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Characteristic boundary transitions in energetic particle data (60–≥260 keV) recorded at comets P/Grigg–Skjellerup and P/Halley by the EPONA instrument on Giotto

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Abstract. An overview of published magnetic field, low energy electron and low to intermediate energy ion data recorded on board Giotto during an encounter with P/Grigg–Skjellerup (G–S) on 10 July, 1992 is presented and these measurements compared with particle data secured by the onboard energetic particles experiment EPONA ($E = 60$ to ≥ 260 keV). It is shown that, in general, the same cometary boundaries (Bow Wave, Bow Shock, Mystery Boundary Transitions (MBTs)) were sensed in energetic particles as by the other experiments. Elevated fluxes of accelerated particles, interpreted to be ions of species $M = 16$–18, were identified in the G–S cometosheath. It is inferred that heavy cometary ions of species $M = 28$–33 were present in the innermost region of the comet (as viewed in the sunward direction). Energetic particles recorded by EPONA on Giotto at P/Halley are considered relative to other particles and fields measurements obtained onboard. Evidence based on pitch angle data indicates that, inbound, the MBTs at G–S and at Halley, were spatially associated with changes from trapped to "flowing" distributions of water group ions, suggesting that mirroring of these particles was taking place during encounter in the magnetic field piled up around each comet. Downstream of the MBTs, outbound, flowing distributions were, in each case, identified. Evidence of MBTs in energetic particle data are, herein, reported for the first time. The roles of various mechanisms in accelerating cometary ions in association with Bow Wave/Bow Shock boundaries at G–S and at Halley are inferred from comparisons between experimental and theoretical spectra pertinent to each comet. Similarities and differences between the signatures of characteristic boundaries recorded in each case are discussed in the light of basic differences between the comets themselves, and between the ambient interplanetary circumstances pertaining during each cometary encounter. © 1997 Elsevier Science Ltd

1. Introduction

One of the key philosophies underlying the decision to command the Giotto spacecraft on to an encounter with comet P/Grigg–Skjellerup (G–S) on 10 July 1992, following its highly successful encounter with comet P/Halley on 13/14 March, 1986, was to compare, using measurements made with the same suite of plasma and fields instruments, a comet having a low gas production rate (G–S) with very active and "fresh" comet Halley.

Since the G–S encounter was duly implemented according to this plan, several papers have appeared containing the first results from the onboard experiments including: for the Magnetometer Experiment MAG (Neubauer *et al.*, 1993a, 1993b; Glassmeier and Neubauer, 1993); for the 3-dimensional electron spectrometer of the RPA-Copernic Experiment which recorded cometary electrons in the range from a few eV to approximately 350 eV (Reme *et al.*, 1993); for the Ion Mass Spectrometer–High Intensity Spectrometer (IMS–HIS) which, at G–S, operated in the energy/charge range 300–1400 eV e^{-1} and responded, since there was no momentum selection, to any mass/charge ions in this energy/charge range (Goldstein *et al.*, 1994); for the Implanted Ion Sensor of the JPA instrument, which recorded ions in the range 86 eV to 86 keV with sufficient mass resolution to distinguish between the major mass groups and to provide 4π coverage (Coates *et al.*, 1993a, 1993b; Johnstone *et al.*, 1993) and, for the energetic particle detector EPONA which recorded pro-

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tons and heavier ions in the range several tens of keV to several tens of MeV (McKenna-Lawlor *et al.*, 1993a, 1993b).

1.1. *The present study*

In the present Section 1 an overview is provided (below) of signatures recorded by the MAG, RPA, IMS and JPA instruments on Giotto during Bow Wave/Bow Shock, and during Mystery Boundary Transitions (MBTs) at G–S. Also, these accounts are compared with preliminary published data recorded in energetic particles ($E \geq 60$ keV) by the EPONA instrument. Against this background, a more detailed comparison than was hitherto made between the published particles and fields records and the EPONA energetic particle data is presented in Section 2 in an attempt to determine if the same cometary boundaries were sensed in energetic particles as were reported by the other experimenters. All of the events discussed are described in terms of Spacecraft Event Time (SCET). MBTs identified in energetic particle data recorded inbound and outbound at G–S are reported (for the first time) in Sections 2.2 and 2.3. Characteristics of the inner region between these transitions are described in Section 2.4. Energy spectra recorded during the inbound and outbound Bow Wave/Bow Shock traversals are presented in Section 2.5. Energetic particle observations made by EPONA at comet P/Halley (Halley hereafter) are presented in Section 3. The characteristics of MBTs identified in the Halley data; of Halley's innermost region and of energy spectra recorded close to the times of inbound and outbound spacecraft traversals of the Halley Bow Shock and Bow Wave surfaces are reviewed in Sections 3.1–3.4.

In Section 4, the various observations presented in Sections 2 and 3 are individually discussed. In Section 4.6 an overview is provided of similarities and differences identified between the energetic particle records obtained at G–S and at Halley and the various observations are attributed (a) to basic differences between these comets and (b) to differences between local interplanetary circumstances pertaining at the time of each comet/spacecraft encounter. General conclusions are contained in Section 5.

1.2. *Overview of reported Bow Wave/Bow Shock transitions at Grigg–Skjellerup*

At G–S, pickup ion-related wave signatures with a frequency close to the local water group ion gyrofrequency were recorded upstream to a distance of 624×10^3 km and downstream to a distance of 424×10^3 km from the nucleus in magnetometer data (Glassmeier and Neubauer, 1993). No shock was observed inbound, in the sense that no jump in the magnetic field vectors between two relatively uniform regions was recorded (Neubauer *et al.*, 1993a). A feature at 14.55 SCET was, however, deemed by the magnetometer team to constitute the magnetic signature of a Bow Wave. The magnetic quantities averaged over a water group cyclotron period increased continuously inbound until a fast variation occurred at the Pile Up Boundary at 15.17 SCET; a maximum was displayed at 15.18.48 SCET and a sharp drop at 15.20 SCET. There was no evidence that a magnetic cavity was traversed. Outbound, a characteristic change noted in the magnetometer data at 15.49 SCET was interpreted to constitute the transition by the spacecraft of a Bow Shock.

A phenomenological study of the electromagnetic plasma waves characterizing the solar wind–comet interaction region at G–S was provided by Glassmeier and Neubauer (1993). See also the complementary paper by Neubauer *et al.* (1993b). Overall, the magnetic data were shown to indicate the presence of very regular wave fields just upstream of the G–S Bow Wave/Bow Shock. It was suggested by Neubauer *et al.* (1993b) that either strong deviations from gyrotopy (see Section 1.3) or nonlinear dispersive effects could be responsible for the production of the regular wave forms observed. Also, the power spectra and polarization observations in combination with the pertaining Alfven Mach number indicate that, in the plasma frame (in contrast to what was observed at P/Halley), left-hand polarized Alfven waves with a propagation direction away from the Sun provided the dominant mode. In the region of transition to the (inbound) Cometosheath, regular waveforms were again displayed (although the properties of the associated convariance tensor were not simple). The Cometosheath itself was characterized by strongly compressive variations produced in connection with the formation of the Bow Wave/Bow Shock.

In RPA electron data, the first unambiguous evidence of any effect on the electron fluxes was detected upstream at 41.8×10^5 km from the nucleus, where periodic modulation of the measured electron fluxes with a period close to the local water group ion cyclotron period was identified—suggesting the ambient presence of waves excited by the pickup of cometary ions (Reme *et al.*, 1993). Nothing prominent was observed inbound in the data at 14.55 SCET. However, traversal of a broad transition region (width $\approx$ 9000 km) interpreted to constitute the inbound Bow Wave, was deduced to occur between about 14.47 and 14.58 SCET. At the latter time, peak electron fluxes which were modulated at the local water group ion cyclotron period abruptly increased at energies up to about 100 eV, thereby clearly indicating that Giotto had entered the Cometosheath. The outbound Bow Shock transition at 15.49 SCET was relatively clear and sharp but, between 15.49 and 16.03 SCET, a "Foreshock" (thickness $\approx$ 12 000 km) was recorded in the electron data.

A comparative study of electron plasma parameters and magnetic field data was carried out by Mazelle *et al.* (1995) around the inbound and outbound shock transitions and at the Magnetic Pile Up Boundary. This latter region was characterized by a sharp magnetic discontinuity in the inner Cometosheath (a location which was marked at Halley by a jump in magnetic field strength correlated with significant changes in the ambient electron plasma (Neubauer, 1987; Mazelle *et al.*, 1989)). These comparisons indicate that the cometary boundaries identified at G–S show strong similarities with those at Halley, and reveal that the G–S plasma environment is highly structured on a length scale smaller than a cometary ion gyroradius.

The IMS–HIS instrument measured fluxes of ions at

G–S from 260×10^3 km before to about 86×10^3 km after Closest Approach. The ions recorded were probably protons, although the presence of heavier ions cannot be ruled out (Goldstein *et al.*, 1994). Bow Wave/Bow Shock crossings were identified to occur at approximately 14.55 and 15.49 SCET respectively and an outbound "Foreshock" was also detected. Strong modulation of the measured fluxes at the water group ion cyclotron period inside the inbound Bow Wave, and the correlation of this modulation with changes in the ambient magnetic field direction, were interpreted to indicate that, close to the nucleus, the ion pitch angle distribution was very narrow and exhibited little evidence of scattering.

The JPA instrument first detected cometary ions in its water group channel at 5×10^5 km from the nucleus inbound, and the last ions were detected at 2.8×10^5 km outbound (Johnstone *et al.*, 1993). A sudden change in the ion plasma flow direction at 14.55.53 SCET (inbound) and at 15.49 SCET (outbound) were deemed associated with shock related boundary transitions. Further analysis of the JPA data showed that the distributions of cometary water group ions were ring-like (see below) until quite close to the shock; also, the fall off of cometary ion density with distance from the nucleus was demonstrated to follow an r^{-2} dependence (Coates *et al.*, 1993a). More detailed studies by Coates *et al.* (1993b) indicate that the pitch angle width of the distributions increased between 60×10^3 km (inbound) and 85×10^3 km (outbound). Non gyrotropy was an important feature of the ion distributions throughout the encounter and the extent of this nongyrotropy increased significantly in the vicinity of the nucleus. This effect was attributed to the relatively low gas production rate of G–S, which results in a significant density gradient of implanted ions relative to the cusp to cusp distance of the nominal cycloidal implanted ion trajectory (see Section 1.3).

The first signature recorded by the EPONA instrument in energetic particles close to G–S was reported to occur at $\approx 480 \times 10^3$ km from the nucleus inbound; similarly, the last signature outbound was identified at about 280×10^3 km from the nucleus (McKenna-Lawlor *et al.*, 1993a). A more recent study by Kirsch *et al.* (1996) shows that, at encounter, the comet was emersed in a Co-rotating Interaction Region (CIR) which added significantly to the energetic particle populations in the comet's environment. Nevertheless, cometary water group ions dominated the records from at least 09.00 SCET inbound on July 10 (when the spacecraft was at $\approx 318 \times 10^3$ km from the nucleus).

According to an energization process, the understanding of which is now mature (see, e.g. Galeev and Sagdeev, 1988; Coates *et al.*, 1993b), neutral molecules in an expanding cometary atmosphere become ionized by various mechanisms and a typical freshly formed ion, which is practically at rest in the comet frame of reference, is then accelerated along the motional electric field. Since it also gyrates around the magnetic field, its resultant path is a cycloid. If the angle between the interplanetary magnetic field and the solar wind flow is α, such "pickup ions" drift at a speed $v_{sw} \sin \alpha$ in the $\mathbf{E} \times \mathbf{B}$ direction and display a maximum energy on the cycloidal trajectory of $E_{max} = 4AE_{SW} \sin^2 \alpha$ (where A is the ion mass in amu and $E_{SW} = m_p v_{SW}^2/2$ is the kinetic energy of a solar wind proton). The shape of the velocity distribution function of these energized cometary ions is a ring in velocity space. This ring is in the plane perpendicular to the magnetic field; it is centered on the component of solar wind velocity perpendicular to the magnetic field and it has a radius equal to the solar wind velocity.

The unstable character of the ring distribution causes energy to go into plasma waves, and the turbulence thereby generated produces pitch angle scattering around a bispherical shell (Coates *et al.*, 1993b). If, in the flow rest frame, efficient pitch angle scattering has occurred, the peak energy of the ions is independent of the magnetic field direction ($E_{max} = 4AE_{SW}$), and the mean direction of motion depends only on the direction of the solar wind flow.

At comet G–S, the angle between the interplanetary magnetic field and the solar wind velocity vector was close to 90° during most of the encounter, thereby making the pickup geometry unusually simple. It was estimated by Johnstone *et al.* (1993) that, under the prevailing interplanetary conditions, water group ions would acquire a maximum pickup energy of 51 keV. At G–S however, close to the Bow Wave/Bow Shock transitions, the JPA instrument detected ions with energies up to 86 keV (the maximum energy detectable by JPA) (Coates *et al.*, 1993b). In the range extending from 60 keV to several tens of MeV covered by the EPONA instrument, particles interpreted by McKenna-Lawlor *et al.* (1993b) to be water group ions with energies from 60 to ≥ 260 keV were contemporaneously detected. This latter observation is in accord with ion energies previously recorded at comet Giacobini–Zinner by Hynds *et al.* (1986), and also at comet Halley, using both the EPONA instrument on Giotto (McKenna-Lawlor *et al.*, 1986) and the Tunde instrument on Vega 1 (Somogyi *et al.*, 1990). In the case of the records secured by EPONA, the fluxes measured at G–S were almost a factor of 100 lower than those at Halley, although the maximum particle energies attained in both cases were similar (≥ 260 keV). An acceleration mechanism in addition to the "pickup process" described above may thus be inferred to have been operative in each case (see also Section 1.5).

1.3. *Non gyrotropy of pickup water group ions at Grigg–Skjellerup*

As observed in JPA data, ring like distributions were present in the outer regions of comet Halley, with broader, partially filled, shells closer to the Bow Shock (Coates *et al.*, 1989, 1990). The timescales for pitch angle diffusion were generally in agreement with the predictions of quasilinear theory, although the observed energy diffusion timescale was longer (Huddleston *et al.*, 1991). At G–S on the other hand, the ion distributions were observed to be ring like until shortly before the Bow Wave crossing inbound. On the outbound pass, one sided pitch angle distributions were present from the Bow Shock (at 20 000 km from the nucleus) to 85 000 km further downstream, when the distributions, again, became ring like. It was inferred from these data that the timescale for energy diffusion may be similar to that for pitch angle diffusion.

Isotropic pitch angle distributions were never seen. Also, at G–S, deviations from gyrotropy were detected throughout the encounter and became more important near Closest Approach, see Fig. 10 of Coates *et al.* (1993b).

In the latter connection, when cometary ions are first injected into the solar wind flow, they follow a cycloidal path perpendicular to the magnetic field which is seen in velocity space as a ring distribution (Section 1.2). If the injection rate is varying along the cycloidal path, the ring will not be uniform and the distribution will not be gyrotropic. The ion injection rate as a function of the distance r from the nucleus is given by

$$\frac{\partial n_i}{\partial t} = \frac{Q}{4\pi L r^2}\exp\left[-\frac{r}{L}\right]$$

where Q is the gas production rate of the comet and L is the ionization scale length. L is the average distance travelled by a neutral before ionization and is of the order of 10^6 km. This is much larger than the scale size of G–S but is comparable with the size of Halley. The relative change in the injection rate over a distance Δr is

$$\frac{\Delta \dot{n}_i}{\dot{n}_i} = -\Delta r\left[\frac{1}{L} + \frac{2}{r}\right]$$

and the variation is only significant if Δr is comparable with r. Just outside the G–S Bow Shock (at a distance of 25 000 km from the nucleus) at the time of the Giotto encounter, the distance between cusps on the cycloid of a 51 keV water group ion in the prevailing magnetic field (16 nT) was estimated by Johnstone *et al.* (1993) to be 28 800 km. The relative change in the injection rate over one cycloid is therefore approximately a factor of two (the effect on the total ion density is less because that depends on the integrated flux picked up over the whole interaction region). The identification by Coates *et al.* (1993b) of nongyrotropic distributions at G–S is of special importance since such distributions can drive instabilities that effect the character of the waves detected by the other plasma instruments (see the discussion of Neubauer *et al.* (1993b)).

1.4. *Overview of reported Mystery Boundary Transitions at Grigg–Skjellerup*

Reme *et al.* (1993) identified two "Mystery Regions" at G–S characterized by the presence of significant fluxes of several hundred eV electrons. These regimes were analogous to Mystery Regions identified earlier at comet Halley (Reme *et al.*, 1987; d'Uston *et al.*, 1987) which were also characterized by (unpredicted) large fluxes of plasma electrons. Entry to the outbound "Mystery Region" at G–S was marked at 15.30.30 SCET by an MBT, beyond which the "Mystery Region" extended as far as the Bow Shock. The inbound "Mystery Region" was more difficult to identify but was deemed to extend between the Bow Wave and a further MBT at 15.12 SCET.

