90° PA enhancements of suprathermal electrons near interplanetary shocks

90° PA ojačitve supertermičnih elektronov v bližini medplanetarnih udarnih valov

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Abstract: In this letter we report the results of the first systematic study of a population of suprathermal electrons in the solar wind, called the 90° pitch angle enhancements. This feature was found in the vicinity of interplanetary shocks. We analyzed 2 hours time intervals centered on the shocks. The enhancements were found at 114 of 232 shocks (49 %), which means that this is a common feature. Statistical analysis of shock properties show no important differences between the shocks associated with the enhancements and those not associated with them. Preliminary analysis of electric field fluctuations revealed possible correlation between the presence of 90° PA enhancements of suprathermal electrons and the wave activity.

Key words: interplanetary shocks, suprathermal electrons, 90° PA enhancements.

Povzetek: V tem pismu poročamo o prvi sistematični študiji tipa populacije supertermičnih elektronov v sončevem vetru, imenovane ojačitve pri 90° PA (*ang. pitch angle*). Ta populacija je bila najdena v bližini medplanetarnih udarnih valov, pri čemer smo analizirali dvourne časovne intervale centrirane na udarnih valovih. Ojačitve pri 90° PA smo našli pri 114 od 232 (49 %) dogodkov, kar pomeni, da je ta tip populacije dokaj pogost v sončevem vetru. Statistična analiza lastnosti medplanetarnih udarnih valov je pokazala, da ni bistvenih razlik v lastnostih med udarnimi valovi ob katerih so bile ojačitve prosotne in tistimi kjer jih ni bilo. Preliminarna analiza fluktuacij električnega polja pa je pokazala, da je njihova aktivnost intenzivnejša v bližini udarnih valov, ob katerih smo našli ojačitve pri 90° PA.

Ključne besede: medplanetarni udarni valovi, supertermični elektroni, ojačitve pri 90° PA.

1. Introduction

The electron distribution function in the normal solar wind (SW) is composed of three main populations: the nucleus is composed of thermal electrons with a temperature of 10 eV and is the coolest of the components. Thermal electrons account for 95 % of all electrons in the SW. Electrons with energies between 70 eV and 2 keV are called suprathermal. They form an isotropic halo and a narrow, antisunward travelling strahl (Montgomery et al.; 1968; Feldman et al.; 1975, 1978; Rosenbauer et al, 1976; Maksimovic et al.; 2005). Apart from these three populations, Lin (1998) reported the existence of another, very tenuous and isotropic population, called the superhalo. The latter is composed of electrons with energies between 2 keV and 100 keV.

Theoretical models showed that part of the electrons is accelerated to suprathermal energies very close to the Sun. These particles then propagate through interplanetary (IP) space and since they are collisonless, they are subject to the pitch angle (PA) focusing due to diverging interplanetary magnetic field (IMF). Hence, a narrow beam or strahl is formed (e.g. Vocks and Mann, 2003; Rosenbauer et al.; 1976; Lemons in Feldman, 1983).. Later, these electrons interact with sunward travelling whistler waves which cause their scattering in PA, thereby widening the strahl and forming the halo (Vocks et al.; 2005; Saito in Gary 2007a, b; Pagel et al.; 2007).

Occasionally there are other electron distributions present in the SW. Gosking et al. (2001) observed strong depletions at 90° PA. The depletions were present occured in the data together with enhancements at acute Pas (between 90° and 180° or between 0° and 90 °), called conics and shoulders. Feldman et al. (1999) and Gosling et al. (2002) found similar distributions were inside the interplanetary coronal mass ejections (ICMEs).

Another type of suprathermal electron distributions were observed upstream of stream interaction regions (SIR) and corotating interaction regions (CIR). These were called the counterstreaming electrons. They were characterized by two strahl features in their pitch angle distributions (PAD), one propagating antisunward and another one propagating sunwards.

All the populations that are sometimes present in the SW were succesfully explained by the adiabatic focusing and mirroring of electrons as they propagate from regions of weak IMF into regions of stronger B-field and vice versa.

Here we report the results of the first systematic study of another type of suprathermal electron populations, the 90° PA enhancements. These were found in the data of the two STEREO spacecraft obtained during the years 2007 and 2011. Two hour time intervals centered on IP shocks were revised. In total the STEREO spacecraft detected 236 IP shocks during this tme period and the plasma data is available for 232 of them. We find 90° PA enhancements downstream of 114 (49 %) shocks. At 52 of them, these enhancements were observed just at the shock ramp. In 11 cases we found them upstream of the shocks. At this moment we still do not know what is the mechanisms for the formation of 90° PA enhancements of suprathermal electrons.

