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Planetary, solar and astrophysical relativistic electrons: Common energization mechanisms?

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Abstract

Direct observations or deduced analysis indicate clearly that formation of intense fluxes of relativistic electrons is an important ingredient in the evolution of numerous active magnetized plasma systems. Examples of relativistic electron energization include the recovery phase of a planetary magnetic storm, post solar flare coronal activity and the afterglow of gamma ray bursts. It is suggested that there exists a universal mechanism, which may explain electron energization at the vastly different magnetized plasma environments. The favorite configuration consists of an inhomogeneous magnetic field anchored at a given magnetic structure and excitation of whistler waves due to external injection of low-energy non-isotropic electrons. The energization proceeds as a bootstrap process due to interaction with the propagating whistler waves along the inhomogeneous magnetic field.

Keywords: Acceleration of particles; Relativistic electrons; Whistler waves; Magnetic fields; Plasma; Gamma rays: bursts; Solar flares

1. Introduction

Electrons form excellent tracers of magnetic field and at the same time constitute an important source of electromagnetic radiation. Generally, due to their small mass, they are attached to a given field line: ignoring collisions and electromagnetic turbulence, they gyrate fast with a small gyroradius and propagate adiabatically over long distances along a given magnetic field. Any observations related to the same electrons at two distinct locations and times on the same field line allow one to assess the timing and position of the source of the analyzed event; similarly, simultaneous observations of electrons at different locations or electrons with different energies at the same location allow one to correlate separate physical processes.

Electromagnetic emissions related to the non-thermal electrons include coherent radiation due to collective plasma processes, and incoherent single particle emissions due to interaction with plasma or with magnetic field. The variety of the measured frequencies together with images of the emissions' locations allows one to discern the physical processes and the required magnetic configurations consistent with remote spectroscopic and in situ measurements. Different active magnetized plasma environments are susceptible to a variety of intense enhancements in the fluxes of relativistic electrons. Although the magnetic configurations at these environments are not necessarily similar, it is of significant interest to inquire whether there exists a common physical process of electron acceleration to relativistic energies.

It is suggested that a common mechanism with an underlying magnetic configuration and electron interaction with whistler waves may be responsible for an acceleration of electrons to relativistic energies in the magnetospheric, solar, and astrophysical plasmas. The availability of a similar mechanism at different environments makes it of particular interest due to a variety of implementations, from the possible adverse effect on human activity in space resulting from planetary and solar processes, to the understanding of some of the most intense astrophysical emissions.

2. Solar and heliospheric observations

Reconfiguration of the magnetically unstable coronal field lines due to loading of magnetic stress by foot-points

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motions may result in an initiation of a luminous flare in a variety of wavelengths, as well as in a detachment and acceleration of a large blob of plasma into the interplanetary medium in the form of a coronal mass ejections (CMEs). Additionally, solar non-thermal electrons are observed in the interplanetary space in conjunction with impulsive phase of flares or fast propagating CME events (Lin, 1985).

More precise timing of observed electron fluxes (Krucker et al., 1999) showed that the emitted electrons could be characterized into two categories: those which are emitted almost instantaneously with the electromagnetic radiation and more energetic with a delay of 10–30 min. Series of investigations (Haggerty and Roelof, 2002; Haggerty et al., 2003) showed that the timing between the metric type-III, hard X-rays (HXR), microwave bursts and H_α emissions are mutually delayed by less than few seconds, while the semi-relativistic fluxes of 30–350 keV are delayed by up to 30–40 min with respect to the electromagnetic emissions. Klassen et al. (2005) investigated the intense Halloween 2003 event and found multiple electron populations: (a) low energy type-III, (b) impulsive, delayed (10 min) semi-relativistic, and (c) long lasting relativistic ejection with an onset of 25 min after the type-III initialization.

