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Electron Acceleration to Relativistic Energies at a Strong Quasi-Parallel Shock Wave

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Abstract: Electrons can be accelerated to ultrarelativistic energies at strong (high-Mach number) collisionless shock waves that form when stellar debris rapidly expands after a supernova [4, 2, 19]. Collisionless shock waves also form in the flow of particles from the Sun (the solar wind), and extensive spacecraft observations have established that electron acceleration at these shocks is effectively absent whenever the upstream magnetic field is roughly parallel to the shock surface normal (quasi-parallel conditions) [16, 8, 10, 17, 14]. However, it is unclear whether this magnetic dependence of electron acceleration also applies to the far stronger shocks around young supernova remnants, where local magnetic conditions are poorly understood. Here we present Cassini spacecraft observations of an unusually strong solar system shock wave (Saturn's bow shock) where significant local electron acceleration has been confirmed under quasi- parallel magnetic conditions for the first time, contradicting the established magnetic dependence of electron acceleration at solar system shocks [16, 8, 10, 17, 14]. Furthermore, the acceleration led to electrons at relativistic energies ($\sim$ MeV), comparable to the highest energies ever attributed to shock-acceleration in the solar wind [16]. These observations suggest that at high-Mach numbers, like those of young supernova remnant shocks, quasi-parallel shocks become considerably more effective electron accelerators. For full details please see: Nature Physics, Volume 9, Issue 3, pp. 164-167.

Keywords: Collisionless shock waves, electron acceleration, quasi-parallel shocks

1 Introduction

It is widely believed that a major fraction of Galactic cosmic rays (energies up to $\sim 10^{15}$eV) are accelerated at collisionless shock waves associated with supernova explosions [4]. The specific acceleration mechanism typically invoked in this context, commonly referred to as Diffusive Shock Acceleration (DSA), is thought to result from a Fermi process where particles bounce between converging scattering centres (e.g. electromagnetic waves) located on either side of the shock [4]. Emissions associated with ultrarelativistic electrons produced at young (<1000 year-old) supernova remnant shocks have been comprehensively studied using both Earth-based and space-based telescopes [2, 19, 15]. However, poorly constrained local conditions at these exotic, distant shocks [20], and in particular the hardly known magnetic field conditions lead to uncertainty surrounding the electron acceleration process.

Observations made by spacecraft during encounters with collisionless shocks in the Solar System can potentially shed light on the physics of these supernova remnant shocks [18]. Shocks are common in the solar wind plasma that flows away from the Sun and carries the solar magnetic field into interplanetary space. Electron acceleration is often observed, although not to the ultrarelativistic (TeV-PeV) energies produced at young supernova remnant shocks, and various acceleration mechanisms have been discussed. Observed electron acceleration is significantly more efficient at quasi- perpendicular shocks than at quasi-parallel shocks [16, 8, 10, 17, 14] (quasi-perpendicular: angle between the shock normal and the upstream magnetic field vector $45^\circ < \theta_{Bn} < 90^\circ$; quasi-parallel: $0^\circ < \theta_{Bn} < 45^\circ$), although even under quasi-perpendicular conditions the detection of relativistic (MeV) electrons is rare [16]. Since solar system shocks are generally far weaker (lower Mach number) than their young supernova remnant counterparts, and also far smaller, it is unclear whether the observed magnetic dependence of electron acceleration also applies to much stronger shocks. Limited observations, and theoretical predictions, suggest that quasi-parallel shocks may become efficient electron accelerators at high Mach numbers [8, 12, 3].

