On a mechanism of highest-energy cosmic ray acceleration

C. Litwin* and R. Rosner*

*Department of Astronomy & Astrophysics, The University of Chicago, 5640 S Ellis Avenue, Chicago, IL 60637

Abstract. A recently proposed mechanism of acceleration of highest energy cosmic rays by polarization electric fields arising in plasmoids injected into neutron star magnetospheres is discussed.

INTRODUCTION

The problem of the origin of ultra-high-energy cosmic rays (UHECR) - those with energy $\gtrsim 10^{19}$ eV - continues to pose a serious theoretical challenge (Hillas 1984, Biermann 1997, Cronin 1999, Bhattacharjee & Sigl 2000, Olinto 2000). No convincing explanation that could account for all main observables – energy, spectrum and flux – has been offered to-date. Of particular interest are cosmic rays in the highest energy range, above $\gtrsim 5 \times 10^{19}$ eV. This radiation does not exhibit any significant anisotropy connected with the galactic disk and is therefore generally assumed to be of extragalactic origin (Blandford 2000). Moreover, the seeming, albeit uncertain, change of slope of the energy spectrum at $\sim 5 \times 10^{19}$ eV is frequently taken as an indication of the appearance of a new, distinctly different (and presumably extragalactic) component of the spectrum. At the same time the UHECR do not exhibit any sign of Greisen-Zatsepin-Kuzmin (GZK) cut-off (Greisen 1966, Zatsepin & Kuzmin 1966). Thus if carried by singly charged particles, light nuclei or photons, this radiation would need to originate at distances $\lesssim 50$ Mpc. Nevertheless, the direction of the incoming radiation does not appear to be correlated with any plausible sources within this distance.

Existing theories of the UHECR generation are usually put into two general categories: the “bottom-up” scenarios, in which particles are accelerated from lower energies to the ultra-high energies; and the “top-down” scenarios in which particles are “born” with ultra-high energies in a decay of some ultra-massive X particles, usually relics of the early universe.

Top-down scenarios, in addition to relying on uncertain physics, face difficulties explaining both the flux and the energy spectrum of UHECR (see Olinto 2000). The primary difficulty for the bottom-up scenarios is the acceleration mechanism.

Acceleration scenarios are generally divided into two types (cf. Hillas 1984): (1) direct acceleration, by electric fields; or (2) statistical Fermi acceleration by shocks in magnetized plasmas.

Statistical Fermi acceleration by supernova shocks (Axford et al. 1977, Krymsky 1977, Bell 1978, Blandford & Ostriker 1978) is considered a source of the cosmic rays.
below the “knee” (∼ 5 × 10^{15} \text{ eV}), which are believed to be of galactic origin. It gives rise to a power law energy spectrum, which combined with the energy dependence of the diffusion coefficient, as inferred from the data on secondary nuclei, yields the energy spectrum similar to the observed one. This mode of acceleration becomes inefficient at higher energies (Lagage & Cesarsky 1983).

The primary difficulty with the direct acceleration scenarios is the existence of sufficiently large voltages. Most commonly considered sources are unipolar inductors, such as rapidly spinning magnetized neutron stars or blackholes. In the case of pulsars, the rotation gives rise an emf too small to accelerate iron nuclei to the UHECR energies (Berezinskii et al. 1990, Blandford 2000). A spinning blackhole in the center of a radiogalaxy generates an emf sufficient to accelerate protons to energies 10^{19} − 10^{20} \text{ eV}. A difficulty with this scenario, however, is the presence of a dense pair plasma and intense radiation which would cause energy losses of accelerated particles. Another argument frequently used (e.g., Hillas 1984) against direct acceleration scenarios is that it is not clear how the power-law energy spectrum, characteristic for cosmic rays, could emerge.

ACCELERATION MECHANISM

We have recently proposed (Litwin & Rosner 2001) an alternative scenario of a galactic or galactic-halo origin of the UHECR. This scenario goes some way toward overcoming some of the main difficulties described in the previous section. We describe this recent work in the present section.

