ONGOING SPACE PHYSICS - ASTROPHYSICS 
CONNECTIONS

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ABSTRACT

I review several ongoing connections between space physics and astrophysics: a) Measurements of energetic particle spectra have confirmed theoretical prediction of the highest energy to which shocks can accelerate particles, and this has direct bearing on the origin of the highest energy cosmic rays. b) Mass ejection in solar flares may help us understand photon ejection in the giant flares of magnetar outbursts. c) Measurements of electron heat fluxes in the solar wind can help us understand whether heat flux in tenuous astrophysical plasma is in accordance with the classical Spitzer-Harm formula or whether it is reduced well below this value by plasma instabilities.

INTRODUCTION

Space plasma physicists take pride in the fact that the physical processes they study are central to general astrophysics. The proximity of the space physics arena and the opportunity for in situ set a standard for detailed confrontation with observations that is not always possible in the study of more distant astrophysical processes. In this introductory talk, I review some of the space physics - astrophysics connections. While they have been around for decades, recent developments in astrophysics have focused renewed attention on them. These connections include particle acceleration, magnetic flares, and heat conduction in a collisionless plasma. Wind termination shocks and particle acceleration at them is another important space-astrophysics connection. (Both the solar wind termination shock and pulsar wind termination shocks are powerful particle accelerators, despite their putative perpendicular geometry.) I will not review termination shocks here, because Lyubarsky will be reviewing this topic in the same volume. Another connection is the planetary...
magnetosphere-pulsar connection that I also will not review because I lack the expertise in
this area to do so.

PARTICLE ACCELERATION

The theory of shock acceleration and its success in explaining the origin of cosmic rays
received further observational support from \textit{in situ} measurements of energetic particles in
heliospheric collisionless shocks. While interplanetary shocks tend to be weak, the Earth’s
bow shock is conveniently a reasonably strong shock ($M \sim M_A \sim 8$, large enough to
contain highly superthermal particles and not significantly distorted by the rotation of
the Earth’s magnetosphere). The solar wind magnetic field at the Earth is typically of
order 30 to 45 degrees from the wind direction, so that we can sample both quasiparallel
and quasiperpendicular shocks there, and there is no better place in the solar system to
make \textit{in situ} measurements. In the 1980’s, we learned that the ion spectra acceleration
efficiencies and acceleration time are all nicely consistent with the predictions of diffusive
shock acceleration when the magnetic field is quasiparallel and, as is nearly always the
case in that geometry, turbulent near the shock. The turbulence is caused by upstream
energetic particles that were presumably injected at the shock out of the solar wind, and,
in a quasiparallel geometry, stream along the upstream magnetic field to the point of
instability. The particle injection efficiency - basically the ratio of energetic particles to
thermal particles, was observed to be close to the theoretical maximum as predicted by the
simple shock model worked out numerically by Ellison and coworkers - a shock-like solution
to the Boltzmann equation with a Krook collisionless operator (Ellison and Moebius, 1987,
Ellison, Moebius and Paschmann, 1990). The spectra and composition of the high energy
particles was also in agreement with the theoretical predictions (see figure). Thermal heavy
ion data was unfortunately not in the AMPTE data. Theoretical predictions made for
thermal heavy ions should now, finally, be testable with the CLUSTER heavy ion detector.

A nice feature of the Earth’s bow shock is that above 10 KeV or so, most of the particle losses seem to be due to diffusion off to the sides, rather than advection behind the shock. This gives rise to an exponential energy per charge spectrum rather than the power law spectrum of an infinite planar shock. Specifically the form of the spectrum is (Eichler 1981)

\[ N(E) = e^{[-(E/Q)/(E/Q)_o]}, \]

where \( Q \) is the charge of the ion and \((E/Q)_o\), the e-folding energy per charge, is given by

\[ (E/Q)_o = \frac{RB\Delta u}{(2\pi\eta)^{(1/2)}c} \]

