Planetary and Space Science 85 (2013) 1–12

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Upstream ion events with hard energy spectra: Lessons for their origin from a comparative statistical study (ACE/Geotail)

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A R T I C L E I N F O

Article history:
Received 10 July 2012
Received in revised form
23 April 2013
Accepted 25 April 2013
Available online 23 May 2013

Keywords:
Upstream ions
Earth's bow shock
Energetic particles
ACE and Geotail missions
Leakage of manetospheric ions
Space weather prediction

A B S T R A C T

In this paper we present statistical results from a comparison of ion events observed almost simultaneously by the Geotail spacecraft near the Earth's bow shock and by ACE moving around the libration point L1 (~220 km). The main result of this study is that important features of the ACE ion events, as for instance, the ion flux, the ion energy spectral slope, and the particle composition, change drastically through propagation from the magnetosphere to the L1 point. Among other results we found that the ACE events show (1) a strong spectral hardening compared to the spectral index $\gamma_{\mathrm{Geotail}}$ value observed just outside the magnetosphere. It is a decreased value by an average factor $<\gamma_{\mathrm{Geotail}}/\gamma_{\mathrm{ACE}}>\approx 3$, and (2) a percentage as low as ~22% of the Geotail electron events which is accompanied by the presence of electrons at the position of ACE. We infer that a short duration ion event with a hard "solar" type energy spectrum, which is non-accompanied by energetic electrons, can originate from the Earth's magnetosphere, and that therefore, these results should be taken into account in space weather prediction research. More detailed information on the varying features of traveling ions and electrons from the bow shock to far distances are important with respect to the problem of their origin and are also presented and discussed in the paper.

1. Introduction

The investigation of wave-particle interaction phenomena is one of the key issues in space physics, which has gained greatly from the investigation of our solar system by many space missions. A useful tool in this direction is exploration of interplanetary phenomena by means of missions in orbit about the Sun – Earth libration point 1 (L1), a location that solar wind disturbances would have to pass before encountering the Earth's magnetosphere. The L1 point is at such a distance (~220 Re) from the Earth that it allows good predictions for magnetospheric and ionospheric phenomena by analyzing solar wind plasma measurements (Barker et al., 2005; Huang, 2008; Lanzerotti, 2010 and references therein).

However, suprathemal plasma (energetic charged particle) phenomena at the L1 point are also important. In particular, short-lived (from some minutes to a few hours) energetic charged particle intensity enhancements observed in near Earth interplanetary space have been attributed to various sources and acceleration sites: interplanetary shock acceleration, acceleration at Earth's bow shock, leakage from Earth's magnetosphere, or Jovian emissions. A shock wave and following magnetic cloud may have significant influence on the Earth's environment, and since an ion intensity enhancement may be observed far from the shock (Zwickl and Roelof, 1981), there is an additional reason for researchers to distinguish the origin of energetic ion events observed around the L1 point (e.g. Posner et al., 2004).

Another main reason to study the energetic ion events around L1 is the determination of their origin as related with leakage from the magnetosphere or acceleration at bow shock. The investigation of the origin of energetic ions, which move in the sunward direction, upstream from the Earth's bow shock, has been a controversial subject in space physics for more than 30 years (see below). Moreover, the study of the ion population detected at distances as far as ~220 Re from the Earth poses additional queries to its understanding because of the changing characteristics during its voyage from Earth's bow shock to L1.

It is generally accepted that the field aligned flows of suprathemal (< ~5–6 keV) or even more energetic (> 2 MeV) ions escaping upstream from the quasi-perpendicular (dusk) side of the bow shock are generated by shock drift acceleration (SDA) of solar wind (Sonnerup, 1969; Paschmann et al.,1981) or a solar ambient energetic ion population (Anagnostopoulos and Sarris, 1983; Shimazu and Tanaka, 2005; Anagnostopoulos et al., 2009).

However, the determination of energetic ion events observed upstream (> 30 Re) from the quasi-parallel (dawn) side of the bow shock has been a controversial issue. Several models of the Fermi acceleration process of solar particles at the bow shock or a

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0032-0633/$ - see front matter
http://dx.doi.org/10.1016/j.pss.2013.04.015

leakage process of energetic particles from the magnetosphere during (sub)storms, have been considered as the main candidate processes to explain the upstream ion events. A significant reason for researchers to determine the principal source of energetic ions upstream from the quasi-parallel bow shock was the fact that several observational features were consistent with both candidate processes. For instance, both models (leakage from the magnetosphere and Fermi acceleration at the quasi-parallel bow shock) are consistent with the following characteristic observational features: (a) the quasi-parallel bow shock as the preferential site for frequent detection of upstream ion events (Ipavich et al., 1981; Lee, 1982; Luhmann et al., 1984; Trattner et al., 1994; Anagnostopoulos et al., 2005b). (b) almost isotropic pitch angle distribution in the solar wind frame of reference (Sibeck et al., 1988), (c) more intense bursts during enhanced solar wind speed (Trattner et al., 1994), (d) inverse velocity dispersion (Ipavich et al., 1981; Anagnostopoulos et al., 2000; Vassiliadis and Anagnostopoulos, 2003). Furthermore, both models have been invoked to explain the similarity in the composition of upstream CNO events with the superthermal ambient population (Mason et al., 1996; Anagnostopoulos, 1998); in particular, both models could be considered responsible for the SEP-like composition (C/O and Fe/O ratios) of upstream CNO events during solar maximum conditions as well as the similarity of the composition (C/O and Fe/O ratios) of upstream CNO events with that measured in the solar wind and/or CIRs during solar minimum conditions (Desai et al., 2006).

