Heliospheric MeV energization due to resonant interaction

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Abstract. The prompt enhancement of relativistic electron flux during active geomagnetic periods, and the impulsive increase in the flux of the heliospheric energetic heavy ions during active solar periods are of major importance with respect to the proper operation of electronics on space-borne spacecraft and the safety of interplanetary human travel, respectively. Both enhancements may be caused by resonant wave-particle interaction with oblique electromagnetic waves on the terrestrial and coronal field lines. Whistler waves, which are enhanced significantly during substorms and which propagate obliquely to the magnetic field, can interact with energetic electrons through Landau, cyclotron, and higher harmonic resonant interactions when the Doppler-shifted wave frequency equals any (positive or negative) integer multiple of the local relativistic gyrofrequency. This interaction occurs over a broad spatial region when a relativistic electron is bouncing in the terrestrial magnetic field. Coronal ions interact selectively with electromagnetic ion-cyclotron (emic) waves which are correlated with impulsive flares. This interaction occurs over a small spatial region when the Doppler-shifted frequency matches the first or higher harmonic of the ion gyrofrequency. Recent new observations of terrestrial MeV X-rays are interpreted as a resonant loss of the radiation belt electrons.

I INTRODUCTION

The electromagnetic response of a planetary magnetosphere is controlled by a core magnetic field which is described by a distorted, shifted and tilted dipole. In this planetary environment, ionized particles participate in several quasi-periodic motions. These motions of charged particles (gyration, bounce and drift), which are determined by the structure of the external magnetic field, generally have very disparate frequencies. The enhancement of the relativistic (1-15 MeV) electron fluxes in the outer radiation (e.g. [1]) belt poses a serious risk to human activity in space; these enhancements depend on the timescale of electromagnetic perturbations, on the characteristic eigen-frequencies of electron dynamics and on the losses due to interaction with the atmosphere, with macroscopic bodies or due to other radiative processes. If the perturbation time scale is much longer than that of the

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quasiperiodic motion of a particle in planetary field, the corresponding adiabatic invariant is conserved; the respective actions (adiabatic invariants) may be violated by perturbations on different time scales. Such processes may violate one or more invariants while preserving the other(s).

Solar MeV ions are frequently observed in interplanetary space. They may pose a major hazard to manned space flights. Very often their abundances and isotopic states are distinctly different from the coronal or solar wind values. The relative abundance of such ions aids our understanding of the intense physical phenomena which occur at the Sun and of their effects on the Earth. Coronal ions are transported from the photosphere by a charge-dependent mechanism, resulting in ion-neutral fractionation and in enrichment of elements with a low first ionization potential (e.g. [2]), and are ejected into the interplanetary medium either as a solar wind at low energies or as solar energetic particles (SEP) at high energies. It is generally believed that the processes which accelerate SEP are initialized by the relaxation of unstable coronal magnetic field configuration. Large SEP events, with a duration of many hours, involve particle acceleration by shock waves due to Coronal Mass Ejections. The resulting energetic ions have similar relative abundances and ionization states as the corona [3].

Both the energization of MeV ions on the coronal field lines and the MeV electrons on the terrestrial field lines may be described via interaction with oblique electromagnetic waves at the electromagnetic ion-cyclotron and whistler modes of propagation, respectively.

II SOLAR ENERGETIC IONS AND EMIC WAVES

There exists an interesting analogy between physical processes on active auroral and flaring coronal field lines, as was investigated by [4-5], Both environments consist of very low β plasmas, are dominated by two majority ion species (H and O at Earth, H and He at Sun), and are subjected to large electron fluxes due to magnetic field reconfigurations. In the corona these electron fluxes are deduced from X-ray emissions, while in the aurora they can be measured in situ by spacecraft. Auroral observations on the S3-3, Freja, Viking, Polar and Fast satellites indicate that electromagnetic ion cyclotron waves are associated with accelerated electrons which are responsible for the discrete aurora. Similarly, one may postulate that the fluxes of streaming electrons along the flaring coronal field lines that generate the solar flare X-ray emissions, are also correlated with several low-frequency plasma modes. The electromagnetic ion-cyclotron waves are of particular interest due to their effective interaction with selective ions and charge states of heavier elements. Smaller and more frequent impulsive flares with a duration of minutes in soft and hard X-ray observations indicate an unusual abundance ratio in heavy ions and a spectacular increase in the isotopic ratio of ^{3}He/^{4}He [6;7]. Flares enriched in ^{3}He are correlated with smaller enrichments by factor 3-10 in heavier ions up through Fe [8], however the degree of the heavy ions enrichment is independent of the degree of

^{3}He enrichment. Therefore, enhancement in the high energy ion fluxes on coronal field lines indicates the existence of a resonant process which accelerates selectively ions with a specific charge-to-mass ratio.