The JPA team reported several coincident sudden changes in the G–S plasma environment close to the reported MBTs (having regard to the 128 s time resolution of their instrument) (Johnstone *et al.*, 1993). These changes (which were similar to others previously identified in JPA data at comet Halley in association with analogous MBTs (Johnstone, 1990; Amata *et al.*, 1991)) included at −7200 km from the nucleus (the location of the inbound MBT), and at +9000 km from the nucleus (the location of the outbound MBT), the appearance of a second line in the cometary ion energy spectrum at energies which decreased as the nucleus was approached. This effect, which was also seen at comet Halley (where it was interpreted by Thompsen *et al.* (1987) to be due to local pickup in a draped magnetic field configuration), occurred at G–S, inbound and outbound, at about half the distance between the nucleus and the shock surface.

1.5. *Overview of Energy Spectra secured at comets*

An important result accruing to spacecraft observations made at comets Giacobini–Zinner, Halley and G–S is the detection in the environment of each of these bodies of particles with energies significantly in excess of the maximum available pickup energy (Section 1.2). Several processes, see for example Ip and Axford (1986), provide candidate mechanisms for producing the observed effect including (a) adiabatic compression occurring in the region of cometary plasma deceleration; (b) First Order Fermi acceleration: arising from the scattering of ions between waves present in the rapidly flowing upstream solar wind and the cometary bow shock surface, and/or waves located in the, downstream, mass-loaded, flow; (c) Second Order Fermi acceleration: a stochastic process of energy diffusion in the presence of strong wave turbulence, leading both to a deceleration and to an acceleration of particles.

Calculations by Ip and Axford (1986) show that adiabatic compression at comets can not, alone, produce the ion energies measured *in situ*. Theoretical spectra calculated by these authors on the basis of Second Order Fermi acceleration of cometary water group ions, were computed for a location along the trajectory of the ICE spacecraft at a distance of 2×10^5 km from the Giacobini–Zinner tail axis (a pick-up region well outside the shock surface). The calculations took into account the effect of adiabatic compression in the cometary flow and an adjustable parameter was provided by the ion mean free path λ, given in terms of the ion gyroradius r_g by $\lambda = kr_g$ (where k is a constant dependent on the level of turbulence). Calculated spectra computed for $k = 1$ and 5 were compared by Richardson *et al.* (1987) with corresponding experimental spectra measured at Giacobini–Zinner. The experimental spectra were thereby found to be considerably softer than the theoretical spectra and it was suspected that the amount of ion scattering assumed theoretically might have been over estimated.

Composite spectra prepared from water group ion measurements made contemporaneously by the EPONA and JPA experiments on Giotto at locations upstream of, and just downstream of, the inbound Halley Bow Shock, were compared by McKenna-Lawlor *et al.* (1989) with theoretical spectra similar to those described above, but this time computed by Ip and Axford for the case of a stream line which would intersect with the Giotto spacecraft when it was at the experimental measurement locations just mentioned. The calculations, as before, took account of adiabatic compression in the flow and assumed various levels of scattering. The results of these comparisons showed that, upstream of the Bow Shock, the k parameter was of the order of 30 whereas, just downstream of the shock, it was of the order of 5. This result, combined with consideration of energy spectra from the Giotto IMS experiment and the (above referenced) study made using Giacobini–Zinner data, led Ip and Axford (1987) to conclude that a relatively weak scattering limit, characterized by a large value of k (≈ 30), should be used when modelling upstream data; near the cometary shock front, however, acceleration mechanisms in addition to the Second Order Fermi effect should be invoked to explain the experimental measurements. In this connection, transit time damping by compressive magnetosonic waves as described by Fisk (1976), and statistical acceleration by lower hybrid waves as discussed by Buti and Lakhina (1987), were suggested to constitute candidate contributors to the observed particle energization.

An interplay between velocity and spatial diffusion was suggested by Gombosi *et al.* (1989) to be responsible for the acceleration of heavy implanted ions in cometary foreshocks. According to this latter scenario, the Second Order Fermi mechanism first accelerates particles to moderate energies, and this process is then followed by (more efficient) diffusive compressive shock acceleration. It was assumed, in this connection, that the entire foreshock serves as a region of diffusive–compressive acceleration for cometary ions, and a power law spectrum with a spectral index of 5–6 (above 100 keV) was predicted to be found.

The energy spectra of water group ions ($E_{H_2O} = 60$ to ≥ 270 keV) measured at a sequence of locations (both inbound and outbound) at comet G–S by the EPONA instrument were considered by Kirsch *et al.* (1991). In the present study, spectra measured in close association with transitions of the inbound and outbound shocks at this comet are presented in Section 2.5 and compared in the discussion of Section 4.4 with corresponding data obtained at Halley.

2. The EPONA instrument/Encounter Geometry

The EPONA Energetic Particle Analyzer features three semiconductor telescopes (T1, 2, 3), each with opening angle 30° and geometric factor $2.0 \times 10^{-2}\,\mathrm{cm}^2\,\mathrm{sr}$, employing similar discriminator levels in complementary channels. T1 and T3 each measure ions and electrons above an energy threshold determined by detector noise. T2 is fitted with a foil which prevents ions of approximately 300 keV from reaching the detectors, while permitting the passage of electrons. T1 and (T2 + T3) are inclined at 45° and 135° respectively to the positive spacecraft spin axis. Measurements made in eight contiguous sectors during each spacecraft spin provide an angular resolution of 45° and a time resolution of 0.5 s. Observations alternate between T1 and (T2 + T3), with T1 taking the odd sectors (1,3,5,7) and (T2 + T3) the even sectors (2,4,6,8).

Particle energies are determined by measuring their energy loss in the solid state detectors. Telescopes 1 and 3 were calibrated before launch for protons; for water group ions and for heavy ions, to each of which the detectors respond. The energy thresholds thus determined of (representative) Telescope 1 (Channels 1–4) are 29, 44, 78 and 217 keV for protons; 60, 97, 144 and 260 keV for water group ions and 92, 127, 206 and 460 keV for heavy (Ar) ions, respectively. Only data measured by Telescopes 1 and 3 in Channels 1–4 are considered in the present paper. A detailed account of the EPONA instrument is contained in McKenna-Lawlor *et al.* (1987).

Figure 1a provides a schematic representation of the encounter geometry at G–S in a plane perpendicular to the ecliptic and to the comet–Sun line, looking towards the Sun. The numbered lines represent the projections of the EPONA look directions onto the page for the individual sectors—solid lines looking out of the page, dashed lines into it. The shorter is a line, the further its look direction is away from the plane of the page. The dashed sectors view to sunward and the full line sectors view in the antisunward direction. See also Table 1 which lists the look directions of the 8 EPONA sectors at the time of Closest Approach to comet G–S (and also to comet Halley) expressed in the Comet Solar Ecliptic (CSE) coordinate system, where $+x$ points directly towards the Sun; the $+y$ axis (east) is parallel to the ecliptic plane in the direction opposite to the motion of the planets and the ecliptic north pole is near the $+z$ axis (i.e. lies in the $+zx$ plane).

2.1. *Energetic particle Bow Wave/Bow Shock signatures (at Grigg–Skjellerup)*

Figure 2 provides an overview of log fluxes (16 s averages) measured by EPONA during G–S Encounter in Channel 1 of T1, Sector 3 (T1,S3). The times of the Bow Wave and Bow Shock Crossings reported by Neubauer *et al.* (1993a) based on magnetometer data are designated by vertical lines and by the letters BW and BS, respectively. Closest Approach (reported by the Spacecraft Tracking Team to occur at 15.18.40 SCET) is designated by CA, and distances from CA on a scale of 10^3 km are provided. A Foreshock identified in the particle data outbound is labeled "F". Figure 3 shows the Foreshock as it appeared in the omnidirectional data (16 s averages) of EPONA's Channel 2, Telescope 1. Figure 4 presents (8 s averages) data recorded in Channels 1–2 of (T1,S3)—top two panels—and (T1,S1)—bottom two panels—within the interval 14.50–15.50 SCET spanning the traversal of G–S from Bow Wave to Bow Shock.

Significant changes in the energetic particle signatures occurred at 15.00 SCET (inbound) and at 15.44 SCET (outbound) in the data of Channel 1 (T1,S3), see Fig. 4. The first of these changes was gradual, the second very steep, and both changes occurred approximately 4600 km deeper inside the comet than the locations of the inbound Bow Wave and outbound Bow Shock reported on the basis of magnetometer data. Since the gyroradius of a singly charged 100 keV water group ion in the prevailing (average) magnetic field of 20 nT is ≈ 9650 km, the particle enhancements mentioned each occurred approximately

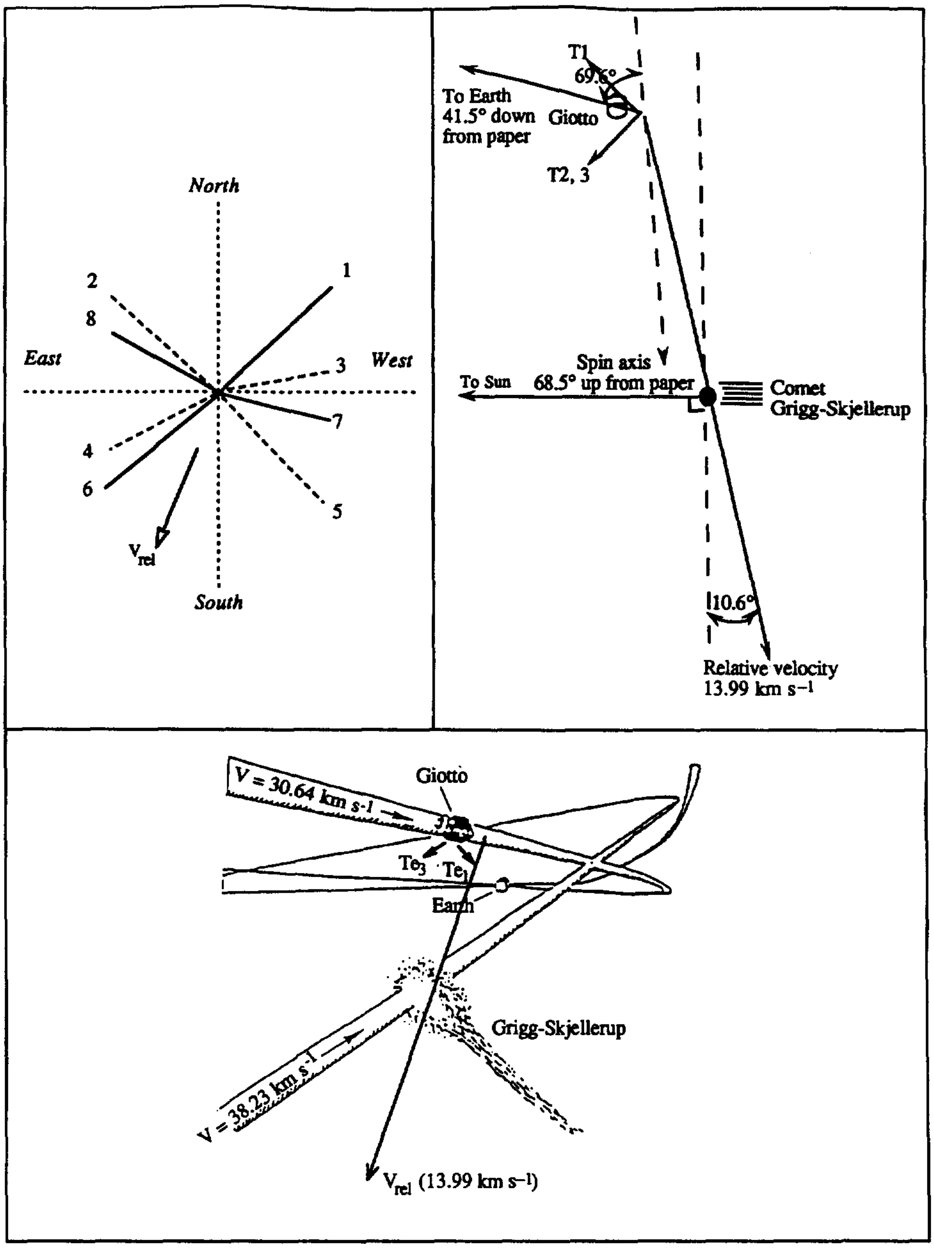

Fig. 1. (top left) Representation of the encounter geometry during the Grigg–Skjellerup flyby in a plane perpendicular to the ecliptic (the east–west axis) and the comet–Sun line, looking towards the Sun. V_{rel} is the direction of the velocity of Giotto relative to the comet, which was traversed in a direction from West to East and from North to South. The numbered lines represent the projections of the various EPONA look directions onto the page (based on eight 45° sectors), solid lines looking out of the page, dashed lines into it. The shorter is a line, the further its look direction is away from the plane of the page. The dashed sectors view to sunward and the full line sectors in the antisunward direction. See also the look direction assignments in the CSE system provided in Table 1. (top right) Representation of the spacecraft trajectory plane, showing V_{rel} and the look directions of the EPONA telescopes. Counts were made every 0.5 s during the 4 s spin of the spacecraft alternating between T1 in the odd (1,3,5,7) and (T2+T3) in the even sectors. (bottom) Computer graphic (from ESA), showing Giotto and comet P/Grigg–Skjellerup approaching each other, as seen from outer space. The spacecraft, comet and the Earth are each moving in roughly the same direction. The comet, passing through the ecliptic plane from the north is, in this representation, about to "catch up" with the spacecraft. The relative flyby velocity is 13.99 km s^{-1}

half a gyroradius deeper within the comet than the reported locations of the Bow Wave and Bow Shock. The well-defined "step" in particle intensities seen in the data of Fig. 4 at 15.44 SCET (see above), provides convincing evidence that the Bow Shock crossing (outbound) was sensed as a sharp boundary in energetic particles. This is consistent with the character of the crossing reported at 15.49 SCET by the other plasma experimenters (see Neubauer *et al.*, 1993b; Coates, 1995).

The small "Foreshock" recorded in energetic particles from 15.49–16.03 SCET (see Fig. 3), was also identified in RPA and IMS data. Glassmeier and Neubauer (1993)

Table 1. EPONA look directions at Grigg–Skjellerup and at Halley

The angles listed below are the CSE polar (θ) and aximuth (ϕ) angles, plus the angles to the sun ($+x$ axis) and to east ($+y$ axis).

Grigg–Skjellerup

At closest approach, the Giotto spin axis (pointing along the direction of motion) has the CSE coordinates $\theta = 90.0°$; $\phi = 90.4°$

From this, the look angles of the eight sectors are:

Sector =	1	2	3	4	5	6	7	8
θ	46.3°	53.4°	81.2°	112.3°	133.7°	126.6°	98.8°	67.7°
ϕ	−101.8°	62.2°	−45.3°	50.3°	−77.4°	118.6°	−133.9°	130.5°
To sun	98.5°	68.0°	46.0°	53.7°	80.9°	112.6°	133.3°	127.0°
To east	135.1°	44.8°	134.6°	44.7°	134.9°	45.2°	135.4°	45.3°
"From"	"West"	"East"	"Sun"				"A-Sun"	

The last line uses the designations used in Fig. 4.

Comet Halley

At closest approach, the Giotto spin axis (pointing along the direction of motion) has the CSE coordinates $\theta = 80.1°$; $\phi = 72.3°$

From this the look angles of the eight sectors are:

Sector =	1	2	3	4	5	6	7	8
θ	142.4°	119.0°	108.0°	62.4°	56.7°	43.2°	86.2°	102.7°
ϕ	125.8°	−49.0°	61.9°	−28.3°	94.4°	−102.8°	150.6°	−111.6°
To sun	110.9°	55.0°	63.4°	38.7°	93.7°	98.7°	150.4°	111.0°
To east	60.3°	131.3°	33.0°	114.9°	33.6°	131.9°	60.7°	155.1°
"From"	"East"	"Sun"					"A-Sun"	"West"

The last line uses the designations used in Fig. 8. Sector 4 was disturbed by sunlight. Otherwise it would have been taken as "Fm Sun".

reported, on the basis of an analysis of magnetometer records, that this was not a "classical" foreshock. Magnetic field lines were not connected to the shock and the region was characterized by smaller, less regular, fluctuations than were recorded further away in the solar wind. Also, the angle between the solar wind velocity vector and the magnetic field direction which displayed values close to 90° within F, slowly decreased to values closer to 60° in the upstream region. A study by Mazelle *et al.* (1995) shows that, at 15.48.42 SCET when a steep gradient in the magnetic field magnitude (the Bow Shock ramp) was recorded in magnetometer data, the electron parameters displayed a clear jump and there was an associated correlation between plasma density and magnetic field strength (B) variations characteristic of a fast mode type shock. A wave-like structure observed in B in the parallel electron pressure data and in the ≈ 300 eV electron flux was present in the interval 15.49–15.52 SCET, and the distance between these wave crests was of the order of the local oxygen gyroperiod in the mean upstream field. In the EPONA energetic particle records, no special enhancement was recorded at 15.49 SCET (at the Bow Shock ramp). Instead, irregular low amplitude fluctuations characterized the Foreshock interval 15.49–16.03 SCET. After 16.03 SCET the fluctuations recorded in the downstream solar wind were, relatively, less pronounced.

