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ION RELEASE EXPERIMENTS IN THE SOLAR WIND

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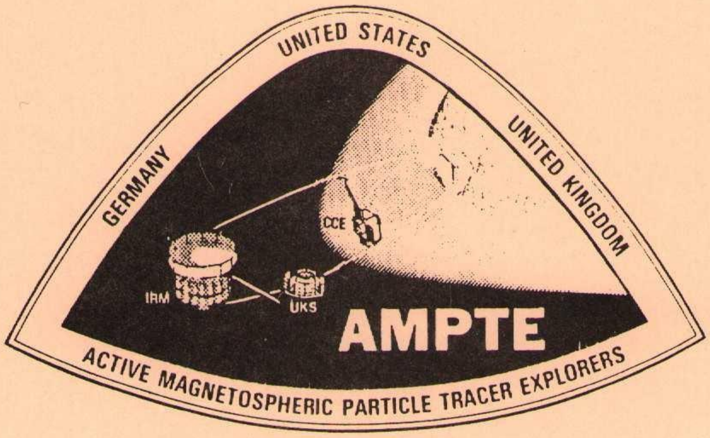

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ION RELEASE EXPERIMENTS IN THE SOLAR WIND

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ABSTRACT

In a new departure in experimental Space Plasma Physics, lithium and barium plasmas were injected into the solar wind approximately 110,000 kms above the Earth's surface. The effects, monitored in-situ by two spacecraft of the AMPTE (Active Magnetospheric Particle Tracer Explorers) mission, included the formation of diamagnetic cavities, a slowing down locally of the solar wind, generation of plasma waves and heating of solar-wind electrons. These comet-like interactions between the solar wind and obstacles presented by the injected plasmas are discussed and compared with the effect of the natural obstacle of the Earth's magnetosphere first encountered by the solar wind at the bow shock. Particular reference is made to the "artificial comet" created by a barium-ion release on 27 December 1984.

INTRODUCTION

A new era in experimental Space Plasma Physics can be said to have begun in August 1984 with the launch of three spacecraft to study the interaction of the solar wind with the Earth's magnetosphere and with plasma injected into the solar wind. The mission explores a wide range of plasma phenomena including collisionless shocks, wave-particle interactions and particle acceleration which have applications in the laboratory as well as in planetary magnetospheres, the sun and astrophysical plasmas. The plasma environment of the Earth offers an excellent, and in many ways even the best, opportunity for studying the microphysics of these plasma processes.

AMPTE

The three-satellite mission AMPTE (Active Magnetospheric Particle Tracer Explorers) employs spacecraft from Germany, the U.S.A. and the United Kingdom (Krimigis and others 1982; Bryant, Krimigis and Haerendel 1985). The Ion Release Module (IRM) built in Germany (Häusler and others 1985) and the UKS from the United Kingdom (Ward and others 1985) operate in tandem in an orbit which, having an apogee of 18.5 Earth Radii, takes them into the solar wind during part of the mission (see Fig. 1). The IRM carried at launch 16 canisters of Ba/CuO or Li/CuO mixtures which on release could be detonated to produce expanding clouds of barium or lithium vapour which became photo-ionized by solar radiation (Haerendel and others 1985). The IRM and UKS carry comprehensive sets of charged-particle, wave and field instruments to study the interactions of the barium and lithium plasmas so produced with the solar wind (see a series of papers in 1985 accompanying those cited above). Three of these interactions, a barium release on 27 December 1984 and lithium releases on 11 and 20 September 1984, form the subject of the present paper. One of the main functions of the Charged Composition Explorer (CCE) from the USA (Dassoulas and others 1985) was to ascertain whether the ions injected into the solar wind, and in later events released inside the Earth's magnetosphere, could be traced into the heart of the Earth's radiation belt. The high-resolution instrumentation on all three spacecraft