We started with the observation that polarization electric fields arise in plasma “blobs” or streams injected at large angles into the magnetic field (Chandrasekhar 1960, Schmidt 1960; more recently, Litwin, Rosner & Lamb 1999 and refs. therein). The appearance of this electrostatic field allows for the plasma stream to penetrate into the magnetic field, as has been demonstrated in numerous laboratory experiments (Baker & Hammel 1965, Meade 1965, Lindberg 1978) and numerical simulations (Galvez & Borovsky 1991, Neubert et al. 1992).

Outside the plasma, the electrostatic field has an approximately dipolar character and has a nonvanishing component along the magnetic field. This field accelerates particles (electrons and ions) out of the plasma and gives rise to the plasma current that leads to the eventual halting of the plasma cross-field motion. The energy of accelerated particles is \( \sim ZeU \) where \( Ze \) is the particle charge and \( U \) is one-half of the electrostatic potential difference across the plasma stream. This phenomenon of particle acceleration and the above estimate of particle energy has been verified in experiments (Lindberg 1978) and in computer simulations (Galvez & Borovsky 1991, Neubert et al. 1992).

For a sufficiently large stream width (much greater than the Larmor radius corresponding to the stream velocity), the energy of an accelerated particle can greatly exceed the kinetic energy of a bulk plasma particle. In particular, for a plasmoid of width \( \sim 10 \text{ km} \), free-falling onto a neutron star with the surface magnetic field \( B \sim 10^{13} \text{ G} \), the voltage \( U \sim 10^{21} \text{ V} \).

We applied the above-described basic physics to a plasmoid injected into a neutron star magnetosphere. Such plasmoids may results from planetoid impacts onto neutron
stars of the type that has been previously discussed in the literature as possible sources of galactic gamma ray bursts (Colgate & Petschek 1981, Lin et al. 1991, Katz et al. 1994, Wasserman & Salpeter 1994, Colgate & Leonard 1996). The motion at distances greater than the Alfvén radius (i.e., where the ram pressure is equal the magnetic pressure) is unaffected by the magnetic field. Following Colgate & Petschek (1981) to describe the process of break-up, and subsequent compression and elongation, of an iron planetoid by tidal forces the density and the size of the impacting plasmoid at the Alfvén point is determined. During the infall the planetoid matter becomes ionized by the motional electric field. In the vicinity of the Alfvén radius it is assumed, as is customary (e.g., Lamb et al. 1973), that the magnetic field penetrates the plasma (due to, e.g., anomalous resistivity). The subsequent cross-field motion leads to plasma polarization, as described by Chandrasekhar (1960) and Schmidt (1960). The magnitude of the accelerating potential due to this polarization electric field is then determined by the energy of particles, accelerated along the magnetic field by the polarization field, from the plasmoid velocity, its size and the magnetic field at the Alfvén radius.

Subsequently we determined the energy of iron nuclei emerging from the magnetosphere, by solving numerically the particle equation of motion in the dipole magnetic field taking into account the radiation reaction force. As expected, the energy of emerging particles is much smaller than the initial energy unless they are accelerated close to the magnetic axis.

The energy of emerging particles is quite sensitive to the angle between the particle trajectory and the magnetic axis. From this, the energy spectrum of cosmic rays generated in a single impact event can be deduced (Litwin & Rosner 2001). For the range of parameters considered (magnetic field $B \sim 10^{12} - 10^{14}$ G, planetoid mass $M_p \sim 10^{22} - 10^{24}$ g), the spectrum depends weakly on the magnetic field and the planetoid mass. To a good approximation the emerging particles have a power-law energy spectrum: $dN/dE \sim E^{\mu}$. The value of the exponent $\mu \sim 2.9 - 3.0$ for magnetic fields in the considered range is within the measurement uncertainty of the value found by AGASA (Takeda et al. 1998).