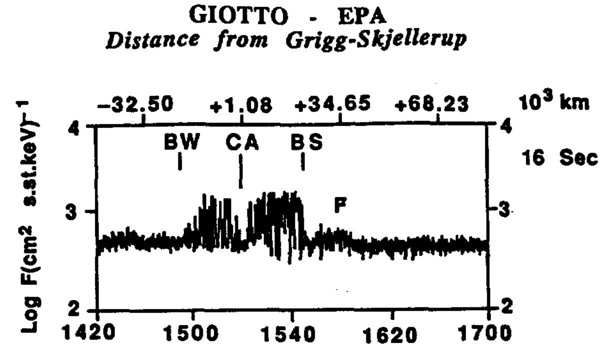

Fig. 2. Log fluxes (16 s averages) measured by EPONA in Channel 1, Telescope 1, Sector 3, within an interval spanning closest approach (CA) to P/Grigg–Skjellerup. The times of the Bow Wave and Bow Shock Crossings (identified by Neubauer *et al.* (1993a) in magnetic data), are designated by BW and BS, respectively. A Foreshock identified outbound is designated by F. Distances from Closest Approach on a scale of 10^3 km are also shown

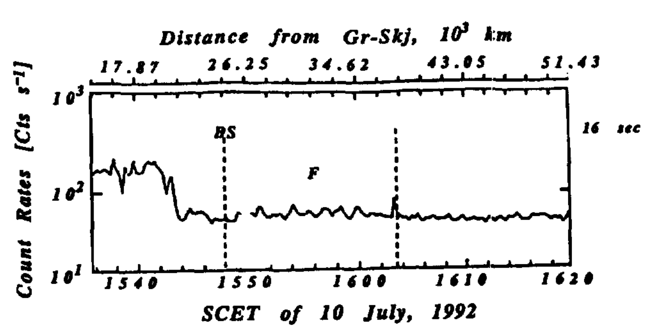

Fig. 3. Omnidirectional counts in the data of EPONA Channel 2, Telescope 1 (16 s averages) encompassing an interval, 15.49–16.03 SCET when a Foreshock signature (F) was recorded in energetic particle data. The location of the Bow Shock crossing identified in magnetometer data is designated by BS

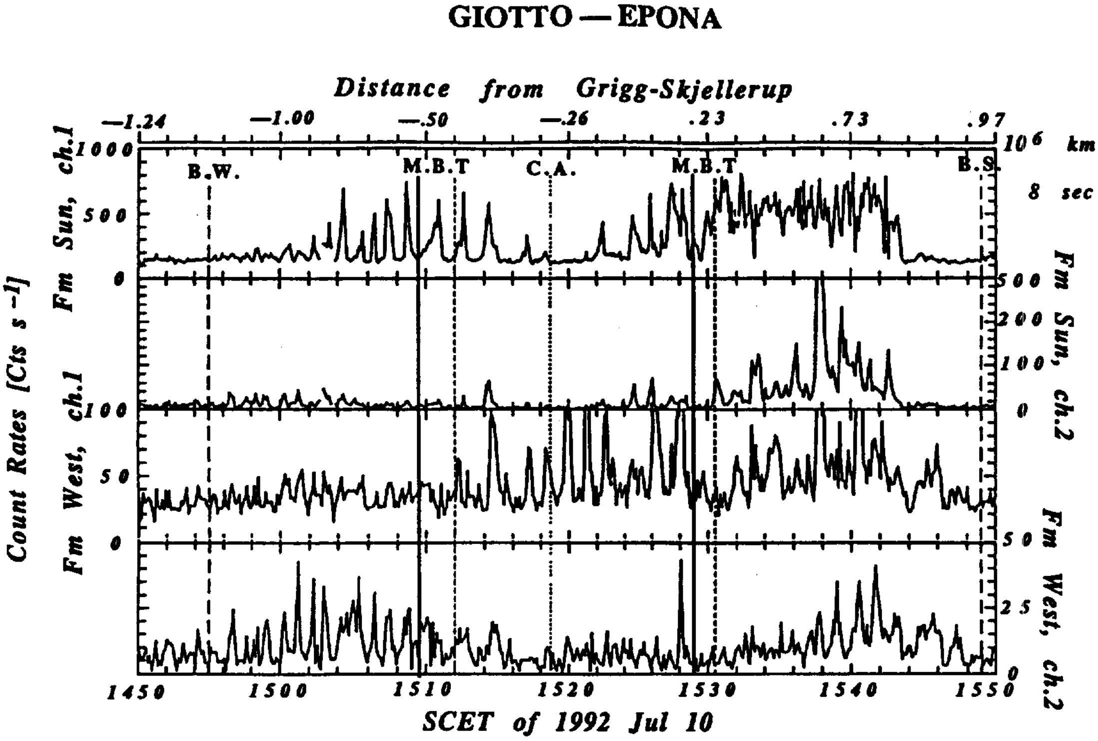

Fig. 4. Count rates (8 s averages) measured by EPONA in Channels 1 and 2 of both Telescope 1, Sector 3 (top 2 panels) and Telescope 1, Sector 1 (bottom 2 panels) between 14.50 and 15.50 SCET on 10 July, 1992. Correspondences between telescope/sector (T/S) combinations and CSE coordinates are provided in Table 1 (top). According to this specification, data from T1,S3 are plotted as coming "from the Sun" and data from T1,S1 as coming "from the west". The times of transition of Bow Wave/Bow Shock crossings reported in magnetometer data are indicated by vertical dotted lines and by the letters BW and BS. The times of Mystery Boundary Transitions (MBTs) identified in energetic particle data and in JPA data are indicated using full vertical lines and dotted vertical lines respectively, and by the letters MBT. Distances from Closest Approach (CA) are based on ESOC tracking data

2.2. *Energetic particle Mystery Boundary Transitions (at Grigg–Skjellerup)*

From 15.00 SCET (inbound) a significant change in energetic particle fluxes was observed in the data of Channel 1 (T1,S3), see Fig. 4 (top panel). A sequence of peaks, superimposed on the general particle background, was recorded with maximum fluxes at 15.04 SCET and at 15.09 SCET, when levels exceeding by about a factor of 5 those pertaining at the Bow Wave were observed (the corresponding data of Channel 2 show only minor changes). These variations are interpreted to represent Cometosheath particle signatures. The local cyclotron period of 100 keV water group ions in the average (20 nT) ambient magnetic field (period $T = 2\pi M/Bq$, where M represents ion mass, B magnetic field strength and q electronic charge) was about 1 min. Thus, the presence of a quasiperiodicity of about 1 min in the energetic particle fluxes recorded in the data of T1,S3 in the (inbound) cometosheath supports an earlier diagnosis, based on spectral analysis, that the particles recorded just upstream of G–S were predominantly cometary and of the water group (McKenna-Lawlor *et al.*, 1993b).

A change in the quasiperiodicity of the particle fluxes from ≈15.10 SCET (±1 min) by a factor of 1.8, without an accompanying change in B, suggests that a different cometary regime was entered by the spacecraft at this latter time. It is recalled (Section 1.4) that Johnstone *et al.* (1993) reported several coincident changes in the plasma environment of G–S at −7200 km (inbound) and that these changes were interpreted to represent traversal of an "MBT" of a type first reported by Reme *et al.* (1987) and d'Uston *et al.* (1987) in association with comet Halley.

The 128 s time resolution (corresponding to 1700 km) of the JPA measurements indicates an agreement between this observation and the EPONA based inference of a change in cometary regime at ≈15.10 SCET ±1 min.

Also, the (inbound) pattern change in energetic particles occurred at least 1 min before a Mystery Boundary crossing reported in low energy electron (RPA) data ($E < 300$ eV) by Reme *et al.* (1993) at 15.12 SCET (Section 1.4). Since the rigidity, and therefore the gyroradius, of energetic heavy ions is much larger than is the case for electrons, one would not expect close correspondences between the electron and energetic ion signatures and, indeed, they are dissimilar. However, the data suggest overall that the designation "MBT" defines a change in regime which can be sensed in energetic particles as well as in JPA and in RPA data. It can be inferred from the observational record that, in energetic particles, the Mystery Boundary (inbound) is not sharp. Rather, the transition from one cometary regime to the other is smooth and about 1000 km in width.

From approximately 15.29 to 15.30 SCET (outbound) the energetic particle data of Channel 1 (T1,S3) displayed a change from the quasiperiodic behaviour first identified at ≈15.10 SCET to a condition where relatively elevated fluxes were recorded, characterized by rapid variations and several very deep minima. The corresponding data of Channel 2 show a large peak at 15.38 SCET and several lesser, but well-defined, peaks that were not especially correlated with the corresponding Channel 1 data. The pattern change from ≈15.29 SCET, which occurred without an accompanying change in B, was time associated with a further MBT reported by the JPA experimenters (at +9000 km outbound), and, again, by the RPA Team at 15.30.30 SCET. The width of the transition in energetic particles is more difficult to determine in this case but it is in the general range 1000–2000 km.

The energetic particle fluxes recorded thereafter in Channels 1–2 (T1,S3) between about 15.29 and 15.44 SCET (see Fig. 4), are interpreted to constitute signatures of the (outbound) Cometosheath. It is noted that there is a considerable difference between the particle records obtained during the inbound and outbound spacecraft traversals of the G–S cometosheath in the data of Channels 1–2 (T1,S3). Inbound, the data showed a periodic structure at the cyclotron period of water group ions in the prevailing magnetic field, superimposed on the existing particle background. Outbound, the changes recorded were relatively random, and the overall flux level was substantially elevated relative to the inbound background level. The data of Channel 2 are not closely correlated with the data of Channel 1.

Figure 4 (bottom two panels), shows EPONA data recorded in Channels 1–2 (T1,S1), where S1 was directed westwards, see Fig. 1b. It is noted that the fluxes recorded in Channel 1 (T1,S1) were nearly a factor of 10 lower than those recorded in Channel 1 (T1,S3) but, when amplified as shown, well-defined fluctuations in the counts occurring between 15.12 UT and 15.29 SCET are highlighted. These variations do not exhibit the symmetry and stability (on the timescale of 20 min required for the spacecraft to traverse this regime) seen in the corresponding (T1,S3) data. Comparisons between the EPONA and magnetic field data indicate that the highest fluxes occurred outside the pileup region (of 15.17–15.20 SCET) and no special correlation between the particle peaks and associated pitch angle determinations was identified. The data of Sectors 2, 4, 6, 7 and 8 (not shown) also displayed very small flux increases near CA and only the records obtained in Sectors 3 and 5 showed minimum counts.

2.3. *Pitch angle distributions at the Grigg–Skjellerup Mystery Boundary Transitions*

Figure 5 presents eight scatter plots of counts versus pitch angles generated for EPONA, Channel 2, omnidirectional data pertaining to various 1 min intervals in the period from 15.05–15.17 SCET on 10 July, 1992. This interval spans a time (identified in energetic particle data to be ≈15.10 SCET ±1 min) of an MBT executed by Giotto inbound at G–S, see Section 2.2. The plots show that a change from a pitch angle distribution that was asymmetric about 90° to one dominant close to 90° took place at 15.09 SCET. Figure 6 presents a further set of eight scatter plots similar to those presented in Fig. 5 but, this time, generated for various 1 min intervals within the period 15.25–15.33 SCET. This interval spans a time (identified in energetic particle data to be ≈15.29–15.30 SCET ±1 min) of an MBT executed by Giotto outbound at G–S, see Section 2.2. The plots of Fig. 6 show that a pitch angle distribution close to 90° is a dominant feature following the MBT (from ≈15.31 SCET).

See Section 3.2 for corresponding effects recorded at comet Halley. Section 4.2 contains a general discussion of the pitch angle distributions at both comets.

2.4. *The central region in energetic particles* (*at Grigg–Skjellerup*)

Between the MBTs the comet displayed very stable structures in the data of Channel 1 (T1,S3), characterized by quasiperiodic variations with a period about 1.8 times longer than those variations recorded in the inbound Cometosheath. The data exhibited inbound/outbound rather symmetrical peaks, with decreasing/increasing "matching" amplitudes about a centre of symmetry at 15.20 SCET. No significant fluxes were present in the centre of this record (see, however, below). Only very minor variations were recorded in the corresponding data of Channel 2 (T1,S3) with, again, minimum values at the centre of symmetry. The reported time of "Closest Approach" was between 15.18.30 and 15.19.30 SCET (Spacecraft Tracking Team). The centre of symmetry observed in energetic particles was slightly displaced (i.e. later by 1.5 min = 1200 km) relative to Closest Approach. Although asymmetric pickup might explain this observation, the overall disposition of the particle signatures rather suggests that the passage of the spacecraft through the comet was not central. Outbound, before the MBT was traversed at approximately 15.29 SCET, the quasiperiodic structure was somewhat less well defined but, nevertheless, identifiably of longer duration than the fluctuations recorded in the inbound Cometosheath.

The fact that the magnetic field magnitude did not significantly change from one side to the other of the MBTs, while the quasiperiodicity displayed by the fluxes increased by a factor of about 1.8 relative to the value recorded in the Cometosheath inbound, allows us to suggest that, while the majority of ions close to the comet and in the inbound Cometosheath are of the species $M = 16$–18 amu (see Section 2.2), the peaks between the MBTs are due to ions with masses in the approximate range $M = 28$–33 amu. Evidence supporting this interpretation is provided by data secured aboard Giotto using the spectral analysis procedure (see Balsiger *et al.*, 1986; Korth *et al.*, 1987; Geiss *et al.*, 1991), which demonstrated the presence of heavy ions close to comet Halley (discussion in Section 4.3). Such particles could consist of cometary pickup ions, which, through the additional acceleration processes now recognized to be typically present in cometary environments (see below), gained sufficient energy to be recorded in the low energy channels of EPONA (see the threshold values given in Section 2).

It is (for completeness), recalled that a comparison between energetic particle fluxes in EPONA data recorded in the Magnetic Pileup regions of G–S and Halley by

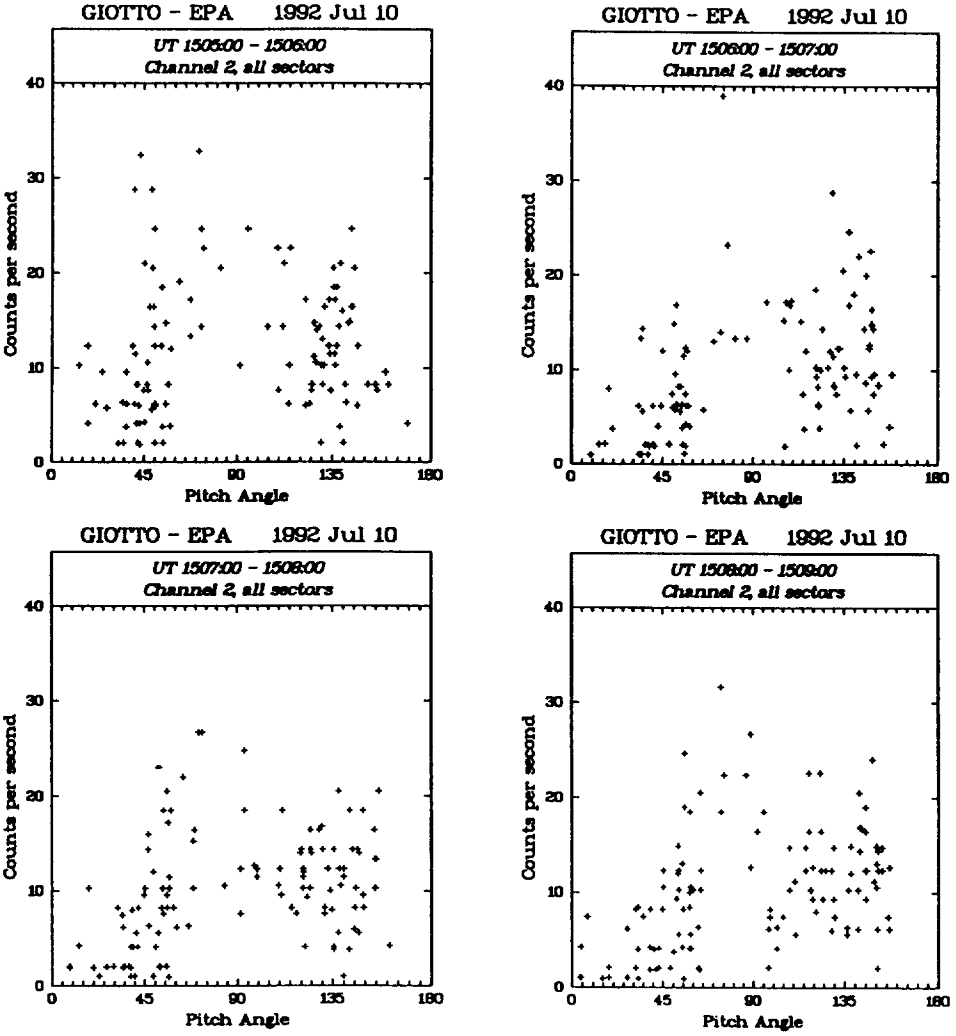

Fig. 5. Scatter plots of omnidirectional counts in EPONA Channel 2, vs. pitch angle for a selection of 1 min intervals within the period 15.05–15.17 SCET on 10 July, 1992 (*continued*)

Kirsch *et al.* (1995) shows that, at G–S, there is no indication of a Cavity Spike at Closest Approach (the "miss distance" at G–S was reported to be 200 km by the Spacecraft Tracking Team). Had such a spike been present, it would have been detectable in the data of Channel 1, Telescope 1 from a distance of < 400 km from the nucleus.

