmic rays that depends primarily upon supernova will have a problem producing the necessary isotropy presently observed (Richardson and Osborn, 1974). From a TeV to 10 to 100 times greater, where shower arrays are most sensitive to anisotropy, this anisotropy is 10^{-3} or less. The lifetime, τ , of cosmic rays is assumed to be $\leq 10^7$ years from the measurements of the decay of ^{10}Be and the arguments leading to the "leaky box" model of cosmic rays in the Galaxy. For a diffusion coefficient of D of particles of a given rigidity there is a characteristic distance, d , within which particles can diffuse to the observer. The anisotropy of the diffusive flux will be of the order of the maximum fractional differences of the source distribution of $N_{\text{supernova}}$ number of events averaged over the time, τ . This fractional difference is of order $(N_{\text{sn}})^{1/2}$. If all the supernova within the galaxy at a typical rate of 1/30 years in the life time of 10^7 years, or 3×10^5 supernova were all equally contributing to the local flux, then the anisotropy would be of the order $(3 \times 10^5)^{-1/2} = 1.8 \times 10^{-3}$ a value somewhat larger than observed. The diffusion distance, d , must then be significantly greater than the dimension of the galaxy, 30 kpc. Under these circumstances the diffusion coefficient must be greater than $3 \times 10^{31} \text{ cm}^2/\text{s}$ or a mean free path for scattering greater than 1 kpc. This is 3×10^4 greater than what is assumed for the necessary scattering for the diffusive shock mechanism where the mean free path is frequently assumed to be roughly 10 Larmor radii at 10 TeV. If this difference in scattering length indeed occurs due to a decrease in hydromagnetic turbulence after the passage of the shock, then one is faced with the further difficulty that the cosmic rays would escape from the galaxy unless the whole galaxy were surrounded by a near perfect "leaky box" with an anisotropic imperfection of diffusive loss ($\sim 1/2$) of less than 10^{-3} . This is hard to imagine in view of current galactic dynamo theory where a dipole field surrounds the Galaxy yet at the same time inside the box cosmic rays diffuse relatively easily. If a smaller diffusion coefficient, D , is imagined, then in a flat Galaxy, N_{sn} is proportional to D and the probable anisotropy due to fluctuations becomes large, proportional to $D^{-1/2}$. Hence an unlikely circumstance must exist of first a very small diffusion coefficient, then a very large one, and finally a near perfectly symmetric surrounding leaky diffusive box of our Galaxy.

Particle Scattering Losses

It is well recognized that in diffusive shock acceleration a particle must traverse the shock many times, $c/v_{\text{shock}} \sim 300$ in order to double in energy. However, in order to return to the shock this number of times by random scattering, the mean number of scattering events becomes the square of this number of crossings, or 10^5 scatterings. One recognizes that the accelerated particles are likely to be the exceptional ones that cross the shock the requisite number of times with fewer scatterings, but exceptional in this case is a fraction less than the total number of particles only by the fraction $1/s$ per doubling where s is the above exponent of the power law. Hence, the fractional loss per scattering must be very small for the average particle, which is the particle "lost" from acceleration by diffusion to convection at each energy. Hence, recognizing the many orders of magnitude of acceleration required, in order not to modify the power-law exponent below the good agreement with theory, the fractional irreversible loss per scattering must be less than $\sim 10^{-5}$ to 6 . This is an extraordinarily small loss in the presence of what must be strong turbulence in order to have the short scattering lengths required (~ 10 Larmor

orbits) to reach the highest energies (Lagage and Caesarsky). One suspects the excitation of at least one mode of non-linear damping of the hydromagnetic waves at the level of 10^{-5} to 10^{-6} . Such non-linear damping induces heating and hence damping of those particles furthest ahead of the shock that excite the waves in the first place. The particles furthest ahead are those of greatest rigidity and therefore most sensitive to modifying the spectrum.

Particle Acceleration by Magnetospheric Shocks

Particle acceleration in quasi-parallel magnetospheric shocks as well as the expected hydromagnetic turbulence have been observed by space craft but at intensity levels that are as low as 10^{-4} of the values both expected and necessary for shock acceleration (Sarris, E.T. and Krimigis, S.M. 1985, and Krimigis, 1992). The perpendicular shocks on the other hand show significant acceleration as one would expect by trapped Larmor orbits (Colgate, S.A. 1959). These accelerated particles, however, represent a small fraction of the necessary acceleration for explaining cosmic rays. One suspects that a power law spectrum of particle velocities is not sufficiently narrow in phase space to excite the hydromagnetic turbulence necessary for back scattering the particles repeatedly across the shock front.