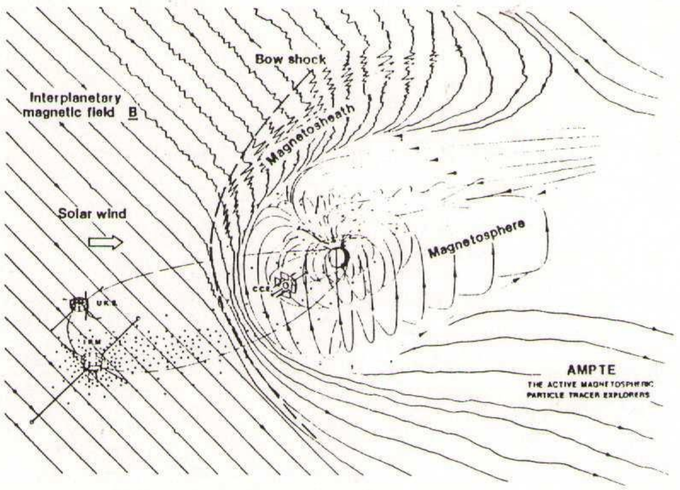

Fig. 1 Schematic of the AMPTE mission showing the orbits of the three spacecraft, IRM, UKS and CCE, in relation to the Earth's magnetosphere, bow shock and solar wind. The orbits, shown in their September 1984 positions, precessed in local time about the Sun-Earth line at approximately 1 degree per day.

made them particularly well equipped also for studying the structure, composition and dynamics of the solar wind and the magnetosphere, and their regions of interaction at the bow shock where the solar wind first encounters the Earth and at the magnetospause where the two plasma regimes meet.

Space Plasmas

The plasmas we shall be investigating normally have number densities of only 1-100 cm^{-3} i.e. 10 or more orders of magnitude lower than in Tokamaks and lasers plasmas. They are so tenous, with Debye lengths of 100m or more, that it might at first be questioned whether they can be expected to exhibit collective plasma behaviour at all. However when one takes into account their vast scale and notes that the number of Debye lengths across the magnetosphere, say, is 10^5 - a figure that is typical also of Tokamaks and laser plasmas - and discovers that the number of particles in a Debye sphere is 10^{13}, it is clear that they can be considered as very high quality plasmas indeed.

While working in such a giant arena poses a number of special problems there is the overwhelming advantage that the processes occurring can be examined without seriously perturbing the environment.

SOLAR WIND IONS AND ELECTRONS AT THE BOW SHOCK

Let us look first at the medium in which the ion-release experiments were conducted, i.e. the solar wind in the region of the Earth's bow shock. The behaviour of ions and electrons here will form a useful reference for that during the releases. The medium appears typically to the plasma instruments of the UKS (Coates and others 1985; Shah and others 1985) as shown in Fig. 2 which is taken from the real-time data display of 12 November 1984. At 11.55 UT and for some 2 minutes after this, the spacecraft in the solar wind observes solar-wind protons with their narrow-band energy spectrum centred on this occasion at approximately 1.5 keV (539 km s^{-1}) flowing directly away from the sun. Before the spacecraft is overtaken at 11.57 UT by an outward excursion of the bow shock, an additional beam of ions can be seen with energies between 5 keV and 20 keV. Further

examination reveals that these ions are travelling upstream after acceleration at the bow shock (A.D. Johnstone, private communication). The Earth is thus seen to be an effective particle accelerater, though the details of the process are as yet far from being understood. Between 11.57 UT and 12.08 UT the spacecraft is immersed in the heated solar-wind plasma which forms the magnetosheath. The proton temperature is clearly higher than in the solar wind proper as is evident from the broader range of energies. The mean flow velocity is lower and the flow more turbulent. After 12.08 UT the spacecraft re-emerges into the solar wind where bow-shock-accelerated ions are again seen. The electron behaviour is different but closely co-ordinated with that of the ions.
The solar-wind electrons have a monotonically falling spectrum with a mean energy, in the measured range of 12 ev - 18 keV, of several tens of electron volts. Within the magnetosheath the mean energy increases to greater than 100 eV and there is also an increase in number density from $5 cm^{-3}$ to $20 cm^{-3}$.