2.5. *Energy spectra at Grigg–Skjellerup*

Figure 7 presents phase space density as a function of particle energy, calculated for (left-hand side) the period 15.00.36–15.10 SCET when the spacecraft was just downstream of the (inbound) G–S Bow Wave. These data are fitted with a power law spectrum, (assuming that mainly oxygen ions were accelerated), and the resulting spectral exponent is $\gamma = 2.75$. This plot may be compared with an already published spectrum, not shown, measured from 12.50–12.55 SCET (McKenna-Lawlor *et al.*, 1993b), which was interpreted to indicate that the mean free path corresponding to random scattering by ambient waves upstream of G–S is of the order of 30 gyroradii. Thus viewed (see Section 1.5), the spectrum of 15.00.36–15.10 SCET implies that acceleration additional to the Second Order Fermi process operative upstream took place near the (inbound) shock.

It was reported by Glassmeier and Neubauer (1993) that the region upstream of the G–S Bow Wave displayed a different character to that observed at comets Halley and Giacobini–Zinner. Uniquely at G–S, regular magnetic field fluctuations along the spacecraft trajectory, which were observed from 14.29 SCET, pervaded this regime and were continuously present up until 15.09 SCET. These reported fluctuations therefore terminated at the location of the MBT identified in EPONA energetic particle data (see Section 2.2). It was postulated by Glassmeier and Neubauer (1993), that the large amplitude, compressible, magnetic fluctuations identified point to the presence, inbound, of a thick pulsation shock (see also Neubauer *et al.* (1993b)). Such shocks are usually observed under quasi-parallel conditions where waves are generated due to ions reflected from the shock surface. At G–S, where the Bow Wave was quasi-perpendicular (Neubauer *et al.*, 1993a), the pulsation shock characteristic was suggested to be due to the fact that pickup ions assumed that role played, in the quasi-parallel case, by reflected ions. In such an environment, charged particles could be scattered and accelerated in moving mag-

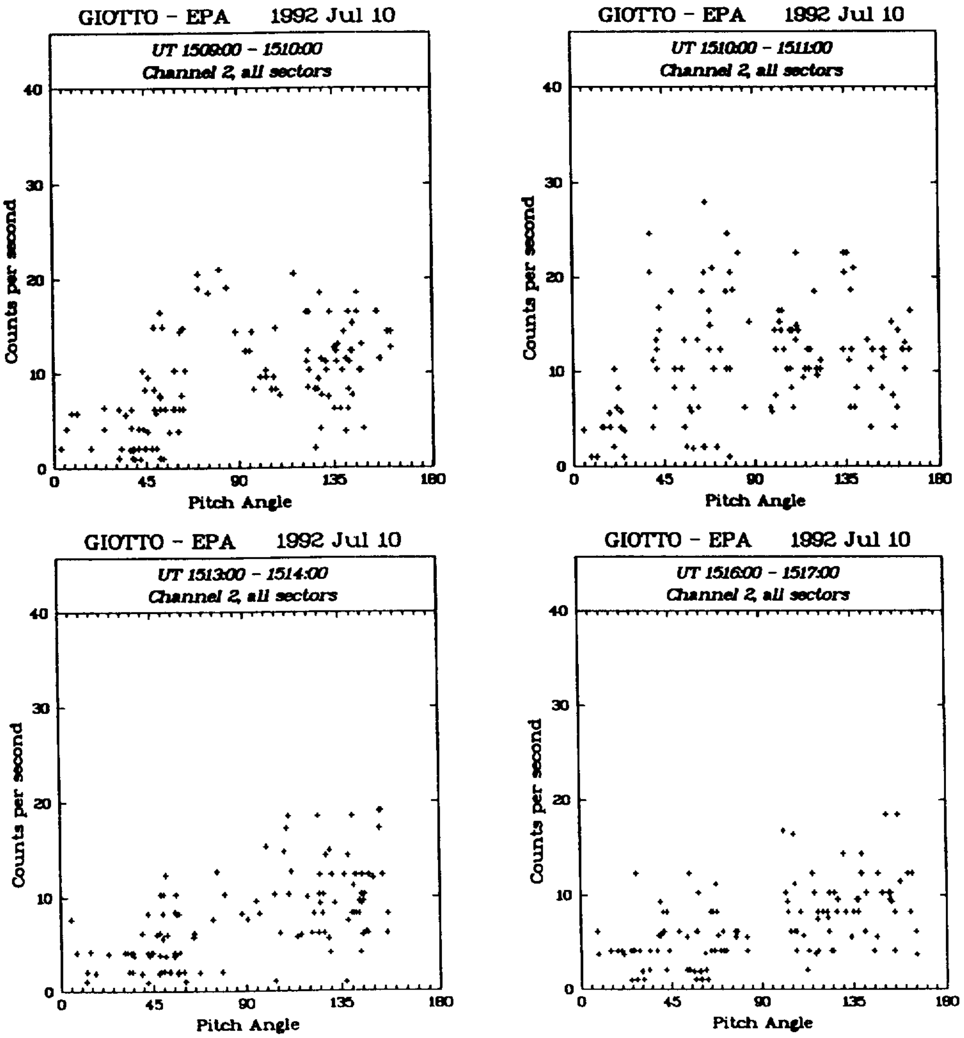

Fig. 5—*continued*

netic gradients via the transit time damping mechanism described by Fisk (1976). This latter acceleration mechanism, unlike the Fermi scattering process, not only results in little pitch angle scattering, but it also does not require the presence of oppositely propagating wave trains with similar magnitudes [as discussed by Ip and Axford (1989), the transverse Alfven waves recorded in the comae of comets G–S and Halley propagated primarily outwards from the Sun]. The spectrum obtained downstream of the (inbound) G–S Bow Wave which is presented in Fig. 7 (left) can, thus, be reasonably attributed to Second Order Fermi acceleration, supplemented by the transit time damping effect.

The spectrum presented in Fig. 7 (right-hand side) was recorded at 15.32–15.42 SCET, just preceding the outbound Bow Shock/Foreshock transition (Section 2.1). Again the data are fitted with a power law spectrum under the assumption that, mainly, oxygen ions were accelerated, and the spectral exponent is $\gamma = 5.09$. A spectrum which (above 100 keV) follows a power law with spectral index in the range 5–6, was predicted by Gombosi *et al.* (1989) to be produced under circumstances where a population of particles, initially accelerated by the Second Order Fermi process, undergoes further diffusive compressive shock acceleration in the region of a Foreshock. A well-defined Foreshock is, indeed, a feature (outbound) at G–S. Thus, the spectrum which is presented in Fig. 7 (right-hand side) can be reasonably attributed to Second Order Fermi acceleration, supplemented by diffusive compressive shock acceleration in the Foreshock region. It is noted that, although the overall energy attained by the ions was higher than that pertaining in the inbound case, in the main only the fluxes of T1,S3 were enhanced.

3. The Giotto encounter with comet Halley

It is of interest to compare the characteristic boundary transitions and energy spectra recorded at G–S with complementary data measured by the same suite of instruments on Giotto at comet Halley, 13–14 March, 1986.

3.1. *Energetic particle signatures (Bow Wave/Bow Shock/MBT) at comet Halley*

The solar wind speed was $\approx 350\,\mathrm{km\,s^{-1}}$ at 14.20 SCET on 13 March, 1986 in the early stages of the Giotto–Halley encounter (Johnstone *et al.*, 1986). In these circumstances,

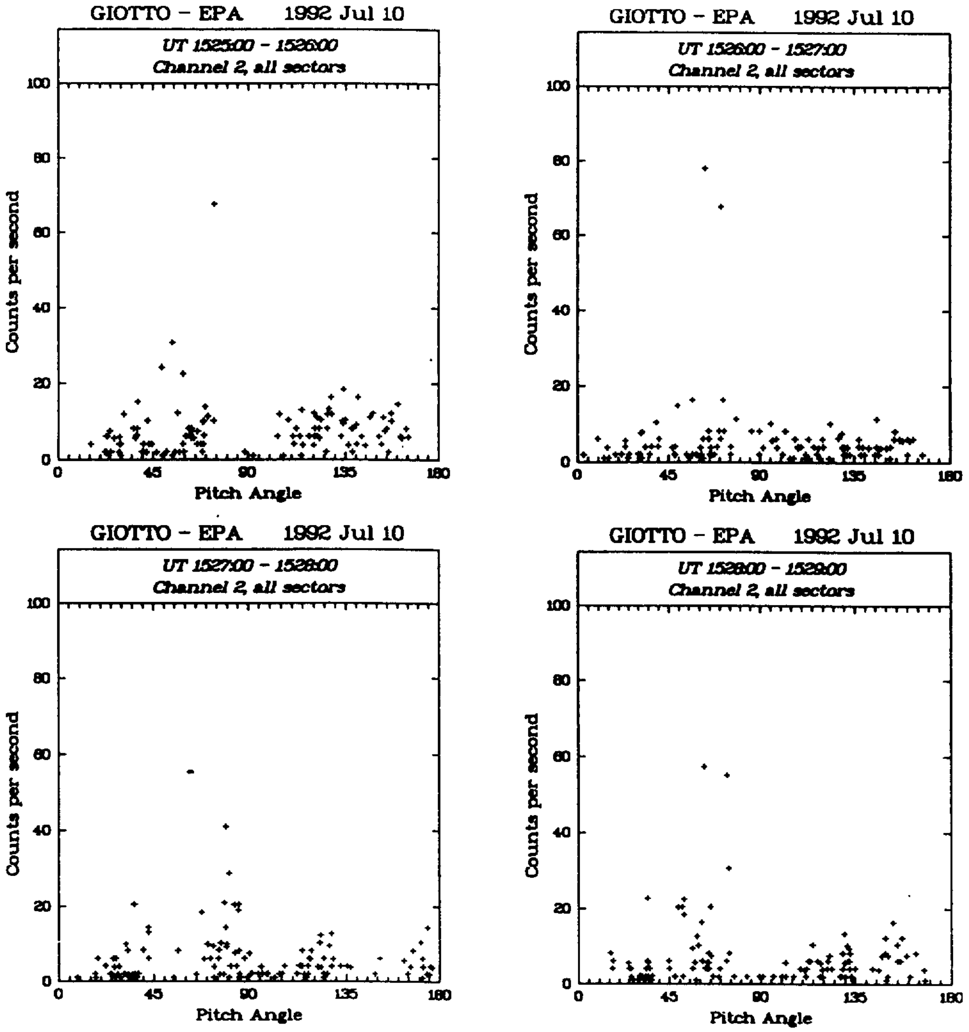

Fig. 6. Scatter plots of omnidirectional counts in EPONA Channel 2 vs. pitch angle for a selection of 1 min intervals within the period 15.25–15.33 SCET on 10 July, 1992 (*continued*)

the maximum energy attainable by a water group ion by the pickup process acting alone would have been below the lowest threshold (60 keV) for detection of these particles by the EPONA instrument. Thus, as at G–S, the observed stimulation of Channels 1–4 indicates the presence, close to the comet, of particles with energies in the range 60 to ≥260 keV (if these signatures are interpreted to have been produced by ions of the water group).

Figure 8 presents ion fluxes recorded by EPONA during the Halley encounter. Ion intensities measured in four spatial directions from 19.00 SCET on 13 March to 04.00 SCET on 14 March 1986 (45 s averages) in Channel 2, Telescopes 1 and 3 are displayed. Data in T3,S2 are described as coming "from the Sun"; in T1,S1 "from the east"; in T1.S7 "from the anti-Sun" and in T3,S8 data "from the west" See also Table 1 (bottom) which provides the look angles of all the EPONA sectors expressed in the Comet–Solar–Ecliptic (CSE) coordinate system described in Section 2.

The inbound Bow Shock transition at comet Halley was reported by Neubauer *et al.* (1986) to occur in the interval 19.22–19.33 SCET, and its transition by the spacecraft is indicated in Fig. 8 by vertical dotted lines and by the letters BS. A Foreshock enhancement, only a part of which is shown in Fig. 8 (see the top two panels), was detected in the (T3,S2) and (T1,S1) energetic particle records from 18.20–19.10 SCET. Thereafter, there was a marked rise in ion intensities from about 19.15 SCET in T3,S2 and in T1,S1. Following the attainment in each case of a significantly enhanced flux level which was sustained, with some superimposed variations, for about 2 h, a gradual decline in these flux levels took place. During this "fall off" period, the appearance, from just before 23.00 SCET, of enhanced fluxes in the "A-Sun" and "West" directions caused the extreme flux anisotropy previously pertaining to almost disappear.

A Mysterious Region, characterized by the unexpected presence of keV electrons, was identified (inbound) in RPA data between 8.5×10^5 and 5.5×10^5 km from the Halley nucleus (Reme *et al.*, 1987; d'Uston *et al.*, 1987). The duration of traversal of this regime is indicated in Fig. 8 by vertical dotted lines and by the letters MR. There is a suggestion in the energetic particle data from the "Anti-Sun" and from "The West", that slightly enhanced fluxes may have characterized this interval. Fluxes recorded in the other two directions were too high to allow correspondingly small increases to be identified in these records. See also the slightly raised flux levels recorded in

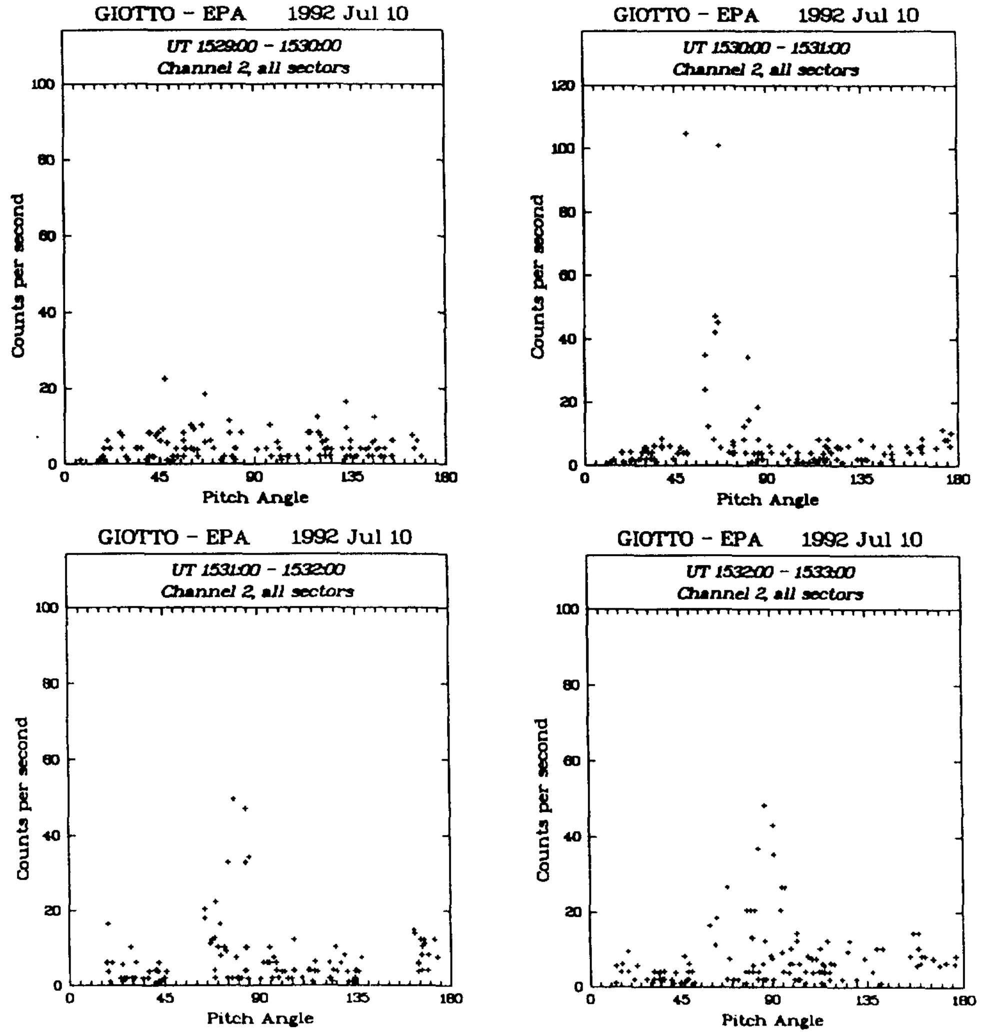

Fig. 6—*continued*

the corresponding Mystery Region outbound presented in panel 3, and (more notably) in panel 4, bottom, of Fig. 8.