The number of particles at given energy produced in a single event can be found (Litwin & Rosner 2001) from the energy spectrum and from the total charge carried by accelerated particles. The latter is determined by integrating the equation of motion. For an iron planetoid, with the fiducial mass of $10^{23}$ g, the number of particles with energies exceeding $10^{19}$ eV is $\sim 2 - 14 \times 10^{28}$.

**MAGNETIC CONTAINMENT, ENERGY SPECTRUM AND FLUX OF UHECR**

Larmor radii of iron nuclei with energies less than $\lesssim 10^{20}$ eV in a magnetic field with strength 3-10 $\mu$G, characteristic of the galactic magnetic field (Kronberg 1994), are less than $\sim 1$ kpc. Thus iron nuclei constituting UHECR would be confined by the galactic magnetic field with a characteristic gradient length scale of 10 kpc. Assuming a steady state, the energy spectrum observed on Earth differs from the source spectrum if the confinement time is a function of energy. It is usually believed (see, e.g., Sigl &
that confinement time decreases with increasing energy. Indeed, the chemical composition of CR in the $1 - 10^3$ GeV per nucleon range can be interpreted as a power law behavior of the diffusion coefficient $D(E) \sim E^\mu$, with $\mu \sim 0.3 - 0.7$ (see Berezinskii et al. 1990). A power law behavior of the diffusion coefficient results also in theoretical models, such as the model of Jokipii (1975) in which particles are scattered by the magnetic field fluctuations which vary only in the direction transverse to the mean field. If the particle Larmor radius is much smaller than the integral scale $L_c$, a power-law fluctuation spectrum, with exponent $\alpha$, results in a power-law dependence of the diffusion coefficient on energy, with the exponent $\mu = (1 - \alpha)/2$. In particular, for the Kolmogorov spectrum ($\alpha = -5/3$), $\mu = 4/3$.

However, the UHECR confinement time dependence on energy may be qualitatively different. First, the small Larmor radius approximation may be inapplicable to the highest energy cosmic rays. If one assumes that the integral scale of the galactic turbulence is 100 pc (Parker 1979), and that the galactic magnetic field is in the range 3-10 $\mu$G (Kronberg 1994), the Larmor radius of iron nuclei is larger than the integral scale for energies higher than $1 - 3 \times 10^{19}$ eV. In this regime, the dependence of the cross-field transport on energy might be significantly different. As a specific example, the previously discussed model of Jokipii (1975) yields in this regime $\mu = -1/2$. Thus the confinement times would increase with energy, assuming that the latter were determined by the cross-field diffusion. On the other hand, if the confinement time were determined by the motion along the magnetic field, it would be independent of energy on the galactic/galactic halo length scales for the ultrarelativistic, collisionless particles in the UHECR energy range.

If the confinement time is known, the rate of planetoid impact events required to generate the observed UHECR flux on Earth can be determined. The upper bound on the confinement time is given by the rate of photodisintegration on the infrared radiation background (Stecker 1998). The lower bound can be obtained from the escape time from the galactic magnetic field at the velocity of the curvature drift, assuming a 10 kpc curvature radius. For $10^{19}$ eV iron nuclei, this escape time is $\sim 10^{13}$ s; the escape time is longer if the field is axisymmetric and possesses closed flux surfaces. A similar estimate is found for the transit time along a spiral magnetic field twisting by $4\pi$ within radial distance of 10 kpc. Thus it is reasonable to expect that the confinement time will be in the range $\sim 10^{13} - 10^{16}$ s. Then assuming that the density of neutron stars is $2 \times 10^{-3}$ pc$^{-3}$ (Shapiro & Teukolsky 1983) the observed flux of UHECR results if the impact rate is $\sim 10^{-4} - 10^{-8}$ yr$^{-1}$ on each neutron star.

