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A flux enhancement measured in energetic particles ($E \sim 60$–100 keV) by the EPONA instrument aboard Giotto close to P/Grigg-Skjellerup, and its interpretation as the signature of a companion comet

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Abstract

A significant flux enhancement in energetic particles ($E \sim 60$–$\geqslant 260$ keV), showing internal fine structure interpreted to represent signatures produced during the traversal of various cometary boundaries in P/Grigg-Skjellerup, was recorded by the EPONA instrument aboard spacecraft Giotto on 10 July 1992. A further internally structured flux enhancement with about the same amplitude, recorded by EPONA in the energy range $\sim$60–100 keV but detected 90×10^3 km further on along the Giotto trajectory, is herein compared with the P/Grigg-Skjellerup record. Possible explanations for the second flux enhancement are individually considered and it is suggested, on the basis of the available evidence, that it constituted the signature of another smaller comet, either having a separate genesis from, or originating in a splitting of, the P/Grigg-Skjellerup nucleus.

1. Introduction

As a result of in situ spacecraft studies, the interaction between plasma flowing continuously outwards from the Sun (the Solar Wind) and sublimating cometary gas is presently well understood (see e.g. Galeev and Sagdeev, 1988; Coates et al., 1989, 1990; Johnstone et al., 1991, Huddleston and Johnstone, 1992; Huddleston et al., 1992a; Galeev et al., 1991, 1995).

Briefly, neutral particles 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 by the $v \times B$ motional electric field of the Solar Wind. 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 $E \times B$ 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 pickup ring distribution is unstable, causing energy to go into plasma waves and the turbulence thereby generated produces pitch angle scattering around a bispherical shell. 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 Solar Wind flow.

On the occasion of an encounter between P/Grigg-Skjellerup and spacecraft Giotto on 10 July 1992, the angle between the interplanetary magnetic field and the Solar Wind velocity vector was consistently close to 90° (Neubauer et al., 1993a), thereby rendering the pickup geometry particularly simple and in accord with the 'classical' case on which mathematical analysis, using quasi-linear theory, of the development of the ion distribution at comets is based (Galeev et al., 1991 and references therein). It was estimated by Johnstone et al., 1993 on the basis of data recorded by the Implanted Ion Sensor of the Johnstone Plasma Analyser (JPA instrument)—which recorded ions in the range 86 eV–86 keV with sufficient mass resolution to distinguish between the major mass groups—that, under the prevailing interplanetary conditions, water group ions would acquire a maximum pickup energy of 51 keV. (Similarly, at comet

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P/Halley, water group ions would have acquired pickup energies of < 60 keV).

In consequence of the energy and momentum imparted to cometary ions by the pickup process, the Solar Wind is progressively decelerated as a comet nucleus is neared. When the number density of pickup ions approaches 1% of the density of the Solar Wind a 'shock' forms, and the frozen-in interplanetary magnetic field begins to drape around the comet. Close to the shock, a variety of mechanisms contribute to further accelerating the pickup ions so that, ultimately, they attain energies of several hundred keV—see reports of in-situ observations obtained at comets P/Giacobini-Zinner, P/Halley and P/Grigg-Skjellerup (Hynds et al., 1986; Somogyi et al., 1990; McKenna-Lawlor et al., 1986, 1993, 1997; Kirsch et al., 1991); and also related theoretical analysis (Ip and Axford, 1986, 1987 and Gombosi et al., 1989).

Unpredicted fluxes of keV electrons located in what are termed 'Mystery Regions' between the shock surface and the nucleus were traversed (both inbound and outbound) at P/Halley and at P/Grigg-Skjellerup by spacecraft Giotto (Reme et al., 1987, 1993; d'Uston et al., 1987, Johnstone, 1990; Amata et al., 1991; Johnstone et al., 1993). These fluxes were discovered in the data of the three-dimensional electron spectrometer of the Reme Plasma Analyser-Copernic Experiment (RPA)—which recorded cometary electrons in the range from a few eV to approximately 150 keV. Characteristic signatures in the fluxes of energetic water group ions ($E = 60$–$\geqslant 260$ keV) marking transitions, termed Mystery Boundary Transitions (MBTs), between the Mystery Regions (recorded inbound and outbound) and the central cometary regime were identified at both comets in data recorded by the energetic particle experiment EPONA on Giotto—which recorded protons and heavier ions in the range several tens of keV to several tens of MeV (McKenna-Lawlor et al., 1997). The MBTs thus recorded were thin structures relative to a cometary ion gyroradius, and their relative positions in the cometosheath were similar at P/Halley and at P/Grigg-Skjellerup. Pitch angle data indicated that, inbound at both comets, 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, 'flowing' distributions were identified downstream of the MBTs in each case, (McKenna-Lawlor et al., 1997).

Studies by Korth et al. (1987) of the composition and radial dependence of cometary ions recorded at P/Halley, conducted using data recorded by the heavy ion analyser RPA2-PICCA (Reme Plasma Analyser—Positive Ion Cluster Composition Analyser), 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. Further, it was shown by Geiss et al. (1991), using IMS (Ion Mass Spectrometer) data, that ions at P/Halley resulting from protonation of molecules with high proton affinity were relatively abundant, and the relative source strengths for H_2, CO, CH_3, OH, HCN and H_2S at the comet were estimated by these authors. Corresponding composition data at P/Grigg-Skjellerup are not available. However, the quasiperiodicity of energetic particle data in the ambient magnetic field was recently used by McKenna-Lawlor et al. (1997) to infer that cometary ions of species $M = 28$–33 were present in the innermost region of P/Grigg-Skjellerup (see also Section 3.3).

Particles and fields data recorded aboard Giotto at P/Grigg-Skjellerup and at P/ Halley respectively allow the Solar Wind interaction with an active comet (P/Halley) to be compared, using the same suite of instruments, with that of a comet having a low gas production rate (the outgassing rate of P/Grigg-Skjellerup was determined to be $Q = 7.5 \pm 1.5 \times 10^{27}$ water group molecules s^{-1} (Johnstone et al., 1993), while the corresponding value at P/Halley was $Q = 6.9 \times 10^{29}$ water group molecules s^{-1} (Krankowsky et al., 1986).

At P/Halley, ringlike distributions were observed in the outer regions of the comet, with broader, partially filled shells closer to the Bow Shock as well as more energetic ions (Coates et al., 1989, 1990). The timescales for pitch angle diffusion were in broad agreement with the predictions of quasi-linear theory, although the observed energy diffusion time scale was longer (Huddleston et al., 1993). At P/Grigg-Skjellerup, the ion distributions were ringlike until shortly before the location of the inbound Bow Shock, due to the fact that the ions spent a shorter time in the flow than at comparable points in the coma of P/ Halley, thereby allowing insufficient time for pitch angle scattering.

The shock transitions inbound and outbound at P/Halley were located at distances of 1.15×10^6 and 0.6×10^6 km, respectively, from the comet whereas, at P/Grigg-Skjellerup, the corresponding distances were about 19,900 and 25,500 km respectively (Neubauer et al., 1993a). The intrinsic length scales of the plasma, meanwhile, were independent of the gas production rate. As shown by Neubauer et al. (1993b) and Motschmann and Glassmeier (1993), a small ratio of interaction to intrinsic scale length can cause the pickup ion phase space density to become nongyrotropic—this aspect of the interaction is due to the fact that the low activity of the comet nucleus produces a significant density gradient of implanted ions when compared to the cusp to cusp distance of the nominal cycloidal implanted ion trajectory. It was demonstrated by Coates et al. (1993a) that nongyrotropy was an important feature of the ion distributions recorded throughout the Giotto encounter with comet P/Grigg-Skjellerup, and that the extent of the observed nongyrotropy increased significantly close to the nucleus. Nongyrotropic pickup ion phase space density induces coupling of the gyrotropic eigen modes, thereby driving instabilities that effect the character of the waves close to a comet. Significantly, the plasma wave activity at P/Grigg-Skjellerup was notable for the simple, regular and high amplitude wave forms recorded in the data of the various particles and fields instruments on Giotto.