Significant evidence exists regarding coronal radio observations near the release time of the (quasi) relativistic electrons. Since the frequency of the emitted electromagnetic radiation is related to the solar height of the event, it was clearly shown that the precursor of the ejection event occurs deeper in the post-CME unstable corona (e.g. Maia and Pick, 2004). Presumably, some incubation mechanism energizes the electrons over tens of minutes behind the CME. Therefore it is conceivable that the process which is responsible for the injection of the (quasi) relativistic electrons takes place in the magnetically distorted coronal plasma, and is not related directly to the flare or the CME. The process through which the electrons are energized, though, is not clear.

3. Magnetospheric observations

Terrestrial magnetic storms are initiated by intense geomagnetic field deformations triggered by a persistent southward interplanetary magnetic field (Baker et al., 1986; Reeves et al., 2003). As a result the plasma convection is enhanced, deforming the magnetic field and modifying the trapped radiation belt population. Typically, in the initial stage of the storm the flux of the relativistic radiation belt electrons decreases by 2–3 orders of magnitude, while at the recovery stage their fluxes often increase by 1–2 orders of magnitude above the pre-storm values. It is generally believed that the initial decrease follows triple-adiabatic processes, while enhancements of the relativistic electrons are due to a set of acceleration processes (e.g. Horne and Thorne, 2003).

Similarly to the solar case, reconfiguration of the magnetically unstable magnetotail terrestrial field lines may result in a detachment and ejection away from Earth of a blob of plasmoid and/or earthward injection of particles into closed field lines. One typical characteristics of a substorm consists of 10–100 keV electrons which are injected into the night side of the magnetosphere (Meredith et al., 2003). Additionally, this injection of anisotropic electrons is correlated with the observed excitation of whistler waves (Smith et al., 2004), which may energize efficiently the tail of the distribution. This process, with a time scale of hours, may contribute to the enhancement of the radiation belt.

4. Astrophysical observations

Gamma ray bursts (GRBs) are believed to form as a result of neutron star/(black hole) binary mergers (short burst) (Eichler et al., 1989), or core collapse of a massive star (long burst) (Paczyński, 1998). They are conjectured to consist of relativistically expanding fireball jet plasmas of electron–positron pairs, photons, as well as a small baryon contamination. The plasma shells which emerge from the "compact central engine" must propagate relativistically to avoid the "compactness" problem (quenching of >1 MeV photons due to pair formation). GRBs are known to be an intense source of synchrotron/jitter radiation that requires strong magnetic fields and substantial electron acceleration. The afterglow is observed when an impulsively injected fireball interacts with an interstellar medium at $\Gamma = 100-1000$, which may be viewed as a relativistic equivalent of the CME.

The observationally required formation and long-term persistence of an intense magnetic field over hundreds of thousands of plasma periods, and the efficient electron energization constitute important open questions. Recently, plasma physics Weibel instability was proposed as a formation mechanism of spatially localized magnetic fields (Medvedev and Loeb, 1999) and was investigated by a series of simulations (Silva et al., 2003; Jaroschek et al., 2004; Frederiksen et al., 2004; Nishikawa et al., 2003, 2005; Hededal et al., 2004). It has been shown for several magnetic configurations, with varying Lorentz factors, that in the nonlinear stage of the instability the magnetic field energy saturates at 1–10% of the initial kinetic energy. The main component of the topologically complex magnetic field (Hededal et al., 2005) is confined to perpendicular loops, (with respect to the jet flow) which are connected by an elongated inhomogeneous parallel field B_z, with $B_z/B_{\mathrm{tot}} = 0.01-0.1$ (Frederiksen et al., 2004; Jaroschek et al., 2005), in resemblance to the solar scenario. On the other hand the electron energization process is generally addressed as "shock acceleration" (e.g. Panaitescu and Mészáros, 1998) or shown as a simulation by-product (Hededal et al., 2004; Nishikawa et al., 2005), occurring behind the shock front, possibly due to transient, fluctuating $\mathbf{E} \times \mathbf{B}$ drifts (Nishikawa et al., 2006). However, sample trajectories of energized electrons (Hededal et al., 2004) indicate that they gyrate around and bounce along the magnetic field, suggesting an efficient energization on the closed field lines. Such observations indicate feasibility of a resonant interaction with propagating whistler waves.

