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РАССЕЯНИЕ ЭЛЕКТРОНОВ ЭЛЕКТРОСТАТИЧЕСКИМИ ВОЛНАМИ НА ГОЛОВНОЙ УДАРНОЙ ВОЛНЕ ЗЕМНОЙ МАГНИТОСФЕРЫ

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ELECTRON SCATTERING BY ELECTROSTATIC WAVES IN THE EARTH'S BOW SHOCK

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Аннотация. Электростатические волны являются одними из самых распространенных видов волновой активности в космической плазме. В частности, недавние спутниковые наблюдения установили их присутствие на головной ударной волне земной магнитосферы, где они наблюдаются в широком диапазоне частот выше 100 Гц. Однако теоретический анализ взаимодействия между такими волнами и заряженными частицами солнечного ветра все еще не был проведен. Мы представляем результаты такого анализа для электростатических волн конкретного типа — так называемых ионных дыр, являющихся доминирующей компонентой электростатической турбулентности на головной ударной волне. Сравнивая оценки на изменение питч-угла в рамках приближения невозмущенных траекторий с результатами прямого численного интегрирования, мы делаем вывод о применимости классического аппарата квазилинейной теории и вычисляем коэффициенты питч-угловой диффузии. Комбинируя квазилинейные коэффициенты диффузии с недавно предложенным механизмом стохастического дрейфового ускорения, мы показываем, что турбулентность ионных дыр может эффективного рассеивать электроны тепловых и сверхтепловых энергий и, удерживая эти частицы в переходном слое ударной волны, давать возможность ускорять их до энергий порядка сотен электронвольт.

Ключевые слова: головная ударная волна, турбулентность, питч-угловая диффузия, ускорение частиц.

Abstract. Electrostatic waves are known to be ubiquitous in space plasma. Recent studies have revealed their presence in the bow shock of the Earth's magnetosphere where they dominate in the frequency range above 100 Hz. Despite that, the effects of their interaction with solar wind particles, especially electrons, have not been yet quantified. In this paper, we present quantitative estimations of electron pitch-angle scattering by a turbulence of ion holes, that make up a substantial part of electrostatic fluctuations in the Earth's bow shock. Taking advantage of direct numerical integration of electron motion equations and comparing these results to that, obtained under the approximation of unperturbed trajectories, we show applicability of the classical quasi-linear theory. This enables us to compute the quasi-linear pitch-angle diffusion coefficients. Making use of the recently proposed theory of stochastic shock drift acceleration mechanism, we show that the obtained diffusion coefficients can provide sufficient scattering rate of thermal and suprathermal electrons and can keep them within the transitional region long enough to support acceleration of thermal electrons by a factor of a few tens, that is up to a few hundred electronvolt.

Keywords: bow shock, turbulence, pitch-angle diffusion, particles' acceleration.

INTRODUCTION

Astrophysical high-Mach number quasi-perpendicular bow shocks are conventionally considered to be the primary source of high energy particles, this idea is supported by numerous remote observations as well as numerical models. The widely accepted mechanism of electron acceleration is the diffusive shock acceleration (DSA), but the problem is, that it becomes effective only for electrons with relatively high energies and thus thermal electrons cannot be directly accelerated by the DSA mechanism. Instead, in the recent paper by [Amano et al., 2020], another (the so-called stochastic shock drift acceleration (SSDA)) mechanism was proposed. In this mechanism, the interaction of thermal electrons with small-scale wave-turbulence in the shock's foot can lead to their temporal trapping which enables their pre-acceleration by the convectional electric field to modest suprathermal energies thus providing the needed seed electron population that can be subsequently injected into the DSA mechanism. Direct verification of this model has only been possible with numerical simulations, which, however, could not be carried out for realistic plasma-parameters. On the other hand, recent spacecraft measurements have demonstrated, that the bow shock of the Earth's magnetosphere also exhibits suprtahermal populations of electrons with energies up to dozens of keV. Despite having relatively modest, yet often supercritical Mach-numbers, the Earth's bow shock provides a unique opportunity for in-situ investigation by spacecraft missions and thus can potentially contribute to our understanding of bow shock's physics. In this work we are going to show that electron scattering by electrostatic fluctuations typical of the Earth's bow shock can lead to electron acceleration from thermal energies of a few dozen electron-volts up to a few hundred electron-volts.