Acceleration of Electrons by Collisionless Ion Shocks

The plasma turbulence associated with the scattering of the accelerated ions back and forth across the shock is presumed to be excited by the anisotropy of the momentum distribution of the ions of the shock. This "current" of ions is subject to a local channeling instability where a local current density, in the z direction, gives rise to a local component of the magnetic field in the θ direction. Hence locally a small region of combined z and θ field or helical field or torsional Alfvén, or hydromagnetic wave is created. The dimension of these helices is of the order of an ion Larmor orbit, so that the time of the existence of such a wave is of the order of an orbit time. Therefore the phases of individual ions will be scrambled and hence, a random group of such waves at the strong turbulence limit should scatter ions in the z direction back and forth along (in the z direction) in some 10 Larmor orbits. This is the usual thickness assumed for the front of the collisionless shock. The question is how can such a picture be made consistent with electron acceleration when the momentum of the electrons is less by the mass ratio and the orbit time less by the square root? The point is that one would expect electrons to follow along the field lines regardless whether the lines are wrapped up in a helix or not. The electrons would remain adiabatic, not change their magnetic moment stochastically like the ions, and so would proceed out ahead of the collisionless shock. Naturally, if many electrons proceeded ahead of the ions, a strong electric field of charge separation would develop, the ambipolar field. The integral of this field along the line, or potential, however, is limited to several times the thermal energy of the electrons, not enough to reflect a few exceptional accelerated electrons that might be reflected back and forth across the shock. Therefore it seems unlikely that a collisionless shock in the lowest order description should accelerate electrons.

Galeev (1984) has discussed the acceleration and heating of electrons in collisionless shocks and finds that one must rely upon the excitation of strong ion sound waves by the streaming ions in order to back scatter energetic electrons. The problem of the excitation of strong ion sound waves by streaming ions has had a long history, and it has never been shown theoretically or experimentally that such excitation takes place.

A laboratory plasma experiment was performed to observe the effect of a strong current in a plasma by transmission of a short pulse, 10^{-8} s, of energetic, 0.5 Mev, electrons. The plasma current, a linear stabilized pinch, was strong enough to excite hydromagnetic turbulence sufficient to scramble the magnetic flux surfaces as would be expected for an ensemble of torsional hydromagnetic waves (Colgate, 1962 and see

appendix Colgate, 1978). However, despite the extreme random distortion of the magnetic surfaces, the high energy electron beam was transmitted through the hydromagnetic turbulence unattenuated. Electron acceleration by collisionless shocks is therefore conceptually a very questionable process.

III The Supernova Envelope Shock Origin of Cosmic Rays

The explosion of Type I supernova leads to a collisional hydrodynamic shock in the envelope of the star, (Colgate and Johnson, 1960, with White 1966, 1970, with McKee and Blivens 1972, with McKee 1973, 1975, with Petschek 1979, and a review 1984.) The spectrum produced by the relativistic shock is one power of E steeper than observed. (The exponent, s is ~ 2.5 rather than the observed 1.6) and so is unlikely to be the primary source of cosmic rays. On the other hand the possibility of accelerating ultrahigh energy particles to $> 10^{18}$ ev is significantly greater than by collisionless shocks in the ism driven by supernova. The non-relativistic hydrodynamic supernova shock becomes relativistic at an external mass fraction of $(1-F) = 3 \times 10^{-6}$ of the star. The resulting ejected relativistic matter energy, $(1-F) M_0 c^2 = 6 \times 10^{48}$ ergs per SN. This is only about 1/5 of what is necessary to explain the galactic cosmic rays energy. The heavy nuclei are partially spelled in the shock transition and partially re synthesized in the post shock expansion for $E < 10^{15}$ ev. depending upon the large number of pairs in the post-shock fluid. Above this energy the shock progresses in the magnetized photosphere, but still as a pair dominated collisional shock. At some point the expanding relativistic matter escapes into the ISM. There have been arguments both for the escape of the accelerated matter (Holman, Ionson, and Scott, 1979, and Colgate 1984) and against by adiabatic expansion in the ISM (Kulsrud and Zweibel, 1975, Kulsrud, 1979 and 1982). The adiabatic expansion argument depends upon the existence of a collisionless shock which contains the relativistic shock ejected matter. The existence of such a collisionless shock in the ISM has the same uncertainties as the above arguments for acceleration. Regardless, the prediction of a too steep spectrum, too little total energy, and a non standard nuclear composition argue strongly against this mechanism. In addition the supernova envelope shock suffers a similar difficulty from anisotropy limited by diffusion in the ISM. In summary a different mechanism is needed for acceleration of cosmic rays that is isotropic, space-filling and extends over the full observed spectrum.