MBTs were reported in JPA data by Amata *et al.* (1991) at Halley inbound between 21.44 and 22.00 SCET on 13 March, and again outbound between 01.15 and 01.31 SCET on 14 March, 1986. These, rather broad, transitions are each indicated in Fig. 8 by vertical dotted lines and by the letters MBT. The special wave signatures that allowed changes in pattern to be detected in association with MBTs at G–S (see Section 2.2) are not present in these data. There is, however, a drop in counts at the location of the MBT (outbound) which is visible in three directions (panels 2–4 of Fig. 8). A small drop in flux is also noted to generally occur at the inner edge of the inbound MBT.

Outbound, a (quasi-parallel) Bow Shock crossing was identified in magnetometer data from 02.30 to 03.05 SCET (Neubauer *et al.*, 1986), and this (broad) transition is indicated in Fig. 8 by vertical dotted lines and by the letters BW. Also, the Halley interaction region was reported to be emersed in an intense magnetosonic wave field, the outermost edge of which was exited by the spacecraft at about 03.40 SCET (Glassmeier *et al.*, 1987). The flux profiles recorded in energetic particles outbound after Closest Approach were characterized by high intensities and varying levels in all directions. A rather minor enhancement (Fig. 8) was associated with the reported location of the outbound Bow Shock itself. Thereafter, a general dip in fluxes in every direction preceded transition of the end of the magnetosonic wave field at 03.40 SCET. The flux levels thereafter rose again in every direction, and fluctuating, high level counts (not shown) remained a feature until the end of the mission at approximately 03.00 SCET on 15 March, 1986. It was reported by Kirsch *et al.* (1991) that the escape of particles along the magnetic field vector at the quasiparallel shock, resulted in these particles acting to "supplement" an already existing population of locally accelerated particles, thereby producing a well-defined anisotropy at Halley in the outbound, relative to the inbound, flux levels.

3.2. *Pitch angle distributions at the Halley Mystery Boundary Transitions*

Figures 9 and 10 present scatter plots of counts vs. pitch angles generated for EPONA Channel 2, omnidirectional, data measured at Halley's comet pertaining to various

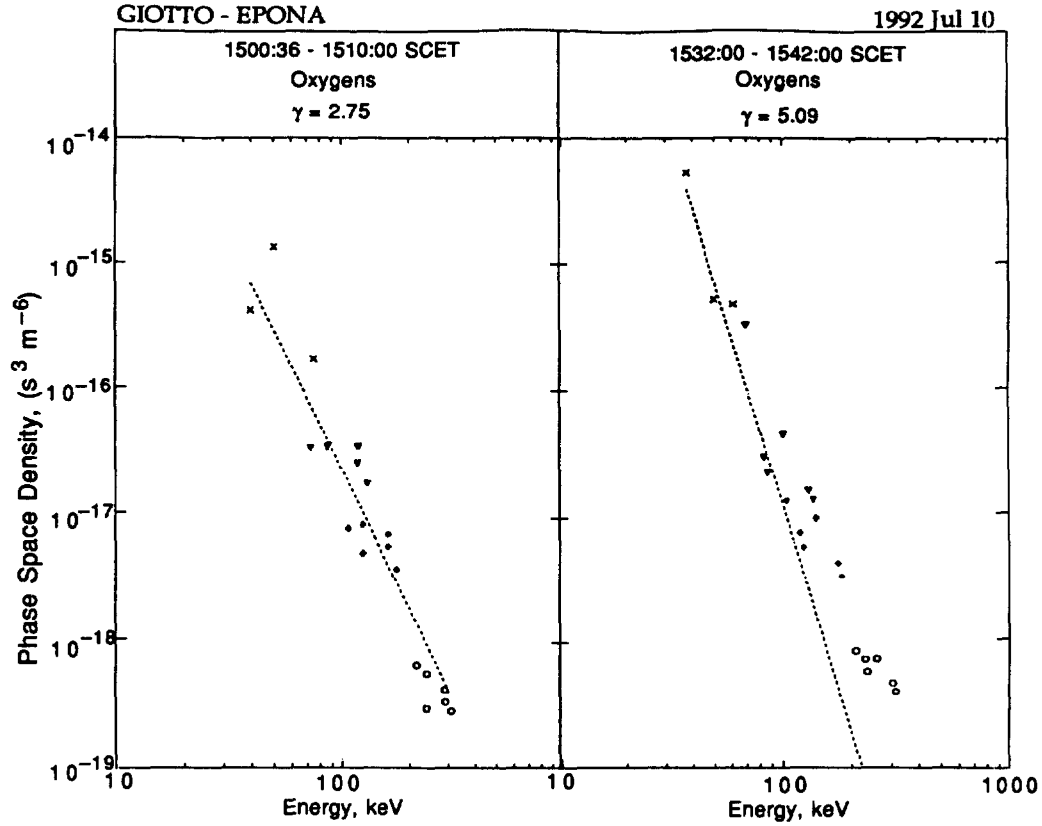

Fig. 7. A pair of energy spectra (phase space density as a function of particle energy) calculated and transformed into the solar wind frame on the assumption that mass = 16 amu, appropriate to the time intervals 15.00.36–15.10.00 SCET and 15.32.00–15.42.00 SCET on 10 July, 1992. At these times, Giotto was respectively "just downstream" and "just upstream" of the inbound and outbound shocks of comet P/Grigg–Skjellerup. The dotted lines are the least square fits of the power law spectra

5 min intervals within the periods 21.40–22.20 SCET on 13 March, 1986 and 01.05–01.45 SCET on 14 March, 1986, respectively. MBTs were identified by the JPA and RPA experimenters to occur within these intervals at 21.44–22.00 SCET on 13 March, 1986 and at 01.15–01.31 SCET on 14 March, 1986, respectively (see Section 3.1). The scatter plots appear as vertical lines because only magnetic data with 1 min averages were available and, thus, we do not see the continuous variation in pitch angle characterizing the corresponding G–S plots (compare with the 1 s data presented in Figs 5 and 6).

Plot 9 shows a pitch angle change from anti-parallel to parallel to 90° going through the inbound transition, while the outbound transition (Fig. 10) shows a change from, essentially, parallel to 90° flow. There is a suggestion in the data obtained, outbound, on 14 March, 1986 of "flapping" of the Mystery Boundary, compare plots 3 (recorded from 01.15–01.20) and 7 (recorded from 01.35–01.40 SCET) which show mutually similar distributions. These records obtained at Halley, and complementary data obtained at G–S (see Section 2.3), are discussed in Section 4.2.

3.3. *The central region of comet Halley*

The large Cavity Spike recorded near Closest Approach at comet Halley was studied by Kirsch *et al.* (1993) and explained in terms of the acceleration in the electric field of a current layer surrounding the Pileup Region of multiple, charged, dust particles (10^{-18}–10^{-20} g), followed by their impact on the detectors to produce the observed peak (semiconductor detectors are microphonically sensitive and can produce false pulses during a mechanical disturbance).

3.4. *Energy spectra at Halley*

Figure 11 (left-hand side) shows an energy spectrum recorded in association with the inbound Halley Bow Shock which was traversed, see the magnetometer data of Neubauer *et al.* (1986), between 19.22 and 1933 SCET. This spectrum, which was measured between ≈19.24 and 1938 SCET, has a spectral index of 4.10. An earlier spectrum (not shown) recorded in the Foreshock Region, which was well defined in energetic particle data from 18.20–19.10 SCET, had a spectral index of 3.34, and a later spectrum recorded somewhat deeper within the Cometosheath between 19.36.54 and 19.47.31 SCET (published by McKenna-Lawlor *et al.* (1989)) had a spectral index of 3.6.

As noted by Kirsch *et al.* (1991), the Foreshock region was observed at a time when $\sin^2\alpha$ was very small (where α = the angle between the solar wind and the magnetic field direction). Also, the angle θ_{BN} was ≈40° (where θ_{BN} = angle between the magnetic field vector and the normal to the shockfront), thereby indicating that the

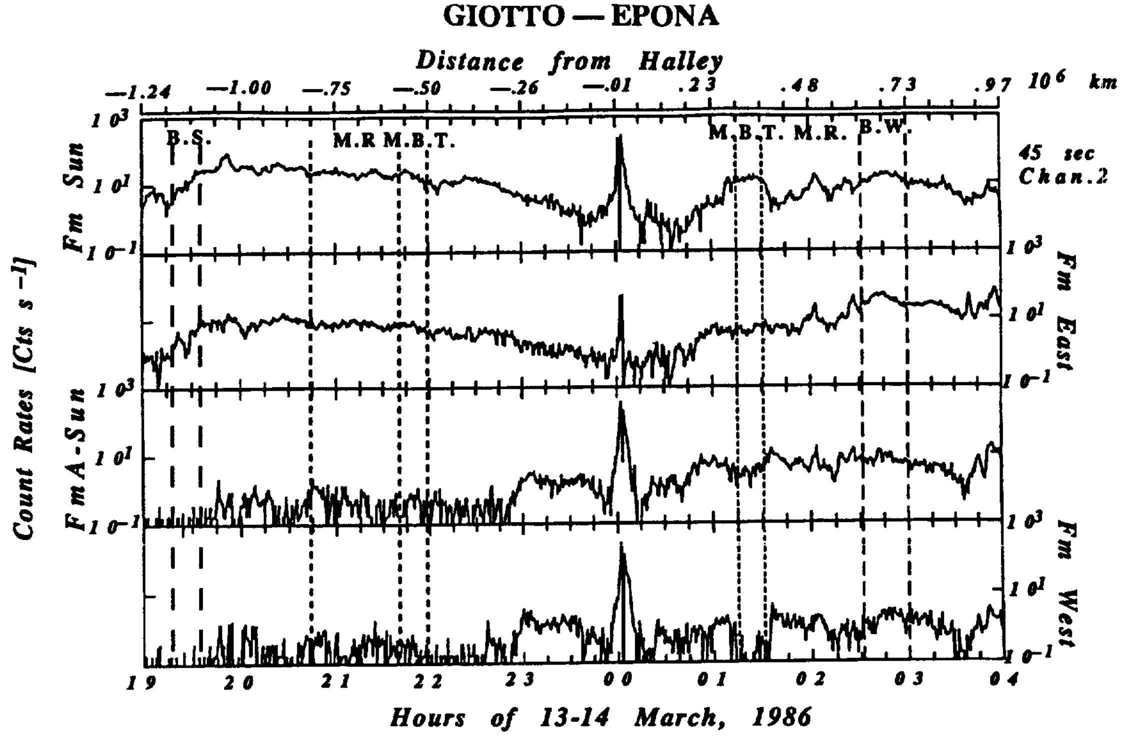

Fig. 8. Ion intensities measured in four spatial directions in Channel 2, Telescope 1 of EPONA on Giotto from 19.00 SCET on 13 March to 04.00 SCET on 14 March, 1986 (45 s averages) during the encounter with comet P/Halley. Correspondences between telescope/sector (T/S) combinations and CSE coordinates are provided in Table 1 (bottom). According to this specification, data from T3,S2 are plotted as coming "from the Sun" and data from T1,S1 as coming "from the east". Correspondingly the data of T1,S7 and T3,S8 are respectively labeled "from the Anti-Sun" and "from the west". The times of transition of a Bow Shock (inbound) and of a Bow Wave (outbound) reported by Neubauer *et al.* (1986) based on MAG data are indicated by vertical dotted lines and by the letters BS and BW respectively. The durations of Mystery Regions reported by Reme *et al.* (1987) based on RPA data are indicated by vertical dotted lines and by the letters MR. The durations of Mystery Boundary Transitions reported by Amata *et al.* (1991) based on JPA data are indicated by dotted vertical lines and by the letters MBT

inbound shock was quasiparallel. This latter circumstance precludes the possibility that the shock drift mechanism described by Armstrong *et al.* (1985) played a role in accelerating the particles, since this process requires the shock to be quasiperpendicular. It is thus reasonable to conclude, using the model of Gombosi *et al.* (1989) already invoked in the "outbound" case at G–S (see Section 2.5), that the Foreshock at Halley served as a region of diffusive–compressive acceleration for cometary ions already accelerated by the Second Order Fermi process. (It is noted that the diffusive–compressive acceleration achievable by this mechanism is limited, in individual cases, by the particular solar wind convection time locally pertaining.)

Outbound, in magnetometer data, a region of increased fluctuation identified from 02.30 SCET was interpreted by Neubauer *et al.* (1986) to signify the commencement of spacecraft traversal of an extensive quasiparallel shock on the dawn side of the interaction region. This structure was later shown from the magnetic data to have a thickness of 120 000 km and it was referred to as a "draping shock" (Neubauer *et al.*, 1990). Figure 11 (right-hand side) presents an energy spectrum recorded in energetic particle data within this shock from ≈02.40–02.50 SCET (spectral index 5.87).

It was reported by Glassmeier *et al.* (1987) that, at comet Halley, large amplitude, low frequency, magnetic field fluctuations with a quasiperiodicity of 3–4 min, suffused the upstream region and the region between the shock transitions, and continued to be present along the spacecraft trajectory after the traversal of the outermost boundary of the outbound shock until about 03.40 SCET. Spectra recorded between 02.40 and 03.40 SCET all showed roughly the same spectral index and, thereafter, the measured index immediately dropped to 3.71 (Kirsch *et al.*, 1991). It can be inferred that the transit time damping mechanism described by Fisk (1976) (a process whereby particles are accelerated by interacting with magnetosonic waves), combined with Second Order Fermi acceleration, is likely to have produced the acceleration observed in association with the outbound shock transition. See also Section 2.5.

4. Discussion

The observations presented in Sections 2 and 3 are discussed in the present section, with particular regard to (i) the relationship between signatures of the Bow Wave/Bow Shock/ForeShock transitions recorded in energetic particles at G–S and complementary signatures recorded by other instruments of the Giotto "particles and fields" payload; (ii) MBTs in energetic particle data; (iii) the inferred composition of the inner region of G–S; (iv) the energization of particles close to G–S and Halley and (v) similarities and differences between the signatures recorded at G–S and at Halley in energetic particles.

4.1. *Signatures of Bow Wave/Bow Shock/Foreshock transitions at Grigg–Skjellerup*

It can be inferred, through comparing the energetic particle (EPONA) records with complementary data recorded by the various particles and fields instruments on Giotto (RPA, IMS, JPA and MAG) at around the time of the G–S Bow Wave crossing, that all of these instruments sensed a transition region, inbound, between the undisturbed solar wind and the cometosheath. The apparent width of this transition region, taking all of the reported data into account, is estimated to be about 9200 km (approximately the gyroradius of a 100 keV water group ion in the prevailing ≈20 nT magnetic field). The different transition times reported by individual experimenters is accounted for (a) by the nature of the various measurements made to detect the boundary (i.e. using magnetic fields, low energy electrons and low and high energy ions at time resolutions particular to the individual instruments) and (b) by directional effects.

