STEREO SEPT observations of velocity dispersion ion events originating from the Earth

Raúl Gómez-Herrero*, **Andreas Klassen***, **Bernd Heber***, **Reinhold Müller-Mellin***, **Robert Wimmer-Schweingruber*** **and Stephan Böttcher***

**Institut für Experimentelle und Angewandte Physik, Christian-Albrechts-Universität Kiel, 24118 Kiel, Germany*

Abstract**. During the first half of 2007, the twin STEREO spacecraft moved in opposite directions from the region upstream the Earth's Bow-shock to their heliocentric orbits ahead and behind the Earth. The low solar activity observed during this period offered an excellent opportunity for the observation of ions accelerated in the Earth's magnetosphere and/or the bow–shock at distances ranging from several tens to several thousands of Earth radii. The Solar Electron and Proton Telescope (SEPT) onboard STEREO measured several hundreds of ion increases in the energy range from 70 keV to <1 MeV clearly originating from the Earth. These events were observed in regions upstream and downstream the Earth's bow–shock and regardless of the distance to the source, the vast majority show no evidence of velocity dispersion. We focus the study in the few events showing clear velocity dispersion. Dynamic energy spectra for these events show a distinct drifting profile. The analysis of these spectra have been used to infer injection times and propagation path lengths. These parameters together with the anisotropy information provided by the different sensor apertures have been used to investigate propagation conditions and the possible source regions for these rare events.**

Keywords**: Upstream Events, Energetic Particles, Magnetosphere**

I. INTRODUCTION

The existence of energetic ions (<1 MeV) upstream of the Earth's bow–shock and in the Earth's magnetosheath has been well known since the 1960s (see e.g. [1]). Most of such upstream bursts were observed near the bow–shock at ∼25 R_E (R_E, Earth's radii)(e.g. [2]), at the libration point L1, at ∼240 R_E [3], [4], [5], but also using STEREO-A observations far away from the bow–shock at distances up to 1100 R_E [6], [7], [8]. STEREO-B detected ion events streaming from the magnetosphere not only upstream the bow–shock, but also behind the Earth's, in regions which are unlikely connected to the upstream region of the bow–shock [8]. We use the generic term "magnetospheric ion events" [9], [8] in order to discern between this global class of events and the more specific subset of upstream events. Traditionally, the upstream ion bursts have been explained in two ways:

1) By the leakage of magnetospheric particles accelerated within the magnetosphere [11], [2], [12].
2) By the acceleration at the bow–shock via Fermi or shock drift acceleration (SDA) (e.g. [4], [13], and references therein).

Velocity dispersion is one of the main observational issues for the understanding of the acceleration and transport processes operating during magnetospheric ion events. Attending to the behavior of velocity dispersion, the events can be classified in three categories: (1) forward velocity dispersion (FVD) when high–energy ions arrive earlier than those of lower energy, (2) inverse velocity dispersion (IVD) when low–energy ions arrive earlier than those at higher energy, and (3) no velocity dispersion (NVD) when the intensity rise at all energies simultaneously. Dynamic spectra showing examples of these three behaviors are presented in Fig. 1.

If all the energies are released simultaneously at the source and the magnetic connection between the observation point and the source remains stable during the event, FVD is expected due to the propagation delay between the lower and higher energies. This delay increases with the increasing distance to the source. The situation is more complex if the acceleration mechanism involves different acceleration times for different energies. The leakage model predicts all these three kinds of velocity dispersion [12], whereas the Fermi acceleration mechanism predicts IVD near to the source in a time scale of several minutes [14]. From the shock–drift acceleration, NVD or FVD are expected. In this paper we present some examples of forward velocity dispersion events observed by both STEREO spacecraft. These events are consistent with simultaneous release of all the energies at the source and a progressive delay due to the propagation between the source and the observation point. The events were detected in the region upstream of the bow–shock and also far away and behind the Earth's magnetosphere, suggesting that in these cases the acceleration mechanism was not Fermi and possibly not SDA.

