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COSMIC RAY SOURCE AND SOLAR ENERGETIC PARTICLES

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The acceleration of particles to the high energy is one of the key issues of solar physics, cis-lunar irradiations, astrophysics, and astroparticle physics. With the development of space astronomy, people started to realize that plasma disturbances in solar flares, Earth's magnetosphere, and interplanetary space can also produce a large population of non-thermal particles. Cosmic ray promotion i.e. selective energization of matter in the cosmos requires, as on earth, three distinct stages: ionization, injection and acceleration to high energy. Supernova remnants and stellar winds of massive stars grouped in associations appear to be excellent celestial accelerators or re-accelerators through the shock waves they induce in their superbubbles. The injection of ions seems devoted to stars, except the smaller ones. In cosmic several mechanisms lead charged particle acceleration. Electrons are accelerated in direction of Earth's poles by long train of electric double layers of small amplitudes. Charged particles are accelerated by the pondermotive force of electromagnetic radiation. Also, in a nonequilibrium current plasma or a plasma with particle flows, a strong electric double layer can be formed, which accelerates charged particles to high energies. The reconnection of the magnetic field lines also leads to the acceleration of charged particles.

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INTRODUCTION

There are several mechanisms of charged particle acceleration which can be important in cosmic plasmas. In particular, charged particles can be accelerated by individual bursts of field, excited in current-carrying plasma or in plasma with particle beam (see [1, 2]). Electrons are accelerated in direction of Earth's poles by long train of electric double layers of small amplitudes (see [3 - 8]). Charged particles are accelerated by the pondermotive force of electromagnetic radiation. Electromagnetic radiation fluxes and beams of charged particles due to the development of self-modulation instability can be broken into a chain of particle bunches (see [9 - 11]) or a chain of electromagnetic pulses (see [12]), which excite a wakefield in the plasma, which effectively accelerate charged particles (see [13 - 16]). Also, due to the development of self-modulation instability, electromagnetic radiation can be broken down into a chain of electromagnetic pulses that excite a wakefield in the plasma, which effectively accelerates charged particles, and they can continue to excite the wakefield and accelerate charged particles to even higher energies (see [17, 18]). Also, in a nonequilibrium current plasma or a plasma with particle flows, a strong electric double layer can form (see [8]), which accelerates charged particles to high energies. Under certain conditions, in a strongly inhomogeneous cosmic plasma, the synchronism of the accelerating field and accelerated particles can be maintained for a sufficiently long time. When active satellite of planet with its own ionosphere moves across the strong magnetic field of the planet, it can lead to the emergence of a large electric field and acceleration of the particle beam by this field. In the vicinity of the satellite Io, an electron beam is formed, which is injected towards Jupiter and, as a result, leads to the formation of a strong double layer near Jupiter (see [19 - 21]). The reconnection of the magnetic field lines also leads to the acceleration of charged particles (see [22, 23]).

1. PARTICLE ACCELERATION IN THE COSMOS

Whereas the expansion of the universe has been extraordinarily accelerated "in the beginning" by a neutral (scalar) field called inflaton and still accelerated today, more modestly, by a weaker avatar of this primordial field, called dark energy, charged particles in astrophysical plasmas can be accelerated to relativistic energies by electric fields. Particle acceleration is a ubiquitous process throughout the Universe, observed in environments as diverse as stellar coronae, active galactic nuclei, the coronae of accretion discs around black holes, the magnetospheres of neutron stars and planetary atmospheres (including our own) interacting with the wind of their star. It operates both in very dynamic and explosive situations and in more steady phenomena where steep gradients, turbulence and instabilities exist.

Natural elitist energization of charged particles in the cosmos requires, as the artificial one at the LHC, RHIC and other accelerators several phases: ionization, injection and acceleration to high energy via strong energy (electrical) sources. Supernova remnants and stellar winds from Wolf-Rayet stars [24], through their shock waves, and the diffuse acceleration they produce [25], appear to be excellent accelerators or re-accelerators through the shock waves they induce in the surrounding medium. All the mystery condenses in the injection mechanism, through first ionization potential [26] or grain sputtering [27].

In very strong accelerating fields, for example, in wakefield acceleration methods, bunches of charged particles can be self-injected up to relativistic energies (see [28]) in a relatively short time interval.