IV Acceleration of CR by Reconnection of Magnetic Helicity

There is a need for a mechanism to accelerate cosmic rays universally over the full energy spectrum, isotropically, and space filling. A theory based upon a series of mechanisms, patched to fit various spectral regions is less satisfactory than a single mechanism that takes place in different circumstances throughout the universe. Furthermore any mechanism that results in a fractional loss in number of particles for a given fractional gain in energy results in a power-law. Whatever mechanism of acceleration that results in the minimum fractional loss per fractional gain results in that particular spectral index that is smallest and hence is likely to dominate over all others. The force-free reconnection of magnetic field twisted by the vorticity motion of all accretion or condensations both within the Galaxy as well as the metagalaxy is a universal circumstance to expect such acceleration. Mass condensation occurs always with finite angular momentum. The winding number occurring during the dissipation of this angular momentum assures that all imbedded flux will of necessity undergo continuous winding until either the angular momentum is dissipated or reconnection takes place. This assures that at least several orders of magnitude of twist i.e., a winding number of at least several hundred or greater will take place. The transition between this picture of transient, multiple, highly twisted, flux-tubes within our galaxy (and between galaxies) and the observed state of relatively ordered flux must occur by reconnection. It is this reconnection of force-free field that of necessity must lead to E-parallel

acceleration. The acceleration of cosmic rays in this picture is then a sum of both individual particles that are accelerated in single coherent regions of high winding number and random diffusion in energy space of particles that stochastically traverse many coherent regions of E-parallel acceleration and deceleration.

The Reconnection Theory of Acceleration

The specific angular momentum of matter in the galaxy rotating at an $\omega = 10^{-8}$ per year and a local radius corresponding to roughly one solar mass, ($\sim 3\text{pc}$) is $3 \times 10^{22} \text{ cm}^2/\text{s}$. This is some 2×10^4 larger than the Keplearian orbit at a solar radius. This large factor of excess angular momentum must be exchanged with the Galaxy as a whole in order to form a star, and still more angular momentum must be removed in order to collapse to a neutron star. The most likely mechanism for the transport of this angular momentum is by a turbulent, α -viscosity in the disk-like accretion of a star through the T-tauri stage. (If the torque is transmitted by magnetic stress, this makes the following effects even larger.). Similarly the magnetic flux threading the original matter at the density of the ISM is also orders of magnitude, $\times 300$, larger than the flux that would allow compression to a solar radius. Furthermore the observed external flux of the sun and typical other stars is $\times 10^{-6 \text{ to } -7}$ times less than this formation limit. Hence magnetic flux must also be expelled from the condensing matter as well. Therefore this flux, in order to escape the matter, must undergo reconnection during the process of condensation. However the subsequent winding or twisting of this residual flux requires a far larger reconnection process since the winding produces a far larger total flux than the original.

The picture at every stage of condensation is that of a helical, twisted flux tube that extends some 50 to 100 turns beyond the source. The number of turns is interpreted observationally from the topology of the "jets" or collimated radio sources which are presumed to be just these helical flux tubes from accretion onto the black holes of AGN. They become illuminated in the radio by the accelerated electrons due to the reconnection of the force-free flux of the twisted flux tube. The same picture applies to the bi-polar flows observed in star formation. The relation between the number of turns and the angle of the "jet" is that the minimum energy force-free field of the helix is close to a 45 degrees where the ϕ and z components of the field are equal. Hence the number of turns, n , will be of the order $(1/\text{jet angle}) \times \ln(L_{\text{max}}/R_{\text{min}})$, or several hundred.

