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Cassini Observations of Saturn's High-Mach Number Bow Shock

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Abstract

The leading explanation for the origin of galactic cosmic rays is particle acceleration at the shocks surrounding young supernova remnants (SNRs), although crucial aspects of the acceleration process are unclear. In addition, the role of ion dynamics in dissipation of supercritical shocks is a subject of active interest in the community. The similar collisionless plasma shocks frequently encountered by spacecraft in the solar wind are generally far weaker (lower Mach number) than these SNR shocks. However, the Cassini spacecraft has shown that the shock standing in the solar wind sunward of Saturn (Saturn's bow shock) can occasionally reach this high-Mach number astrophysical regime. In this regime Cassini has provided the first *in situ* evidence for electron acceleration under quasi-parallel upstream magnetic conditions and the timescale of specularly reflected ions at the shock front. Here we review the most recent published work based on Cassini data taken at Saturn's bow shock. We then present an interpretation and discussion of the sum of the Cassini findings to date, with emphasis on ion dynamics and the implications for shock-acceleration of charged particles.

1. Introduction

The planetary bow shocks, from Mercury to Uranus provide a unique resource in terms of parameter range for understanding shocks in other astrophysical systems. At the bow shock the flow is slowed and heated, and the density and magnetic field increase, with conservation of mass, momentum and energy giving a set of jump conditions which locally relate the flow parameters upstream and downstream of the shock. The solar wind is essentially collisionless, with a collisional mean free path orders of magnitude greater than the width of the shock transition layer. Therefore the transition is attained by coupling between the electric and magnetic fields and the particles, involving both microinstabilities and particle trajectories in the macroscopic fields of the shock transition.

Within the framework of a fluid description where dissipation is provided by resistivity (or in the case of a collisionless plasma, by anomalous resistivity), shock solutions are possible up to a limiting Mach number, the critical Mach number M_c. For supercritical shocks ($M > M_c$), there is excess energy in the directed bulk flow that cannot be converted into thermal energy within the current-carrying transition layer in the timescale of the fluid element's crossing since the energy dissipation required by the jump conditions cannot be provided solely by resistive heating. Observations and simulations show that supercritical shocks compensate for the shortfall in dissipation by reflecting some fraction of the incoming ions back upstream. At such high Mach number shocks, the structure becomes inherently dependent on the ion dynamics, and a fluid description is inadequate. Saturn's orbit is at a heliocentric distance of ~10 AU, a region characterized by significantly higher Mach numbers normally not accessible in near-Earth space. The Cassini spacecraft therefore offers a unique opportunity to investigate the near-Saturn plasma conditions in addition to its principal objectives in planetary science.

Although electrons comprise a minor fraction of primary cosmic rays (1–2%), electron acceleration at supernova remnant shocks is far easier to access remotely because it always leads to the efficient production of high-energy emission. Such radiative signatures at radio and x-rays (through synchrotron emission), and most likely also gamma-ray energies (through inverse-Compton and relativistic bremsstrahlung processes) have been comprehensively studied using both Earth-based and space-based telescopes, indicating that ultrarelativistic electrons with energies exceeding tens of TeV are produced at young (<1000 year-old) supernova remnant shocks. These emissions provide us with valuable information about the shock environment, highly relevant for understanding the process of both ion and electron acceleration. However, local conditions at these exotic, distant shocks remain poorly constrained. In particular, the hardly known magnetic field conditions lead to uncertainty surrounding the particle acceleration process.

Here we review a set of recent studies that have reported *in situ* spacecraft observations of some of the highest Mach number shock waves ever encountered in a collisionless space plasma: *Masters et al.* (2013) and *Sulaiman et al.* (2015). All observations were made by NASA's Cassini spacecraft while in orbit around the planet Saturn, repeatedly crossing Saturn's bow shock wave. The parameters of this relatively strong Solar System shock occasionally approach the high-Mach number regime of young supernova remnant shocks, making Saturn's bow shock a space plasma laboratory of significant scientific interest, with the potential to bridge the gap between Solar System and astrophysical shock physics. Here we aim to highlight this emerging sub-field of collisionless shock physics, and discuss future directions. For details of the previous studies beyond those given in this review we refer the reader to these publications.