5. Model description

In the above-mentioned examples one may find several features inherently correlated to electron energization process. Principally, they consist of (i) an inhomogeneous, stretched magnetic field configuration, with minima in the magnetic strength (“equator”) between the main anchored field sources, and (ii) a mechanism for an excitation of propagating electromagnetic waves, possibly through an injection of non-isotropic distribution of electrons. As such, the process may be viewed as a bootstrap: the free magnetic energy is partly converted into non-isotropic electron energy; the injected electrons excite electromagnetic waves which energize the tail of the distribution. The energization proceeds via resonant interaction between the waves and the electrons: the parameter space of these resonances increases significantly when the waves acquire a perpendicular wavenumber, which occurs when the wave propagates along the increasing magnetic field and denser plasma, as simulated often at the terrestrial magnetosphere (e.g. Bortnik et al., 2002). The efficiency of the energization processes involves the ability to interact with multiple resonances, which depends on the structure of the magnetic field and on the particular whistler excitation due to the injection process.

Direct derivation from the linearized Vlasov equation results in a perturbed electron distribution with a gyroradius ρ and gyrofrequency Ω, interacting with waves of frequency ω and wavenumber $(k_\parallel, k_\perp)$: $\delta f \sim J_n(k_\perp \rho) \cos[k_\parallel z - (\omega - n\Omega/\gamma)t]$, indicating that as an electron and a whistler propagate along the magnetic field lines, they may encounter numerous locations where the phase of the perturbations is almost stationary, resulting in a resonance condition

$$k_\parallel v_\parallel = \omega - n\Omega/\gamma \quad (1)$$

which can modify non-adiabatically their pitch angle/energy and wavenumber/amplitude, respectively. Here $\Omega[\mathbf{x}(t)] = qB[\mathbf{x}(t)]/mc$ denotes the non-relativistic gyrofrequency which changes slowly along the particle trajectory (due to a varying dispersion relation), and γ is the relativistic factor. Since the Bessel functions J_n are non-negligible only when their argument reaches values of a fraction of the integer n, the interaction with higher resonances increases with the energy/gyroradius. Therefore, one expects the bouncing solar/planetary electrons to interact at any segment of the magnetic field while the super-relativistic GRB electrons will encounter a very large number of wave resonances, decreasing substantially their energization time scale.

5.1. Simulation results

The simulation model follows test particles in the presence of an inhomogeneous magnetic field and oblique whistler waves. Since the main feature required by the inhomogeneous field is the availability of resonant domains for a bouncing particle, the curved magnetic coordinates are approximated by Cartesian coordinates and the magnetic field is described by

$$\mathbf{B}(x, y, z) = B_0[1 + z(z\hat{z} - x\hat{x} - y\hat{y})/D^2], \quad (2)$$

where z is chosen along the field axis, x, y are the perpendicular coordinates, $\hat{z}$ denotes a unit vector along z (with similar notations for x and y), D denotes the scale length of the magnetic field (which is orders of magnitude larger than the gyroradius). The magnetic field satisfies div $\mathbf{B} = 0$ and B_0 is its minimum (“equatorial field”).