A further characteristic of the observations at P/Grigg-Skjellerup was the presence of one sided pitch angle distributions i.e. the distributions were asymmetric and showed scattering in pitch angle on one side of the ring but not on the other—on the outbound pass, one sided pitch angle distributions were recorded from the Bow Shock, at 20,000 km from the nucleus, to a distance of $\sim$85,000 km outbound, (Coates et al., 1993b). Beyond this, the distributions were ringlike again. The expected asymptotic pitch angle distribution was a bispherical shell—comprising the low-energy portions of characteristic surfaces centered on the parallel propagating Alfven wave velocities $\pm V_A$, intersecting at $v_{\text{injection}}$ (Galeev and Sagdeev, 1988; Huddleston and Johnstone, 1992). Under the prevailing interplanetary circumstances ions would scatter easily on upstream propagating waves—the circle centered on $(+V_A)$, but not around the downstream circle centered on $(-V_A)$. This was interpreted to be due to the fact that the resonant frequency in the Solar Wind frame was very high and any wave power generated would have been absorbed by thermal ions in the Solar Wind. In such a scenario it was inferred that there would be no resonant waves to produce the scattering and, thus, the one sided distributions observed would result.

A phenomenological study of the electromagnetic plasma waves characterizing the Solar Wind-comet interaction at P/Grigg-Skjellerup was carried out by Glassmeier and Neubauer (1993). (See also a complementary investigation by Neubauer et al. (1993b) and a review by Glassmeier et al. (1997)). The observations allow it to be concluded that low frequency waves and fluctuations in a Solar Wind–comet interaction region are governed by two important parameters. These are (i) the projected Mach number M_{ar} (where $M_{ar} = V_{SW}|(\cos\alpha|/V_A$, as defined by Thorne and Tsurutani (1987), and (ii) the gas production rate $Q.M_{ar}$ which controls the wave modes that can be generated due to free energy resulting from the pickup of cometary particles by the Solar Wind flow (the importance of this latter parameter was established through comparing theoretical results obtained using linear instability theory, with actual observations of wave polarization and wave energy transport). The production rate (Q) determines the scale length of the interaction region and thereby 'sets the stage' on which, in individual cases, the generated waves evolve.

The different wave forms observed in the close environments of the three comets hitherto investigated in situ by spacecraft (P/Grigg-Skjellerup, P/Halley and P/Giacobinni-Zinner) were considered by Neubauer et al. (1993b) to most probably result from scale length differences. A theoretical analysis by these authors of power spectra and polarization observations, combined with determinations of M_{ar}, suggests that, at P/Grigg-Skjellerup in the plasma frame, left-hand polarized waves, i.e. Alfven waves with a propagation direction away from the Sun, must have constituted the dominant mode although, at some locations left-hand polarized waves propagating towards the Sun would also have been present (no observational proof of the wave propagation direction is possible). In contrast, right hand waves propagating towards the Sun in the same frame of reference were deemed to be dominant at comets P/Halley and P/Giacobini-Zinner.

As already indicated above, among these three comets, P/Grigg-Skjellerup exhibited the lowest ($Q = 7.5 \pm 1.5 \times 10^{27}$ water group molecules s^{-1}) and P/Halley the highest ($Q = 6.9 \times 10^{29}$ water group molecules s^{-1}) activity. For comets in this range of outgassing, the Bow Shock and Contact Surface are the most significant plasma boundaries and their positions are well described by classical MHD models (see for example Schmidt and Wegmann, 1982). However, the observation of unexpected plasma (Mystery) boundaries at P/Halley and P/Grigg-Skjellerup (Reme et al., 1987; 1993) indicates that the classical one-fluid approach has a limited applicability, even for very active comets where the gyroradii of typical pick-up ions exceed the characteristic extension of the interaction region.

More recently, the plasma environment of a weakly outgassing comet has been considered within the frame of 2D bi-ion fluid simulations (Bogdanov et al., 1996). The results show that, for cometary ion production rates lower than a threshold value of $\sim 5 \times 10^{26}$ water group molecules s^{-1} no Bow Shock is formed (only a Mach cone). The heavy cometary ion fluid moves along a cycloidal path, undergoing, simultaneously, structuring of its density profile. This structuring takes the form of heavy ion bunching along the trajectory of the cycloid, and may be described also in terms of consecutive clumps of heavy ion fluid detaching themselves periodically from the source region and beginning to move in a soliton like density enhancement, keeping to the cycloid.

The possible formation of short-scale discontinuities within a bi-ion fluid model was also studied by Sauer et al. (1994, 1995a) and this approach to the problem of weak mass-loading later applied in considering observed cases where the characteristic dimension of the heavy ion source is much smaller than the gyroradius of the pick-up ions. In this connection it was argued that pronounced oscillations of the Solar Wind parameters measured during the AMPTE Ba and Li releases (Haerendel et al., 1986) can be explained by the formation of moving bi-ion magneto-acoustic discontinuities (Sauer et al., 1996). Yet another measurement possibly related to bi-ion magneto-acoustic pulsations at weak Solar Wind mass loading was suggested to be the magnetic field oscillations (with a periodicity of about 30 s) recorded aboard the Phobos-2 spacecraft when crossing the Deimos Mach cone. Another object possibly belonging to the same category was suggested to be Pluto, assuming that it has no intrinsic magnetic field or only a very weak one (Sauer et al., 1995b; 1996).

These results and predictions suggest that the bi-ion fluid approach already provides a useful method to describe effects related to weak Solar Wind mass-loading—such as would be provided by a comet of low Q value—before going over to more complex kinetic simulations (e.g. 2D and 3D hybrid code simulations).

It is noted that observations made by the magnetometer aboard the Galileo spacecraft in December 1995 provide evidence that, under conditions of weak mass loading, large amplitude, highly monochromatic ion cyclotron waves were recorded—starting at a radial distance of about 18 R_{Io}—during a flyby of Jupiter's satellite Io (Kivelson et al., 1996). These were interpreted to constitute L-mode waves excited by gyroresonant molecular (mainly SO_2+) ions. The conditions at Io, however, differ from those at comets in that the pertaining background magnetic field was relatively much larger, and the bulk velocity much lower (Warnecke et al., 1997).

1.1. The present study

In the present paper, an overview is first provided of the signatures recorded by the energetic particle analyzer EPONA ($E \sim 60$–260 keV) during Bow Wave (BW), Bow Shock (BS) and Mystery Boundary Transitions (MBTs) at comet P/Grigg-Skjellerup on 10 July 1993, hereafter called Event I (see also McKenna-Lawlor et al., 1997). A further internally structured flux enhancement with about the same amplitude recorded by EPONA in the energy range ($E \sim 60$–100 keV) approximately 90×10^3 km further on along the Giotto trajectory, hereafter called Event II, is thereafter described in detail for the first time.

In Section 2 a brief description is given of the EPONA instrument. In Section 3, an overview is provided of the cometary boundaries (Bow Wave, Bow Shock, Mystery Boundary Transitions) already identified by McKenna-Lawlor et al. (1997) in energetic particles in Event I (P/Grigg-Skjellerup), together with an account of the inferred characteristics of the innermost regime of this comet. Section 4 contains an account and explanation of several minor particle enhancements recorded close to Events I and II. In Section 5, Event II is described and compared with contemporaneous magnetic data. Section 6 reviews several mechanisms whereby Event II might have originated from Event I. Section 7 considers the possibility that Event II constituted an autonomous comet while Section 8 presents an account of the possible genesis of such a body in close proximity to Event I. Overall conclusions are contained in Section 9.