exact as observed (Ipavich 1981). Here \( B \) is the magnetic field strength, \( R \) is the radius of the shock, \( \Delta u \) is the velocity jump across the shock. The quantity \( \eta \) is a dimensionless number of order unity that is best determined by observations. It expresses the perpendicular coefficient in units of \( r^2_g/\tau \), where \( r_g \) is the gyroradius and \( \tau \) is the scattering time. Because the geometric mean of the parallel and perpendicular diffusion coefficients depends on energy per charge, the exponential dependence of the energy spectrum on energy is predicted by shock acceleration theory to in fact be energy per charge (as opposed to, say, energy per nucleon). The observations of Ipavich et al. confirmed that while the e-folding energy per charge could vary from one observation to the next as the field strength of the solar wind, during any given observation the e-folding energy per charge was observed to be identical, to within experimental error, among all of the ion species. This confirms the idea that the energetic particle escape is via cross field diffusion off to the sides of the shock and that the maximum energy attainable by shock acceleration is set by this process.

The above point is not obvious \textit{a priori}. Free streaming of ions ahead of the shock is observed and is a significant loss mechanism for the ions. In fact, it is often taken to
be a separate loss mechanism from cross field diffusion. However, free streaming occurs once the level of energetic particles is below the critical level needed for self-confinement, and this applies both to field lines connected to the shock and those at the flanks that are fed high energy particles by the cross field diffusion. The critical level for free streaming at any given particle energy forms a closed surface around any finite shock, and outside of it, all energetic particles free stream. Were free streaming along shock-connected field lines the primary loss mechanism - that is, if the problem were to a good approximation one-dimensional - the resulting spectrum would not be the observed exponential form.

The issue of maximum energy attainable in shock acceleration has attracted much attention in recent years in the context of the origin of the highest energy cosmic rays. The "puzzle" is often stated as follows: Because the highest energy cosmic rays are observed to exceed the GZK cutoff of $6 \times 10^{19}$ eV, beyond which cosmic rays must be de-energized by photopion production off the cosmic microwave background, they must be produced nearby, within 50 Mpc or so according to detailed calculations. On the other hand, the maximum energy attainable by a particle undergoing shock acceleration is about $eBR$. The minimum luminosity of a source whose outflow yield $BR$ is the associated Poynting flux $\pi R^2 B^2 c/4\pi$. Thus, to achieve an maximum energy of $3 \times 10^{20}$ eV, one needs a value for $BR$ of $10^{18}$ G-cm, and hence a Poynting flux of $\sim 10^{46}$ erg/s. But the nearby bright sources are all known, and none seem to be that bright. So goes the description of the "puzzle" of highest energy cosmic rays. On the other hand, UHE cosmic rays could come from transient outbursts with these luminosities, such as AGN outbursts or gamma ray bursts. Moreover, it is hard to set an upper limit to the beam power of any source since one cannot be sure what the efficiency is for converting the beam energy to radiation. The difficulty in setting a firm upper limit was illustrated when it turned out that the gamma ray luminosities of AGN ($L \geq 10^{48}$ erg/s) were far higher than luminosities that had been previously inferred from radio emission plus equipartition arguments ($L \geq 10^{46}$ erg/s). So the debate goes on (Olinto
2000), with one side claiming that local AGN such as NGC5128 can provide the necessary Poynting flux and others claiming that GRB-scale Poynting fluxes $\sim 10^{50} \text{erg/s}$, though sustainable for only a short time, are the more likely source of the highest energy cosmic rays. A third side suggests that the highest energy cosmic rays come not from astrophysical acceleration but rather from the decay of extremely heavy relic particles or strings.

The large room for disagreement and debate, as in many instances in life, is in proportion to the uncertainties. One does not know the size of the system, the magnetic field strength, plausible Poynting flux, etc. to better than a factor of 3 or so. Moreover, the energy resolution of the airshower experiments also introduces some error, and, at the time of this writing, there is some disagreement between different air shower experiments. Were it not for the Earth’s bow shock, we could wonder indefinitely whether shocks could accelerate particles to a value of $eBR\Delta u/c$, or whether the true limit, with duly realistic facts of life properly taken into account, was in fact a factor of 10 or so lower. The factor of $2\pi$ that appears in the denominator of $(E/Q)_{o}$ should be of particular concern as it lowers the predicted highest possible energy considerably. Moreover, the Poynting power requirements on the UHECR source would be proportional to the square of this numerical factor. If it can be pinned down by careful simultaneous measurement of $B$, $(E/Q)_{o}$, and $\Delta u$ at the Earth’s bow shock, with CLUSTER I hope, then such data would allow us to speak with a bit more authority about the highest energy to which shocks can accelerate cosmic rays.