2. Observations

For the purpose of this study we use observations obtained by the two STEREO (Solar Terrestrial Relations Observatory) spacecraft. We use the data from the following instruments: IMPACT (In-Situ Measurements of Particles and CME Transients) MAG (magnetic field measurements) and SWEA (Solar Wind Electron Analyzer, meritve elektronov) instruments , STEREO WAVES (measurements of electric field fluctuations in the radio part of the spectra) and PLASTIC (PLAsma and SupraThermal Ion Composition, podatki za ione) (e.g. Luhmann et al.; 2008a, b; Sauvaud et al, 2008; Acuña et al.; 2008; Galvin et al.; 2008). B-field data are available in three time resolutions: 1 Hz, 8 Hz and 32 Hz. The data in 32 Hz resolution are available only occasionally, when the burst operational mode is switched on. The 1 Hz and 32 Hz resolution data is available continuously. SWEA measures the electron distribution function in energy range between 1 eV and 2 keV. The distribution function is measured every four seconds (every two seconds before April 16, 2009), although the data with this resolution are available only when the burst mode is switched on. The normal time resolution of the data is 20 seconds (30 seconds before April 16, 2009). There are some problems with charging of the instrument, that does not allow the measurements of electrons with energies less than 50 eV. However this problem does not affect the suprathermal electron data. Finally, PLASTIC data are available with 1 minute time resolution.

2.1. Case study

In this section we present IP shock observed on May 7, 2007 at 08:11:54 UT (Figure 1). It was detected by the STEREO A spacecraft. Panels in the Figure show the following quantities: I) magnetic field strength in units of nanoTesla (nT), II) magnetic field components in RTN coordinate system in units of nT, III)-VIII) evolution of pitch angle distribution (PAD) of suprathermal electrons. Data from three energy channels with central energies 93.5 eV (III and IV), 246.6 eV (V and VI) and 400.6 eV (VII and VIII) is shown. The colors on panels III, V and VII represent the logarithm of electron distribution function (f_{dist}), while on panels IV, VI and VIII they represent the normalized f_{dist}. The latter is normalized to its highest value at each measurement. The letters A and B mark the times of 1-D f_{dist} shown in Figure 2. The RTN coordinate system is designed so that the ***R*** represent the radial component, which is positive in the antisunward direction. $\boldsymbol{T}=(\boldsymbol{\omega}\times\boldsymbol{R})/|\boldsymbol{\omega}\times\boldsymbol{R}|$, where $\boldsymbol{\omega}$ is a unit vector parallel to the solar rotational axisand $\boldsymbol{N}$ completes the right hand system.

We see in Figure 1 that before the IP shock, the suprathermal electron PAD is composed of two component: the blue color represent the isotropic halo, while the green and the red colors near 0° PA represent the strahl. In this Figure and even better in Figure 2 we see that the upstream PAD exhibits enhanced values also near 180° PA. The difference between the intensity of the primary and the secondary strahls is largest for the 93,5 eV energy channel.

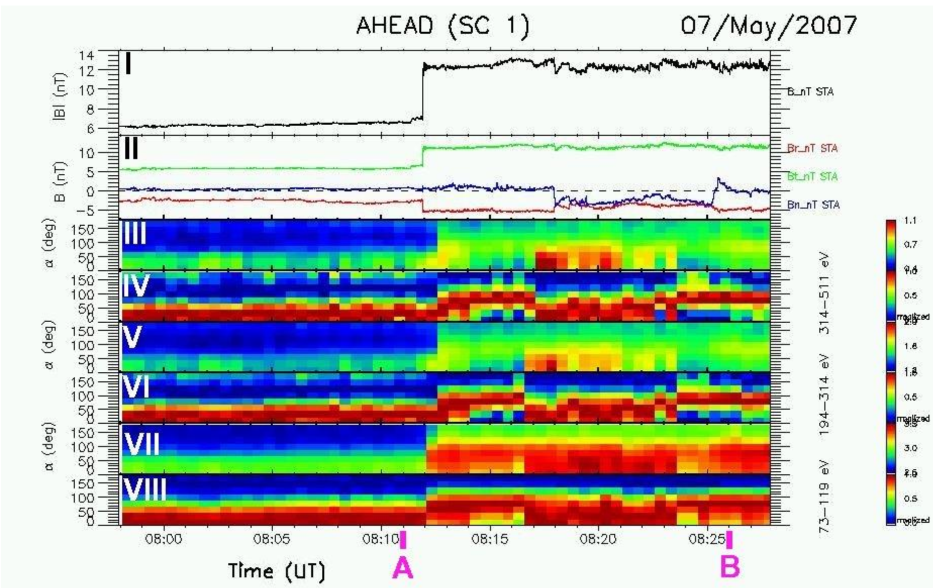
Immediately behind the shock, the PAD exhibits maximum at 90°±15° PA until ~08:17:00 UT and again after ~08:23:30 UT. The fact that the shape of the PAD changes is a consequence of the braiding of IMF lines along which propagate different types of electron populations. We see that this is true on panel II) in Figure 1, since the IMF undergoes string rotations at 08:17:00 UT and 08:23:30 UT. IMF before and after this time interval has approximately the same orientation. In Figure 2 we also see that the 90° enhancement is a dominant feature of the f_{dist} in the region downstream of the shock.