One can speculate whether such an impact rate is plausible. If one assumes (Lin et al. 1991, Nakamura & Piran 1991, Colgate & Leonard 1996) that the planetoids originate in the accretion disk, formed from the estimated $10^{29} - 10^{32}$ g of matter captured by the neutron star following the supernova explosion, then the rate of accretion of $10^{23}$ g planetoids in a galaxy cannot exceed $\sim 10^4 - 10^7$ yr$^{-1}$, assuming the neutron star birth rate to be $10^{-2}$ yr$^{-1}$. Since $\sim 10^{29}$ particles with energies higher than $10^{19}$ eV are generated in each impact event, the upper bound on the rate of UHECR generation is $\sim 10^{33} - 10^{36}$ yr$^{-1}$. From the observed flux (Takeda et al. 1998) it follows that the density of particles in this energy range is $6 \times 10^{-29}$ cm$^{-3}$. Assuming that the radiation is confined in a sphere of 10 kpc radius, this would require a confinement time exceeding $10^4 - 10^7$ years. The estimated confinement time, mentioned in the previous paragraph, is greater than or comparable to this lower bound.
CONCLUSIONS

In this talk we reviewed a model (Litwin & Rosner 2001), which can potentially solve some of the problems, discussed in the Introduction. This model is an example of a direct acceleration process that explicitly results in a power-law energy spectrum of UHECR. The source spectrum agrees, within experimental uncertainties, with the observed spectrum. While the latter has not been calculated, it is plausible that the energy dependence of the confinement time will not result in a steepening of the spectrum in the UHECR range of energies. Also the magnitude of the observed UHECR flux results from a plausible rate of impact events; and the resulting spectrum may be only weakly anisotropic both due to the confining effect of the magnetic field and because the sources are neutron stars both in the galactic disk and in the galactic halo (cf. Bulik, Lamb & Coppi 1998).

ACKNOWLEDGMENTS

The authors thank Attilio Ferrari, Roger Hildebrand, Don Lamb, Angela Olinto and Simon Swordy for illuminating discussions. Useful comments by Pasquale Blasi, Willy Benz, Sterling Colgate, Walter Drugan, Carlo Graziani, Cole Miller, Don Rej and Eli Waxman are also gratefully acknowledged. This research has been supported by the Center for Astrophysical Thermonuclear Flashes at the University of Chicago under Department of Energy contract B341495.