2. The energetic particle experiment on Giotto

The energetic particle experiment EPONA on Giotto utilized three semiconductor telescopes (T1, 2, 3), each with opening angle 30° and geometric factor 2.0×10^{-2} cm^2 ster, designed to record ions with energies in the keV–MeV range. T1 and (T2+T3) were respectively inclined at 45° and 135° to the positive spacecraft spin axis. Measurements were made in eight contiguous subsectors during each (4 s) spacecraft spin (angular resolution 45°), alternating between T1 and (T2+T3), with T1 taking the odd subsectors—S1, S3, S5 and S7 and (T2+T3) the even ones—S2, S4, S6 and S8. Table 1 lists the look directions of the eight EPONA sectors at the time of Closest Approach to P/Grigg-Skjellerup 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 (in the zx-plane). See also Fig. 1 of McKenna-Lawlor et al. (1993) for a schematic representation of the encounter geometry and of the look directions of the EPONA telescopes during the P/Grigg-Skjellerup flyby. It is noted that Comet P/Grigg-Skjellerup was traversed by the spacecraft in a direction from West to East, while simultaneously progressing from North to South either to sunward or to tailward of the nucleus, this latter point is as yet not decided (see, however, Section 7.3.).

Particle energies were determined by measuring their energy loss in the solid state detectors. Only data measured in Telescope 1 (Channels 1–4) are considered in the present paper. Telescope 1 was 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 for the first four channels of Telescope 1 were 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. A detailed account of the instrument is contained in McKenna-Lawlor et al. (1987).

3. Overview of energetic particle and complementary magnetic data

Figure 1, panels 1–4 (top) provides an overview of count rates (16 s averages) measured by EPONA in Channel 1, Telescope 1, Sectors 7, 5, 3 and 1 during the interval 12:00–18:00 SCET (Spacecraft Event Time) on 10 July 1992. A significant flux enhancement in energetic particles ($E > 60$ keV) featuring two well defined maxima showing internal fine structure is visible in the data of Channel 1, Telescope 1, Sector 3 {Ch. 1 (T1, S3)} in the interval

Table 1
EPONA sector look directions at P/Grigg-Skjellerup

	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°	−133.9°	130.5°
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 angles listed above are the CSE polar (θ) and azimuth (φ) angles, plus the angles to the Sun (+axis) and to the east (+y) axis at comet P/Grigg-Skjellerup. At Closest Approach, the Giotto spin axis (pointing along the direction of motion) had the CSE coordinates $\theta = 90.0°$; $\varphi = 90.4°$.

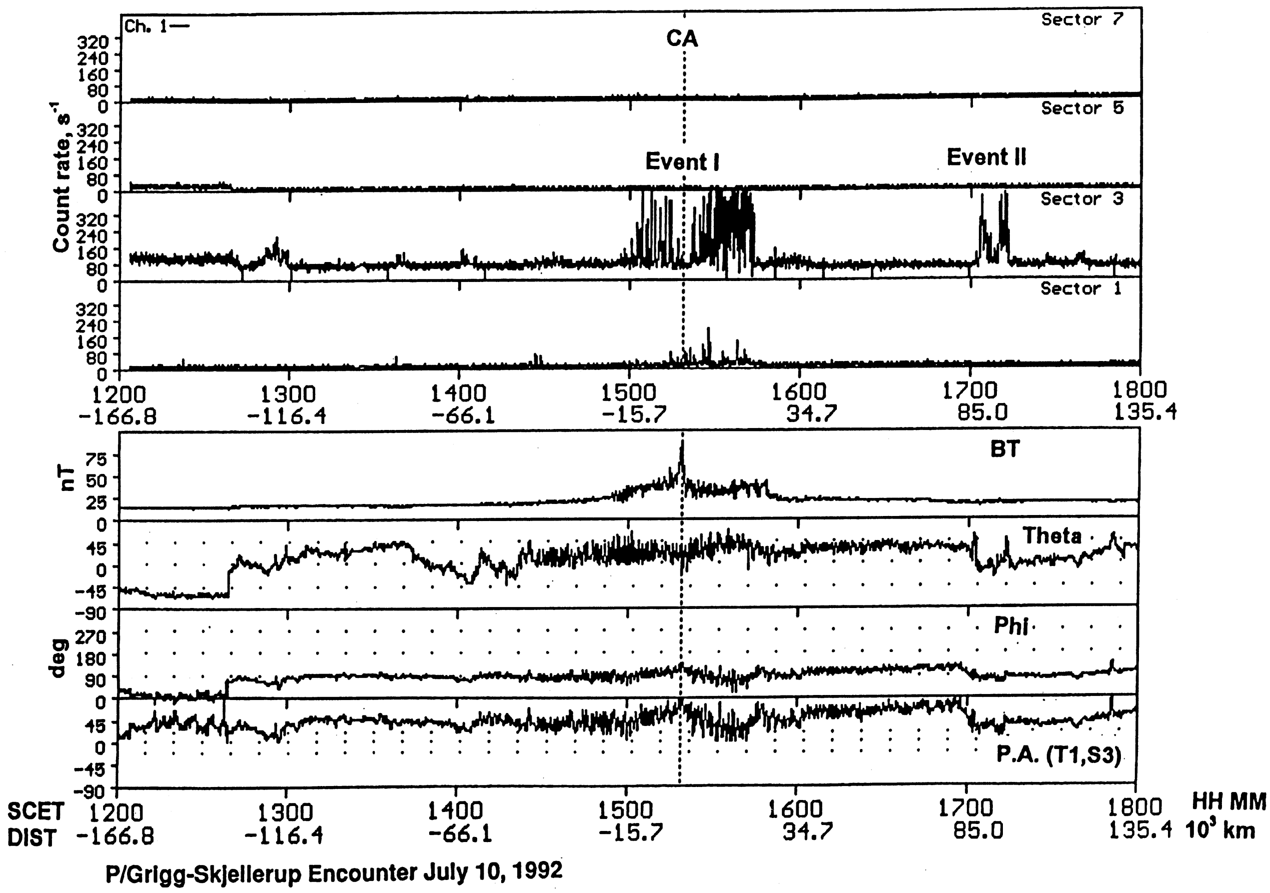

Fig. 1. Panels 1–4 (top) show count rates (16 s averages) measured by the EPONA instrument aboard Giotto within the interval 12:00–18:00 SCET on 10 July, 1992 in Channel 1, Sectors 7, 5, 3 and 1 of Telescope 1 (these data are individually presented on the same linear scale, see also the text). The data of Sector 3 show two large enhancements (Events I and II). Event I is the particle signature recorded by EPONA during traversal by the spacecraft of P/Grigg-Skjellerup. Distances from Closest Approach (CA) in units of 10^3 km, are based on ESOC tracking data (designated negative inbound and positive outbound). Panels 5–8 provide corresponding magnetometer data recorded by Neubauer et al. (1993a) presented in the Comet–Sun–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 (in the zx-plane). Panel 5: $B_T = B_{Total}$; panels 6–7: elevation (θ) and azimuthal angles (φ) of the magnetic field vectors; panel 8: instantaneous pitch angles ($P.A.$) for (T1, S3) estimated from the magnetic field data, where ($P.A.$) is the angle between the velocity vector of the ion and the magnetic field direction.

~15:00–15:44 SCET, detailed aspects of which are already interpreted by McKenna-Lawlor et al. (1997) to represent characteristic signatures produced in energetic particles during the traversal of various cometary regimes in P/Grigg-Skjellerup. This complex enhancement, which shows a minor accompanying increase in the data of (T1, S1), is generally referred to, for convenience, in the present text as Event I. It is noted that the sector data are presented on the same linear scale to emphasize the predominance of Event I in (T1, S3). Closest Approach (reported by the Spacecraft Tracking Team to occur at 15:18 SCET) in designated by CA, and distances from CA on a scale of 10^3 km are provided inbound and outbound. Distances from Closest Approach measured inbound are defined to be negative while outbound distances are, correspondingly, defined to be positive.