II. INSTRUMENTATION

STEREO consists of two nearly identical non-rotating spacecraft launched on October 25, 2006. Both spacecraft are placed in heliocentric orbits following the orbital motion of the Earth. STEREO-A is placed slightly closer to the Sun than the Earth, and STEREO-B slightly

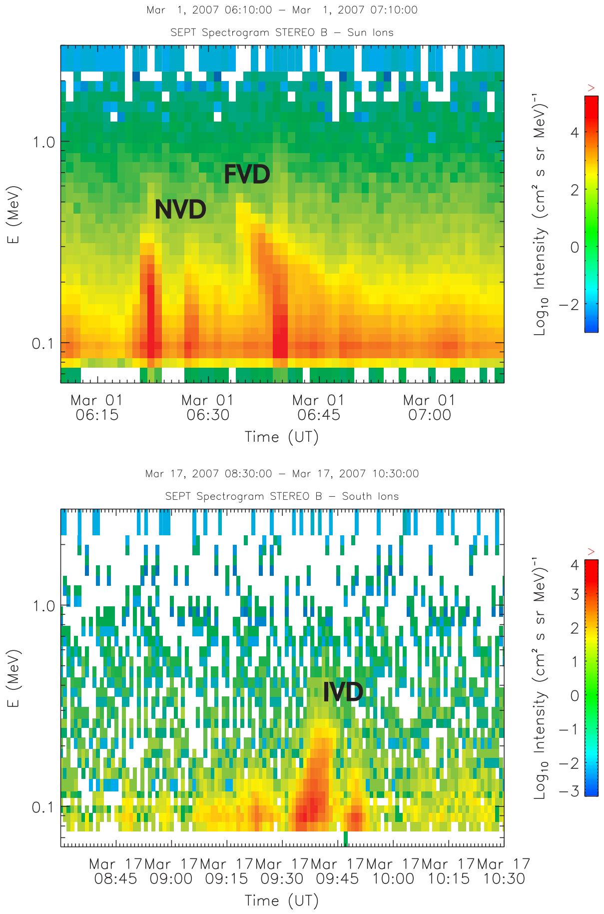

Fig. 1: Ion dynamic spectra showing observations of magnetospheric ion events with three different types of velocity dispersion. Time resolution is 1 minute.

outside Earth's orbit. This small radial separation leads to an increasing angular separation with respect to the Earth at a rate of ∼22 degrees/year for each spacecraft. STEREO-A is always located ahead of the Earth and STEREO-B is trailing behind. Both spacecraft remain always very close to the ecliptic plane (Fig. 2).

STEREO observations of energetic ions analyzed in this work were carried out by the Solar Electron and Proton Telescope (SEPT) [15], part of the IMPACT investigation. SEPT consists of two dual double-ended magnetic/foil particle telescopes: SEPT-E in the ecliptic plane along the Parker spiral and SEPT-NS perpendicular to the ecliptic-plane. This setup provides four looking directions for each spacecraft: one looking to the Sun along the nominal Parker spiral 45 degrees west from the spacecraft-Sun line, another looking along the Parker spiral but in the anti-solar direction, and two additional apertures looking North and South in perpendicular to the ecliptic. The nominal energy range is 70 keV-6.5 MeV for ions and 30-400 keV for electrons. Temporal resolution is 1 minute. Most of the time protons are the dominant contribution to the ion channels, however SEPT is not capable of elemental resolution, therefore other species (particularly helium) can sometimes contribute significantly to the ion channels.

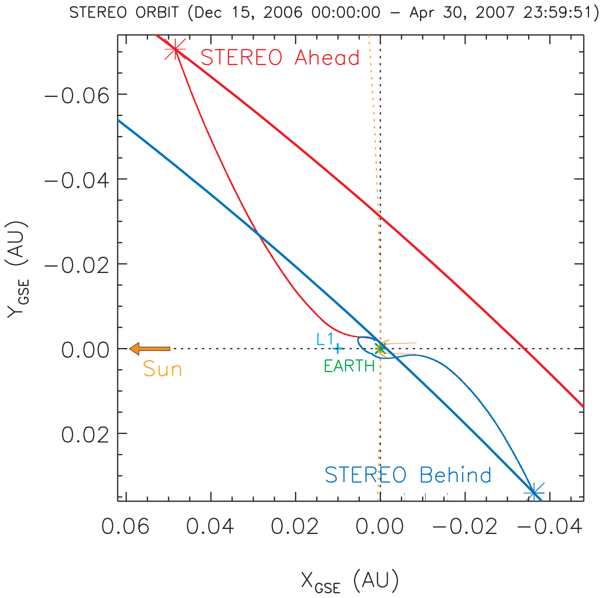

Fig. 2: STEREO-A and B trajectories during the period 15-Dec-2006 to 30-Apr-2007. The diagonal lines represent nominal interplanetary magnetic field lines for the final positions.