As matters stand now the old AMPTE data of Ipavich et al. confirm that $(E/Q)_{o}$ is within an order of magnitude of $eBR\Delta u/c$ (probably even within a factor of 3 by my estimates) and that the spectrum is exponential. The shock can thus be depended upon to generate particles with a power law spectrum all the way up to within an order of magnitude of $eBR\Delta u/c$, and an exponential form is predicted for the spectrum beyond this point. This could be compared with UHE airshower data when the AUGER and similar
projects accumulate enough data above $10^{20}$ eV.

To summarize, my main intent is to call attention to the space physicists that there is motivation, coming from the interests of the high energy cosmic ray community, to pin down this numerical factor experimentally while CLUSTER is active.

It may be that the highest energy cosmic rays do not come from shocks but rather from magnetic reconnection, and this is discussed further in the next section.

**THE SOLAR FLARE - SGR CONNECTION**

Soft Gamma Repeaters (SGR’s) are so named because they produce soft gamma ray bursts repeatedly. The small, repeating flares typically show $10^{38}$ to $10^{42}$ erg/s, and the energy outputs exhibit distributions reminiscent of earthquakes and solar flares. It seems that in the course of their relaxation, something ”gives” every so often. There have been two giant flares($E \geq 10^{44}$ergs) observed to have occurred on SGR’s, on March 5, 1979 from SGR 0536-36 and on August 27, 1998 from SGR 1900+14. Another semi-giant flare was observed to occur on SGR 1900+14 on April 18, 2001, so this SGR repeated even large flares.

There is little question that at least the giant flares are powered by magnetic energy. No acceptable alternative explanation has been given. The periodic light curve, the signature of emission from a rotating, unevenly hot surface, changed during the Aug. 27 flare from a complex pattern to a simple sinusoidal one. This indication of a rearrangement from a complex to simple field geometry took place during the flare.

The field strength needed to explain the energetics exceeds $10^{14}$G, hence the name magnetars. While smaller than solar flares in spatial extent, magnetar flares are far more powerful, and, importantly, the mass motions expected from magnetic reconnection are
expected to be ultra-relativistic; bulk Lorentz factor of up to $\sigma^{1/2} \sim 10^7$ are possible! Here $\sigma$ is the magnetic energy per proton and can exceed $10^{14}$ in magnetar magnetospheres. Moreover, in the Petschek model of reconnection (Petschek 1975), the fluid may be either heated by magnetic dissipation (Lyutikov and Uzdensky, 2003) or remain highly magnetized (Lyubarsky, 2005) and could in principle be further accelerated to anywhere up to the theoretical maximum of $\sigma$. This means that the radiation from such flares might extend into the UHE regime (Eichler 2003). For example, a gamma ray of 1 MeV (just below the pair production threshold in the rest frame of an ultrarelativistic fluid element) could have an energy of order a TeV or more in the observer frame, enough to be detected by the MILAGRO array. Neutrons produced in photopion reactions could be generated with Lorentz factors of up to $\sigma$, and, because their lifetime is extended by their Lorentz factor, they could easily survive their trip across the Galaxy before decaying, and could be detected by giant airshower arrays more or less simultaneously with the gamma rays from the flare.

Imparting an energy of $\sigma \sim 10^{14}$ to an ion would make it more energetic $10^{23}$ eV than any cosmic ray that has ever been detected to date, so this topic too may be of some relevance for the origin of the highest energy cosmic rays. However, ion synchrotron losses become important here, to an extent that depends on the details of how the reconnection event accelerates the plasma. At the present time there are several unresolved questions regarding this matter.