The wave electric field is given by $[E_x \cos\psi, E_y \sin\psi, E_z \cos\psi]$ with $E_x = E_0$ denoting the wave amplitude and $\psi = [\int \mathbf{k}(\delta z)\,\mathrm{d}\mathbf{x} - \omega t + \phi]$, where ϕ is an arbitrary phase. Once the amplitude of one electric field component is chosen, the other components are determined from the dispersion relation $\tilde{\mathbf{\Delta}}(\mathbf{E}) = 0$, the magnetic components are obtained from Faraday’s law, and the $\delta \sim D^{-1}$ functional dependence emphasizes the slowly changing wavenumber (obtained locally from the dispersion relation) $\mathbf{k} = (k\sin\theta, 0, k\cos\theta)$ along electron trajectory due to the varying magnetic field and density. In the cold, non-relativistic limit the square of the refractive index $n^2 = c^2k^2/\omega^2$ is given by $[B - (B^2 - 4AC)^{0.5}]/2A$, with

$$A = \varepsilon_1 \sin^2\theta + \varepsilon_3 \cos^2\theta,$$

$$B = \varepsilon_1\varepsilon_3 + \varepsilon_1 A - \varepsilon_2^2 \sin^2\theta,$$

$$C = \varepsilon_3(\varepsilon_1^2 - \varepsilon_2^2),$$

where ε_j $(j = 1, 3)$ denote the non-zero components of the dielectric tensor:

$$\varepsilon_1 = \Sigma[\omega_i^2/(\omega^2 - \Omega_i^2)],$$

$$\varepsilon_2 = \Sigma[\omega_i^2/(\omega^2 - \Omega_i^2)]\Omega_i/\omega,$$

$$\varepsilon_3 = \Sigma[\omega_i^2/\omega^2],$$

the summation extends over all populations i, while $\omega_i(\mathbf{x})$, $\Omega_i(\mathbf{x})$ denote the slowly varying plasma and cyclotron frequencies of species i due to changing density and magnetic field, respectively. Since the energetic electron density in the magnetospheric and solar applications is very small vs the non-relativistic, whistler supporting populations, whose thermal spread is negligible with respect to the phase velocity, the cold, non-relativistic dispersion relation for the whistler waves is justified. The standard procedure in GRB simulations employs cold interacting beams, hence in the above expressions one replaces the plasma and cyclotron frequencies with their relativistic counterparts.

We integrate the relativistic electron equation of motion in a medium with a varying dispersion relation due to external magnetic field along the electron trajectory (the density is kept constant for simplicity), and follow the non-adiabatic changes whenever the electron enters a resonance along its trajectory. Fig. 1 examplifies electron phase space trajectory with planetary parameters. Solar or astrophysical parameters will include higher values of density, background magnetic field with an extended deformation, and more intense electric wave field. The figure describes (a) the temporal evolution of the relativistic kinetic energy $W = mc^2(\gamma - 1)$, (b) the (non-relativistic) adiabatic invariant μ, (c) the projected momentum pitch angle to the magnetic minimum ("equator") α and (d) the calculated time-dependent mismatch to a resonance $v(t) = [\gamma(t)\omega - k_{\parallel}p_{\parallel}(t)]/\Omega(\mathbf{x}(t))$. μ is calculated by its lowest order approximation at the electron position $v_{\perp}^2/B(\mathbf{x})$, α is obtained by adiabatically projecting the instantaneous pitch angle to the magnetic minimum (Eq. (2)), $\alpha = tg^{-1}[p_{\perp}/[p_{\perp}^2(z/D)^2 + p_{\parallel}^2(1+(z/D)^2)]^{1/2}]$, where $p_{\parallel}(p_{\perp})$ denotes the parallel (perpendicular) momentum. Each crossing of an integer value of v (Fig. 1d) causes changes in W, μ and α, as observed in Figs. 1a–c. In the simulation few thousands of electrons with varying initial conditions (energies between 100 keV and 2.5 MeV and pitch angles $5^{\circ} - 60^{\circ}$) are initialized at $z = 0$. These changes indicate that for an electric field amplitude of 2–5 mV/m an average energy diffusion of theorder of 100 keV will occur in few minutes. Most terrestrial measurements cite smaller amplitudes, consistently with enhancement of the radiation belts over several hours, although much faster enhancements were reported intermittently. The value of the magnetic minimum used in the simulation occurs at the equatorial terrestrial (Jovian) distance of $L = 4(9)$. Jovian (solar) surface magnetic field is one (two) orders of magnitude larger than the terrestrial field, hence the more intense waves and the size of the magnetosphere (corona) allows for shorter energization time scales. Simulations of whistler ray paths with Jovian parameters showed wave propagation and mirroring, confirming similarity to terrestrial phenomena (Wang et al., 1998). The ultra-relativistic dynamics of GRBs allows for much larger number of