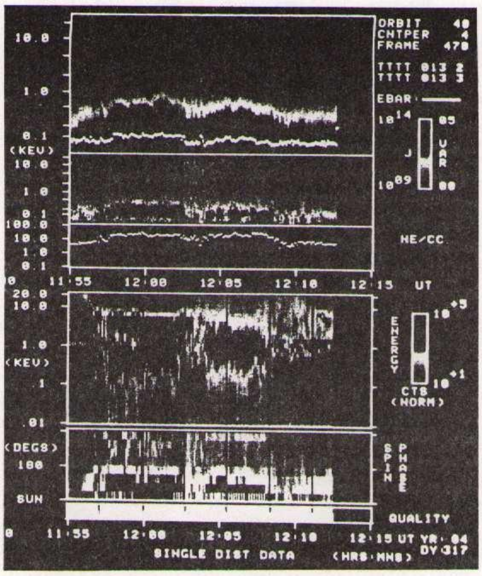

Fig. 2 Electrons and positive ions recorded from the UKS in the vicinity of the bow shock on 12 November 1984 between 11.55 and 12.15 UT. The panels taken from the real-time display show from top to bottom as functions of time:- electron intensity versus energy with mean energy (EBAR) indicated, the variability over a 5-sec period of electron intensity (variance/expected variance), electron density, positive-ion count rate versus energy, the azimuthal distribution of ion count rate and a measure of data quality. For discussion see text. A colour version of this figure is available on request.

THE BARIUM ION RELEASE OF 27 DECEMBER 1984

Ion Release

A cloud of barium vapour expanding at 1 km s^{-1} was created by releasing from the IRM two canisters containing a Ba/CuO mixture which was subsequently ignited (Haerendel and others 1985). The 3.4 x 10^{24} barium atoms (0.79 kg) released by this means became photoionized with a time constant of ≈28s to form a barium plasma expanding into the solar wind on the dawn flank of the magnetosphere upstream from the bow shock.

Diamagnetic Cavity

The expanding barium plasma created a diamagnetic cavity in the solar-wind magnetic field. The cavity, whose radius of 75 km was determined by a balance between the kinetic pressure of the expanding plasma and the pressure of compressed solar-wind magnetic flux on the outside, did not extend to the UKS located 170 kms away. The UKS however observed the enhanced magnetic field outside the cavity which the IRM also observed after a period of 70 s when the cavity moved downstream due to a pressure imbalance. The details of this motion are still the subject of investigation. Figure 3 shows the magnitude of the magnetic field observed at the IRM and UKS following the release. The close correspondence at the two spacecraft of the enhanced fields after 12.34:20 UT demonstrates

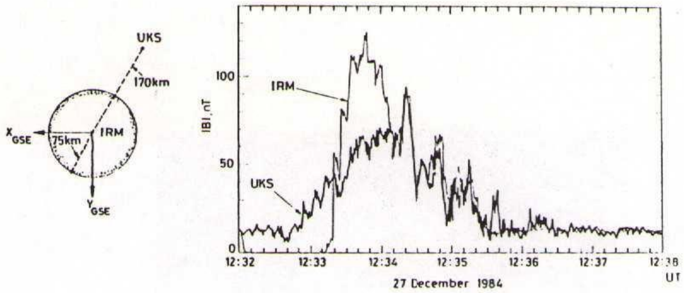

Fig. 3 Diamagnetic cavity created by barium-ion release at 12.32 UT 27 December 1984. The cavity is evident from the depression to zero of the magnetic field at the IRM at the centre of the cavity. Enhanced magnetic fields are recorded by the UKS outside the cavity and by the IRM when it emerges. In the Geocentric Solar Ecliptic co-ordinate system employed above X is directed towards the sun, and Y forms a right-handed system with Z (not shown) directed towards the ecliptic pole. On this occasion B remained approximately in the X-Y plane. (Courtesy H Lühr and D J Southwood)

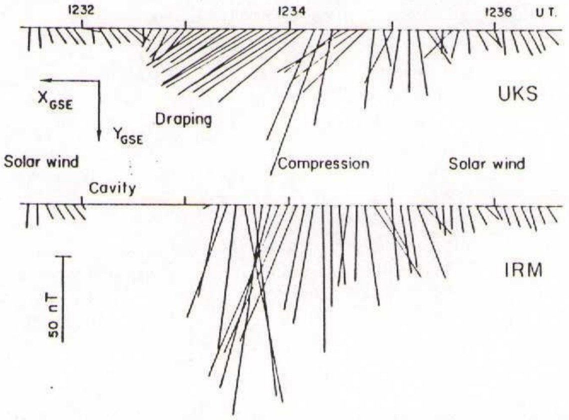

Fig. 4 Magnetic vectors at the UKS and IRM following the barium-ion release illustrating the diamagnetic cavity (at the IRM), field draping (at the UKS) and magnetic flux compression encountered by both spacecraft. The field remained approximately in the X-Y plane throughout the event. (Courtesy H Lühr and D J Southwood).

the coherence of the disturbance over at least the spacecraft separation distance of 170 km. The sequence of magnetic-field vectors shown in Fig. 4 exhibits, in the pronounced sunward component which develops at the UKS between 12.32:30 UT and 12.35:00UT, the "magnetic draping" anticipated for the interaction between the solar wind and obstacles in its path such as unmagnetized planets and comets.