2. SHOCK ACCELERATION

It is generally accepted that most of the observed high-energy particles originate from energization of charged species in astrophysical plasmas, through stochastic acceleration by turbulent electromagnetic fields, diffusive shock acceleration and magnetic reconnections (Fig. 1). High-energy astrophysical observations shed light on the underlying physical processes in violently evolving celestial environments and cosmic ray abundances play an essential role in exploring the underlying physical processes. For a pure, hydrodynamical, strong shock, the ratio of upstream and downstream speed, or compression ratio $r = 4$, determines the spectral index of cosmic ray nuclei as $\gamma = (r+2)/(r-1)$, thus resulting in the canonical E^{-2} spectrum. It is set by the opposition between the relative momentum increment to the probability of diffusive escape downstream of the shock. However, this calculated index does not match with measured cosmic ray spectra above the atmosphere with intensities proportional to $(\mathrm{Rigidity})^{-2.8}$. A rigidity-dependence of the diffusion coefficient proportional to R power 0.3 to 0.5 as inferred from measurements of nuclear secondary-to-primary ratios, e.g. boron-to-carbon, improves the agreement between expectations and observations [29]. Note that the discrepancy gets worse if the feedback of CR pressure on the velocity profile is considered, since the predicted spectrum is even harder in this case.

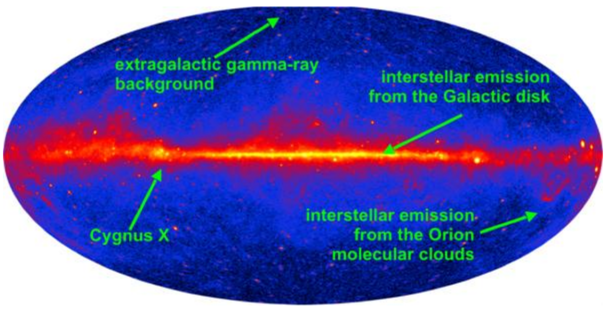

Fig. 1. Gamma ray skymap (from Fermi-LAT) Image credit: NASA/DOE/Fermi LAT Collaboration. The all-sky image drawn by gamma ray photons (E>1 GeV) shows us how the cosmos would look if our eyes could detect radiation 150 million times more energetic than visible light. Associations of massive stars in the galactic disk would be conspicuous since their combined wind and explosions enhance greatly – through their induced shock waves – the energy of encountered fast protons and nuclei. Continuum diffuse gamma-ray emission is produced in our Galaxy by interactions of high-energy cosmic rays with interstellar matter and low-energy radiation fields. The Larmor radius of these particles, in the typical magnetic field of few μG found in the ISM, is of the order of ~ 10^{12} cm, which is many orders of magnitude smaller than any typical Galactic length scale (e.g. coherence length of the ISM magnetic field, radius of the Galactic disk, etc.). This fact fits nicely with a scenario where CRs are accelerated within the Galaxy and effectively confined there. This is determined by the ratio of the energy acquired inside and the degree of magnetization of charged particles

3. SOLAR COSMIC RAYS AND CORONAL ABUNDANCES

Solar Energetic Particle (SEP) events are transient exhalations (fragrances) of high-energy particles from the Sun (Fig. 2). Our star provides us with an exceptional celestial laboratory for understanding the fundamental process of particle acceleration. These events are broadly classified into gradual and impulsive [30]. Gradual events, associated to solar flares, typically last a few hours and are generally confined to field lines connected to the flare site. At variance, impulsive events are strikingly rich in ^{3}He and in heavy elements such as iron, i.e. too rich compared to Cosmic Ray Source abundances (Fig. 3).

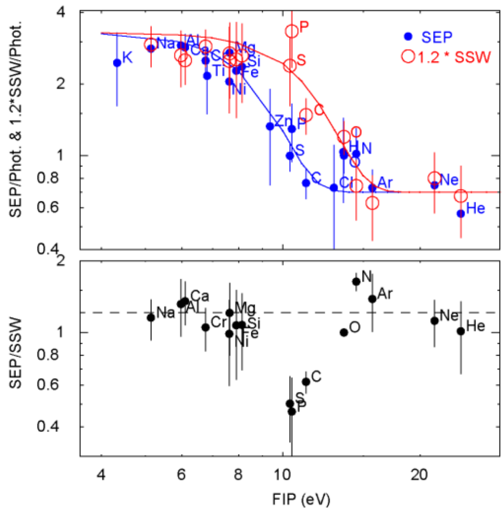

Fig. 2. Ratio of SEP to slow solar wind normalized to O and SEP/ SSW abundances relative to the photosphere both with respect to the first ionization potential of the diverse elements (from [31])