The question is whether these various forms of exotic radiation could escape from the strong magnetic field of a magnetar. The answer is that practically no isolated particle, could pass across a static magnetic field of $3 \times 10^{14}$ G (i.e. as measured in the zero electric field frame), with a Lorentz factor of $10^5$ or more, unless its motion were nearly parallel to the field (not even a photon above the pair production threshold, and not even a sufficiently energetic neutron can pass through such a strong field! The latter is pulled apart by the
Lorentz forces on the oppositely charged quarks). On the other hand, bulk plasma motion establishes the plasma’s own frame as the zero electric field frame, and in this frame the field is much weaker. To put it another way: ultrarelativistic bulk plasma motion might deliver UHE quanta to infinity by distorting the field lines in such a way that the UHE quanta within are far less energetic in the zero electric field frame, and, not being energetic enough to pair produce in this frame, therefore escape to infinity intact. It is necessary that the UHE quanta remain within the ultrarelativistic fluid element on their way out to infinity. (A related phenomenon has probably been seen in gamma ray bursts, where non-thermal gamma rays well above the pair production threshold are observed to have escaped rather compact regions. It is generally accepted that the escape of these gamma rays was possible only because the gamma rays and any plasma in the vicinity are beamed out at high Lorentz factor.)

Bulk plasma motion in magnetic reconnection is poorly understood. Part of the reason for this is that it is a difficult, complicated theoretical problem. I suspect that a contributing factor is the difficulty in finding clear cut observational differences in the exact pattern of fluid motion during a reconnection event in, say, the solar corona. With the increasingly high resolving power of solar of solar flare observations, this may improve somewhat, but I am not certain how interesting the greater space physics community finds the detailed "weather pattern" of a solar flare.

However, I suggest that magnetars and perhaps gamma ray bursts provide great motivation to understanding mass motions during solar reconnection events. In particular, the question as to whether fluid can be hurled to infinity at a high Alfven Mach number without "snagging" on the field lines that run through it (as opposed to the opposite extreme of being dominated by the field and having to follow along curved field lines) has far reaching implications for magnetar flares and other problems in high energy astrophysics.
To summarize the point: Astrophysical outflows are of great interest to astrophysicists, magnetic reconnection is of great interest to space and solar physicists, and a question that I hope interests both communities is whether and how magnetic reconnection causes outflow to infinity.

HEAT CONDUCTION

The question of heat conduction has featured prominently in the study of rich clusters of galaxies. They typically feature intracluster gas, $T \sim 3 \times 10^7$K, which emits hard X-rays. Many have long expected that, because the central gas of these clusters cools well within a Hubble time, that the bottom should fall out of the pressure supported gas, and inward "cooling flow" should ensue (e.g. Fabian 1994). However, recent X-ray observations have failed to reveal the softer X-ray emission that would be expected from the cooler gas. This suggests that either a) the central temperature is sustained by some continual heating process, or by heat conduction from the hotter periphery, b) the pressure of high energy cosmic rays (which cool more slowly) supports the gas or c) the heat conduction is inhibited so thoroughly that hot gas is essentially in contact with cold gas (i.e. too cold to emit even soft X-rays) and that heat is conducted across steep gradients from the hot gas to the cold gas, where it would presumably emerge as long wavelength emission (e.g. IR from dust).

In order to sustain the inner pressure by heat conduction, the heat conductivity would have to be of order the classical value, the Spitzer-Harm conductivity (e.g. Narayan 2001), perhaps reduced somewhat by finite mean free path effects. On the other hand, it has been argued by Pistinner, Levinson and myself (Pistinner and Eichler 1998, Pistinner, Eichler, and Levinson 1996, Levinson and Eichler 1992) that heat flux instabilities would inhibit heat flow in clusters of galaxies, and that the heat flux would be reduced enough to allow cooling flows in rich clusters of galaxies. In fact, our analysis, performed under the
assumption of a Maxwellian thermal distribution, predicts that the maximum heat flux is 
\[ Q_{\text{max}} \simeq v_{th} U_B \]
where \( v_{th} \) is the electron thermal velocity and \( U_B = B^2 / (8\pi) \) is the magnetic energy density.

Does the absence of cooling flows disprove the hypothesis of heat flux inhibition? We can turn to the heliosphere for help. Measurements reported by Gary and co-workers (Gary 1999, Gary 1999a) of heat flux distributions in the solar wind show a striking "edge" to the heat flux distribution at about \( v_{th} U_B \). Several thousand data points fall below this value, many well below, and only several dozen are above it. These several dozen are not far above it and within the uncertainties, given the non-Maxwellian nature of the "thermal" electron distribution.