In the presence of two or more ion species, the oblique emic wave propagates in a frequency range below the hydrogen gyrofrequency and above the two-ion-hybrid frequency. The mechanism of ion acceleration is based on the gyroresonant interaction of ^{3}He and heavy ions. When the wave which propagates along the inhomogeneous magnetic field passes through Doppler-shifted gyrofrequency of ^{3}He or higher gyroharmonic of the heavier ions, these ions are resonantly accelerated. The residence time in the resonance region is determined by the local gradient of the magnetic field which affects the mirror force, and by the propagation direction of the waves with respect to the magnetic field. Waves propagating into stronger magnetic fields produce a parallel ion acceleration that balances the effects of the mirror force and increases the residence time, thereby enhancing the ion heating.

The waves are damped near the H and ^{4}He gyrofrequencies; at the high coronal temperatures above 4 MK ^{4}He and the main isotopes of CNO are fully ionized with a charge-to-mass ratio of 0.5 (in units of the H), hence they are not significantly affected by the waves. The lack of O^6 enhancement in impulsive flares, in contrast to its observation in the solar wind, indicates that the source of the accelerated ions is located at high temperatures. Therefore CNO nuclei, which are among the main products of stellar nucleosynthesis due to nuclear processes, are underabundant in the impulsive flares due to atomic processes (which are determined by the coronal temperature) and by plasma processes (which result from interaction with the emic waves). Similarly, heavy elements and isotopes which are not fully ionized at the coronal temperatures may be enhanced in impulsive flares.

III TERRESTRIAL RELATIVISTIC ELECTRONS AND WHISTLER/EMIC WAVES

An enhancement in the fluxes of magnetically trapped relativistic electrons occurs generally as a result of processes which are initiated by: (i) an external impulse (ii) external catalyst or (iii) internal source. Mechanism (i) consists of a direct, strong electromagnetic impulse which abruptly deforms the magnetic configuration and energizes the electrons (and protons) by breaking their third invariant when a subset of particles is in phase with a single "coherent" wave [9] or when they are subjected to a large-amplitude ULF waves [10]. It occurs infrequently and requires a Storm Sudden Commencement (SSC) pulse excited by a fast interplanetary shock wave or intense ULF waves excited by a strong Coronal Mass Ejection (CME) perturbation. Mechanism (ii) applies external perturbations which enhance the radial diffusion of a distribution function with a positive radial gradient, violating the flux (third) invariant by a random walk due to broad-band, small-amplitude, low-frequency electromagnetic perturbations [12]. It tends to flatten the distribution $f(L)$, where L denotes the equatorial distance in units of radius, but cannot describe separately the increase in the lower L shells which is observed during geomagnetically active periods. Mechanism (iii) applies resonant interaction with higher frequency waves on the order of gyration or bounce timescales which violate one or both of the first two invariants [11].

The violation of an adiabatic invariant occurs when the particle and the wave interact strongly by satisfying a particular resonance condition. For a gyrating particle, the local resonance condition equates the Doppler-shifted frequency with the harmonics of the relativistic gyrofrequency,

$$\omega - k_{||}v_{||} = n\Omega/\gamma \tag{1}$$

where the wave is characterized by its frequency ω and parallel wavenumber $k_{||}$ and the resonating electron by its parallel velocity $v_{||}$, local gyrofrequency Ω and the relativistic factor γ, while n is an integer.

Radial diffusion is a dominant factor in transferring the electrons across the dipolar field lines. The physical mechanism is based on breaking the flux adiabatic invariant. Since the distribution function has generally a positive gradient in L, the diffusion tends to bring the electrons towards lower L-shells; preservation of the first two invariants increases the energy of the electrons. Due to the different time scales of the three eigenfrequencies, this physical process is almost time independent over the gyro/bounce time scales. However, those particles which undergo diffusion due to low-frequency modes can simultaneously interact with the magnetized plasma and undergo additional radiative processes which can affect the higher-frequency adiabatic invariant. The modifications in the distribution function due to the violation of the the third adiabatic invariants is given by

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial \mu}(\dot{\mu} F)_{rad} = L^2 \frac{\partial}{\partial L}[\frac{D_{LL}}{L^2}\frac{\partial F}{\partial L}] - \frac{F}{\tau_{coll}} \tag{2}$$

Eq. 3 describes the most commonly used equation for radial diffusion. A study with a time-dependent D_{LL} due to the changing outer boundary conditions [12] gave a good fit to the observed electron fluxes at low first adiabatic invariant ($\mu = 100 - 300$ MeV/G), but a significant discrepancy at higher μ values, indicating that an additional process which may violate the first or second adiabatic invariant operates for higher energy electrons.

Another natural candidate for an acceleration of the energetic electrons which bounce along magnetic field lines are oblique whistler waves [11]. These magnetospheric whistler waves acquire significant oblique wavenumbers along their paths due to the changing magnetic field and density profile and therefore are able to interact resonantly at several regular and anomalous gyroharmonic resonances. The interaction at higher and anomalous gyroharmonics is particularly efficient for relativistic particles with gyroradii of the order of the whistler wavelengths. This interaction violates the first and the second adiabatic invariants, and the resulting diffusion in pitch-angle and in energy results in hardening in the spectrum of the relativistic electrons over time-scales much shorter than those related to the L-diffusion.