It is assumed that the reconnection dissipates the total current associated with the B_ϕ component of the field. If this current is interrupted as a sequence of multiple reconnection events, but phased along a local flux surface at c by the accelerated particles themselves, the total potential becomes of the order:

$$V = n B_{\text{max}} R_{\text{min}} 300 (2\pi \ln n) = 2 \times 10^{22} \text{ ev.}$$

where $B_{\text{max}} = 10^3$ gauss, and $R_{\text{min}} = 1 \text{ au}$.

Accretion onto neutron stars, cataclysmic variables, and T-tauri stars will all lead to tearing mode reconnection associated with all mass condensations. The energy of these condensations is should be sufficient to maintain the cosmic rays of our Galaxy. Let us assume that the star formation rate is $10 M_\odot$ per year and that magnetic field decouples from the accreting matter at a disk radius of 1 AU where pressure support of the forming star would become dominant over the α -viscosity. Then the energy released by star formation at this decoupling radius becomes;

$$\dot{E} = \dot{M} \frac{M}{R} = 2 \times 10^{47} \text{ ergs s}^{-1}$$

and in the life time of cosmic rays of 10^7 years corresponds

The bi-polar flows that are now frequently observed in the radio maps or star forming regions also correlate with this process.

V) Experiments

In order to choose which of the many complicated processes are primary in producing the extraordinary acceleration of cosmic rays, we need to perform laboratory experiments. Since every proposed mechanism for the acceleration of cosmic rays depends upon the existence of relatively strong magnetic fields, either stellar or Galactic, where "strong" implies equipartition between dynamical stress and magnetic field stress, the most fundamental process is the dynamo itself. Although a large amount of effort has been spent on the theory and numerical modeling of the dynamo process (see Roberts and Soward, 1992, for a current review), no experiment has yet been able to demonstrate that the models are correct. In preparation for this meeting, such an experiment was designed.

The importance of plume type convection to the " α " deformation of the α - ω was recognized which allows the possibility of an experimental analog using the hydromagnetic fluid of the liquid metal sodium or sodium - potassium alloy, called "NaK". Similarly we can perform laboratory plasma experiments to observe reconnection in the near vacuum limit and the resulting parallel electric field and hence acceleration. Without laboratory experiments, shock acceleration is uncertain because of nonlinear plasma effects. A partial list of astrophysical experiments relevant to acceleration follows:

- 1) A mock-up of the α - ω dynamo process using liquid Na as a hydromagnetic fluid. The origin of the α component of dynamo theory in real circumstances like stars, galaxies, and planets is questionable. An experiment can demonstrate that a diverging plume in a rotating frame produces the necessary α effect where as smaller scale uniform turbulence is unlikely to.
- 2) A plasma "pinch" experiment can be done that simulates the formation of a collimated radio source originating from an accretion disk, either around a black hole, or collimated jets formed by accretion disks at an early stage of star formation.. Both the hydromagnetic configuration of a force-free helical field as well as the expected acceleration due to reconnection should be observable. The plasma code numerical simulation would give a greater degree of confidence of extending the experimental results to astrophysical circumstances.
- 3) The self-triggering of a reconnection event in a force free, sheared (current carrying) plasma by relativistic run-away electrons. This would simulate one explanation of the acceleration of the highest energy cosmic rays. This needs to be done in a tokamak that has been retired from active fusion research.
- 4) The formation of a strong hydromagnetic shock in the laboratory with enough Larmor orbits in dimension (about 100). This would allow the investigation of the Fermi first order shock acceleration process. The presumed excitation of the pre-shock hydromagnetic waves can be diagnosed by a pulsed electron beam that maps the shear in a bundle of lines or flux tube on which torsion hydromagnetic waves, which are self

excited by anisotropic high energy ions. These flux lines would be those that threaded along the oblique lines of force.