The comet-like nature of the event is very apparent in the low-light-television image (Fig. 5), taken from an aircraft flying above the Pacific Ocean, of the 400-km diameter coma of excited barium atoms and ions and its extension downstream into a tail many thousands of kilometres long. It was in order to obtain this profile view of the phenomenon that the release had been performed on the (dawn) flank of the magnetosphere. A second "artificial comet" has since been produced in the magnetosheath on the dusk flank of the magnetosphere.

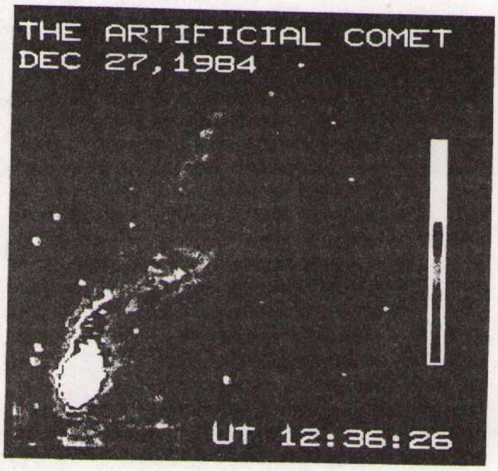

Fig. 5 The "artificial comet" created by the barium-ion release recorded by a low-light television camera of the Max Planck-Institute for Extraterrestrial Physics, Munich, on an aircraft of the Argentinian Airborne Station. (Courtesy A. Valenzuela).

Perturbation to solar wind-ions

Figure 6 shows the effect of the release on solar-wind ions reaching the UKS. The ions are temporarily retarded by approximately a factor of 2 in velocity. A similar effect was observed at the IRM within the diamagnetic cavity, clearly representing a local breakdown of the "frozen-in-field" condition. First indications are that the retardation was accompanied by little, if any, rise in temperature, though there were marked changes of flow direction. There is clearly more than a superficial resemblance to events at the Earth's bow shock as depicted in Fig. 2.

At 12.34:20 UT barium ions which had been accelerated in the $\underline{E} = -\underline{V} \times \underline{B}$ electric field can be seen, $\underline{V}$ being the solar-wind velocity and $\underline{B}$ the magnetic field. These ions are in the initial stage of a cycloidal motion constituting their "pick-up" by the solar wind, so demonstrating another feature anticipated for the interaction between comets and the solar wind.

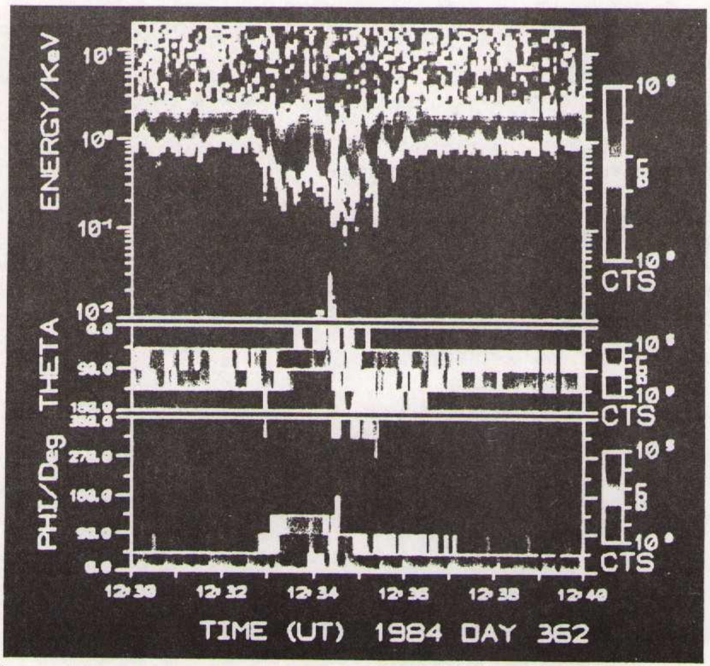

Fig. 6 Perturbation to solar-wind ions caused by barium release. The panels show from top to bottom:- ion (proton)count rate versus energy and summed over all directions, count rate versus elevation in GSE co-ordinates and summed over energy and azimuth, and count rate versus azimuth summed over energy and elevation.
(Courtesy A.D. Johnstone). A colour version of this figure is available on request.