A second internally structured flux enhancement with about the same amplitude as Event I, recorded by EPONA in the energy range $E > 60$ keV and detected $\sim 90 \times 10^3$ km further on along the Giotto trajectory, is shown in Fig. 1 in the data of Ch.1 (T1, S3), where it is labeled 'Event II'. The subject of the present paper is to consider the characteristics of Event II relative to Event I, and to discuss the possible identity of Event II.

Panels 5–8 show magnetic data recorded simultaneously by the magnetometer (MAG) instrument aboard Giotto (Neubauer et al., 1993a). These data are presented in the Comet–Sun–Ecliptic (CSE) coordinate system (see Section 2). Panel 5 provides a plot of the total magnetic field, $B_T = B_{Total}$; panels 6–7 display, respectively, the corresponding elevation angles (θ) and azimuthal angles (ϕ). Panel 8 presents the instantaneous pitch angles ($P.A.$) for the data of Ch. 1(T1, S3) estimated from the magnetic field measurements—where ($P.A.$) is the angle between the velocity vector of the ion and the magnetic field direction.

3.1. Bow wave/bow shock transitions

Figure 2 (panels 1–4 top) provides an expanded view of count rates (16 s averages) measured by EPONA in Channel 1, Sectors 7, 5, 3 and 1 of Telescope 1 during the interval 14:50–15:50 SCET—closely spanning the interval when Giotto was traversing P/Grigg-Skjellejerup from Bow Wave to Bow Shock (Event I). The data of Channel 1 (T1, S3) show a major signature. The complementary enhancement in Channel 1 (T1, S1) was relatively minor.

The times of the Bow Wave and Bow Shock Crossings reported by Neubauer et al. (1993a), based on magnetometer data, are indicated by vertical lines and by the letters BW-M and BS-M respectively. As in Fig. 1, the time of Closest Approach (CA) and the inbound and outbound distances from CA on a scale of 10^3 km are provided. Panels 5–8 show the contemporary magnetic data recorded by Neubauer et al. (1993a) using the onboard magnetometer (MAG) instrument presented in Comet–Sun–Ecliptic coordinates—as described in Section 2.

Significant changes in the energetic particle signatures recorded by EPONA in the data of Ch.1 (T1, S3) occurred at 15:00 SCET (inbound) and at 15:44 SCET (outbound). The first of these changes was gradual, the second very steep, and both changes (which are designated on the diagram by B1-E, denoting Boundary 1-EPONA), occurred approximately 4600 km deeper inside the comet than the locations of the inbound Bow Wave and outbound Bow Shock reported by the magnetometer team. Since the gyroradius of a singly charged 100 keV water group ion in the prevailing (average) magnetic field of 20 nT was ~ 9630 km, the particle enhancements recorded each occurred approximately 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 at 15:44 SCET suggests that the (outbound) Bow Shock crossing was sensed as a sharp boundary in energetic particles, see also complementary data recorded in magnetometer and in JPA data (Neubauer et al., 1993a; Coates, 1995).

A small 'Foreshock' identified in energetic particles from 15:49–16:03 SCET was also recorded in the data of other onboard instruments (see McKenna-Lawlor et al., 1997 and also Sections 3.4. and 4).

3.2. Particle signatures recorded inbound (Event I)

A striking feature of the particle data is the quasiperiodicity of the recorded peaks in the count rates. That sequence of peaks superimposed on the general background recorded from 15:00 SCET to $\sim$ 15:10 SCET (see Fig. 2) in the data of Channel 1 (T1, S3) was interpreted by McKenna-Lawlor et al. (1997) to occur in the (inbound) cometosheath. 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 supports an earlier diagnosis, based on spectral analysis (McKenna-Lawlor et al., 1993), that the particles recorded by EPONA close to P/Grigg-Skjellerup were predominantly of the water group.

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. This observation is in accord (taking into account the 128 s time resolution of the JPA instrument) with a report by Johnstone et al. (1993) of the traversal by the spacecraft at this time of a Mystery Boundary Transition (MBT)—similar to that first reported by Reme et al. (1987) and d'Uston et al. (1987) in association with comet P/Halley (see also Section 1). Compare in addition the report by Reme et al. (1993) of the related detection of an (inbound) MBT transition in RPA data at P/Grigg-Skjellerup. In EPONA data, the transition from one cometary regime to the other across the inbound MBT was smooth, and about 1000 km in width.

In Fig. 2, the times of the (inbound) MBT transition as recorded by EPONA, JPA and RPA are indicated by