III. Observations and Data Analysis

We concentrate in the period between December 15, 2006 and April 30, 2007. Fig. 2 shows the projection in the ecliptic plane of the spacecraft trajectories during this interval, which starts just before the first lunar flyby by both spacecraft. After the lunar encounter STEREO-A moved away from the Earth from 600R_E to 2000R_E. STEREO-B moved in the region upstream the bow–shock and returned for a second lunar flyby on January 21, 2007, later it moved away from the Earth in antisolar trajectory crossing the bow–shock and the magnetosheath. At the end of the period, STEREO-B was located 1170R_E far from the Earth. This period, in coincidence with the solar minimum between solar cycles 23 and 24, was characterized by very low solar activity. The contribution of solar energetic particle events to the ion fluxes measured by SEPT was minor and the main source of background particles were the recurrent increases associated to Co-rotating Interaction Regions (CIRs) [9]. These quiet conditions offered an optimal opportunity for the study of ion bursts of magnetospheric origin observed along both spacecraft trajectories.

During the period under study, the two STEREO observed several hundreds of ion bursts of unambiguous terrestrial origin. They are typically very anisotropic events, commonly observed only by one telescope, with steep spectra (typical spectral indices $\geq$4) which mixes with the background fluxes beyond ∼1 MeV. Typical durations range between a few minutes and 1 hour. The inspection of the dynamic spectra during these events revealed that the majority of the events lack of velocity dispersion, showing simultaneous onset and decay over the whole energy range. Only 28 events showed velocity dispersion signatures. This pronounced tendency to the absence of velocity dispersion regardless the large distances to the source, suggests that at the observation point the typical convection times of the magnetic field lines connecting to the source are small compared with the duration of the events.

At the beginning of January 16, 2007, the SEPT sensor pointing in anti-solar direction onboard STEREO-A observed a ion increase showing clear velocity dispersion. The top panel in Fig. 3 shows the dynamic ion spectrum measured during the event. The middle panel shows the pitch-angle distribution and panels 3, 4 and 5 show the magnetic field magnitude and angular coordinates. The bottom panel shows the location of the spacecraft in the ecliptic plane. This event is one of the most clear examples of forward velocity dispersion observed by SEPT. When the $1/\beta$ *vs onset time* fit commonly used for solar events (see e.g. [10]) is performed (solid line in Fig. 3 top panel), the event is consistent with a total propagation path of (0.014 ± 0.002) AU ($330 R_E$) and an injection time at January, 16 00:08 UT $\pm$ 1 min. The dashed line correspond to the predicted behavior for ^{4}He assuming the same injection time and total propagation path. The drift is in very good agreement with the second increase observed during the event, suggesting that the two parallel drifting structures correspond to protons and ^{4}He released simultaneously at the same source.

The event shown in Fig. 3 took place when STEREO was located 289 R_E far from the Earth and was observed only by the sensor pointing in antisolar direction, which is consistent with a narrow pitch-angle distribution. It was not accompanied by energetic electrons in the energy range covered by SEPT. Calibrated plasma data from PLASTIC instrument onboard STEREO were not available for this period, but SWEPAM onboard ACE (very close to STEREO-A) measured almost constant solar wind speed between 520 and 530 km/s. The magnetometer onboard STEREO-A measured a smooth behavior of the interplanetary magnetic field, showing no strong directional variation during the event. The arrows in the bottom panel of Fig. 3 are the average magnetic field vectors measured during the event. The local magnetic field vector pointed permanently more radial than expected for an ideal Parker spiral, represented in the figure by diagonal solid lines. The shadowed box delimits the most probable source area for this event taking into account the distance to the source inferred from the velocity dispersion analysis and the magnetic field direction measurements from 50 minutes before the event up to the end of the event.

Fig. 4 shows a second example of FVD event observed by STEREO-B on January 31, 2007, near the boundary of the magnetopause. The event was observed by the telescopes looking in antisolar and South directions. In this case the nominal pointing was affected by a space-