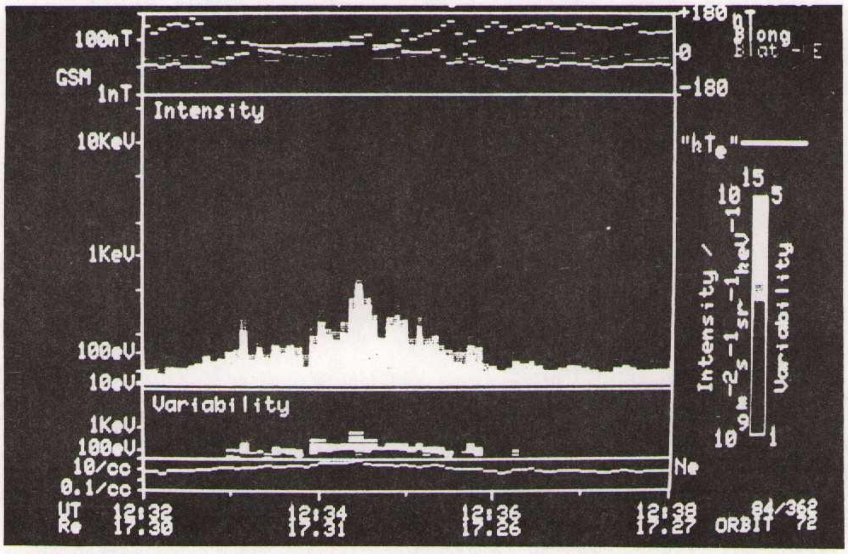

Fig. 7 Perturbation to solar-wind electrons caused by barium release. The top panel gives as a reference (Courtesy D J Southwood) the magnitude (strong line) and longitude (weaker line) of the magnetic field. The latitude trace is indistinct in this black-and-white reproduction. The main panel shows electron intensity versus energy with 2/3 mean energy (kT_e) indicated. Variability over a 5-sec period (variance/expected variance) and density are also shown. A colour version of this figure is available on request.

Perturbation to solar-wind electrons

Electron intensities at the UKS (see Fig. 7) showed a marked increase following the release (Bryant, Hall and Chaloner 1985), due primarily, we believe, to an energization of solar-wind electrons, causing a given velocity-space density or intensity (proportional to velocity-space density x energy) to appear at a higher energy. A possible contribution from the barium photoelectrons, currently being assessed, is thought to be limited to energies below those being observed (6 eV - 25 keV). Comparison of Fig. 7 with Fig. 2 reveals a marked similarity between energization by the release and that occurring naturally at the bow shock.

The distortion to the electron distribution function can be evaluated by comparing a spectrum taken near the maximum of the effect with the solar wind spectrum in Fig. 8a. These spectra are averaged over all directions of motion and thus permit only an initial analysis at this stage. Using the reference line whic corresponds to a uniform energy gain of 160 eV at all energies it can easily be seen that energization takes places preferentially at initial energies above 30 eV, while lower energies are hardly affected. A very similar effect was observed at the IRM (G. Paschmann, private communication) both within and outside the cavity.

Possible mechanisms currently being considered for the energization are betatron acceleration in the enhanced magnetic field, acceleration through a potential drop and acceleration due to wave-particle interactions. We favour the last of these since lower-hybrid waves which travel with phase velocities parallel to $\underline{B}$ equal to or greater than the electron thermal velocity would resonate only with the higher energy portion of the electron spectrum and thus provide a natural explanation for the preferential acceleration of higher energy particles (Bryant, Hall and Chaloner 1985). This mechanism was advanced earlier to explain electron acceleration in the aurora (Bingham, Bryant and Hall 1984). Further study is needed to establish the appropriate value of the electron thermal velocity in a spectrum as strongly non-Maxwellian as that of the solar-wind electrons (velocity - space density being approximately a power law in energy) with an admixture of photoelectrons at very low energies. Strong wave activity was observed at both the UKS and IRM (Hausler, and Woolliscroft, private communication) though in view of the very low lower-hybrid frequency applying in the barium-rich plasma it is not yet possible to confirm whether the lower-hybrid mode was indeed present. Figure 8b illustrates for direct comparison electron acceleration at the bow shock. The processes occurring here and as a result of the barium release are clearly very similar.