2. Summary of Results

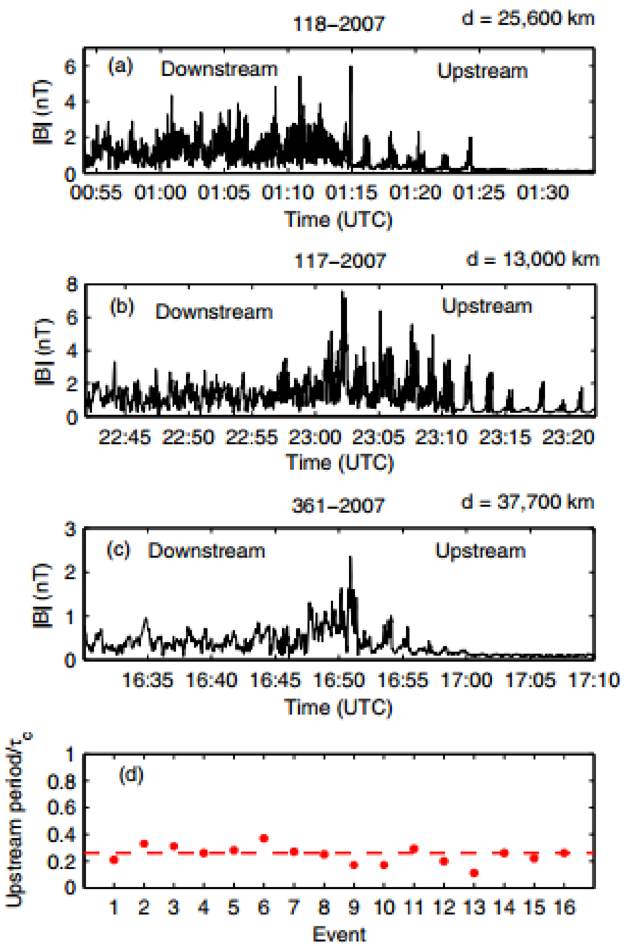

Figure 1. The top three panels (a)–(c) are three example magnetic field plots of quasiperpendicular Saturnian bow shock crossings with reformation cycles upstream. Panel (d), displays the average period of the upstream cycles of each event compared to their respective ion gyroperiods.

- For the first time, we show evidence for cyclic reformation controlled by specular ion reflection occurring at the predicted time scale of ~$0.3\tau_c$, where τc is the ion gyroperiod (See Figure 1).

- 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 (See Figure 2).

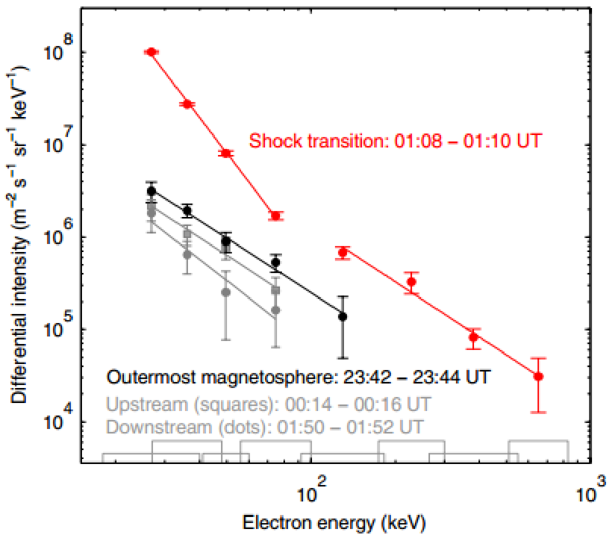

Figure 2. High-energy electron observations made by Cassini surrounding the 3 February 2007 encounter with Saturn's bow shock under high-Mach number, quasi-parallel conditions. From *Masters et al.* (2013).

6. Acknowledgements

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7. References

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