IV HARD X-RAY MICROBURSTS

Energetic electrons which are pitch-angle diffused into the loss cone and are able to reach low altitudes and interact with the denser ionospheric plasma are observed through the X-ray emissions at balloon altitudes of 40 km. While the electrons lose a significant fraction of their energy via Coulomb collisions, the Bremsstrahlung is the most important observational method for their detection. Balloons form a stationary platform for observations at a particular field line; they were the first to observe X-ray emissions due to precipitating electrons into the atmosphere [13].

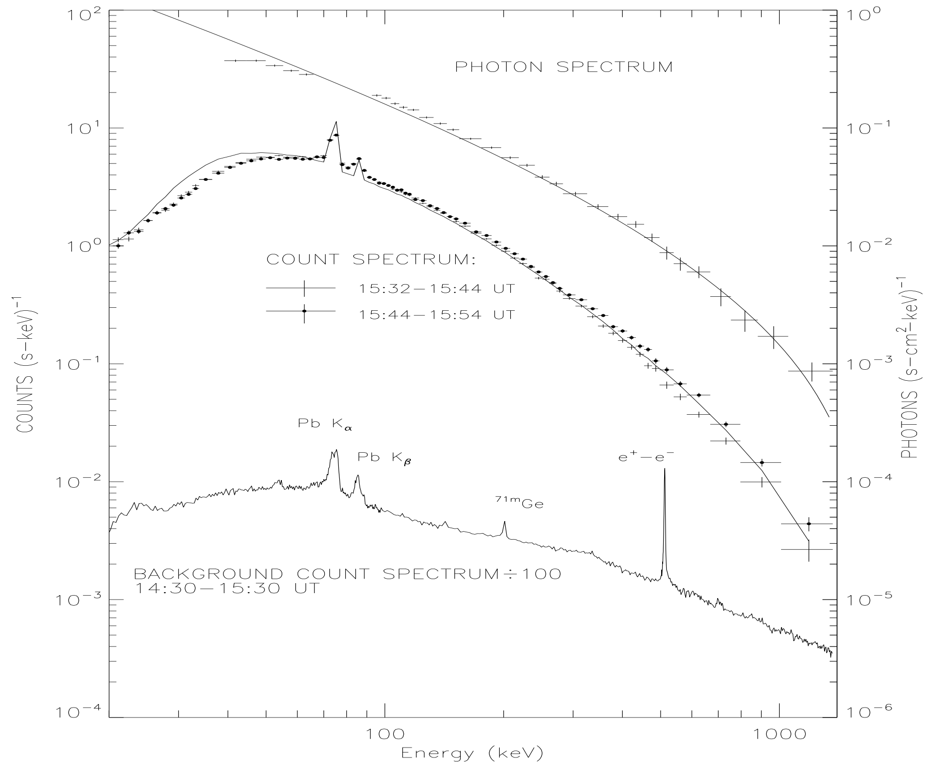

FIGURE 1. Background count spectrum (bottom), the measured count spectrum with correction due to Compton scattering and an analytical fit assuming an electron δ function (middle) and the photon spectrum which includes only the Coulomb scattering of the electrons (top).

The analysis of the event amounts to a deconvolution of electron fluxes from the observed X-ray spectra. The bremsstrahlung cross-section is well known and choosing a model of plasma density allows one to simulate the electron Coulomb as well as photon Compton scattering for a given source of electron distribution all the way to the balloon instrument. The measured spectra with and without instrument and atmospheric corrections due to Compton scattering are shown in Fig. 1 of [14], together with a fit assuming a δ function at 1.7 MeV for the electron source. Power-law electron distribution does not fit the data, indicating that the radiation-belt electrons are selectively affected by a particular set of waves.

V CONCLUSIONS

Resonant interaction between electrons and whistlers on geomagnetic field lines, or between selective ions and emic waves on coronal field lines can be of major importance in the formation of populations of energetic particles. The increased fluxes of the energetic ions and relativistic electrons are of great importance with respect to a safety of interplanetary travel and to spacecraft operation, respectively.

The emic interaction with the coronal ions in impulsive flares can enrich the heliospheric population of heavy ions over short periods of time. These ions can pose a significant risk to interplanetary manned missions. The ACE satellite observes enhanced ^{3}He abundances due to impulsive flares as well as increased average isotopic ratio ^{3}He/^{4}He over long periods of days during gradual events.

The whistler interaction with the bouncing electrons can enhance the flux of relativistic electrons in a fraction of an hour, which is much smaller than the radial transport timescale. These enhanced fluxes of electrons, trapped in stable orbits, can pose a significant risk to the electronic devices on board of Earth orbiting satellites. The resonant whistler or emic interaction with the radiation belt electrons can also explain the MeV X-ray emissions observed at balloon altitudes.

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