THE LITHIUM ION RELEASES OF 11 and 20 SEPTEMBER 1984

Lithium clouds expanding at 4.5 km s^{-1} were produced by Li/CuO reactions on 11 and 20 September 1984 upstream from the sub-solar point of the Earth's bow shock (Haerendel and others 1985). The 1.1 x 10^{25} atoms (0.13 kg) became photo-ionized with a time constant of $\sim$1hr. Ion production was slower but more sustained than in the case of the barium release with the main purpose of creating a source of tracer ions in the solar wind for later detection by the CCE within the magnetosphere. Diamagnetic cavities were neverthless produced by the initial pressure of expansion as shown in Fig. 9. The UKS had been manoeuvred close to the IRM for these events and, due to the marginally different inter-planetary conditons, was just reached by the cavity on 11 September while on 20 September it remained just outside.

The obstacles presented by the diamagnetic cavities again resulted in enhanced magnetic fields, retardation of solar-wind ions, wave generation and electron energization. Electron spectra at the height of the disturbances are shown in Figs. 8c and 8d. While the effects of the relatively small obstacles are naturally weaker than during the barium release and at the bow shock, they are evidently of the same kind.

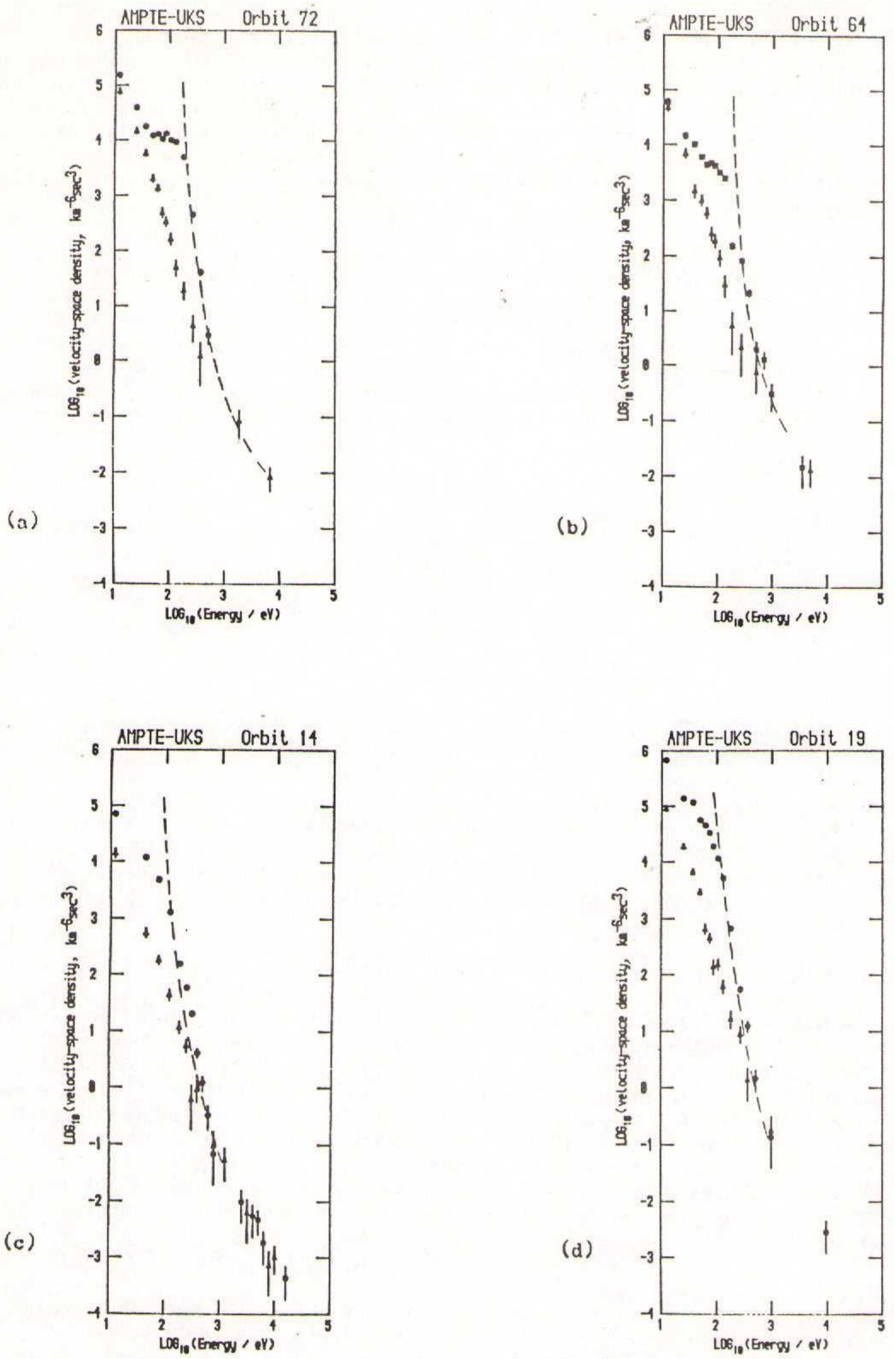

Fig. 8 Electron velocity-space density spectra in the solar wind (†) compared with those (ϕ) encountered (a) following the barium release of 27 December 1984, (b) in the magnetosheath, (c) following the lithium release of 11 September 1984 and (d) following the lithium release of 20 September 1984. The dashed lines represent uniform acceleration of solar wind electrons of 160 eV, in (a) and (b) and 80 eV in (c) and (d).

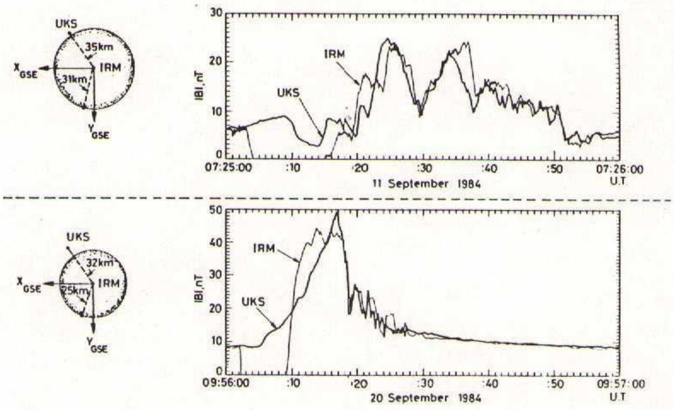