My admittedly biased opinion is that astrophysicists should not ignore this result about heat conductivity. \textit{In situ} measurements in the solar wind provide a unique opportunity to directly measure heat flux in tenuous plasma, Although it is expedient and tidy to simply invoke the Spitzer-Harm conductivity in galaxy clusters, it is not obviously justified. If there is a more subtle phenomenon at work, it would be a shame if it were swept under the rug before it was discovered.

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Fig. 1.— Omnidirectional differential flux vs. energy per charge for the 1984 September 5 bow shock event from the time period 01:50 - 02:50 UT. Solid lines are the results of the simulation calculated at a position $1.2\lambda_0$ upstream from the shock where $\lambda_0$ is the particle mean free path of an incoming particle among the magnetic scatterers. (The plasma parameters assumed are $T_{pl} = 1.5 \times 10^5 K$, $T_{e1} = 2 \times 10^5 K$, $u_i = 450 km s^{-1}$, $n_2/n_1 = 4.1$, a free escape boundary at $2.1\lambda_0$ and a charge state for CNO of +6). All spectra are in the shock frame. Data points with no error bars have errors less than the size of the points. This figure is reprinted from Ellison and Moebius (1987) courtesy of the Astrophysical Journal.
REFERENCES

Eichler, D., Energetic particle spectra in finite shocks - The earth’s bow shock, Astrophys. J. Part 1, **244**, 711–716, 1981.

Eichler, D., Ultrahigh Energy Neutrals from Extreme Magnetic Flares, Phys. Rev. Lett., submitted, astro-ph/0303474, 2003.

Ellison, D. and E. Moebius, Diffusive shock acceleration - Comparison of a unified shock model to bow shock observations, Astrophys. J., **318**, 474–484, 1987.

Ellison, D. E. Moebius, and Paschmann, G., Particle injection and acceleration at earth’s bow shock - Comparison of upstream and downstream events, Astrophys. J., **352**, 376–494, 1990.

Fabian, A., Cooling Flows in Clusters of Galaxies, Ann. Rev. Astron. & Astrophys., **32**, 277-318, 1994.

Gary, S.P., Neagu, E., Skoug, R.M. & Goldstein, B.E. Solar wind electrons: Parametric constraints, J.Geophys. Res., **104**, 19843-19850, 1999.

Gary, S.P., Skoug, R.M. & Daughton, W. Electron heat flux constraints in the solar wind, Phys. Plasmas, **6**, 2607–2612, 1999a.

Ipavich, F.M., Galvin, A.B., Gloeckler, G., Scholer, M. & Hovestadt, D. A statistical survey of ions observed upstream of the earth’s bow shock - Energy spectra, composition, and spatial variation, J.Geophys. Res., **86**, 4337–4342, 1981.

Levinson, A. & Eichler, D. Inhibition of electron thermal conduction by electromagnetic instabilities, Astrophys. J. Part 1, **387**, 212–218, 1992.

Levinson, A. & Eichler, D. Baryon Purity in Cosmological Gamma Ray Bursts as a Manifestation of Event Horizons, Astrophys. J., **418**, 386–390, 1993.
Lyubarsky, Y., 2005, On the relativistic magnetic reconnection, M. N. R. A. S. 358, 113, 2004.

Lyutikov, M. and Uzdensky, D. 2003, Astrophys. J., 589, 893L

Narayan, R. & Medvedev, M.V. Thermal Conduction in Clusters of Galaxies, Astrophys. J., 562, L129-L132, 2001.

Olinto, A.V., Ultra high energy cosmic rays: the theoretical challenge, Physics Reports, 333, 329-348, 2000.

Petschek, H.E., Magnetic Field Annihilation, AAS - NASA Symposium on the Physics of Solar Flares, NASA Spec. Publ SP-50, p 425-439, 1964, Vasyliunas, V.M., Reviews of Geophysics and Space Science, 13, 303, 1975.

Pistinner, S. & Eichler, D. Self-inhibiting heat flux, M. N. R. A. S., 301, 49–58, 1998.

Pistinner, S., Eichler, D. & Levinson, A. Can Electromagnetic Instabilities Driven by Temperature Gradients Inhibit Thermal Conduction in Cluster Cooling Flows? Astrophys. J., 467, 162–167, 1996.