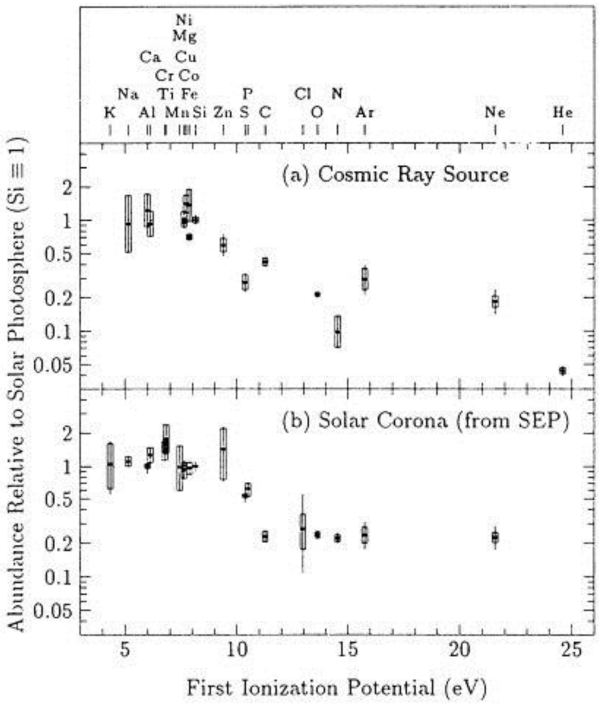

Fig. 3. Cosmic ray source and coronal abundances with respect to that of the solar photosphere versus ionization potential

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The abundance ratio of Solar Energetic Particles to photospheric ones shows a dependence on the first ionization potential (FIP) of the chemical species. The low FIP elements, like Mg, Si, Fe, are those that can be predominantly photoionized in the chromosphere, while the high FIP elements (He, O, Ne, Ar) remain mostly neutral. A mechanism involving ion-neutral separation in the solar chromosphere is clearly identified. A steady flow of photospheric material possibly channeled by tangled magnetic fields feeds the corona where particles are energized. The ion-neutral separation caused by the ponderomotive force must compete with mixing caused by turbulence. Turbulence, magnetic reconnection, and shocks produce explosively unstable plasmas, forming a new electromagnetic environment, favorable to large energy gain by a minority of ions [32]. The heating and the acceleration of particles is the result of the synergy of stochastic (second order Fermi) and systematic (first order Fermi) acceleration inside fully developed turbulence. Stellar coronae also exhibit this effect as well as the inverse [33]. The anomaly of S, P in C in the solar wind absent in Galactic Cosmic rays seems to indicate, if this feature is generic, that flare particles are more efficiently accelerated by passing shock waves than slow wind particles.

The correlation of coronal abundances with the first ionization potential breaks down for M stars (red dwarf), the lighter of them, leaving room to an anticorrelation. So, empirically, they are excluded as cosmic ray injector. This seems indicates that cosmic rays are accelerated in OB (massive star) associations.

CONCLUSIONS

The similarities between the composition of galactic cosmic rays at their sources (i.e. corrected for spallation in the course of propagation) and solar energetic particle/ coronal composition suggest that stars serve as cosmic injectors and supernovae as cosmic accelerators. The mapping of the Milky Way through high energy gamma rays corroborates this proposal. Acceleration of matter by shock, magnetic reconnection, negative pressure or otherwise is a superb subject of research but not yet a mature field. With all reserve in mind we dare to suggest that massive and intermediate stars are the injectors of galactic cosmic rays. More details, namely on the key element germanium and on the anti-FIP correlation are postponed to a future article. In cosmic several mechanisms lead charged particle acceleration. Charged particles can be accelerated by long train of electric double layers of small amplitudes or by single quasi-stationary or nonstationary strong double layer. Charged particles are accelerated by the pondermotive force of electromagnetic radiation. The reconnection of the magnetic field lines also leads to the acceleration of charged particles.

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ДЖЕРЕЛО КОСМІЧНИХ ПРОМЕНІВ ТА СОНЯЧНІ ЕНЕРГЕТИЧНІ ЧАСТИНКИ

M. Cassé, В.І. Маслов

Прискорення частинок до високої енергії є одним із ключових питань фізики Сонця, астрофізики та астрофізики частинок. З розвитком космічної астрономії люди почали усвідомлювати, що плазмові збурення сонячних спалахів, магнітосфери Землі та міжпланетного простору також можуть породжувати велику популяцію нетеплових частинок. Просування космічного випромінювання, тобто вибіркова активізація матерії в космосі, вимагає, як і на Землі, трьох різних етапів: іонізації, інжекції та прискорення до високої енергії. Залишки наднових і зоряні вітри масивних зірок, які згруповані в асоціації, виявляються чудовими небесними прискорювачами або повторними прискорювачами через ударні хвилі, які вони викликають у своїх супербульбашках. Інжекція іонів, здається, присвячена зіркам, за винятком малих. У космосі кілька механізмів призводять до прискорення заряджених частинок. Електрони прискорюються в напрямку полюсів Землі довгою серією подвійних електричних шарів малих амплітуд. Заряджені частинки прискорюються пондермоторною силою електромагнітного випромінювання. Крім того, у нерівноважній плазмі зі струмом або плазмі з потоками частинок може утворюватися сильний подвійний електричний шар, який прискорює заряджені частинки до високих енергій. Перез'єднання силових ліній магнітного поля також призводить до прискорення заряджених частинок.