ESTIMATIONS ALONG UNPERTURBED TRAJECTORIES

According to the recent spacecraft measurements, the predominant part of the electrostatic fluctuations in the Earth's bow shock is made of ion holes [Wang et al., 2021]. Ion holes are Debye-scale non-linear solitary waves with negative potential. Despite having almost planar geometry, ion holes can still drive effective pitch-angle scattering via the cyclotron resonance due to their oblique propagation with respect to the magnetic field [Vasko et al., 2018]. Ion hole potential profile can be relatively well fitted by a gaussian

$$\Phi = \Phi_0 \exp\left(-\left(z\cos(0) + y\cos(0) - V_s t\right)^2 / 2l^2\right).$$

Here Φ_0 stands for the amplitude of the electrostatic potential, l is the width of the ion hole. The speed of the ion hole (V_s) lies in the YZ plane and inclined by an angel θ with respect to the background magnetic field (pointed along Z-axis).

Assuming that on the time scale of interaction the magnetic field is essentially uniform, we have the following electron's equations of motion

$$m_e \frac{\mathrm{d}V_\parallel}{\mathrm{dt}} = \frac{\partial}{\partial z}\Phi,$$

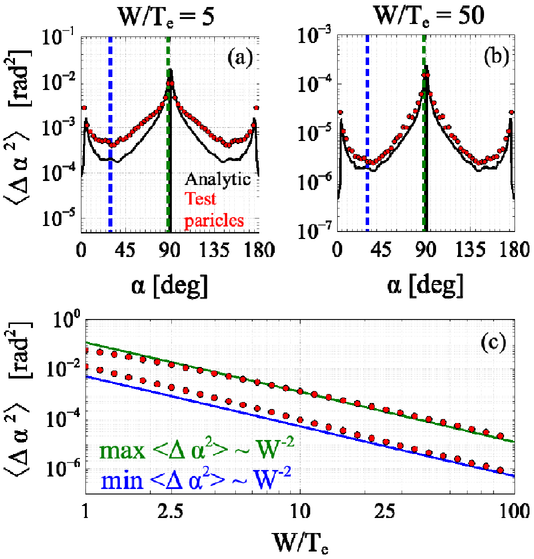
$$m_e \frac{d\mathbf{V}_\perp}{\mathrm{dt}} = -m_e\omega_{ce}\left(\mathbf{V}_\perp \times z\right) + \nabla_\perp\Phi$$

where m_e stands for the electron mass, ω_{ce} is electron cyclotron frequency, Φ is the electrostatic potential of the ion hole multiplied by the elementary charge (ion hole potential in units of eV).

These equations can be integrated along unperturbed electron's trajectories, i. e., Larmor rotations, and used to estimate the perturbation of the electron's pitch-angle Δα. The gyro-phase average equals zero $\left\langle\Delta\alpha\right\rangle = 0$, however, the dispersion is not zero $\left\langle\Delta\alpha^2\right\rangle \neq 0$,

$$\left\langle\alpha^2\right\rangle = \frac{4\pi\Phi_0^2}{W^2\sin^2(2\alpha)} \times$$
$$\times \frac{\omega_{ce}^2 l^2 \left(V_s\cos^2(\alpha) - V_\parallel\cos(\theta)\right)^2}{\left(V_s - V_\parallel\cos(\theta)\right)^4} \times$$
$$\times \sum_{n=1}^{\infty} n^2 j_n^2 \left(\frac{nV_\perp\sin(\theta)}{V_s - V_\parallel\cos\theta\}}\right) \exp\left[-\frac{\omega_{ce}^2 l^2 n^2}{\left(V_s - V_\parallel\cos\theta\right)^2}\right].$$