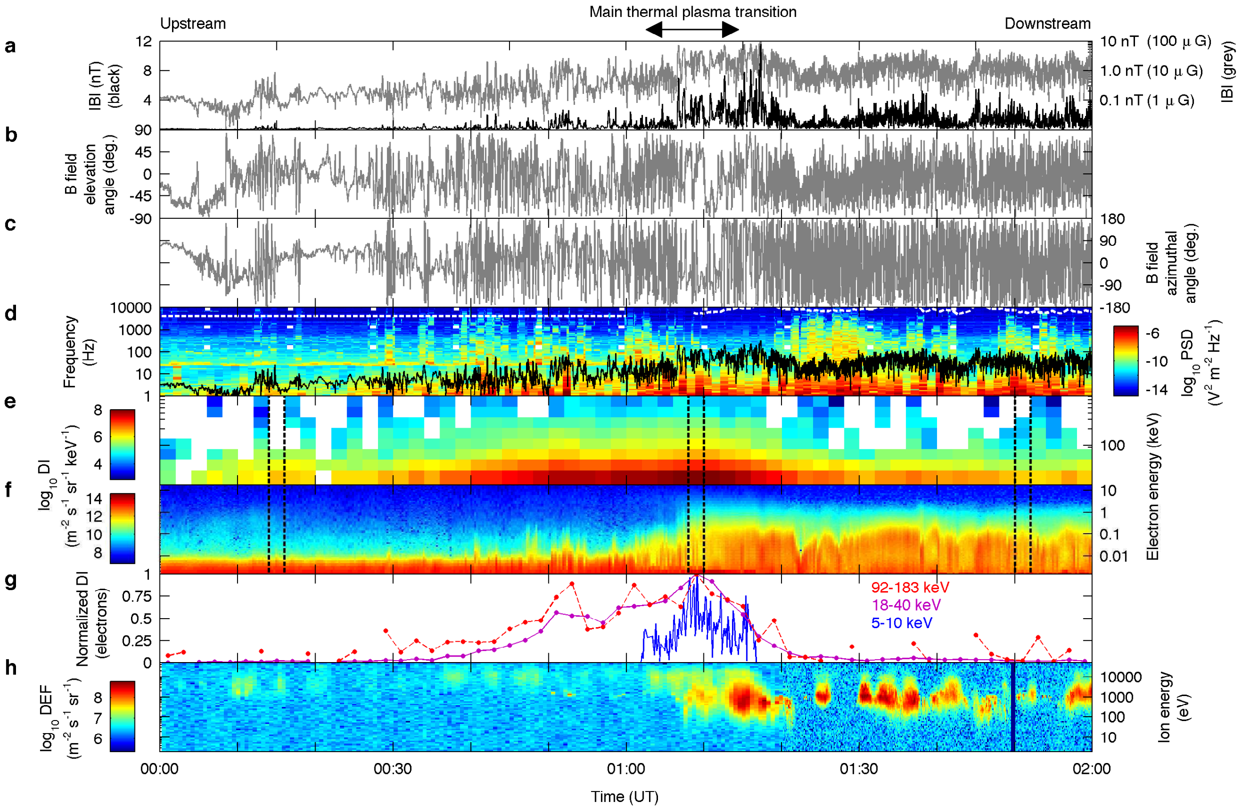

Figure 1: Observations made by Cassini during a bow shock shock crossing on 3 February 2007 (00:00 to 02:00 UT). a, Magnetic field magnitude on both linear and logarithmic scales [6]. b, Magnetic field elevation angle. c, Magnetic field azimuthal angle. d, Frequency-time spectrogram of electric field Power Spectral Density (PSD) [9]. e and f, Energy-time spectrograms of electron Differential Intensity (DI) [22, 11]. g, Normalized electron DI in three energy ranges. h, Energy-time spectrogram of ion Differential Energy Flux (DEF) [11].

2 Cassini Observations

Here we present in situ spacecraft observations of an unusually strong quasi-parallel shock wave. NASA's Cassini spacecraft has made hundreds of crossings of the shock that stands in the solar wind in front of Saturn (the planetary bow shock) due to the obstacle presented by the planet's intrinsic magnetic field (the planetary magnetosphere) [1, 21, 13]. A set of 94 Cassini crossings of Saturn's bow shock have been analysed in a previous study, resulting in an Alfvén Mach number (M_A, related to the upstream speed of Alfvén waves) for each [13]. The highest M_A case (~ 100) is presented here, and is the only quasi-parallel crossing associated with clear evidence for shock-acceleration of solar wind electrons.

The crossing took place at $\sim 01{:}10$ Universal Time (UT) on 3 February 2007. In situ observations made by Cassini between 00:00 and 02:00 UT are shown in Figure 1. Under these quasi-parallel magnetic conditions a collisionless shock is a broad and complex transition between upstream and downstream plasma states [5, 7] and the observations presented in Figure 1 are consistent with this expectation. The spacecraft began the interval upstream, observed the major heating and compression of thermal plasma during a roughly 10-minute-long interval centred on $\sim 01{:}10$ UT (Figures 1f and 1h), and ended the interval downstream. The weak magnetic field strength upstream of this shock encounter (~ 0.1 nT, Figure 1a) was primarily responsible for the calculation of $M_A, \sim 100$, which is very high for a solar system shock [13]. Using typical electron and ion temperatures in the near-Saturn solar wind [1] we estimate both the sonic and fast magnetosonic Mach numbers as ~ 25.

The main thermal plasma transition (centred on $\sim 01{:}10$ UT) was the only occasion when intensities above the one-count level were measured between 5 and 10 keV (Figure 1g). This is clear evidence for the shock-acceleration of solar wind electrons, which is a well-observed phenomenon at (weaker) quasi-perpendicular shocks [16, 8, 10, 17, 14]. Coincident with the peak of this lower energy signal, all higher energy channels were above background (including the highest, which approaches MeV energies), and all recorded peak intensities (Figures 1g and 2). Intensities in the *gtrsim* 100 keV channels revealed a flatter spectrum at these higher energies, as shown in Figure 2.

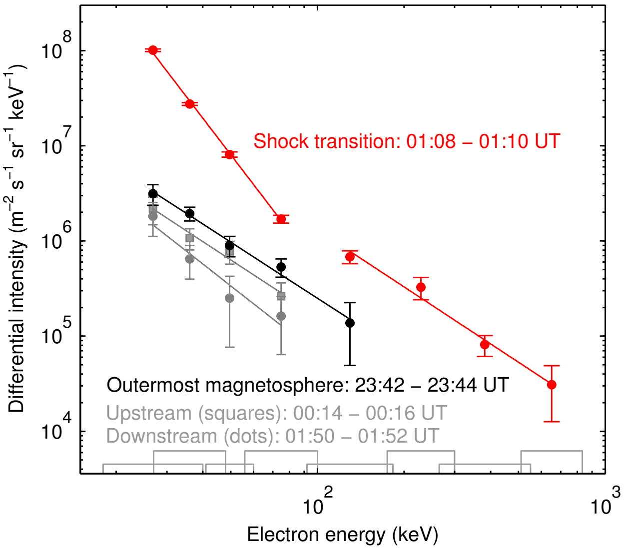

Figure 2: Comparison of high- energy electron spectra. Grey rectangles indicate the range of each energy channel. Data have been background-subtracted, and no data point in an energy channel indicates intensity at the background level. Power law fits are shown as straight lines.

3 Conclusions

We identify this combined electron signature as the first in situ evidence for significant acceleration of solar wind electrons (to relativistic energies) at a quasi- parallel shock wave. The electron dynamics at this shock encounter remains to be fully understood. The change in spectral shape at ~ 100 keV suggests the operation of more than one acceleration mechanism (Figure 2). We note that the intensity of the shock-accelerated electrons detected by LEMMS does not remain constant downstream, as predicted by simple one-dimensional DSA theory, and such differences must be explained by any proposed model of electron acceleration and transport.

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