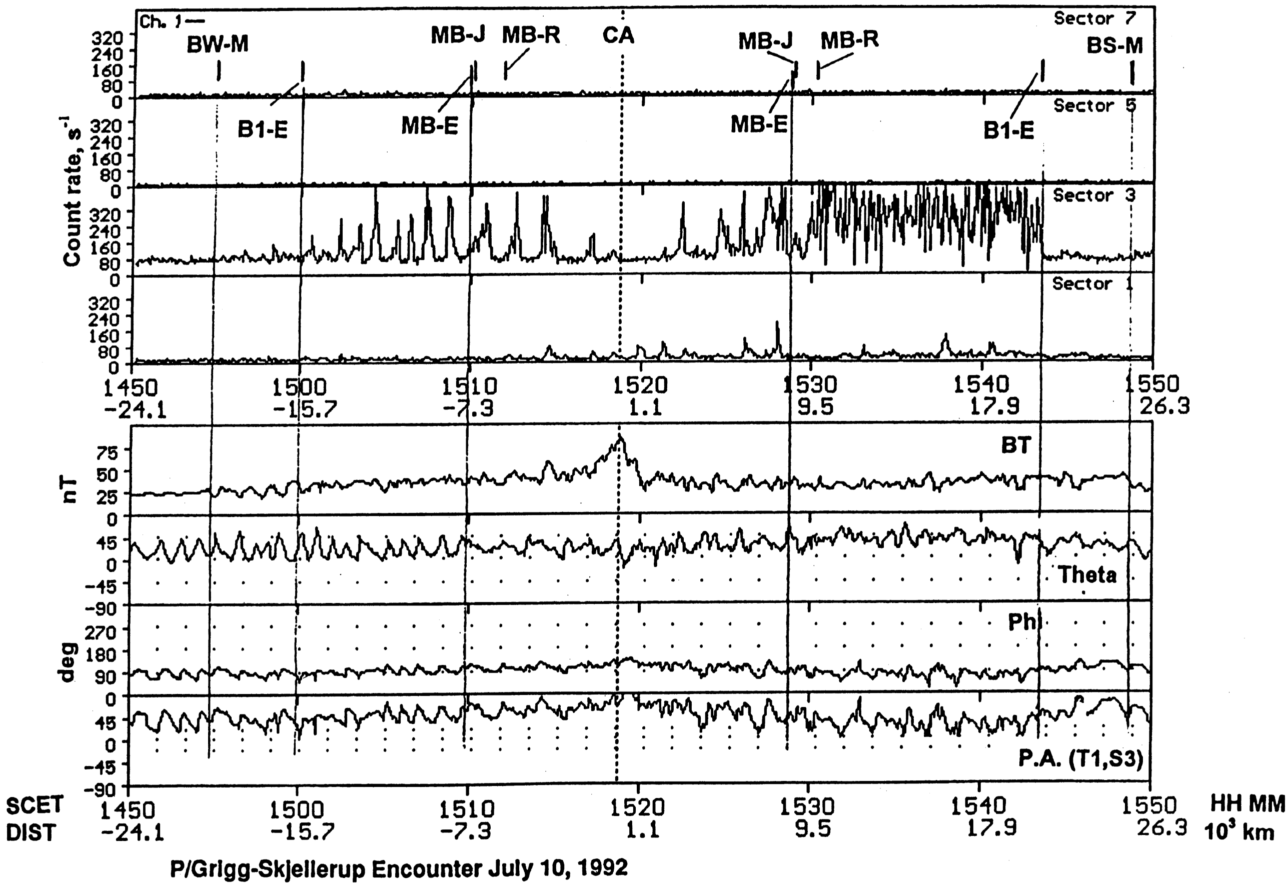

Fig. 2. The particle and magnetic data recorded during spacecraft traversal of P/Grigg-Skjellerup (Event I, see Fig. 1), are presented on an expanded time scale (14:50–15:50 SCET, 10 July 1992) using the conventions already described in the caption to Fig. 1. Distances from Closest Approach (CA) at P/Grigg-Skjellerup in units of 10^3 km are based on ESOC tracking data (designated negative inbound and positive outbound). The times of transition of Bow Wave/Bow Shock crossings reported in magnetometer data are indicated by the letters BW-M and BS-M. The times of significant changes in the energetic particle signatures recorded inbound and outbound by EPONA (which each occurred about half a gyroradius deeper within the comet than the reported locations of BW and BS), are designated by the letters B1-E. Also, the times of Mystery Boundary Transitions inbound and outbound identified in EPONA, JPA and RPA data (see text) are respectively indicated by the letters MB-E, MB-J and MB-R respectively.

vertical lines and by the letters MB-E, MB-J and MB-R respectively. 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 (time resolution of the EPONA measurements 0.5 s per sector, 4 s per spin). Since 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 they are, indeed, dissimilar. However, the records 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.

3.3. The central region in Event I

After traversal of the inbound MBT, the energetic particle data displayed very stable structures in the record of Channel 1 (T1, S3), characterized (see Section 3.2.), by the presence of quasiperiodic variations with a period about 1.8 times longer than those recorded in the inbound Cometosheath. The data further exhibited, inbound and outbound, rather symmetrical peaks, with decreasing, then increasing, 'matching' amplitudes about a center of symmetry at 15:20 SCET. No significant fluxes were present in the center of this record. Only very minor variations were recorded in the corresponding data of Channel 2 (T1, S3) with, again, minimum values at the center of symmetry.

As is evident in Fig. 2, the center of symmetry was slightly displaced by 1.5 min (1.5 min = 1200 km) relative to the time of Closest Approach. It is argued by McKenna-Lawlor et al. (1997) that this displacement was likely to have been a consequence of the non central traversal of the comet by the spacecraft. Although, outbound, before an MBT was again traversed at ~15:29 SCET (see Section 3.4), the quasiperiodic structure was less well defined than in the inbound case, the fluctuations again exhibited an identifiably longer duration than those recorded in the inbound Cometosheath.

The fact that the magnetic field magnitude did not significantly change from one side of the MBTs to the other, while the quasiperiodicity displayed by the fluxes increased (inbound) by a factor of about 1.8 relative to the value recorded in the Cometosheath, lead McKenna-Lawlor et al. (1997) to suggest that, while the majority of ions close to the comet, inbound, were of species $M = 16$–18 amu, the peaks recorded between the MBTs were due to ions with masses in the approximate range $M = 28$–33 amu (see spectral data complementary to this interpretation recorded at comet P/Halley by Balsiger et al., 1986; Korth et al., 1987; Geiss et al., 1991; also see Section 1).

Comparisons between the Channel 1 (T1, S3) data and the magnetic record show that the highest fluxes recorded near Closest Approach occurred outside the pileup region (15:17–15:20 SCET) and no special correlation between the particle peaks and associated pitch angle determinations was identified. The data of Sectors 1 and 7 and of 2, 4, 6 and 8 (not shown) displayed extremely tiny flux increases close to CA. In this sense, only the sunward related Sectors 3 and 5 displayed minimum counts at this location (see also Section 7.2).

3.4. Particle signatures outbound (Event I)

A further pattern change identified in the EPONA data of Channel 1 (T1, S3) outbound from ~15:29 SCET (designated in Fig. 2 by MB-E) which occurred without a change in B, was time associated with the traversal of a further MBT, reported by the JPA and RPA experimenters (at times respectively designated by MB-J and MB-R). The width of this transition in the EPONA data was in the range 1000–2000 km. Thereafter, up until about 15:44 SCET, the energetic particle record displayed relatively elevated fluxes, characterized by rapid variations and several very deep minima. The corresponding data of Channel 2 displayed peaks that were not especially correlated with the corresponding Channel 1 data. These data were interpreted by McKenna-Lawlor et al. (1997) to constitute signatures of the outbound Cometosheath.

A sharp 'step' in the particle intensities at 15:44 SCET indicates 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 Neubauer et al. (1993a) (see also Section 3.1). The signature of a small 'Foreshock' recorded in energetic particle data from 15:49–16:03 SCET was also recorded by the magnetometer (Glassmeier and Neubauer, 1993). A study by Mazelle et al. (1995) using RPA data shows that, at 15.48.42 SCET when a steep gradient in the magnetic field magnitude (the Bow Shock ramp) was recorded, 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. In the EPONA record, no significant enhancement was recorded at 15:49 SCET, although irregular low amplitude fluctuations characterized the record up until 16:03 SCET (McKenna-Lawlor et al., 1997).

3.5. Overall characteristics of event I

In general, the same cometary boundaries (Bow Wave, Bow Shock, inbound/outbound Mystery Boundary Transitions) were sensed in energetic particles at P/Grigg-Skjellerup (Event I) as by the other particle and fields instruments aboard Giotto. Elevated fluxes of accelerated particles, interpreted, on the basis of the periodicity of peaks in the count rates to correspond, under the prevailing ambient conditions, to the gyrofrequencies of ions of species $M = 16$–18 amu, were identified in the Cometosheath. Also, it was inferred that heavy cometary ions of species $M = 28$–33 amu were present in the innermost region of the comet (as viewed in the sunward direction).

4. Minor energetic particle enhancements at 12:39, 13:30, 13:40, 14:00 and 15:49 SCET

Before proceeding to discuss Event II, it is pertinent to describe and explain one minor outbound, and several minor inbound enhancements visible in the data of Channel 1 (T1, S3) close to Events I and II (see Fig. 1), lest the question arise that these variations might themselves represent minor versions of Event I and/or II.

4.1. The Event of 12:39 SCET inbound

Overall, the fluxes recorded in the environment of the comet were dominated, from at least 09:00 SCET, by water group ions (Kirsch et al., 1997) and, from 09:00 SCET up until 12:39 SCET, the ion flux recorded in Telescope 1, Channels 1–4 ($E_{\mathrm{Max}} \geqslant$ (260 keV), increased continuously during the approach of Giotto to a tangential discontinuity in the magnetic field, reported to be traversed by the spacecraft at 12:39 SCET (Glassmeier and Neubauer, 1993). This discontinuity acted as a barrier and scattering centre for the energetic water group ions recorded by EPONA. Sector measurements indicate that only the fluxes in Telescope 1, Sectors 3 and 5 increased, thereby indicating that the scattering centre was located to sunward of Giotto and in its flight direction. A small flux enhancement superimposed on the general, gradual, background rise, marked traversal by the spacecraft of the magnetic discontinuity itself. This enhancement did not show any special internal structure. After 12:39 SCET, the background flux level recorded by EPONA before 09:00 SCET was restored, and Giotto was interpreted to be again immersed in the 'normal' flux of a locally present Corotating Interaction Region (Kirsch et al., 1997).