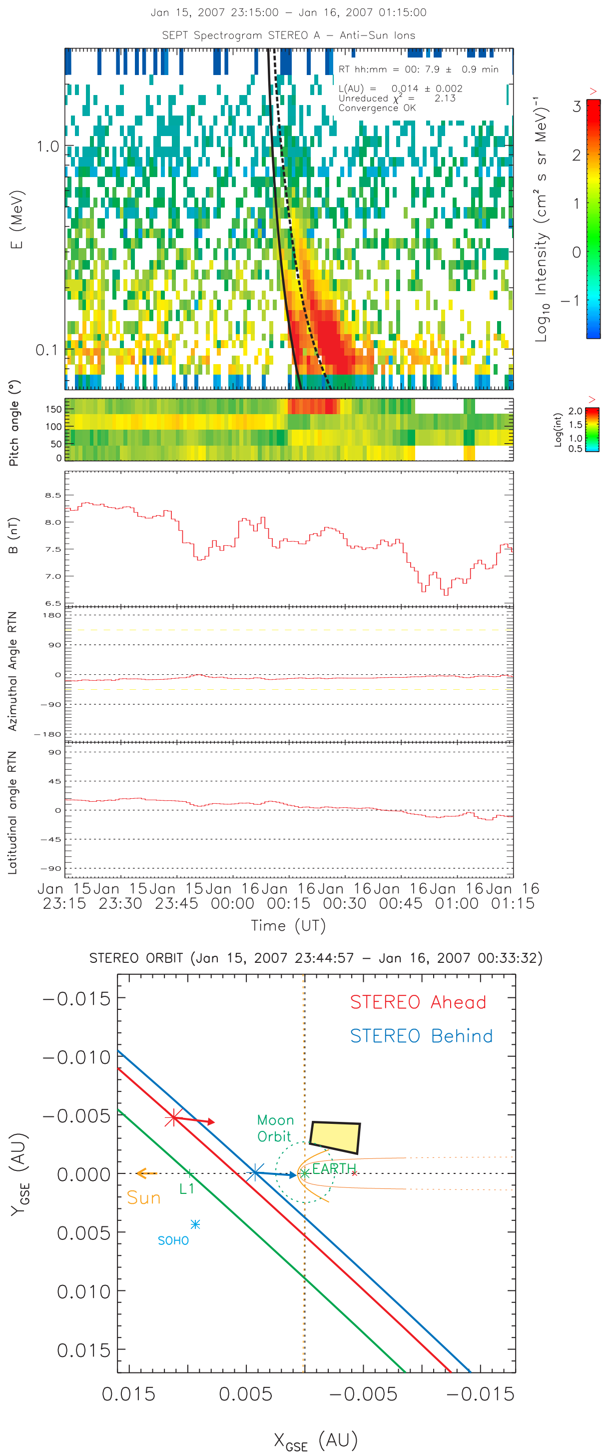

Fig. 3: Magnetospheric ion event with FVD observed by STEREO-A on January 15, 2007. The double drifting structure was observed only by the telescope pointing in antisolar (Earthward) direction.

craft rotation maneuver, however both sensors pointed permanently in the antisolar hemisphere. This anisotropy strongly suggest that the source was not located in the bow–shock region, but just in opposite direction, in the far magnetotail. The analysis of the velocity dispersion during this event is consistent with an injection time at

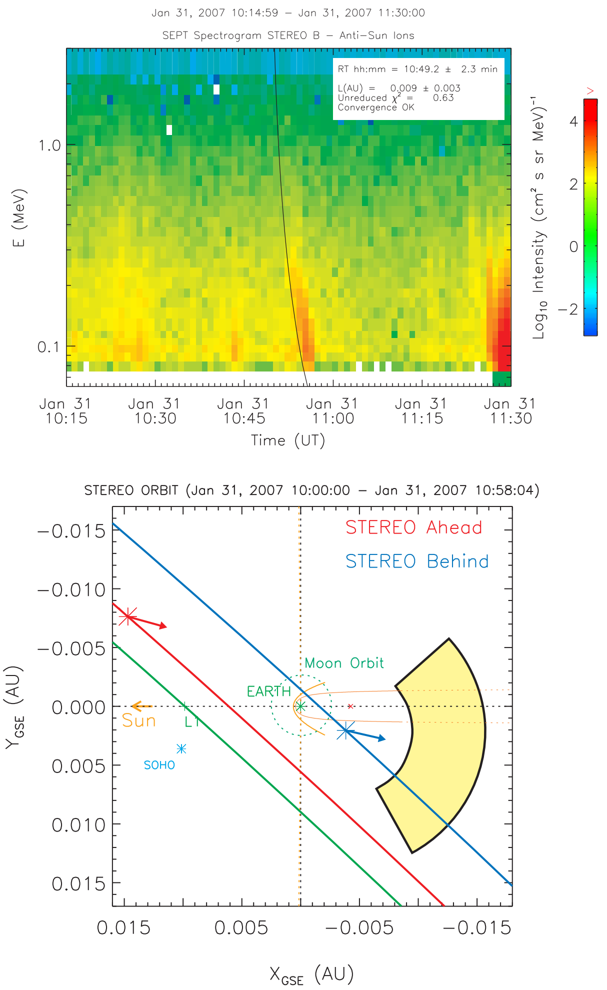

Fig. 4: Magnetospheric ion event with FVD observed by STEREO-B on January 31, 2007, and the possible source region (shadowed area).

January 31 10:49 UT $\pm$ 2 min and a total propagation path $L = (0.009 \pm 0.003)$ AU (210 R_E). The shadowed area shows the most probable source region taking into account the magnetic field variations and the inferred distance to the source. Energetic electrons were observed some minutes before the event. This common occurrence of electrons and ions makes possible to explain the event via the leakage model (see e.g. [12]).