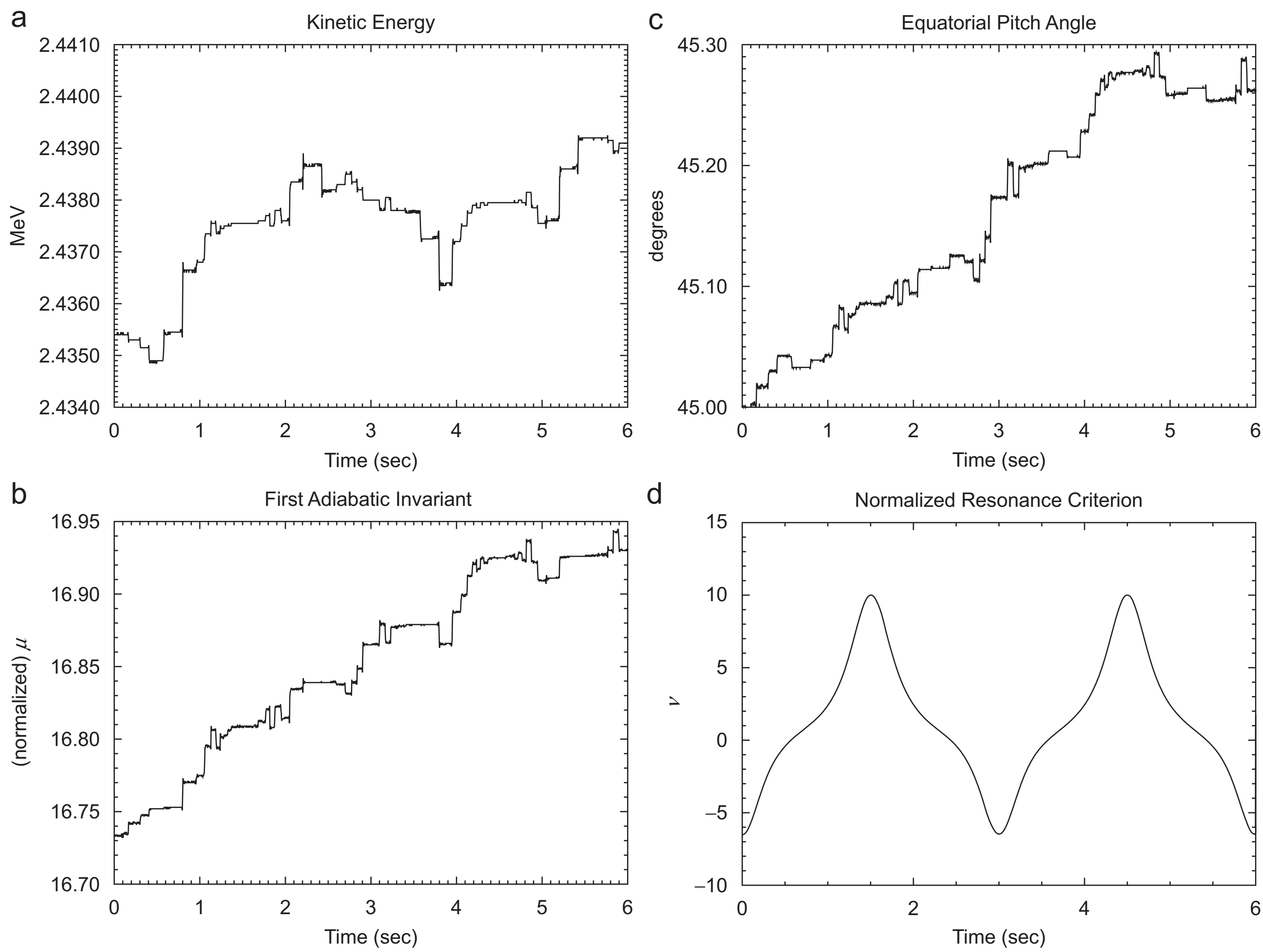

Fig. 1. Temporal evolution of (a) relativistic kinetic energy W, (b) adiabatic (non-relativistic) invariant μ, (c) "equatorial" pitch angle α and (d) resonance criterion v. $B_0 = 0.01\ G$, $D = 10\,000$ km, $E_0 = 1$ mV/m, initial $k_{\perp} = 10\,\mathrm{km}^{-1}$, density $= 10\,\mathrm{cm}^{-3}$, initial pitch angle $\alpha_0 = 45^{\circ}$.

resonances and more frequent encounters over small spatial scales, shortening additionally the energization times.

6. Conclusions and summary

Energization of charged particles and formation of non-thermal populations in magnetized plasma can be viewed on the single particle level as a violation of one or more of the adiabatic invariants. In the presence of an inhomogeneous magnetic field with partially closed field lines and local minima in the magnetic field strength, the electrons conserve several invariants as they gyrate around, bounce along and drift across the magnetic field. Both the undisturbed electrons and the electromagnetic whistler waves change their character along the field lines: due to the magnetic field inhomogeneity the adiabatic electrons modify their pitch angles and mirror when their pitch angle reaches 90°; the whistlers propagate with a group velocity approximately along the field lines while their phase velocity changes in the geometric optics approximation due to variations in magnetic field and density, which results in mirroring whenever it becomes perpendicular to the magnetic field. An electron propagating along the magnetic field may interact resonantly with a spectrum of waves, violating one or more of the adiabatic invariants if the Doppler shifted frequency matches any harmonic of the (relativistic) electron gyrofrequency. These waves may be excited due to external perturbation in the various discussed plasmas.