REFERENCES

1. Axford, W.I., Leer, E., & Skadron, G., 1977, The acceleration of cosmic rays by shock waves, in Proc. 15th Int. Cosmic Ray Conf. (Plovdiv), 11, 132 (1977)
2. Baker, D. A., Hammel, J. E., 1965, Experimental studies of the penetration of a plasma stream into a transverse magnetic field, Phys. Fluids, 8, 713
3. Bell, A.R., 1978, The acceleration of cosmic rays in shockfronts I., Mon. Not. R. Astron. Soc. 182, 147.
4. Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., Ptuskin, V. S., 1990, Astrophysics of cosmic rays, (Amsterdam: North-Holland), edited by Ginzburg, V.L.
5. Bhattacharjee, P., Sigl, G., 2000, Origin and propagation of extremely high-energy cosmic rays, Phys. Rep. 327, 247
6. Biermann, P. L., 1997, The origin of the highest energy cosmic rays, J. Phys. G: 23, 1
7. Blandford, R. D., Ostriker, J. F., 1978, Particle acceleration by astrophysical shocks, Astrophys. J. Lett., 221, L29
8. Blandford, R. D., 2000, Acceleration of ultra-high energy cosmic rays, Phys. Scripta T85, 191
9. Bulik, T., Lamb, D. Q., Coppi, P. S., 1998, Gamma-ray bursts from high-velocity neutron stars, 1998, Astrophys. J., 505, 666
10. Chandrasekhar, S., 1960, Plasma Physics (University of Chicago Press: Chicago).
11. Colgate, S.A., Petschek, A.G., 1981, Gamma ray bursts and neutron star accretion of a solid body, Astrophys. J. 248, 771.
12. Colgate, S.A., Leonard, P.J.T., 1996, Gamma-ray bursts from fast, Galactic neutron stars, AIP Conf. Proc. 366, 269 (1996)
13. Cronin, J. W., 1999, Cosmic rays: the most energetic particles in the universe, Rev. Mod. Phys., 71, 165
14. Galvez, M., Borovsky, J. E., 1991, The expansion of polarization charge layers into a magnetized vacuum: theory and computer simulations, Phys. Fluids B, 3, 1892
15. Greisen, K., 1966, End to the cosmic-ray spectrum?, Phys. Rev. Lett. 16, 748.
16. Hillas, A. M., 1984, The origin of ultra-high-energy cosmic rays, Ann. Rev. Astron. Astrophys. 22, 425
17. Jokipii, J. R., 1975, Motion of charged particles normal to an irregular magnetic field, Astrophys. J., 198, 727
18. Katz, J. I., Toole, H. A., Unruh, S. H., 1994, Yet another model of soft gamma repeaters, Astrophys. J., 437, 727
19. Kronberg, P. P. 1994, Extragalactic magnetic fields, Rep. Prog. Phys. 57, 325
20. Krymsky, G.F., 1977, A regular mechanism for the acceleration of charged particles on the front of a shock wave, Dokl. Acad. Nauk SSR 234, 1306 (1977)
21. Lagage, P. O.; Cesarsky, C. J., 1983, The maximum energy of cosmic rays accelerated by supernova shocks, Astron. Astrophys., 125, 249
22. Lamb, F. K., Pethick, C. J., Pines, D. A, 1973, Model for compact X-ray sources: accretion by rotating magnetic stars, Astrophys. J., 184, 271
23. Lin, D. N. C., Woosley, S. E., Bodenheimer, P. H., 1991, Formation of a planet orbiting pulsar 1829 - 10 from the debris of a supernova explosion, Nature, 353, 827
24. Lindberg, L., 1978, Plasma flow in a curved magnetic field, Astrophys. Space Science, 55, 203
25. Litwin, C., Rosner, R., Lamb, D. Q., 1999, On accretion flow penetration of magnetospheres, Mon. Not. R. Astron. Soc., 310, 324
26. Litwin, C., Rosner, R., 2001, Plasmoid impacts on neutron stars and highest energy cosmic rays, Phys. Rev. Lett., to be published
27. Meade, D. M., 1965, Experimental study of plasma motion in a toroidal octupole magnetic field, PhD thesis, University of Wisconsin
28. Nakamura, T., Piran, T., 1991, The origin of the planet around PSR 1829 - 10, Astrophys. J., 382, L81
29. Neubert, T., Miller, R. H., Buneman, O., Nishikawa, K.-I., 1992, The Dynamics of low-β plasma clouds as simulated by a three-dimensional, electromagnetic particle code, J. Geophys. Res., 97, 12057
30. Olinto, A.V ., 2000, Ultra high energy cosmic rays: the theoretical challenge, Phys. Rep. 333-334, 329-348
31. Parker, E. N., 1979, Cosmical Magnetic Fields, (Clarendon: Oxford)
32. G. Schmidt, Plasma motion across magnetic fields, 1960, Phys. Fluids 3, 961
33. Shapiro, S. L., Teukolsky, S. A., 1983, Black Holes, White Dwarfs and Neutron Stars (New York: Wiley).
34. Stecker, F. W., 1998, Origin of the highest energy cosmic rays, Phys. Rev. Lett., 80, 1816
35. Stix, M., 1975, The galactic dynamo, Astron. Astrophys., 42, 85
36. Takeda,M., Hayashida, N., Honda, K., Inoue, N., Kadota, K., Kakimoto, F., Kamata, K., et al., 1998, Extension of the cosmic-ray energy spectrum beyond the predicted Greisen-Zatsepin-Kuzimijmin cutoff, Phys. Rev. Lett., 81, 1163
37. Wasserman, I., Salpeter, E. E., 1994, Baryonic dark clusters in galactic halos and their observable consequences, Astrophys. J., 433, 670
38. Zatsepin, G.T., Kuzmin, V.A., 1966, Upper limit of the spectrum of cosmic rays, JETP. Lett. 4, 78.