Fig. 9 Diamagnetic cavities created by lithium ion releases at 07.25 UT on 11 September and at 09.56 UT on 20 September 1984. The cavities are evident from the depressions to zero of the magnetic field at the IRM in the centre. Enhanced magnetic fields are recorded by the UKS outside the cavities except around 07.25:12 on 11 September, and by the IRM when it emerges.
(Courtesy H. Lühr and D.J. Southwood).

CONCLUSIONS

While a full and careful appraisal of these ion release experiments needs to be carried out, a number of preliminary conclusions can already be drawn. There is a strong similarity between the effects of the artificial obstacles to the solar-wind flow and the effect of the Earth's bow shock: solar-wind energy appears to be converted into wave turbulence and thence into electron energization with strikingly similar characteristics in all cases. It can be anticipated, therefore, that the AMPTE ion release experiments will prove valuable also in understanding the natural interaction between the solar wind and the magnetosphere and the intriguing plasma processes occurring there. It can be hoped further that the phenomena revealed in considerable detail in these space plasmas may prove useful in understanding and ultimately harnessing parallel phenomena in the laboratory.

ACKNOWLEDGEMENTS

The above report outlines just some of the wide range of topics currently under discussion within the AMPTE Joint Science Working Group. The views expressed owe much to these discussions, though at this early stage they do not necessarily represent a consensus. I am especially indebted to Drs. A.D. Johnstone, H Lühr, D.J. Southwood and A. Valenzuela for allowing results to be included prior to publication.

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