4.2. The Events of 13:30, 13:40 and 14:00 SCET (inbound)

These minor enhancements, which were each considerably 'weaker' than the event of 12:39 SCET, were individually accompanied by correspondingly smaller directional discontinuities in the interplanetary magnetic field. The individual minor particle enhancements recorded were also seen in JPA data, where they were shown to be characterised by pitch angle diffusion, and interpreted to be associated with cometary ions coming into the JPA detectors due to local changes in the magnetic field direction (Johnstone et al., 1993). It is pertinent to note that none of these enhancements showed internal fine structure at the high time resolution of the EPONA experiment and they are interpreted, as by the JPA Team, to represent flux increases consequent on local changes in the magnetic field direction.

4.3. The Event of 15:49 SCET outbound

An enhancement recorded in the energetic particle data from 15:49–16:03 SCET was shown by McKenna-Lawlor et al. (1997) to constitute the signature of a Foreshock associated with P/Grigg-Skjellerup (see also Section 3.4).

5. Description of Event II

5.1. Energetic particle record of Event II

Figure 3 presents on the same linear scale (panels 1–4 top) particle data recorded in Channel 1, Sectors 7, 5, 3 and 1 of Telescope 1 (16 s averages) during an interval 16:40–17:40 SCET spanning Event II. Corresponding magnetic data recorded by Neubauer et al. (1993a) are presented in CSE coordinates in panels 5–12.

Event II, like Event I, was characterized by two rather symmetrical maxima in Channel 1 (T1, S3) data—compare Fig. 3 with Fig. 1. The individual maxima recorded displayed fine structure which was internally asymmetrical. This structured enhancement was 90×10^3 km further along the Giotto trajectory than the location of Event I. It appeared only in the data of Telescope 1, Sector 3 where it stimulated Channel 1 and, to a lesser extent, Channel 2 (recorded range for water group ions $\sim$ 60–100 keV).

Inbound during Event II, (see Fig. 3), the particle record shows a very minor peak, relative to the background, which seemed to be associated with a pitch angle variation. This was followed by a sharp increase in flux, heralding entry to a regime characterized by a series of peaks of gradually decreasing amplitude, each reverting progressively towards the background flux level and each showing a duration close to 2 min. Outbound, a series of four peaks was observed, the first of which had a duration close to 2 min, while those that followed each had a duration close to 1 min. These latter variations displayed closely similar amplitudes which did not, at their minima, return to the background level. Thereafter, a further minor enhancement marked the location of a sharp drop to 'background'. Event II was $\sim 9.2 \times 10^3$ km in extent.

As in the case of Event I, the quasiperiodicity of peaks in the count rates correspond, under the prevailing ambient conditions, to the gyrofrequencies of ions of species $M = 28$–33 amu and to ions of species $M = 16$–18 amu. See also the discussion in Section 6.1.

5.2. Magnetic signatures during Event II

Figure 3, panels 5–12 displays magnetic data recorded during Event II presented in CSE coordinates (as in the case of Figs 1 and 2). Panels 5–8 represent, respectively, B_{Total}, the elevation angles (θ); the azimuthal angles (ϕ) and the instantaneous pitch angles ($P.A.$)—for the data of Channel 1 (T1, S3). Panels 9–11 present the B_z, B_x and B_y components of the magnetic field. Panel 12 shows deviations of B_{Total} from B_{Average} (averaging was made for each value by using a seven point running window, the resulting amplitude was then amplified by 10 and plotted relative to the 20 nT level).

The magnetic records show well defined changes as the spacecraft entered and exited the spatial location of Event II. In particular, two distinct variations in the B-direction occurred at the inbound and outbound boundaries of this structure in B_z and B_y (on a scale of 9000 km), matched by corresponding enhancements in the elevation angle (θ). An increased 'quasiconstant' component B_x was recorded between these variations. This latter 'sunward' increase in x was superimposed on a general transition between two more or less stable situations in the Solar Wind on either side of Event II (see Section 6.5). Inbound, the changes in B_z and B_y were recorded during the transition between these two stable regimes of the interplanetary magnetic field (IMF). The energetic particle Event II was recorded just when the second stable state of the IMF had been reached (compare the particle record shown in panel 3 with the magnetic data). There was some degree of anti-correlation, outbound, between the particle data and variations in the magnetic field.

Enhanced fluctuations of the average magnetic field were recorded at both boundaries of the particle enhancement as well as at it's 'center'. There was, however, no close (point by point) correlation between the energetic

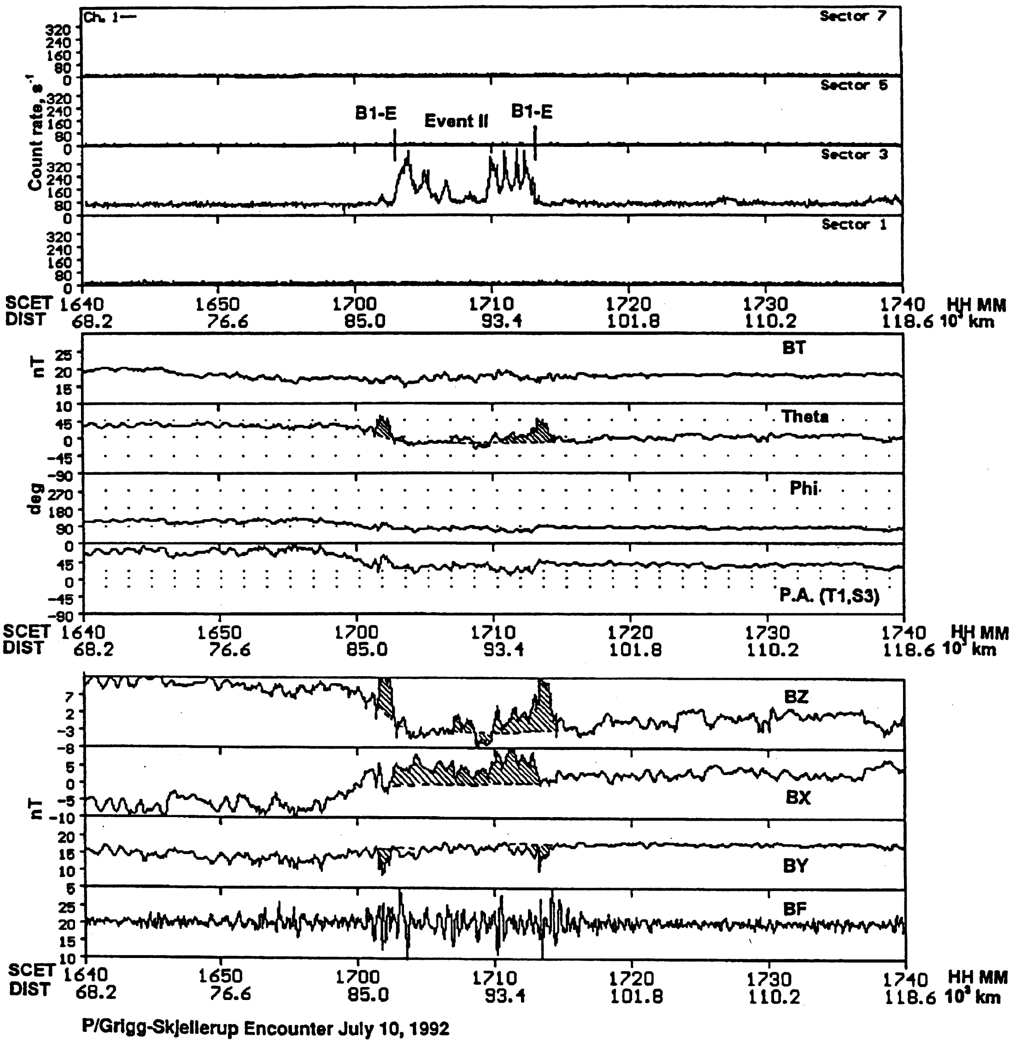

Fig. 3. The particle and magnetic data of Event II (see Fig. 1) are presented in panels 1–8 on an expanded time scale (16:40–17:40 SCET on 10 July 1992) using the conventions already described in the caption to Fig. 1. Panels 9–11 provide the magnetic B_z, B_x, and B_y components presented in the CSE system (see the caption to Fig. 1). Panel 12 (B_F) shows deviations of B_{Total} from B_{Average} (averaging was made for each value by using a seven point running window, the resulting amplitude was then amplified by 10 and plotted relative to the 20 nT level). Distances from Closest Approach (CA) at P/Grigg-Skjellerup in units of 10^3 km are based on ESOC tracking data (all values are designated to be positive outbound from Closest Approach to Event I).

particle count rates and the magnetic parameters. Also, there was no distinct signature in B_T.