Finally we mention that an acceleration mechanism in the cusp was also suggested as a significant source of some high energy (1.5–2.0 MeV) ion events observed near the bow shock (Chen and Fritz, 1999, 2001), but our understanding is that the observations pose some serious questions about the possibility to accept this source as a major contributor to the upstream ion population (Anagnostopoulos et al., 2009, and references therein; Niehof1 et al., 2012).

Several observational features suggest that the magnetosphere is the main source of the upstream ion events. Some of these features are the following: (1) the high percentage (~80% of ion events) accompanied by the presence of magnetospheric >220 keV electrons (Anagnostopoulos et al., 1999), (2) the percentage of upstream ion events associated with the presence of ionopsheric O^+ (Posner et al., 2002; Keika et al., 2004) and (3) the high percentage of events with forward or no velocity dispersion at their onset phase (Vassiliadis and Anagnostopoulos, 2003). Furthermore, it is worth noting that independent research groups in the last decade have reached the conclusion that enhanced magnetospheric activity is responsible for the generation of most upstream ion events (Posner et al., 2002; Keika et al., 2004; Anagnostopoulos et al., 2005a,b; Klassen et al., 2008; Kronberg et al., 2011). A few studies reached the conclusion that they could not clearly distinguish between bow shock acceleration and leakage from the magnetosphere as the agent of the ion events observed far from the bow shock (Mason et al., 1996; Haggerty et al., 1999; Desai et al., 2000).

One of the problems raised from the observations made at far distances upstream from the bow shock is the percentage of energetic ion events accompanied by the presence of energetic electrons. This question is crucial because the presence of energetic electrons in upstream ion events is a signature of particle leakage from the Earth's magnetosphere (Sarris et al., 1978; Scholer et al., 1981; Sibeck et al., 1988). However, although there is evidence that magnetospheric energetic ions propagate more easily than electrons to far distances (Anagnostopoulos et al., 2005a), the absence of energetic electrons at L1 in some ion events, allows the impression that no magnetospheric ions are present in these cases, and, moreover that a large percentage of far upstream ion events are of non-magnetospheric origin. Furthermore, some evidence exists from case studies on simultaneous observations that the (ion) spectrum far upstream from the bow shock is harder than that near the Earth's magnetosphere.

The present paper addresses the lack in the scientific literature of a systematic study on the flux and spectral variation of energetic ions and electrons from the Earth's bow shock environment to L1. For this reason, in this study we performed an extended statistical analysis of simultaneous particle observations (188 ion events) obtained by Geotail (G) outside the magnetopause and ACE (A) around the L1 point, in order to gain information about the propagation of energetic charged particles escaping from the environment of the Earth's magnetosphere in the sunward direction. We infer that several features of the energetic charged particles (flux, spectrum, composition) change drastically throughout their trip from the magnetopause/bow shock to the L1 point. In particular, we found that both electron flux and ion spectrum (and flux) are strongly controlled by the distance from the magnetopause and that in most cases magnetospheric electrons do not reach the L1 point.

2. Spacecraft and instruments

The database for the present study was formed by data from the Energetic Particles and Ion Composition (EPIC) instrument onboard Geotail spacecraft and the Electron, Proton and Alpha Monitor (EPAM) experiment onboard ACE. The Geotail orbit is limited to the near Earth ($<$~30 R_E) region in order to investigate the near Earth space environment (magnetosphere, magnetosheath, bow shock upstream region), while ACE moves around the Libration Point L1 (~235 R_E), where the gravitational force of Earth equals that of the Sun.

For the needs of this study we used data from the channels P1 to P8 (protons), ED1 and ED2 (electrons) of the Ion Composition Subsystem (ICS) of the Geotail EPIC experiment, and the channels P′1–P′8 (ions), E1,E2 and DE1 (electrons) from the LEMS120, LEFS150 and LEMS30 telescopes of the EPAM instrument, respectively; the numbers of these telescopes designate the angular orientation in degrees (150, 120 and 30) from the center of each channel with respect to the spacecraft spin axis which is always directed at the Sun (Williams et al., 1992). From channels ED1 and ED2 we derived the differential flux in the energy range 38–110 keV, which we will call channel “ED”(Gold et al., 1998). In the case of electrons at ACE, we used the differential fluxes of the LEFS150 E1 and E2 energy channels in order to derive the differential flux in an energy range (44–104 keV: channel “E”) similar to that considered at Geotail in order to compare electron observations at similar energies. We also compare the LEFS150 data with those of the LEMS30 ones in order to confirm the actual presence of electrons at ACE (since LEMS30 telescope uses a magnetic field to separate electrons below ~300 keV).

3. Event selection criteria

3.1. Geotail ion events

In order to create a database of energetic ion events observed by Geotail outside the magnetosphere, we posed the following criteria:

1. The Geotail spacecraft should be placed outside a model magnetosphere (Shue et al.; 1997; with the following parameters: $B=10$ nT, $D_p=1$ nPa, $r_o=11.53$ R_E, $\alpha=0.4848$),
2. The differential intensity of Geotail 58.1–77.3 keV ions (P2 channel) should be

$$j_{P2} \geq 10 \text{ particles/cm}^2 \text{ s sr keV},$$