IV. Conclusions

Between December 2006 and April 2007, the SEPT instrument onboard STEREO detected several hundred of ion increases of magnetospheric or bow–shock origin. A minority of these events showed clear forward velocity dispersion signatures. These events were observed by both spacecraft, not only in the region upstream of the Earth's bow–shock but also behind the Earth. In some cases the anisotropy information suggests that the source region is located near to the far magnetotail rather than at the bow–shock region.

Some of the FVD events (eg. Jan 16, 2007) were clearly not associated with energetic electrons. Previous works [12] found a 86% association rate between ion events from magnetospheric leakage and energetic electrons. Consequently, the events which are not associated with electrons are difficult to explain using the leakage model.

Fermi acceleration mechanism predicts inverse velocity dispersion (IVD) in time scales up to few minutes [14], thus the existence of FVD is an observational evidence contradicting Fermi acceleration. In addition, the FVD event observed by STEREO-B on January 31, 2007 streamed from the magnetotail/anti–bow–shock direction, which also contradicts Fermi and SDA mechanisms.

The FVD events show a clear drifting profile consistent with simultaneous release at the source for all the energies followed by propagation along path lengths which are compatible with the distance from the spacecraft to some region of the magnetosphere. Such kind of velocity dispersion contradicts the model of rigidity dependent escape (a variant of the Leakage model proposed in [12]).

V. Acknowledgements

The STEREO/SEPT and SOHO/COSTEP projects are supported under grant No. 50 OC 0105 and 50 OC 0902 by the German Bundesministerium für Wirtschaft through the Deutsches Zentrum für Luft- und Raumfahrt (DLR).

References

[1] Asbridge, J. R., Bame, S. J., and Strong, I. B., J. Geophys. Res., 73, 5777-5782, 1968.
[2] Krimigis, S. M., Venkatesan, D., Barichello, J. C., and Sarris, E. T., Geophys. Res. Lett., 5, 961-964, 1978.
[3] Balogh, A., Hynds, R. J., van Rooijen, J. J., Stevens, G., Domingo, V., Sanderson, T. R., and Wenzel, K.-P., Eos Trans. AGU, 59, 1174, 1978.
[4] Scholer, M., Hovestadt, D., Ipavich, F. M., and Gloeckler, G., J. Geophys. Res., 86, 9040-9046, 1981.
[5] Klassen, A., Gómez-Herrero, R., Böhm, E., Müller-Mellin, R., Heber, B., and Wimmer-Schweingruber, R., Annales Geophysicae, 26, 905-912, 2008.
[6] Müller-Mellin, R., Gómez-Herrero, R., Böttcher, S., Klassen, A., Heber, B., Wimmer-Schweingruber, R., Duvet, L., Sanderson, T.R., Proc. of the 30th ICRC, Vol. 1, pp 371-374, 2008.
[7] Desai, M. I., Mason, G.M., Müller-Mellin, R., Korth, A., Dwyer, J.R., and von Rosenwinge, T.T., J. Geophys. Res., 113, A08103, 2008.
[8] Klassen, A., Gómez-Herrero, R., Müller-Mellin, R., Böttcher, S., Heber, B., Wimmer-Schweingruber, R., and Mason, G. M., Ann. Geophys., 27, 2077-2085, 2009.
[9] Gómez-Herrero, R., Klassen, A., Müller-Mellin, R., Heber, B., Wimmer-Schweingruber, R., and Böttcher, S., J. Geophys. Res., 114, A05101, 2009.
[10] Krucker, S., Larson, D. E., Lin, R. P., and Thompson, B. J., ApJ, 519, 864-875, 1999.
[11] Sarris, E. T., Krimigis, S. M., Bostrom, C. O., and Armstrong, T. P., J. Geophys. Res., 83,4289-4305, 1978.
[12] Anagnostopoulos, G. C., Rigas, A.G., Sarris, E.T., and Krimigis, S. M., J. Geophys. Res., 103, 9521-9533,1998.
[13] Burgess, D., Lect. Notes Phys. 725, 161-190, 2007.
[14] Ipavich, F.M., Galvin, A.B., Gloeckler, G., Scholer, M., and Hovestadt, D., J. Geophys. Res., 86, 4337, 1981.
[15] Müller-Mellin, R., Böttcher, S., Falenski, J., Rode, E., Duvet, L., Sanderson, T. R., Butler, B., Johlander, B., and Smit, H., Space Science Reviews, 136, 363-389, 2008.