6. Discussion of event II

6.1. Cometary identity of the ions in Event II

Event II displayed fine structure in energetic particle data showing, under the ambient conditions, quasiperiodicity in the range 1–2 min, suggesting as was the case in Event I, the local presence of cometary ions of species $M = 16$–18 amu and $M = 28$–33 amu. Protons would have been the predominant species in the Solar Wind. The predominance of cometary type ions in Event I also precludes the possibility that Event II was a solar related structure traversed by the spacecraft.

The fact that in Event II the same particle amplitudes were observed inbound left and outbound right after the establishment of magnetic quasistable state (2), see Fig. 3 and also Section 6.5, supports the idea that Event II did not constitute a large influx of ambient cometary particles brought into the field of view of the telescope due to a local change in the magnetic field.

6.2. Possible derivation of Event II from Event I

Several different possibilities can next be considered as providing a candidate source for Event II. These include

(a) that Event II originated in debris from Event I; (b) that Event II represented the traversal of a jet emanating from Event I; (c) that ions from Event I were transferred to the location of Event II by the interplanetary magnetic field; (d) that Event II constituted a consequence of plasma structure formation in the environment of a weakly outgassing comet.

6.3. The possibility that Event II originated in debris from Event I

On the premise that Event II represents a signature of cometary type ions, it is possible that the observed ions originated from debris produced by P/Grigg-Skjellerup.

If 'debris' are taken to comprise small pieces of cometary material (fragments/grains) elevated from the surface of the nucleus (e.g. by outgassing jets of neutral gas), these objects should exit with velocities $V_d \ll V_{neutrals}$ (i.e. $\ll \sim 1$ km s^{-1}). Whipple (1951) predicted velocities of a few tens of meters per second for such ejecta, depending on particle size.

Most probably the emission of debris occurs only from that part of a nucleus that is illuminated by the Sun. Immediately after the Giotto flyby of comet P/Halley, it was obvious that the dark side of the nucleus was essentially inactive (at least so far as the production of dust was concerned). Further, only a minor part of the illuminated surface was active in the sense of supporting the unrestricted sublimation of water ice, while large parts of the surface were covered by a non-volatile crust or mantle (Keller, 1990a; Keller et al., 1994).

Sublimation/evaporation from debris constitutes an additional source of neutral gas production around a comet—followed by the ionization of these neutrals and, subsequently, ion pickup. The contributing lifetime of a particular fragment depends on its size and rate of loss of gas. Sufficiently large debris emitted from Event I could survive long enough to reach the general location of Event II (90,000 km distant). Such objects would travel for approximately $90{,}000/0.1 = 250$ h, if their velocity is taken to be $V_d = 0.1$ km s^{-1}. In actuality, the value of V_d should be much smaller and the predicted travel time, correspondingly, of the order of a few tens of days.

The space density of debris emitted from Event I should be greatest near the comet nucleus and, thereafter, fall off with distance due to a combination of sublimation/evaporation and the $1/r^2$ effect. Such objects could produce neutral molecules continuously and, thus, neutrals produced by debris near to a particular nucleus can be considered jointly with neutrals produced by that nucleus itself. Debris which reached the location of Event II may have contributed to the count rates measured at this position. However it is improbable that, at a distance of 90,000 km from the major nucleus when the spacecraft would already have flown from a dense to a relatively rarefied density of such debris, that a significant bunching of such fragments occurred at Giotto. A realistic supposition is that only a single piece would have been at the proper location to produce the flux enhancement recorded by EPONA.

Gas production by a particular fragment/grain depends upon its size (as $\sim 1/r^2$). If we take the comet radius to be $R_c = 1$ km and the radius of a representative grain $R_g = 1$ cm, then the ratio of local gas production by the grain to that of the comet will be only (1 cm:1 km)$^2 = 10^{-10}$. Approximately the same count rate was, however, measured during the major encounter as during Event II (see Fig. 1). To produce the same count rate, the grain should be comparable in size to the major nucleus and, in this case, we would have a second nucleus rather than a grain (piece of cometary debris).

Even if we assume that a sufficient number of fragments were locally present to produce the observed count rate, it is highly improbable, due to the typical random pattern of production of such ejecta at the surface of the main body (and the $1/r^2$ effect), that such objects would have composed a compact group capable of producing the sharp boundaries of Event II. These considerations allow us to exclude debris from Event I as a possible explanation of Event II.

6.4. Possibility that Event II represented the traversal of a jet emanating from Event I

Event II, which was located at 90,000 km from the main nucleus, was observed from 17:03–17:14 SCET i.e. over a length of 9200 km along the spacecraft trajectory. If Event II was produced by pickup ions originating from neutrals arriving at the location of Event II within a jet having sharp boundaries, then the angle 2A of the jet should be 5.8°, where $A = \arctan(4600/90{,}000) = 2.9°$.

It was reported by Szego et al. (1995) that, within the dust coma of P/Halley, jets were observed that looked like straight rays. As the Vega 1 and Vega 2 spacecraft flew closer to the nucleus, these features were found to be composed of finer and finer radial structures. The corresponding source regions could not, however, be resolved visually. On the other hand, image processing of photographs taken at P/Halley using the Giotto Multicolour Camera not only revealed the presence of radial fine structures within the volumes of the main jets, but, further, showed them to be connected to small scale features of the active surface (Keller et al., 1994). The structures identified had a width of about 500 m close to their sources.

To produce the observed count rates (which were comparable with the count rates measured near the P/Grigg-Skjellerup nucleus), the local density of neutrals at the location of Event II (D_{EII}) should be comparable with that density pertaining near Event I. If now we assume the radius of the jet aperture to be (say) ~ 100 m then, with this simple geometry, the density present in the jet source should be 10^{10} times larger than D_{EII}—which is unrealistic. This simple geometric estimate is made on the assumption that, inside the jet, there are no collisions and the neutral particles follow straight paths - which, at least in the source region, is not the case.

Close to the source, inside a collision dominated sphere, the angular width of a jet should significantly expand due to collisions. According to Moroz (1985) the radius of such a sphere is given by $R_c = Q\sigma/4\pi u$ (where Q, is the gas production rate, σ is the collision cross-section and u the expansion rate). For comet P/Halley where $Q = 6.9 \times 10^{29}$ water group molecules s^{-1} (Krankowsky et al., 1986), calculations yield values for $u = 0.65$ km s^{-1}, and the corresponding value for $R_c = 10^4$ km. As the gas production rate of P/Grigg-Skjellerup was $\sim 10^{28}$ water group molecules s^{-1} (Johnstone et al., 1993), the value of R_c is ~ 100 km. This implies that, at this comet, particles constituting a representative jet would travel inside the collision dominated sphere for approximately $(100/0.65) = 140$ s. It is estimated that each particle of the jet would experience at least one collision with particles of the ambient neutral atmosphere, resulting in strong angular expansion of this feature and in the destruction of its sharp boundaries. These considerations militate against the supposition that Event II, which exhibited well defined boundaries, constituted a jet or filament extending from Event I.