Therefore, it is conjectured that there exists a universal mechanism that may explain the relativistic electron energization at the vastly different plasma environments. The required conditions of an inhomogeneous magnetic field anchored at a given magnetic structure and excitation of whistlers (due to external injection of non-isotropic electrons) are applicable to several plasmas: enhancement of planetary relativistic fluxes at the recovery phase of magnetic storm, post solar flare delayed release of relativistic electrons, and heating of super-relativistic electrons during the afterglow period of GRB. The magnetospheric observations of correlations between the substorm injection of low-energy populations due to the unstable magnetotail configuration, in-situ measured whistler waves and the concurrent intensification of the relativistic fluxes adds credence to this scenario. In the solar process we conclude that in the delayed energization due to resonant interaction with the whistlers, neither the flare nor CME participate directly in the energization, except of indirect formation of an unstable configuration and opening venue to the interplanetary medium, respectively. The whistler wave acceleration may also help in resolving the (a) lack of non-thermal characteristics in some GRB simulations (e.g. Frederiksen et al., 2004; Spitkovsky, 2005), and the (b) inconsistency between the experimental deduction of the distribution power law in the GRBs and the diffusive Fermi acceleration (Baring and Braby, 2004). The small spatial scale of the GRB Weibel structures may decrease the time scale for the ultra-relativistic, whistler-interacting electrons. The final energy distribution is determined mainly by the characteristics of the specific injection and the availability of resonant interactions. Since the whistler wave amplitude scales with the background magnetic field it is expected that the time scale of the solar energization process is significantly shorter (tens of minutes) than the magnetospheric time scale (several hours to a day), while the availability of a huge number of resonances for the GRB electrons makes the energization of the super relativistic electrons extremely fast (fraction of a second).

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