At both the inbound and outbound Bow Wave and Bow Shock transitions, enhanced signatures in energetic particles were, in each case, recorded approximately 4600 km deeper inside the comet than the locations of the Bow Wave and Bow Shock crossings reported in magnetometer data, i.e. at a distance of about half the gyroradius of a 100 keV water group ion in the, average, ambient magnetic field. The outbound Bow Shock presented a sharp boundary transition in the data of all of the particles and fields instruments. A Foreshock was detected outbound in energetic particles (15.49–16.03 SCET), characterized by somewhat irregular, but well-defined, fluctuations relative to those variations recorded further downstream. Although, at 15.49 SCET, a steep gradient in the magnetic field magnitude (the Bow Shock Ramp) was recorded in magnetic data outbound, accompanied by a corresponding jump in electron related parameters, no accompanying enhancement was recorded in energetic

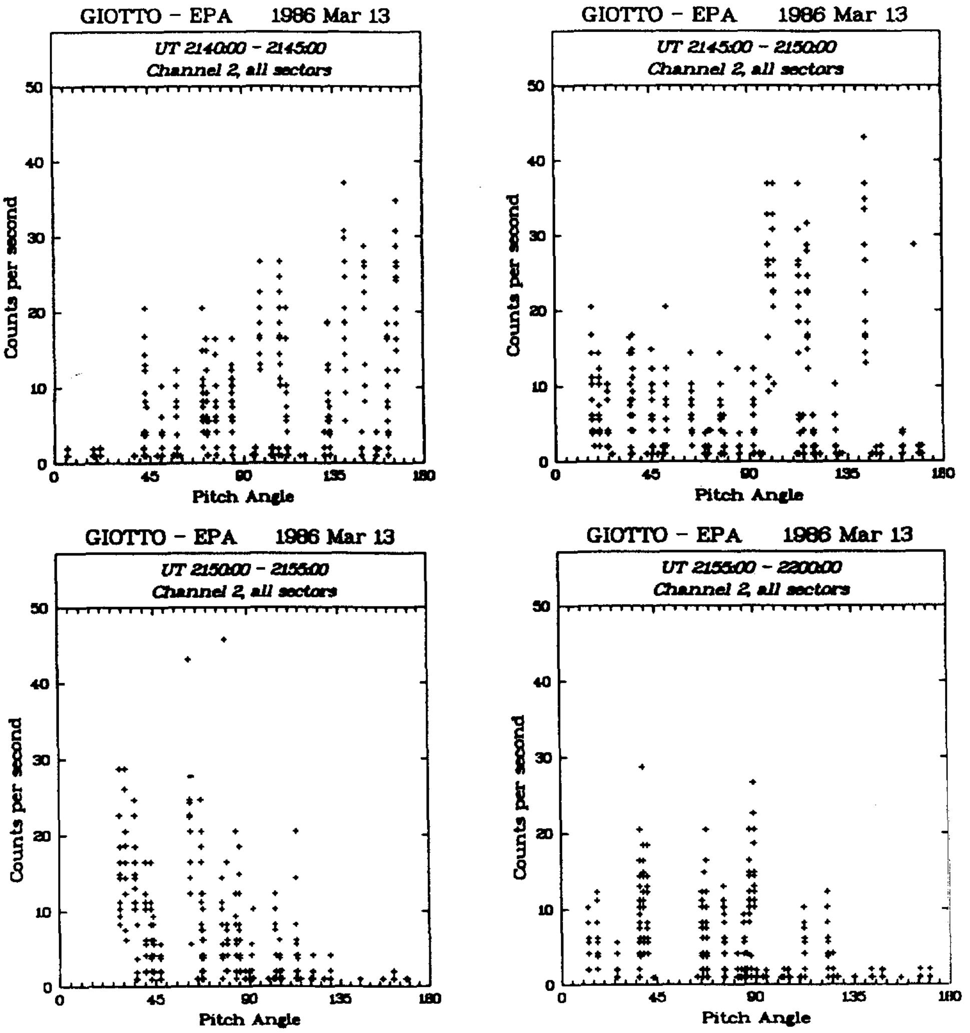

Fig. 9. Scatter plots of omnidirectional counts in EPONA Channel 2 vs. pitch angle for 5 min intervals within the period 21.40–22.20 SCET on 13 March, 1986, spanning the reported time in JPA data of the inbound (21.44–22.00 SCET on 13 March, 1986) Mystery Boundary Transition by Giotto at Halley's comet (*continued*)

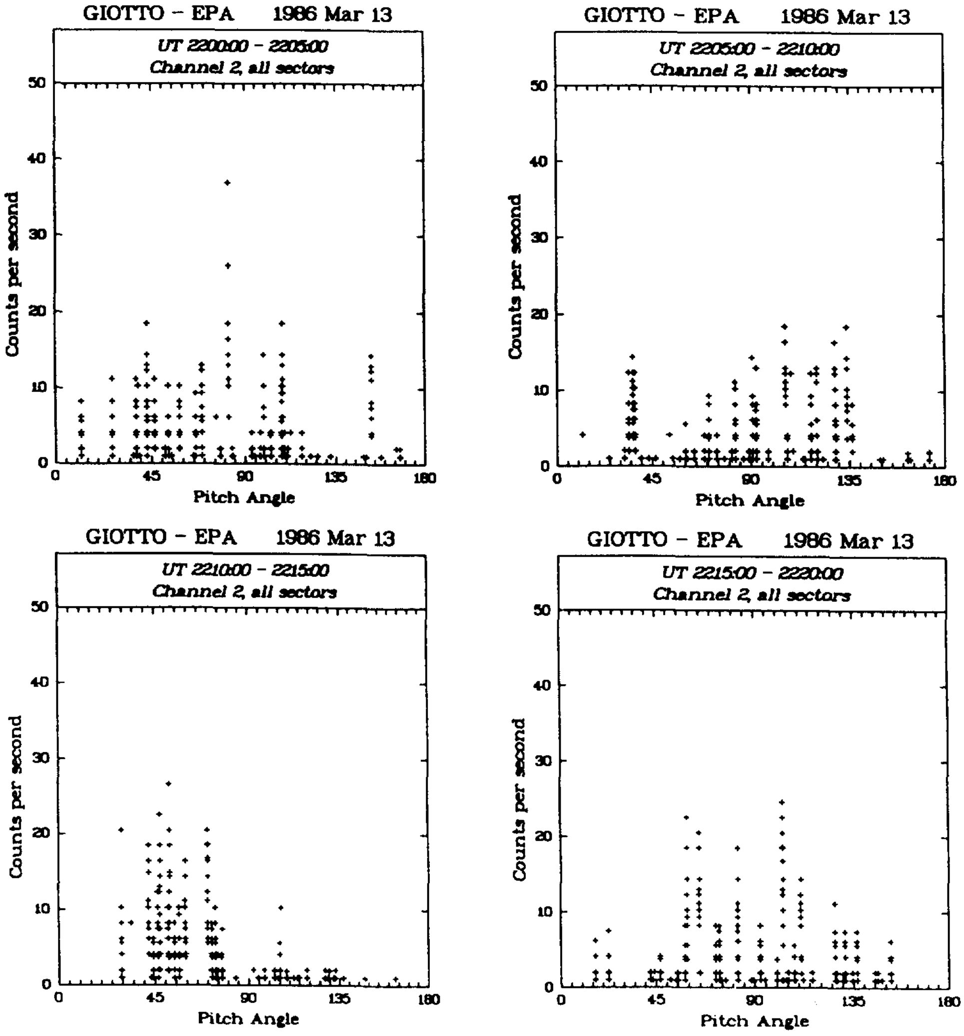

Fig. 9—*continued*

particle data (see Fig. 3). The observations also indicate that, outbound, the gyrotropic motion of the energetic ions recorded by EPONA at G–S ended 5 min earlier than that of the low energy electrons identified by the RPA experimenters (Reme *et al.*, 1993).

4.2. *Characteristic signatures of Mystery Boundary Transitions in energetic particles*

There is a suggestion in the Halley energetic particle records that slightly enhanced fluxes may have characterized the locations of the Mystery Regions identified in RPA and JPA data. At G–S, where the Mystery Regions identified in RPA and JPA data extended on the one side from the Bow Wave to the MBT and on the other side from the corresponding MBT out to the Bow Shock, the energetic particle fluxes recorded in these regimes in (T1,S3) were elevated relative to those fluxes recorded between the MBTs.

The present study presents the first ever report in energetic particles of MBTs (recorded in G–S data). The presence of these boundaries is inferred from the observation of pattern changes in particle fluxes recorded in the measurements of T1, S3 (the closest viewing sector to the Sun). The variations concerned are correlated, within the time resolution of the reported observations, with MBTs reported in JPA data.

EPONA Channel 2, omnidirectional counts plotted versus pitch angle during intervals spanning MBTs at Halley show (inbound) a change in pitch angle from anti-parallel, to parallel to 90°, while outbound there was a change from, essentially, parallel to 90° flow (see Section 3.2). Corresponding plots obtained at G–S showed, albeit less clearly, the same effect (see Section 2.3). The data suggest that, in each case inbound, a component of the EPONA Channel 2 particles may have exhibited "mirroring", thereby producing an identifiable change from a trapped to a "flowing" distribution as the magnetic field piled up close to each comet. There are a number of factors that would tend to obscure such an effect, e.g. variability in the generally enhancing background magnetic field; the width of the energy channel utilized (97–144 keV for water group ions); the 45° opening angle of each measuring sector; flapping of the boundary, etc. Also, the plots presented are computed for a single energy and do not take into account the Compton–Getting effect. Nevertheless, there is a clear indication of a change in the flow direction in the vicinity of boundaries (MBTs) associated with entry to a central regime at each comet characterized by the presence of relatively heavy ions. Outbound, "flowing" distributions were identified downstream of the Boundary Transitions, thereby revealing a difference between the inbound and outbound measurements.

A more detailed analysis of these data in a subsequent paper will take into account energy transformation effects when considering the pitch angle distributions.

4.3. *The inner region of Grigg–Skjellerup*

The fact that the magnetic field magnitude did not significantly change from one side to the other of the MBTs while the quasiperiodicity displayed by the fluxes increased by a factor of about 1.8 relative to the value recorded in the cometosheath inbound, allows us to suggest that, while the majority of ions close to the comet are of the species $M = 16$–18 amu, the peaks between the MBTs are due to ions with masses in the approximate range $M = 28$–33 amu, see Section 2.4. Candidate cometary pickup ions might be O_2^+, CO^+, N_2^{2+} or NO^+ (see also below) which, through the additional acceleration processes now known from *in situ* measurements to be typically present in cometary environments, gained sufficient energy to be recorded in the low energy channels of EPONA (see Section 2.5). In considering these, and other, candidate possibilities, it is recalled that Balsiger *et al.* (1986), on the basis of data recorded with the Giotto Ion Mass Spectrometer (IMS), reported a pileup of heavy ions at a distance of approximately 10^4 km from the Halley nucleus and commented on a notable lack of nitrogen in the coma. Studies by Korth *et al.* (1987) of the composition and radial dependence of cometary ions at Halley conducted using the Giotto heavy ion analyser (RPA2–PICCA) indicate that, while water group ions dominated the overall composition in the inner coma of this comet, the second most abundant ions detected were of the CO group. More recently, Geiss *et al.* (1991) established an absolute mass scale that enabled ions in the mass per charge range 25–35 amu e^{-1} to be identified in IMS Halley data. This study shows that ions resulting from protonation of molecules with high proton affinity were relatively abundant, and relative source strengths for H_2, CO, CH_3, OH, HCN and H_2S were estimated. Although comp-

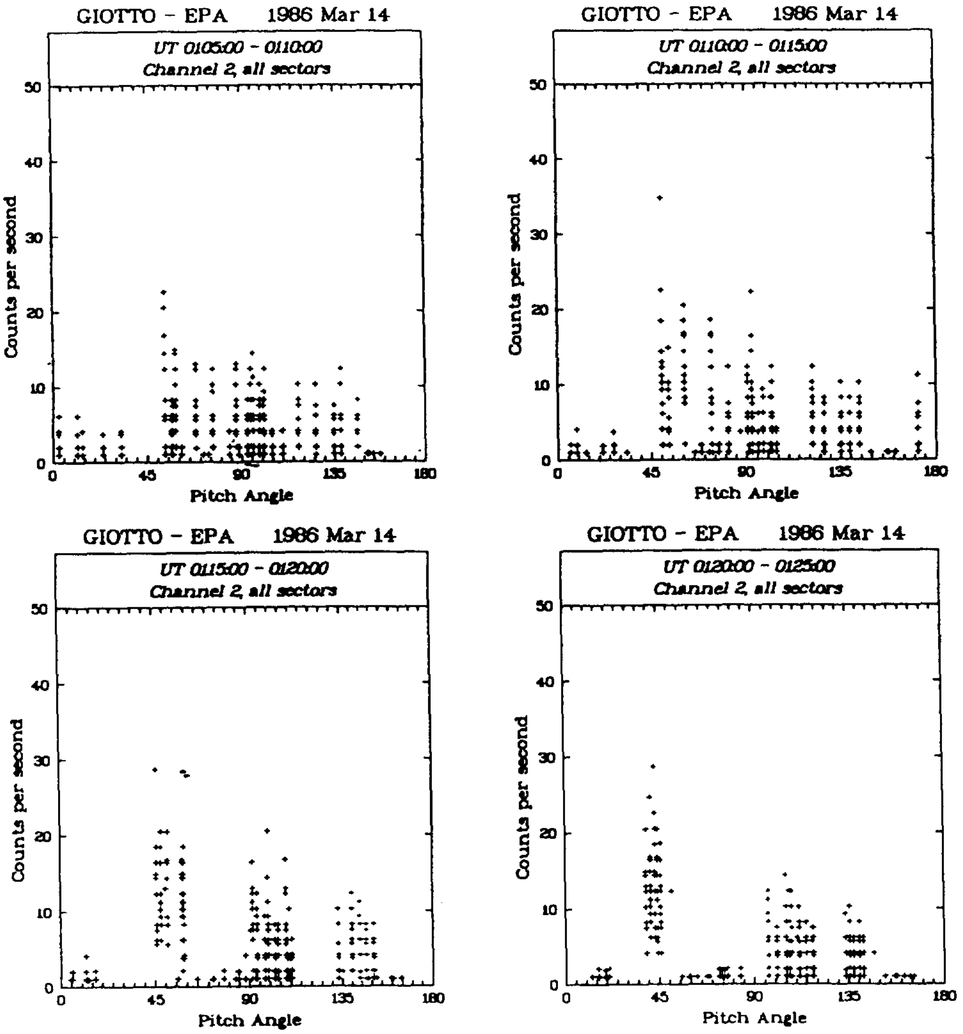

Fig. 10. Scatter plots of omnidirectional counts in EPONA Channel 2 vs. pitch angle for 5 min intervals within the period 01.05–01.45 SCET on 14 March, 1986, spaning the reported time in JPA data of the outbound (01.15–01.31 SCET on 14 March, 1986) Mystery Boundary Transition by Giotto at Halley's comet (*continued*)

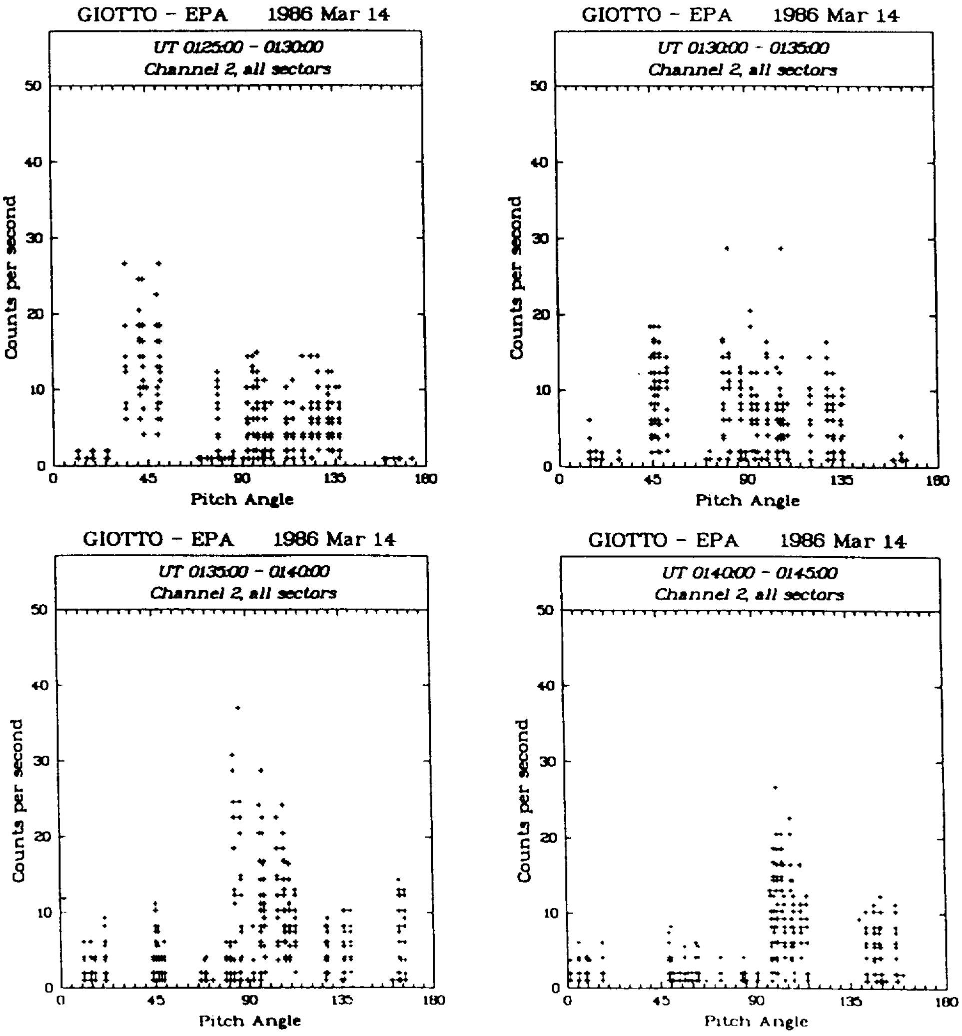

Fig. 10—*continued*

lementary observations at G–S are not available, the inference made from energetic particle data that heavy ions in the range 28–33 amu were present close to G–S appears, from the Halley composition measurements, to be reasonable.

