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Electron energization in lunar magnetospheres

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Abstract. The interaction of the solar wind with lunar surface magnetic fields produces a bow shock and a magnetosphere-like structure. In front of the shock wave energetic electrons up to keV energies are produced. This paper describes how resonant interactions between plasma turbulence in the form of lower-hybrid waves and electrons can result in field aligned electron acceleration. The turbulent wave fields close to the lower-hybrid resonant frequency are excited most probably by the modified two-stream instability, driven by the solar wind ions that are reflected and deflected by the low shock.

1. Introduction

The Apollo missions to the Moon revealed the existence of significant remnant magnetism on the Moon. Analysis of early moon rock samples from Apollo 11, Apollo 12, and Apollo 14 exhibited clear signs of remanent magnetism [1, 2]. The Apollo 12 and 14 missions left magnetometers on the surface and these both recorded measurable magnetic fields [3, 4]. Apollo 15 and 16 subsatellite measurements also established that remanent magnetization exists over much of the Moon's surface [5]. More recently, the magnetometer and electron reflectometer experiment on Lunar Prospector has obtained detailed maps of lunar crustal magnetic field. It also directly observed the interaction of the solar wind with several regions of strong crustal magnetic fields in the lunar southern hemisphere and from an altitude of 100 km [6]. These strong crustal magnetic field structures are all antipodal to the major basin-forming impacts and the magnetic field is strong enough to deflect the solar wind and form a miniature (i.e. 100 to several 100 km diameter) magnetosphere, magnetosheath and bow shock system [6].

Magnetic Fields have also been measured by the satellite Galileo as it approached the asteroid Gaspra [9]. The generation of magnetic fields on asteroids and the Moon have been explained by a plasma mechanism during an impact with another object [10, 11].

One of the interesting observations made by Lunar Prospector is the electron energization with energies in the range of 100 eV [6, 7]. These electrons are used as

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evidence for the formation of a shock wave produced by the interaction of the solar wind and lunar magnetic anomaly. Lunar Prospector recorded the presence of a large magnetic ramp, upstream of which plasma turbulence is also present coinciding with the region of electron energization [6]. Lunar Prospector flew through the southern hemisphere lunar magnetic anomaly in July, 1999 and saw clear evidence of a density cavity in the solar wind – the expected signature of a mini-magnetosphere [8].

This paper describes a possible mechanism that can explain the enhanced electron energies based on the interaction of lower-hybrid waves generated close to the bow shock.

2. Model

The resonant interaction between lower-hybrid turbulence and electrons can result in field aligned electron acceleration [9, 11]. These waves are most probably excited by the modified two stream resulting from the interaction between the solar wind and the lunar magnetic field. In this interaction a pressure wave or shock wave forms resulting in the reflection and deflection of the ions from the lunar magnetic cavity. These ions under the action of $\underline{E} \times \underline{B}$ pick-up from a monoenergetic ion ring distribution in the plasma. This distribution of ions derives the modified two stream instability described by the following dispersion relation [12]

$$\frac{\omega_{lh}^2}{\omega^2} + \frac{\omega_{ce}^2}{\omega^2}\frac{k_\parallel^2}{k^2 + \omega_{pe}^2/c^2} + 8\pi^2 i \int \mathrm{d}v_\parallel \int_{\omega/k_\perp}^{\infty} \mathrm{d}v_\perp \frac{\partial f_i/\partial v_\perp}{\sqrt{k_\perp^2 v_\perp^2 - \omega^2}} = 1 + \frac{\omega_{pe}^2}{k^2 c^2}, \tag{1}$$

where $f_i\left(v_\perp, v_\parallel\right)$ is the distribution function of the reflected ions. We assumed that as a result of ion gyration in the solar wind magnetic field, particles are completely mixed over phase of rotation and establish a gyrotropic distribution $f\left(v_\perp, v_\parallel\right)$, contrary to the case of non-gyrotropic plane beam distribution. The instability excites lower-hybrid waves having the following dispersion law

$$\omega^2 = \frac{\omega_{lh}^2\left(1 + \frac{\beta}{2k^2\rho^2}\right) + \omega_{ce}^2\frac{k_\parallel^2}{k^2}}{\left(1 + \beta/2k^2\rho^2\right)^2} \tag{2}$$

where $\beta = \frac{8\pi n_o T_p}{B_o^2}$ is the ratio of the plasma kinetic pressure in the solar wind to the magnetic pressure, $\rho = \sqrt{\frac{T_p}{m_e}}\frac{1}{\omega_{ce}}$ is the electron gyroradius calculated with the proton temperature.

The integral over $v_\perp$ on the l.h.s. of (1) can be easily calculated giving the following expression for the growth rate [12, 10],

$$\gamma = \frac{n_i}{2n_o}\frac{m_p}{m_i}\frac{\omega^2\omega_{lh}^2}{k^3 v_\perp^3}\frac{1}{1 + \frac{\beta}{2k^2\rho^2}} \tag{3}$$

In order for the instability to be viable it needs to develop on a distance scale of something like

$$r \approx 10u/\gamma \tag{4}$$

which must also be shorter than the physical dimensions of the interaction region, where u is the solar wind speed.

The wave spectrum is centered on the average energy ε_e, which can be obtained from energy balance between the ions mass loading the solar wind and the accelerated electrons

$$\alpha n_i m_i u^3 \approx n_{Te}\varepsilon_e \left(\frac{\varepsilon_e}{m_e}\right)^{1/2}, \tag{5}$$

where α is the transformation efficiency from ions to electrons, their density n_{Te} can be estimated by balancing the growth rate of the instability initiated by pickup ions with Landau damping due to electrons moving parallel to the magnetic field

$$\gamma_i + \gamma_e \sim \frac{\partial f_i}{\partial v} + \frac{m_i}{m_e}\frac{\partial f_e}{\partial v_\parallel} \approx 0 \tag{6}$$

This equation can be rewritten as

$$\frac{n_{Te}}{\varepsilon_e} \approx \frac{n_i}{m_i u^2}, \tag{7}$$

and together with the above equation for the energy balance it gives the following estimations for the average energy ε_e of the accelerated electrons and their number density [10]

$$\varepsilon_e \approx \alpha^{2/5}\left(\frac{m_e}{m_i}\right)^{1/5} m_i u^2, \tag{8}$$

$$n_{Te} \approx n_i \alpha^{2/5}\left(\frac{m_e}{m_i}\right)^{1/5} \tag{9}$$

Noting the weak dependence of the result from the energy transformation coefficient α, we can use the value of $\alpha \sim 0.1$. Then near the bow shock where the ion energy $m_i u^2 \sim 1\,\text{keV}$, we can obtain the typical electron energy $\varepsilon_e \sim 100\,\text{eV}$, and the density of the accelerated electrons is $n_{Te} \simeq 0.1 n_i$. Even this simple estimate demonstrates the large efficiency of electron acceleration by lower-hybrid waves.

3. Conclusions

We have identified a possible mechanism to explain the observations of energetic particles from the solar wind interacting with lunar magnetic anomalies. The mechanism relies on the formation of a collisionless bow shock that reflects solar wind ions. These reflected or deflected ions form either a ring distribution in velocity space as a result or a simple counterstreaming population. In both cases such ion distribution functions give rise to the generation of plasma turbulence with typical wave modes close to the lower-hybrid resonance. These lower-hybrid waves are ideal for accelerating electrons parallel to the magnetic field through wave particle resonance. Estimates show that the model can produce the electron energies found in the observations made by lunar prospectus.

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