The Dynamo Experiment

An α - ω dynamo depends upon wrapping-up a magnetic field in a differentially rotating conducting fluid. An initial threaded magnetic flux can be greatly amplified in the toroidal mode. This flux will reside wholly within the conducting fluid, and therefore can not be viewed as a dynamo. A further deformation, the α effect, must capture a fraction of this toroidal flux and transport it towards an "insulating" surface, rotate it, and then release it in the poloidal plane such as to increase the original bias field. Such an α - ω dynamo is characterized by a "dynamo number" defined by the product of the two Reynolds numbers, R_ω of the ω deformation and R_α of the α deformation, or $R_\omega R_\alpha$. This product has been estimated to be required to be as large, like 1000 in order achieve positive gain, i.e., to make a dynamo work. However, the minimum value of this number depends upon the ratio of the characteristic dimensions of the two different deformations. These two Reynolds numbers can be defined in terms of the magnetic diffusion coefficient, D_{Na} , of the liquid metal at 100 C or of D_{plasma} of a plasma or D_{copper} etc. Here $D = \eta_{emu}/4\pi$, where $\eta_{emu} = 10^9 \eta_{ohms}$. In cgs units: $D_{Na} = 716$, $D_{copper} = 135$, and $D_{plasma} = 2.0 \times 10^6 Z T_{ev}^{-3/2} \text{ cm}^2 \text{ s}^{-1}$ (Here $\ln \Lambda$ is chosen = 10.). Liquid sodium is the optimum analog, or experimental hydromagnetic fluid because of density and electrical resistivity (Colgate, Furth, and Haliday, 1960). The alkali metal alloy, Na plus K is more convenient to use because it is liquid at room temperature, but its resistivity is more than four times greater than liquid Na at its melting point of 100C. Using this for the experimental fluid, the magnetic Reynolds number becomes:

$$R_{mag} = v r / D, \text{ or } D_{Na} = v r / 716$$

where v and r are the characteristic velocity and dimension of the respective flows, α and ω . If the boundary of the flow has a dimension L then the dissipation due to fluid friction over the surface area, $A = 4\pi L^2$ becomes:

$$\text{power} = A \rho v^2 C_f.$$

If the flow dimensions are a fraction, δ , of the boundary dimensions such that $r = \delta L$, then the power becomes

$$\text{power} = 4\pi (D_{Na}/\delta)^3 C_f R_{mag}^3 / L.$$

For liquid sodium the coefficient of fluid friction, C_f , is approximately 1/400, corresponding to high (fluid) Reynolds number flow, neglecting the enhanced friction due to Eckman layer flow. Also for the ω flow one might achieve $\delta = 1/2$. Then

$$\text{power} = 10^{-2} R_\omega^3 / L \text{ kilowatts.}$$

For example a 120 cm diameter cylinder, 60 cm in length driven by 5 kw of power might achieve a value of $R_{mag} = 32$ for the ω term.

The α flow is created by episodic plumes of dimension $r/4$ at a velocity roughly $2 \times v$. Hence $R_\alpha = 16$. The product of the two magnetic Reynolds numbers, the dynamo number, is 500, somewhat less than the presumed to be required 1000, but the frequency of the episodic plumes is an additional variable that can decrease this limit.

The experiment would use a finite bias poloidal magnetic field so that the magnetic sensors are less expensive, but in addition if the dynamo gain is less than unity, then a very much smaller gain, less than 1% , can be detected as an incremental change, or increase in the bias field. Therefore one can explore dynamo action on very much smaller scales provided the goal of exponentiating gain is given up. Figures 1 - 4 illustrate such an experiment.

The Plasma Pinch/ collimated radio source Experiment

The helical hydromagnetic field structure produced by an accretion disk is shown in Fig.5 and an experiment to produce this field configuration is shown in Fig. 6. The objective of the design is to minimize the cost and yet maintain a high enough magnetic Reynolds number that the conducting limit is achieved. The limiting temperature in a laboratory or one-ended pinch is discussed in the context of solar flares in (Colgate, 1978) and references are given to the corresponding laboratory work. The agreement between the laboratory scale and the solar flare scale gives confidence to the scaling parameters. Hence, one can estimate a mean plasma temperature of roughly 10 ev where ionization of a hydrogen plasma is complete. (Neutral atoms strongly damp the desired hydromagnetic effects because of charge exchange.). Then the magnetic diffusion coefficient of the plasma becomes,

$$D_{\text{plasma}} = 2.0 \times 10^6 Z T_{\text{ev}}^{-3/2} \text{ cm}^2 \text{ s}^{-1} = 2 \times 10^4 \text{ cm}^2 \text{ s}^{-1} .$$