Between the MBTs in the data of Channel 1 (T1,S3), G–S displayed very stable structures with decreasing/increasing "matching" amplitudes (less clearly defined outbound) about a centre of symmetry at 15.20 SCET. The charge exchange mechanism can be invoked to explain the marked fall off, and later rise, in overall ion amplitudes recorded by T1,S3 during the spacecraft traversal of the inner region of this comet, see the analysis of complementary Halley data by McKenna-Lawlor and Verigin (1993c). However, only the sunward related sectors 3 and 5 showed minimum counts. The data of Sectors 1, 2, 4, 6, 7 and 8 all displayed minor flux increases at Closest Approach.

The enhanced fluxes recorded in representative Channel 1 (T1, S1) were nearly a factor of 10 lower than those recorded in Channel 1 (T1, S3). They displayed well-defined fluctuations in counts and the enhancements concerned were clearly produced by energetic particles rather than by dust. The highest fluxes occurred outside the Pileup region (recorded in magnetometer data between 15.17 and 15.20 SCET), and there was no distinct correlation between the particle peaks and associated pitch angle determinations. It can be inferred that some process/es was operative at this location which was not fully controlled by the magnetic field. It would be expected that the scattering of particles from the ring distribution that pertained until just before the Bow Wave inbound (reported in JPA data; Coates *et al.*, 1993a, 1993b), would result in the detection by EPONA of pickup ions in sectors other than S3. Interpretation of the data is, however, complicated by the possible disturbing influence on the measurements of the piled up magnetic field around the comet nucleus (McKenna-Lawlor *et al.*, 1993b). The impact of a dust particle with the spacecraft also disrupted the data recorded in some of the sectors near the time of Closest Approach. A detailed study to determine the role played by pitch angle scattering on the disposition of the particles recorded in all directions at Closest Approach, having regard to the complicating factors mentioned above, is presently planned, It may be that this investigation will provide, at the high time resolution of the instrument, a picture of the "global" configuration of the fluxes which will enable us to deduce from these data if

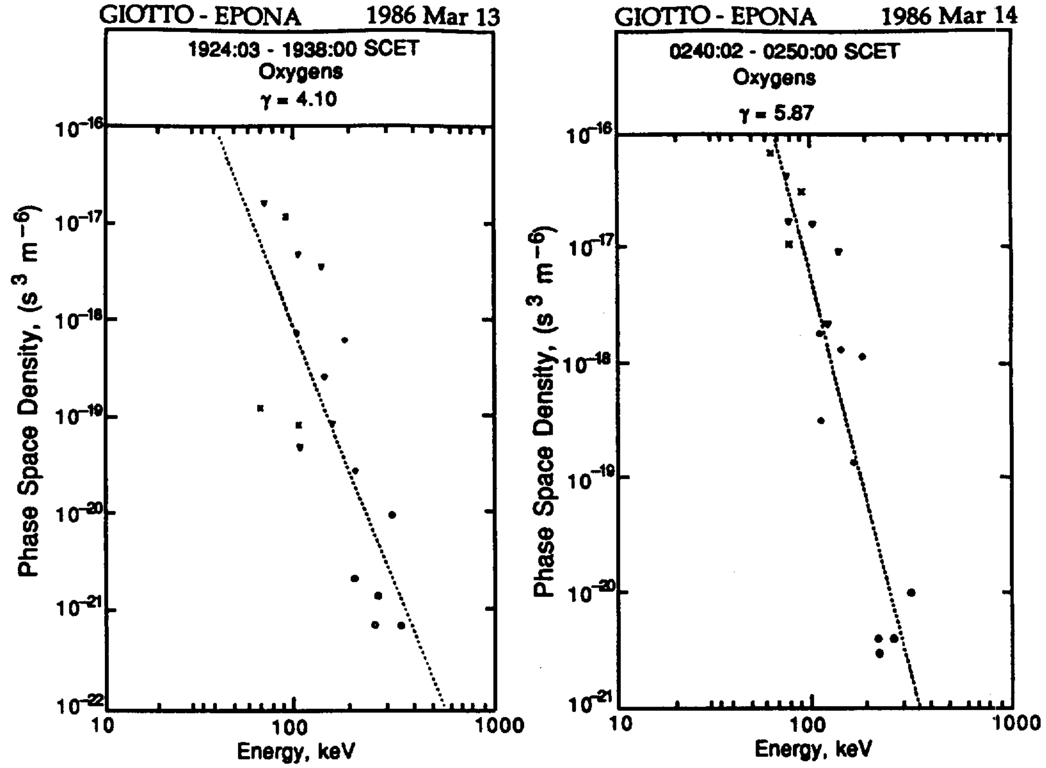

Fig. 11. A pair of energy spectra (phase space density as a function of particle energy) calculated and transformed into the solar wind frame on the assumption that mass = 16 amu, appropriate to the time intervals 19.24.03–19.38.00 SCET on 13 March and 02.40.02–02.50.00 SCET on 14 March, 1986. At these times, Giotto was traversing, respectively, the inbound and outbound shocks of comet P/Halley. The dotted lines are the least square fits of the power law spectra

the spacecraft traversed the comet downstream or upstream of the nucleus.

4.4. *The energization of particles close to Grigg–Skjellerup and Halley*

In conformity with their different gas emission rates, the fluxes of energetic particles measured at comets G–S and Halley differed by a factor of 10^2. However, the ion energies measured by EPONA in the environments of both comets were the same (measured range 60 to ≥ 260 keV for water group ions). This is, in each case, considerably in excess of the maximum energy attainable by the pickup process acting alone under the prevailing interplanetary conditions and it can be inferred that an additional mechanism/s must have been operative to thus energize the particles.

Comparisons between measured and theoretical spectra pertinent to the upstream regions of comets Giacobini–Zinner and Halley (Richardson *et al.*, 1987; McKenna-Lawlor *et al.*, 1989; Ip and Axford, 1986, 1987), show that there are limitations to the efficiency of Second Order Fermi acceleration upstream of the Bow Shock. In particular, the mean free path corresponding to random scattering by Alfven waves appears to be of the order of 30 ion gyroradii upstream of Halley, and this situation may be interpreted in terms of a weak energy diffusion process. See also the review of acceleration mechanisms near a comet by Coates (1991), and the comparison between experimental and modeled data performed by Huddleston *et al.* (1992).

In the present study it was shown (see Sections 2.5 and 3.4) that, at G–S outbound and at Halley inbound a model developed by Gombosi *et al.* (1989) of diffusive compressive acceleration in the Foreshock region of particles already accelerated by the Second Order Fermi process, provides a reasonable explanation of the experimental data. Inbound at G–S, and outbound at Halley, the additional acceleration of particles already accelerated by the Second Order Fermi Process through their interaction with magnetosonic waves close to the shock, provides a reasonable explanation of the observations.

Clearly, each individual case (taking account of both inbound and outbound transitions) should be considered when discussing how particles are accelerated close to cometary shocks since the circumstance of whether a particular shock is quasiperpendicular or quasiparallel will effect the outcome, as will the presence or absence of large, local, fluctuating wave fields, the production of which, in turn, depends on the gas production rate of the comet concerned.

It should be noted that other mechanisms for accelerating particles in close cometary environments can be operative in addition to shock related enhancements. Ip and Mendis (1976), Niedner and Brandt (1978), Ip and Axford (1982) and Russell *et al.* (1986) for example predicted that magnetic field line merging could be realized in a cometary magnetosphere, and evidence for such a process at Halley was provided by Kirsch *et al.* (1989a) on the basis of EPONA data. Also, the Shock Drift Acceleration Mechanism of Decker and Vlahos (1986), combined with the First Order Fermi Process, was suggested by Kirsch *et al.* (1989b, 1990) to be responsible for the production of a spike recorded by EPONA from 06.45 SCET to ≈09.00 SCET on 14 March 1986 during the Giotto outbound pass.

4.5. *The outgassing rates of Grigg–Skjellerup and Halley and conditions in the interplanetary medium at each comet*

Three important factors basic to differences identified in the energetic particle signatures of comets G–S and Halley are the following (i) the low outgassing rate of G–S, namely $Q = 7.5 \pm 1.5 \times 10^{27}$ water group mol s^{-1} (Johnstone *et al.*, 1993), as compared with the corresponding value at Halley, $Q = 6.9 \times 10^{29}$ water group mol s^{-1} (Krankowsky *et al.*, 1986); (ii) the unusually high Alfven speed (105 ± 20 km s^{-1}) pertaining at G–S, caused by an exceptionally strong interplanetary magnetic field (16 ± 1 nT) associated with an interplanetary structure (a Co-rotating Interaction Region; Kirsch *et al.*, 1996) in which G–S was emersed during the encounter; (iii) the orientation of the interplanetary magnetic field which, unusually, was such that the angle between the solar wind velocity and the magnetic field vector was close to 90° during most of the G–S encounter, thereby rendering the pickup geometry especially simple.

In consequence of the factor of approximately 100 between the gas production rates (Q) of Halley and G–S, the sizes of their respective interaction regions were significantly different. Thus, at Halley, the shock transitions inbound and outbound were found at distances of 1.15×10^6 and 0.6×10^6 km respectively from the comet nucleus whereas, at G–S, the corresponding distances were about 19 900 and 25 500 km, respectively (Neubauer *et al.*, 1993a). The intrinsic length scales of the plasma (e.g. the pickup ion gyroradius; the distance a freshly created ion travels due to the streaming solar wind, etc.) were, meanwhile, independent of the gas production rate. As described by Neubauer *et al.* (1993b) and Motschmann and Glassmeier (1993), a small ratio of interaction to intrinsic scale length may cause the pickup ion phase space density to become nongyrotropic. This has the consequence of coupling the gyrotropic eigenmodes, thereby driving instabilities that effect the character of the waves in the close cometary environment. The plasma wave activity at G–S was notable for the simple, regular and high amplitude waveforms recorded in the data of the various particles and fields instruments on Giotto. The frequency of these waves was close to the water group ion cyclotron frequency and the nature of the waves was deemed by Neubauer *et al.* (1993b) to be related to the ring and nongyrotropic distributions identified by Coates *et al.* (1993b) in JPA data. The frequency of the waves was close to the ion cyclotron frequency because the angle between the interplanetary magnetic field and the solar wind flow was close to 90° during most of the G–S encounter, a configuration which is consistent with the bispherical ion distribution derived by Johnstone (1995).

Overall, similarities and differences observed between G–S and Halley in the various data sets are a consequence of the difference between the gas production rates of these two bodies, and of differences in those interplanetary circumstances pertaining at the time of spacecraft encounter.

4.6. *Comparisons between the signatures recorded at Grigg–Skjellerup and at Halley in energetic particles*

Because of the different flyby geometries, the inbound (outbound) pass of the Giotto spacecraft at G–S corresponds to the outbound (inbound) pass at comet Halley. Comparison of relevant records reveals that the Foreshocks detected in energetic particles at G–S and at Halley were recorded, in each case, on the same "dusk" side of the comet–sun line, if one envisages a direct rotating body instead of the comet. (It is noted that a similar dusk/dawn asymmetry in magnetic field and electron plasma data was reported with respect to the inbound/outbound shock boundaries at G–S and at Halley by Mazelle *et al.* (1995).)

A marked anisotropy was detected at Halley in the recorded level of outbound relative to inbound energetic particle fluxes. No such anisotropy was observed at G–S. It was reported by Kirsch *et al.* (1991) that, at Halley, the escape of particles along the magnetic field vector at the quasiparallel outbound "draping" shock was facilitated by a lowering of pitch angles associated with the operation of the transit time damping mechanism at this location. In consequence, the escaped particles supplemented the existing fluxes of locally accelerated particles to produce the observed outbound asymmetry.

It is an interesting feature, given in each case the radically different ratio of the pickup scale length to the size of the comet obstacle, that the Bow Wave/Bow Shock transitions identified in particles and fields data at G–S occurred in analogous locations to those recorded at Halley. The MBTs identified at G–S in energetic particles were thin structures relative to a cometary ion gyroradius, and their relative positions in the cometosheath corresponded fairly closely to those identified at Halley in JPA and in RPA data.

At G–S, because of its low Q value, the energetic ions recorded by JPA exhibited nongyrotropic behaviour close to the shock transitions, while no such effect was observed in the Halley data. At G–S (outbound) the gyrotopic motion of the energetic ions recorded by EPONA ended 5 min earlier than the corresponding motion of the low energy electrons recorded by RPA.

Pitch angle data indicate that, inbound at G–S and at Halley, the Mystery Boundaries were spatially associated with transitions from trapped to "flowing" distributions of water group ions, suggesting mirroring of these particles in the magnetic field piling up around each comet. Outbound, in contrast, "flowing" distributions were identified downstream of the MBTs at each comet.

In EPONA data at comet Halley, signatures of ion cyclotron waves were only prominent in the particle fluxes near the inbound and outbound Bow Shock (Kirsch *et al.*, 1991), whereas high amplitude wave forms were present in the energetic particle data throughout the encounter of Giotto with G–S. This was a consequence of the large wave fields present at G–S, as reported by Glassmeier and Neubauer (1993) and Neubauer *et al.* (1993b). The possibility to detect MBTs through changes in the quasiperiodicity of particle fluxes, thus did not exist during the Halley transition. A well-defined drop in particle fluxes in three directions at the position of the MBT (outbound), and a less pronounced drop at the inner edge of the MBT inbound, was observed. The outbound MBT at G–S was also characterized by low fluxes. This effect was less pronounced inbound.

At comet Halley the presence of a large Cavity Spike near Closest Approach was interpreted by Kirsch *et al.* (1993) to be associated with the impact on the detectors of accelerated, charged dust particles. The absence of evidence of a Cavity Spike at G–S is a consequence of the relatively dust free nature of this comet.

At Halley, the initial highly anisotropic character of the inbound particle fluxes was substantially reduced near Closest Approach in consequence of the appearance, in this vicinity, of enhanced fluxes from the A-Sun and from the West. Outbound, rather high levels of fluxes were observed in all directions. At G–S, the inbound and outbound fluxes were also highly anisotropic (McKenna-Lawlor *et al.*, 1993a). At Closest Approach very slightly enhanced counts were recorded in all but the sunward directions.

5. Conclusions

The energetic particle experiment EPONA on Giotto recorded, in general, the same cometary boundaries (Bow Wave, MBTs and Bow Shock) at G–S as those identified by the MAG, RPA, IMS and JPA experiments. Mechanisms, in addition to the Second Order Fermi Process, inferred to contribute to the enhanced energization of cometary ions close to the Bow Wave and Bow Shock surfaces at G–S included, as at Halley, diffusive compressive acceleration in the Foreshock region and transit time damping. The present paper contains the first report in energetic particles, based on G–S and Halley data, of MBTs. It is inferred that heavy ions were present in the inner region of G–S.

Although the characteristic boundaries identified by the particles and fields instruments at G–S occurred in analogous locations to those identified at Halley, many differences have been observed between the boundary signatures recorded in energetic particles at each comet. This is attributed (a) to differences of the order of 100 between the Q values of each comet, and (b) to differences in the interplanetary circumstances pertaining during each encounter.

References

Amata, E., Formisano, V., Torrente, P. and Giovi, R. (1991) The plasma parameters during the inbound and outbound legs of the Giotto trajectory. In *Cometary Plasma Processes*, Geophys. Monograph, Vol. 61, pp. 131–138. American Geophysical Union, Washington.

Armstrong, T. P., Pesses, M. E. and Decker, R. D. (1985) Shock drift acceleration. In *Collisionless Shocks in the Heliosphere. Reviews of Current Research*, eds B. T. Tsurutani and R. G. Stone, Geophysical Monograph Series, Vol. 35, pp. 271–285, Washington.

Balsiger, H., Altwegg, K., Buhler, F., Geiss, J., Ghielmetti, A. G., Goldstein, B. E., Goldstein, R., Huntress, W. T., Ip, W.-H., Lazarus, A. J., Meier, A., Neugebauer, M., Rettenmund, U., Rosenbauer, H., Schwenn, R., Sharp, R. D., Shelley, E. G., Ungstrup, E. and Young, D. T. (1986) Ion composition and dynamics at comet Halley. *Nature* **321(6067),** 330–334.

Buti, B. and Lakhina, G. S. (1987) Stochastic acceleration of cometary ions by lower hybrid waves. *Geophys. Res. Lett.* **14,** 107–110.

Coates, A. J. (1991) Cometary plasma energisation. *Ann. Geophys.* **9,** 158–169.