Here J_n stands for the Bessel function of the first-kind, W represents electron's kinetic energy. It is worth noticing, that in order to account for different possible parameters (l, Φ, V_s, θ) of ion-holes, i.e., to find a "typical" ion hole, we average $\left\langle\Delta\alpha^2\right\rangle$ over data-driven probability distribution of these paraments (see [Wang et al., 2021] for details). The results for pitch-angle dispersion $\left\langle\Delta\alpha^2\right\rangle$ can be compared with direct numerical integration of electron's equations of motion. Figure presents the comparison between $\left\langle\Delta\alpha^2\right\rangle$ computed analytically under the approximation of unperturbed orbits (black line) and by direct numerical integration of electron's equations of motion (red dots). We see that unperturbed orbits provide a relatively good approximation to the numerical results. Since the quasi-linear theory comprises the assumption of unperturbed orbits, our results indicate its applicability for the turbulence of ion holes.



The gyrophase-averaged pitch-angle variations $\left\langle\Delta\alpha^2\right\rangle$ of electrons scattered by a "typical" ion hole, computed using analytical approach and test-particle simulations

ESTIMATION OF THE MAXIMUM ENERGY GAIN

The acceleration mechanism presented by [Amano et al., 2020] provides the following expression for the maximum energy gain due to the scattering by a given wave-turbulence, which is characterized by a pitch-angle diffusion coefficient $D_{\alpha\alpha}$

$$W_{\max} = 6\nu\frac{m_e V_n^2}{2\cos^2\left(\theta_{Bn}\right)}\frac{D_{\alpha\alpha}}{\omega_{ci}}$$

here m_e stands for electron's mass, V_n is the upstream plasma velocity along the normal to the shock's front, θ_{Bn} represents the angle between the upstream magnetic field and the normal, $D_{\alpha\alpha}$ and ω_{ci} are pitch-angle diffusion coefficient and ion cyclotron frequency respectively, ν is a numerical factor on the order of one and such that $\nu V_n / \omega_{ci}$ gives the spatial width of the shock transition region along the normal.

In order to compute $D_{\alpha\alpha}$ for the turbulence of ion holes, we take advantage of the classical quasi-linear expression for the pitch-angle diffusion coefficient [I. Lerche, 1968]. By combining it with the datasets of typical ion hole parameters (provided by [Wang et al., 2021]), we obtain the following estimation for pitch-angle diffusion coefficient.

$$D_{\alpha\alpha} \approx 0.1\omega_{ce}\left(W / T_e\right)^{-3/2}$$

here ω_{ci}, W and T_e are electron gyro-frequency, electron energy and electron temperature respectively. By inserting this expression into the formula for $W_{\max}$, we can resolve it with respect to the maximum electron energy and for the parameters typical of the Earth's bow shock we obtain

$$W_{\max} = \frac{2T_e}{\left|\cos\left(\theta_{Bn}\right)\right|^{4/5}} \approx 0.1 \div 0.5\ \mathrm{keV}.$$

Which indicates that electrostatic fluctuations in the Earth's bow shock are capable of accelerating thermal electrons up to the energies of a few hundred eV, where (as [Amano et. al., 2020] have shown) they can be further accelerating by whistler turbulence, that effectively scatters electron with energies $\geq 1\ \mathrm{keV}$, and subsequently passed on to the conventional DSA mechanism.

CONCLUSIONS

In conclusion, our study demonstrates that electron scattering by electrostatic fluctuations can be efficient in the energy range below 1 keV, where scattering by whistler waves is not effective enough. Thus, in the Earth's magnetosphere the SSDA mechanism may provide direct acceleration of thermal electrons and generate the needed seed population of high-energy particles that can be further injected into the conventional DSA mechanism.

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