so that $R_{\text{cm}} = r v / D = 1.8 \times 10^3$ for $r = 30 \text{ cm}$ and $v = 10^7 \text{ cm s}^{-1}$. This is sufficiently large so that one might observe a winding number of $R_{\text{cm}} / (3 \times 2\pi) = 100$ turns. Here the factor of $1/3$ is an estimate of the radius where the inner half of the current flows. The reason for choosing such a high axially velocity of the helix (figuratively the velocity of the jet) is that one desires a velocity high enough so that the initial neutral gas will be ionized by the electron drift energy (Colgate, 1961) which in turn is due to the kinetic energy of the ions. At 10^7 cm s^{-1} the kinetic energy of a deuterium ion, the preferred ion, is 100 ev. This is high enough to ensure complete ionization, as well as make up for losses. Since the magnetic helix is presumed to be force free in the astrophysical circumstance, in the experimental case, the hydromagnetic velocity must be larger than the axial velocity, or roughly $v_{\text{hydromag}} = 3 \times 10^7 \text{ cm s}^{-1}$. This large hydromagnetic velocity means that the density must be low, or the field strength large. If the field strength is large, the magnetic energy supplied by the capacitors must be large and therefore the cost will be excessive. A low density, on the other hand, is limited by the electron velocity of the current carriers that would induce Alfvén wave instabilities. A compromise of all these factors suggests an electron or ion density of $n_e = 2 \times 10^{14} \text{ cm}^{-3}$. A gradient of the initial gas density (as from a pulsed valve), allows the initial discharge to form at higher density, but then the helix should progress ahead of this higher density plasma into a region of lower density where the force-free condition is more closely met. In addition the run-away condition (i.e., acceleration) would take place due to the lower density as well as reconnection instabilities.

Tokamak run-away Acceleration Experiment

As the density of the plasma decreases in a tokamak discharge due to diffusion processes, the current must be carried by a smaller number of electrons. The inductive energy or magnetic energy of this current then accelerates fewer and fewer electrons to higher energy. Because of the high degree of perfection of the magnetic surfaces, the run-

away particle confinement is good and the accelerated electrons remain within the field configuration. Hence their energies can become very great, 10 to 100 Mev, and the total energy of the run-away beam is enough to do damage to the walls of the confinement vessel (). This damage is expensive to repair, a hole melted through the vacuum vessel liner, and so the circumstances of this "fault" occur rarely and in successful machines not at all. This process is therefore to be avoided with great care in the usual plasma experiments. A pulsed gas valve ensures that the density never falls low enough to approach the run-away condition. On the other hand this is just the circumstances that are most likely to demonstrate acceleration in astrophysics. Nearly all of the free energy of the field configuration is transformed to accelerated particles.

This condition can be induced and experimentally investigated in a tokamak machine that is no longer dedicated to fusion plasma confinement experiments. Of course care would be needed to prevent a concentrated dumping of the accelerated beam energy at one point, but coils that destroy the perfection of the magnetic surfaces should allow a more gradual and more dispersed in area dumping of the beam. One should then be able to investigate the most important process to acceleration, of an induced tearing mode instability, phased by the accelerated particles themselves.

Collisionless Shock Acceleration Experiment

A collisionless shock experiment in the laboratory requires driving a strong shock into a pre-ionized magnetized plasma. The only practical piston is another rapidly rising magnetic field. The constraints that must be met are: 1) The number of Larmor orbits in dimension must be large enough to make a valid test of collisionless shock theory, a number of the order of 100.

2) The damping by collisions must be small enough so that velocity phase space instabilities are not stabilized by isotropization. The number of collisions should then be less than $1/(\text{number of Larmor orbits})$.

3) The cost determines feasibility. The cost is nearly proportional to the magnetic energy, or in turn to the size of the capacitor bank required to supply the energy. A reasonable goal for a university scale experiment is a total capacitor bank energy less than several times 10^5 joules.