Coates, A. J. (1995) Heavy ion effects on cometary shocks. *Adv. Space Res.* **15,** 403–413.

Coates, A. J., Johnstone, A. D., Wilken, B., Jockers, K. and Glassmeier, K.-H. (1989) Velocity-space diffusion of pickup ions from the water group at Comet Halley. *J. Geophys. Res.* **94,** 9983–9993.

Coates, A. J., Johnstone, A. D., Wilken, B., Jockers, K. and Glassmeier, K.-H. (1990) Correction to Coates *et al.* (1989). *J. Geophys. Res.* **95,** 4343.

Coates, A. J., Johnstone, A. D., Huddleston, D. E., Wilken, B., Jockers, K., Borg, H., Amata, E., Formisano, V., Bavassano-Cattaneo, M. B., Winningham, J. D., Gurgiolo, C. and Neubauer, F. M. (1993a) Pickup water group ions at comet Grigg–Skjellerup. *Geophys. Res. Lett.* **20,** 483–486.

Coates, A. J., Johnstone, A. D., Wilken, B. and Neubauer, F. M. (1993b) Velocity space diffusion and nongyrotropy of pickup water group ions at comet Grigg–Skjellerup. *J. Geophys. Res.* **98,** 20985–20994.

Decker, R. B. and Vlahos, L. (1986) Modeling of ion acceleration through drift and diffusion at interplanetary shocks. *J. Geophys. Res.* **91,** 13349–13356.

Fisk, L. A. (1976) The acceleration of energetic particles in the interplanetary medium by transit time damping. *J. Geophys. Res.* **81,** 4633–4640.

Galeev, A. A. and Sagdeev, R. Z. (1988) Alfven waves in a space plasma and its role in the solar wind interaction with comets. *Astrophys. Space Sci.* **144,** 427–438.

Geiss, J., Altwegg, K., Anders, E., Balsiger, H., Ip, W.-H., Meier, A., Neugebauer, M., Rosenbauer, H. and Shelley, E. G. (1991) Interpretation of the ion mass spectra in the mass per charge range 25–35 amu/e obtained in the inner coma of Halley's comet by the HIS-sensor of the Giotto IMS experiment. *Astron. Astrophys.* **247,** 226–234.

Glassmeier, K.-H. and Neubauer, F. M. (1993) Low-frequency electromagnetic plasma waves at comet P/Grigg–Skjellerup: overview and spectral characteristics. *J. Geophys. Res.* **98,** 20921–20935.

Glassmeier, K.-H., Neubauer, F. M., Acuna, M. H. and Mariani, F. (1987) Low frequency magnetic field fluctuations in comet P/Halley's magnetosheath: Giotto observations. *Astron. Astrophys.* **187,** 65–68.

Goldstein, R., Altwegg, K., Fuselier, S. A., Goldstein, B. E., Balsiger, H., Jost, F., Coates, A., Neubauer, F. M. and Rosenbauer, H. (1994) Giotto ion mass spectrometer measurements at comet P/Grigg–Skjellerup. *J. Geophys. Res.* **99,** 19255–19265.

Gombosi, T. I., Lorencz, K. and Jokipii, J. R. (1989) Combined first and second order Fermi acceleration at comets. *Adv. Space Res.* **9,** 3337–3341.

Huddleston, D. E., Johnstone, A. D., Coates, A. J. and Neubauer, F. M. (1991) Quasilinear pitch angle and energy diffusion of pickup ions near comet Halley. *J. Geophys. Res.* **96,** 21329–21341.

Huddleston, D. E., Coates, A. J. and Johnstone, A. D. (1992) Quasilinear velocity space diffusion of heavy cometary pickup ions on bispherical diffusion characteristics. *J. Geophys. Res.* **97,** 19163–19174.

Hynds, R. J., Cowley, S. W. H., Sanderson, T. R., Wenzel, K.-P. and van Rooijen, J. J. (1986) Observations of energetic ions from comet Giacobini–Zinner. *Science* **232,** 361–365.

Ip, H. W. and Axford, W. I. (1982) Theories of physical processes in the cometary comae and ion tails. In *Comets*, ed. L. L. Wikening, pp. 588–634. University of Arizona Press, Tucson, Arizona.

Ip, H. W. and Axford, W. I. (1986) The acceleration of particles in the vicinity of comets. *Planet. Space Sci.* **34,** 1061–1065.

Ip, H. W. and Axford, W. I. (1987) A numerical simulation of charged particle acceleration and pitch angle scattering in the turbulent plasma environment of cometary comas. In *Proc. 20th Int. Cosmic Ray Conf.*, Moscow, Vol. 3, pp. 233–236. International Union of Pure and Applied Physics, Moscow.

Ip, H. W. and Axford, W. I. (1989) Cometary plasma physics. In *Physics of Comets in the Space Age*, ed. W. F. Huebner. Springer, Heidelberg.

Ip, H. W. and Mendis, D. A. (1976) The generation of magnetic fields and electric currents in cometary plasma tails. *Icarus* **29,** 147–151.

Johnstone, A., Coates, A., Kellock, S., Wilken, B., Jockers, K., Rosenbauer, R., Studemann, W., Weiss, W., Formisano, V., Amata, E., Cerulli-Irelli, R., Dobrowolny, M., Terenzi, R., Egidi, A., Borg, H., Hultquist, B., Winningham, J., Gurgiolo, C., Bryant, D., Edwards, T., Feldman, W., Thomsen, M., Wallis, M. K., Biermann, L., Schmidt, H., Lust, R., Haerendel, G. and Paschmann, G. (1986) Ion flow at comet Halley. *Nature* **321(6067),** 344–347.

Johnstone, A. D. (1990) The solar wind interaction with comet Halley as seen by the Giotto spacecraft. In *Comet Halley, Investigations, Results, Interpretations*, Vol. 1, *Organisation, Plasma, Gas*, ed. J. Mason, Chap. 4, pp. 57–78. Ellis Horwood, Chichester, U.K.

Johnstone, A. D. (1995) Cometary ion pickup processes: Halley and Grigg–Skjellerup compared. *Adv. Space Res.* **16(4),** 11–19.

Johnstone, A. D., Coates, A. J., Huddleston, D. E., Jockers, K., Wilken, B., Borg, H., Gurgiolo, C., Winningham, J. D. and Amata, E. (1993) Observations of the solar wind and cometary ions during the encounter between Giotto and comet P/Grigg–Skjellerup. *Astron. Astrophys.* **273,** L1–L4.

Kirsch, E., McKenna-Lawlor, S., Daly, P., Korth, A., Neubauer, F. M., O'Sullivan, D., Thompson, A. and Wenzel, K.-P. (1989a) Evidence for the field line reconnection process in the particle and magnetic field measurements obtained during the Giotto–Halley encounter. *Ann. Geophys.* **7,** 107–114.

Kirsch, E., McKenna-Lawlor, S., Ip, W.-H., Daly, P. W., Thompson, A., O'Sullivan, D. and Neubauer, F. M. (1989b) A correlation of energetic particle flux anisotropies with magnetic field variations in- and outside the coma of comet Halley. *Adv. Space Res.* **9(3),** 343–346.

Kirsch, E., McKenna-Lawlor, S., Daly, P., Ip, W.-H., Neubauer, F. M., Thompson, A., O'Sullivan, D. and Wenzel, K.-P. (1990) Particle observations by EPA/EPONA during the outbound pass of Giotto from comet Halley and their relationship to large scale magnetic field irregularities. *Ann. Geophys.* **8,** 455–462.

Kirsch, E., McKenna-Lawlor, S., Daly, P. W., Neubauer, F. M., Coates, A., Thompson, A., O'Sullivan, D. and Wenzel, K.-P. (1991) Energetic water group ion fluxes ($E_{H_2O} >$ 60 keV) in a quasiperpendicular and a quasiparallel shock front as observed during the Giotto–Halley encounter. In *Cometary Plasma Processes*, Geophysical Monograph, Vol. 61, pp. 357–364. American Geophysical Union.

Kirsch, E., McKenna-Lawlor, S., Thompson, A., O'Sullivan, D., Korth, A., Schwenn, R. and Wenzel, K.-P. (1993) Analysis of comet Halley's heavy ion and micro-dust fluxes and discussion of possible acceleration processes. In *COSPAR Colloquia*, Vol. 4, *Plasma Environments of Non-magnetic Planets*, ed. T. I. Gombosi, pp. 89–92. Pergamon Press, Oxford.

Kirsch, E., McKenna-Lawlor, S., Korth, A. and Schwenn, R. (1995) Particle fluxes observed in the magnetic pileup regions of comets Halley and Grigg–Skjellerup. *Adv. Space Res.* **16**(4), 29–34.

Kirsch, E., Daly, P. W., McKenna-Lawlor, S., Neubauer, F. M. and Coates, A. J. (1996) Observation of interplanetary particles in a Corotating Interaction Region and of energetic water group ions from comet Grigg–Skjellerup. *Planet. Space Sci.* (in press).

Korth, A., Richter, A. K., Mendis, D. A., Anderson, K. A., Carlson, C. W., Curtis, D. W., Lin, R. P., Mitchell, D. L., Reme, H., Sauvaud, J. A. and d'Uston, C. (1987) The composition and radial dependence of cometary ions in the coma of comet P/Halley. *Astron. Astrophys.* **187,** 149–152.

Krankowsky, D., Lammerzahl, P., Herrewerth, I., Woweries, J., Eberhardt, P., Dolder, U., Herrmann, U., Schulte, W., Berthelier, J. J., Illiano, J. M., Hodges, R. R. and Hoffman, J. H. (1986) *In situ* gas and ion measurements at comet Halley. *Nature* **321(6067),** 326–329.

McKenna-Lawlor, S., Kirsch, E., O'Sullivan, D., Thompson, A. and Wenzel, K.-P. (1986) Energetic ions in the environment of comet Halley. *Nature* **321(6067),** 347–349.

McKenna-Lawlor, S., Kirsch, E., Thompson, A., O'Sullivan, D. and Wenzel, K.-P. (1987) The lightweight energetic particle detector EPONA and its performance on Giotto. *J. Phys. E.: Sci. Instrum.* **20,** 732–740.

McKenna-Lawlor, S., Daly, P., Kirsch, E., Wilken, B., O'Sullivan, D., Thompson, A., Kecskemety, K., Somogyi, A. and Coates, A. (1989) *In situ* energetic particle observations at comet Halley recorded by instrumentation aboard the Giotto and Vega 1 Missions. *Ann. Geophys.* **7(2),** 121–128.

McKenna-Lawlor, S. M. P., Daly, P. W., Kirsch, E., O'Sullivan, D., Thompson, A., Wenzel, K.-P. and Afonin, V. (1993a) First results from the energetic particle analyzer (EPONA) on the Giotto Extended Mission during P/Grigg–Skjellerup encounter. In *COSPAR Colloquia*, Vol. 4, *Plasma Environments of Non-magnetic Planets*, ed. T. I. Gombosi, pp. 5–7. Pergamon Press, Oxford.

McKenna-Lawlor, S. M. P., Daly, P. W., Kirsch, E., O'Sullivan, D., Thompson, A., Wenzel, K.-P. and Afonin, V. (1993b) Energetic ions at comet Grigg–Skjellerup measured from the Giotto spacecraft. *Nature* **363,** 326–329.

McKenna-Lawlor, S. M. P. and Verigin, M. (1993c) Explanation and modeling of the pronounced decline in energetic particle flux intensities (observed range ≈100–300 keV) recorded by the EPONA and Tunde-M instruments on Giotto and Vega-1 on approaching the cometopause of P/Comet Halley. In *COSPAR Colloquia*, Vol. 4, *Plasma Environments of Non-magnetic Planets*, ed. T. I. Gombosi, pp. 109–112. Pergamon Press, Oxford.

Mazelle, C., Reme, H., Sauvaud, J. A., d'Uston, C., Carlson, C. W., Anderson, K. A., Curtis, D. W., Lin, R. P., Korth, A., Mendis, D. A., Neubauer, F. M., Glassmeier, K.-H. and Raeder, J. (1989) Analysis of suprathermal electron properties at the magnetic pile-up boundary of comet P/Halley. *Geophys. Res. Lett.* **16(9),** 1035–1038.

Mazelle, C., Reme, H., Neubauer, F. M. and Glassmeier, K.-H. (1995) Comparison of the main magnetic and plasma features in the environments of comets Grigg–Skjellerup and Halley. *Adv. Space Res.* **16,** 441–445.

Motschmann, U. and Glassmeier, K.-H. (1993) Nongyrotropic distribution of pickup ions at comet P/Grigg–Skjellerup: a possible source of wave activity. *J. Geophys. Res.* **98,** 20977–20983.

Neubauer, F. M. (1987) Giotto magnetic-field results on the boundary of the pile-up region and the magnetic cavity. *Astron. Astrophys.* **187,** 73–79.

Neubauer, F. M., Glassmeier, K.-H., Pohl, M., Raeder, J., Acuna, M. H., Burlaga, L. F., Ness, N. F., Musmann, G., Mariani, F., Wallis, M. K., Ungstrup, E. and Schmidt, H. U. (1986) First results from the Giotto magnetometer experiment at comet Halley. *Nature* **321(6067),** 352–355.

Neubauer, F. M., Glassmeier, K.-H., Acuna, M. H., Mariani, F., Musmann, G., Ness, N. F. and Coates, A. J. (1990) Giotto magnetic field observations at the outbound bow shock of comet Halley. *Ann. Geophys.* **8(7-8),** 463–472.

Neubauer, F. M., Marschall, H., Pohl, M., Glassmeier, K.-H., Musmann, G., Mariani, F., Acuna, M. H., Burlaga, L. F., Ness, N. F., Wallis, M. K., Schmidt, H. U. and Ungstrup, E. (1993a) First results from the Giotto Magnetometer experiment during the P/Grigg–Skjellerup encounter. *Astron. Astrophys.* **268,** L5–L8.

Neubauer, F. M., Glassmeier, K.-H., Coates, A. J. and Johnstone, A. D. (1993b) Low-frequency electromagnetic plasma waves at comet P/Grigg–Skjellerup: analysis and interpretation. *J. Geophys. Res.* **98,** 20937–20953.

Niedner, M. B. and Brandt, J. C. (1978) Interplanetary gas — XXIII. Plasma tail disconnection events in comets: evidence for magnetic field line reconnection at interplanetary sector boundaries? *Astrophys. J.* **223,** 655–670.

Reme, H., Sauvaud, J. A., d'Uston, C., Cros, A., Anderson, K. A., Carlson, C. W., Curtis, D. W., Lin, R. P., Korth, A., Richter, A. K. and Mendis, D. A. (1987) General features of comet P/Halley. Solar wind interaction from plasma measurements. *Astron. Astrophys.* **187,** 33–38.

Reme, H., Mazelle, C., Sauvaud, J. A., d'Uston, C., Froment, F., Lin, R. P., Anderson, K. A., Carlson, C. W., Larson, D. E., Korth, A., Chaizy, P. and Mendis, D. A. (1993) The electron plasma environment at comet Grigg–Skjellerup: general observations and comparison with the environment at comet Halley. *J. Geophys. Res.* **98,** 20965–20976.

Richardson, J. G., Cowley, S. W. H., Hynds, R. J., Tranquille, C., Sanderson, T. R., Wenzel, K.-P. and Daly, P. W. (1987) Observations of energetic water group ions at comet Giacobini–Zinner: implications for ion acceleration processes. *Planet. Space Sci.* **35,** 1323–1345.

Russell, C. T., Saunders, M. A., Philips, J. L. and Fedder, J. A. (1986) Near tail reconnection as the cause of cometary tail disconnection. *J. Geophys. Res.* **91,** 1417–1423.

Somogyi, A. J., Axford, W. I., Erdos, G., Ip, W.-H., Shapiro, V. D. and Shevchenko (1990) Particle acceleration in the plasma fields near Comet Halley. In *Comet Halley, Investigations, Results, Interpretations,* Vol. 1, *Organisation, Plasma, Gas,* ed. J. Mason, Chap. 13, pp. 202–219. Ellis Horwood.

Thompsen, M. F., Feldman, W. C., Wilken, B., Jockers, K., Studemann, W., Johnstone, A. D., Coates, A., Formisano, V., Amata, E., Winningham, J. D., Borg, H., Bryant, D. and Wallis, M. K. (1987) *In-situ* observations of a bi-modal ion distribution in the outer coma of comet P/Halley. *Astron. Astrophys.* **187,** 141–148.

d'Uston, C., Reme, H., Sauvaud, J. A., Cros, A., Anderson, K. A., Carlson, C. W., Curtis, D., Lin, R. P., Korth, A., Richter, A. K. and Mendis, A. (1987) Description of the main boundaries seen by the Giotto electron experiment inside comet P/Halley–solar wind interaction region. *Astron. Astrophys.* **187,** 137–140.