2.2.Statistical analysis

In total we analyze the data in the vicinity of 232 IP shoks. We find the 90° PA enhancements upstream of 114 events. In 52 cases we find them immediately downstream of the shock ramp. We also find the enhancements upstream of 11 IP shocks. In the next step we compare observational properties of IP shocks that are associated with the enhancements to those that are not. We compare the following shocks properties: their strengths ($B_{downstream}/B_{upstream}$), angles between the local shock normals and the upstream IMF (θ_{Bn}), angles between the local shock normals and the radial direction (θ_{BR}), upstream β (the ratio between the B-field and thermal pressures), the magnetosonic Mach numbers (M_{ms}) and the criticality ratios (M_{ms}/M_c), where the M_c is the first critical Mach number, at which the shocks become supercritical and start dissipating part of the kinetic SW energy by reflecting a fraction of the incoming SW particles.

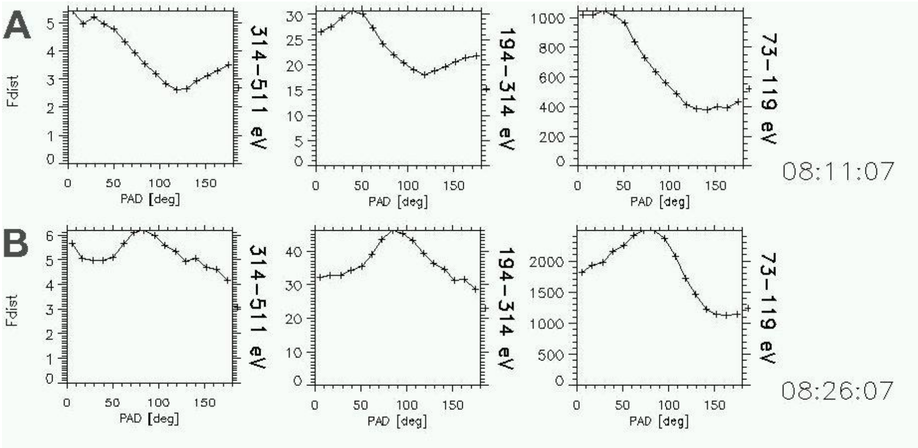
Statistical analysis does not reveal any major differences between the properties of the two groups of IP shocks. The largest difference is in the average θ_{Bn}, which was 64° for shocks with enhancements and 55° for events without the enhancements.

We should also mention that the preliminary analysis of STEREO WAVES data points to the stronger wave activity at shocks that are associated with the 90° PA suprathermal electron enhancements. Further analysis of the waves will show what are the modes of these fluctuations are (whistler waves or lower hybrid waves) and whether they are the cause of the 90° PA enhancements (or vice versa).



Slika 1. IP shock observed on May 7, 2007. The panels show I) B-field intensity in units of nanoTesla (nT), II) B-field components in RTN coordinate system (nT) in III)-VIII) time evolution of the suprathermal electron pitch angle distribution (PAD). Shown are the data from three energy channels with central energies 93,5 eV (III and IV), 246,6 eV (V and VI) ter 400,6 eV (VII and

VIII). Colors in panels III, V and VII represent the logarithm of the electron distribution function, while in panels VI, VII in VIII they represent the normalized distribution function. The latter is normalized to its highest value at each measurement. The letters A and B mark the times of the 1-D PAD shown in Figure 2 in the upstream and downstream regions of the shock.



Slika 2. 1-D PAD upstream (A) and downstream (B) of the shock.

3. Conclusions

In this letter we report the first results of the first systematic study of 90° PA enhancements of suprathermal electrons in the vicinity of IP shocks. Eventhough similar distributions have been reported in the literature (Feldman et al.; 1983; Hull et al.; 2001; Skoug et al.; 2006; Kajdič 2013), they have not been studied in a systematic manner. Statistial analysis of observational properties of IP waves revealed no major differences between the shocks that are associated with the enhancements and those that are not. At this point we still do not know the mechanism responsible for their formation. Pure focusing and mirroring due to adiabatic effect of the IMF on electron distributions are probably cannot account for 90° PA enhancements. Preliminary comparison of the presence of 90° PA suprathermal electron enhancements and the wave activity showed some correlation between the two phenomena. Further analysis will show whether this correlation is statistically important an whether electric field fluctuations could be the cause of thje 90° PA enhncements or vice versa.

Interplanetary shocks are important particle accelerators in the solar system. A lot of effort has been invested in recent decades in trying to understand acceleratoin processes at IP shocks. New particle populations such as those described in this paper may eventually provide us with further insight of how particles are being processed as they come accross different kinds of discontinuities in the IP space.

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