Let the distance the shock traverses be L , measured in Larmor orbits, R_L , so that $L = \Gamma R_L$ where Γ is the primary measure of the test of the plasma physics of the experiment. In addition the preferred ion is deuterium because it has the minimum scattering cross section for maximum mass and minimum radiation loss. Then

$$L = \Gamma R_L = 200 \Gamma E_{ev}^{1/2} / B \text{ cm.}$$

Since the build-up of velocity phase space instabilities is likely to be very sensitive to the velocity distribution function and therefore to the smallest collisional damping, the number of scatterings in the distance L , should be of the order $1/\Gamma$, so that the mean free path, λ , should be

$$\lambda = \Gamma^2 R_L .$$

Since the coulomb cross section is a function of energy and only weakly, logarithmically, a function of density, it can be approximated to give

$$\lambda = 1.6 \times 10^{12} E_{ev}^2 / n_D \text{ cm.}$$

where n_D is the plasma number density.

The shock must be driven at a velocity, v_s , such that the particle pressure is approximately the magnetic pressure, or equivalently that the shock speed is the hydromagnetic speed. This gives the relation that

$$\rho v_s^2 = B^2 / 8\pi.$$

With these relationships and expressing the results in terms of $\Gamma = 100$, or Γ_{100} and the kinetic energy of the ions in units of a kev one obtains:

$$L = 3.3 E_{kev}^{-2} \Gamma_{100}^3 \text{ meters}$$

$$B = 1.9 E_{kev}^{5/2} \Gamma_{100}^{-2} \text{ kg}$$

$$n_D = 4.8 \times 10^{13} E_{kev}^4 \Gamma_{100}^{-4} \text{ cm}^{-3}.$$

The total energy, W , becomes

$$W = 13 E_{kev}^{-1} \Gamma_{100}^5 \text{ MJ},$$

and the time for the shock to traverse the dimension, L becomes

$$t_s = 10 E_{kev}^{-5/2} \Gamma_{100}^3 \text{ } \mu\text{s}.$$

For $\Gamma = 100$, the energy is of the "Zeus" capacitor bank at Los Alamos, dismantled several years ago, but for $\Gamma = 50$, and $E = 300 \text{ ev}$ the dimensions and energy are feasible. The turbulence excited on the field lines by the anisotropic velocity distribution of the shocked particles can be measured by a pulsed electron beam as in Colgate (1978) and Birdsall et. al. (1962). Therefore a modest test of particle acceleration by a collisionless shock can be performed in the laboratory, but the relativistic, truly collisionless case is uniquely the domain of astrophysical space.

Summary

Five problems of shock acceleration for the production of cosmic rays have been discussed in the context of astrophysical conditions. Because of these difficulties, an alternate explanation has been given where reconnection of twisted magnetic fields (from condensation, accretion, and conservation of angular momentum) accelerates particles along field lines. The acceleration is coherent provided the reconnection is coherent, in which case the total flux, as for example of collimated radio sources, predicts single charge accelerated energies much greater than observed. The same acceleration process should occur during the formation of stars associated with the T-tauri phase and bi-polar outflows. Because of the ubiquitous nature of matter condensations in the universe, the acceleration is inherently isotropic and space-filling in nature.

Four laboratory experiments are suggested that would form the basis of a substantiated science of plasma processes of acceleration. These include an α - ω dynamo using liquid sodium, a one-ended plasma pinch that simulates the formation of collimated radio sources or bi-polar out-flows, reconnection in a tokamak which simulates acceleration by coherent reconnection, and finally a collisionless shock experiment to simulate shock acceleration.

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References:

- Axford, W.I., Leer, E., and Skadron, G., 1977, ICRC.. 15th ICRC, 11, 132.
Bell, A.R., 1978, MNRAS, 182, 147.
Birdsall, D. H., Furth, H. P. Hartman, C. W., and Spoerlein, R. L., "Particle Motion on Magnetic Flux Surfaces in Stabilized and Hard-Core Pinches", Nuclear Fusion, Suppl, Pt. 3, 955-967, 1962.
Blanford, R.D. and Ostriker, J.P., 1988, ApJ, 221, L29.
Blanford, R.D. and Eichler, D., 1987, *Physics Reports*, 154, 1, 1987.
Colgate, S.A., 1959, Phys. Fluids 2, 495.
Colgate, S.A., Furth, H.P., and Halliday, F.O., 1960, *Physics*, 37, Modern 744-747.
Colgate, S.A. and Johnson, M. H., "Hydrodynamic Origin of Cosmic Rays", 1960, Phys. Rev. Let.,
Colgate, S.A., "Ionization in Crossed Electric and Magnetic Fields", Proc. of Symposium on "Electromagnetics and Fluid Dynamics of Gaseous Plasma," Polytechnic Inst. of Brooklyn, 373, April 4-6, 1961.
Colgate, S.A. and McKee, C. R., 1973, Ap. J., 181, 903.
Colgate, S.A., 1978, Ap. J., 221, 1068.
Galeev, A.A., 1984, Adv. Space Res. Vol. 4, No 2-3, 255
Hillas, A.M., 1984, Ann. Rev. Astron. Astrophys., 22, 425
Holman, G D, Ionson, J A and Scott, J S, 1979, Ap. J. 228, 576.
Krimigis, S.M., 1992, Space Sci. Rev., 59, 167.
Kulsrud, R.M. and Zweibel, E.G, 1975, 14th Int. CR Conf., Munich, 0-9-1-12.
Kulsrud, R.M, 1979, 16th Int. CR Conf. Kyoto, 12, 128.
Kulsrud, R.M, 1982, Physica Scripta, T2/1, 177.
Parker, E.N., 1979 "Cosmical magnetic fields, their origin and their activity", Oxford: Clarendon.
Roberts, P.H. and Soward, A.M., "Dynamo Theory", 1992, Ann.Rev. Fluid Mech., 24, 459-512.
Sarris, E.T. and Krimigis, S.M., 1985, Ap.J., 298, 676.

List of figures:

Figure 1 shows the experiment. Here meridional circulation within a cylindrical tank of liquid sodium is driven by a turbine at one end. A piston within a smaller diameter cylinder drives axial jets. These jets in turn create axial plumes directed towards the opposite end of the tank.

Figure 2 shows the field created by the bias coil. This field is poloidal and is primarily radial in the central region where meridional flow creates a region of differential rotation.

Figure 3 shows the meridional flow with ω proportional to r^{-2} .

Figure 4 shows the increased toroidal field due to "wrapping up" or twisting of the radial bias field. Axial jets are also shown that diverge as a plume when they reach the end wall. They carry a fraction of the toroidal flux to the end wall where the divergence of the flow both exposes the trapped flux to the lower conductivity (or insulator) of the end wall allowing the lines of the flux loop to escape the tank as a potential field. A twist of the loop occurs because the plume increases in radius as it diverges at the end wall. At roughly constant angular momentum its angular velocity decreases relative to the parent fluid so that the ω of the plume is roughly 1/2 to 1/4 of the ω of the meridional flow. This differential rotation is depicted by the fewer circulation arrows of the plumes relative to the main flow. The relative twist produced by this difference in ω rotates the loop of flux into the poloidal plane. The merging of these poloidal loops adds to the original, poloidal, bias field.

Figure 5 shows the hydromagnetic field configuration produced by poloidal bias magnetic field convected by the accreting plasma of an accretion disk. The vertical helical structure is the nested twisted flux tubes produced by the lines of force threading the accretion disk. The differing pitch of the lines of force is due to both the force-free field condition as well as the radially differing orbital velocities of the Keplerian accretion disk. (figure by Raymond Laflamme, T-6, LANL)

Figure 6 shows a laboratory plasma physics experiment that should permit the observation of the helical flux surfaces produced by an accretion disk. The bias field coils are arranged so that the poloidal field strength simulates the axial field component expected, $B = B_0 r^{-3/2}$. The bias field flux lines close outside the insulating walls of the vacuum system. The electrodes are rings connected to a series of condenser banks. The respective voltages and the resulting electric fields, $E = E_0 r^{-2}$, produce the azimuthal velocities corresponding to the Keplerian orbits of an accretion disk. The length of the actual experiment should be enough to demonstrate roughly 10 turns of the inner half diameter, or 10 diameters.

Figure 7 shows the bias field lines for the above one-ended plasma pinch. The magnetic field distribution is shown below the coils and bottom electrodes. A peak field of roughly 5 kg falls off as $r^{3/2}$ in order to simulate the axial field advected in and diffused outward in an accretion disk (G. Willett, 1991). The values chosen for the voltage and stored energy of the capacitor banks in figure 6 are chosen to simulate the Keplerian velocity at various radii, proportional to $r^{-1/2}$.

Radial helical flow produces ω by
conservation of angular momentum

cylindrical
tank

Helical flow, driven at one
end by turbine

Differential rotation due to conservation of angular momentum, produces the α effect

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