6.5. *Possibility that ions from Event I were transferred to the location of Event II by the magnetic field*

During the interval (17:03–17:14 SCET) when the spacecraft was traversing Event II, the interplanetary magnetic field (IMF) displayed two superimposed changes

(a) A large scale transition between two quasi-stable states (1) and (2)

azimuth angle of (1) $\varphi_1 = 130°$, elevation angle of (1) $\theta_1 = 38°$
azimuth angle of (2) $\varphi_2 = 90°$, elevation angle of (2) $\theta_2 = 0°$

(b) Smaller scale structure in θ (with 2 distinct maxima), see Fig. 3, during Event II
The first maximum in θ (left) coincided with the start of Event II
The second maximum in θ (right) coincided with the end of Event II
The value of θ in these two maxima is in the range 46–50°.
The first maximum in θ coincided with, and was superimposed on, the transition between the quasi-stable states (1) and (2) of the IMF. The remaining small scale structure in θ, including its second distinct maximum as well as particle Event II, were observed during quasi-stable state (2).

Figure 4 shows the geometry of the Event II encounter, presented in comet-centered (CSE) coordinates. Relevant vectors are given in Table 2.

The straight line from the upper left to the lower right corner in Fig. 4 represents the spacecraft trajectory in the X_{CSE}–Z_{CSE} plane (side view of the encounter). The elevation angle θ_{sc} of the spacecraft trajectory in the Y_{CSE}–Z_{CSE} plane (perpendicular to the comet–Sun line) is close to

$$\theta_{sc} = arc\tan(-12.8/-5.1) = 68.3°$$

Accordingly, the angle β_o between the magnetic field direction and the spacecraft trajectory is given by

$$\beta_o = arc\cos(-5.1/V_{sc}) = 111.5°$$

i.e. the magnetic field was roughly perpendicular to the spacecraft trajectory.

To have magnetic connection by straight magnetic field lines, the elevation of B should be $\sim 70°$ out of the ecliptic

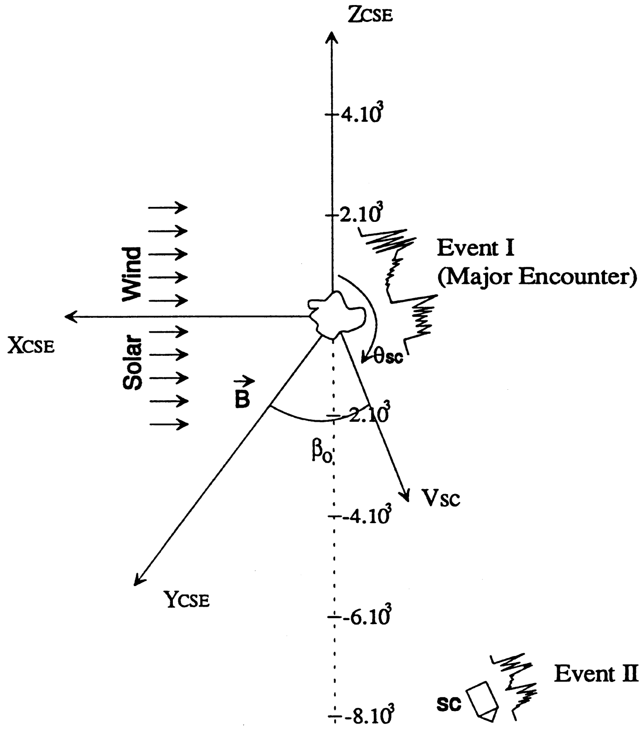

Fig. 4. Geometry of the Event II encounter presented in CSE coordinates.

Table 2

	X_{CSE}	Y_{CSE}	Z_{CSE}
Solar wind velocity V_{sw}	$-V_{sw}$	0	0
Magnetic field, state (2)	0	B_t	0
SC velocity V_{sc}, km s^{-1}	−2.60	−5.03	−12.8

plane, which is not the observed case either for state (2) with $\theta_2 = 0°$, or for state (1) $\theta_1 = 38°$.

All the measurements of B obtained are of 'single point' type (i.e. these measurements apply only at the specific location of the spacecraft). This means that, when measurements were made at the location of Event II, the corresponding situation at the location of Event I was not precisely known. It is in this situation conceivable that there was some complicated magnetic field configuration involving curved field lines which connected Event I and Event II at the time when the spacecraft traversed Event II. Although the associated requirement of a change of about 180° in azimuth, and the generally quasi-stable behavior of B during the period considered render this supposition improbable, it cannot, on these grounds alone, be excluded.

We can, however, readily exclude such a possibility from a 'scaling' point of view. If it is assumed that Event II, since it was very similar in structure to Event I, was a 'magnetic field projection' of Event I, then the magnetic field intensity at Event II should be larger than at Event I by a factor $(L_1/L_2)^2$—where $L_1 = 40{,}000$ km and $L_2 = 9200$ km are characteristic lengths of these two events giving, thereby, an increase by about a factor of 19, which was not observed. It may thus be deduced that there was no direct B connection between the main nucleus and the location of Event II and that, in this situation, the direct transportation of ions picked up near the main nucleus along the magnetic field to the location of Event II was not supported.

6.6. *Possibility that Event II constituted a consequence of plasma structure formation in the environment of a weakly outgassing comet*

Comet P/Grigg-Skjellerup had a measured production rate of $7.5 \pm 1.5 \times 10^{27}$ water group molecules s^{-1} (Johnstone et al., 1993) during the Giotto encounter, and the characteristic features it displayed are in acceptable agreement with the predictions of MHD models developed (for example) by Baumgartel and Sauer (1987) and by Gombosi et al. (1994) based on a classical paper of Biermann et al. (1967) (see also Section 1). However, the observation of Mystery Boundaries at P/Halley and P/Grigg-Skjellerup has indicated that the classical one-fluid approach has some limitations and thus Sauer et al. (1994, 1995a) have laterally started to investigate, using a bi-ion fluid model approach, the possible formation of a short scale discontinuity (protonopause) at such objects.

In addition, the plasma environment of weakly outgassing comets has been considered by Bogdanov et al. (1996) who have described how, under conditions where no Bow Shock is formed, heavy cometary ion fluid moves along a cycloidal path, while simultaneously undergoing structuring of its density profile. This theory does not apply in the present case since Event I, does not meet the criterion of displaying a low gas production rate (such that the characteristic extension of the cometary source region is much smaller than the gyroradius of the pickup ions). Further, since the direction of the local magnetic field was roughly perpendicular to the spacecraft path (see Section 6.5.), the cycloid would in no way deliver ions to the location of Event II.

7. Possibility that Event II constituted an autonomous comet

During the Event I and Event II encounters, the magnetic field was primarily perpendicular to the Solar Wind flow vector (see Fig. 3), thereby rendering conditions for the pickup of cometary ions especially simple (Galeev et al., 1991). In the vicinity of P/Grigg-Skjellerup the ambient magnetic field strength (see Fig. 1) and the Alfven speed (105 ± 20 km s^{-1}) were quite high, while the magnetosonic speed (110 ± 20 km s^{-1}) and the Mach number of the flow (3.2 ± 0.6) were individually unusually low (Johnstone et al., 1993). Therefore, if a second comet like body were rather closely spatially associated with the location of Event I, the external appearance of its interaction with the Solar Wind should be similar to the P/Grigg-Skjellerup interaction. General similarities and dissimilarities between the two objects include;

Similarities:
- Double maximum structure
- Sharp boundaries
- Approximately equal amplitudes of fluxes
- Internal fine structure
- Decreasing amplitudes, inbound
- Asymmetrical depression at the centre
- Outbound variations that did not return to the background level
- Preferentially enhanced fluxes outbound
- Particle energies in both events above the maximum available pickup energy ($\sim$ 50 keV) for water group ions under the prevailing Solar Wind conditions
- No special correlation between the particle peaks and associated pitch angle determinations
- Periodicity of the peaks in countrates (close to 1^{min} and 2^{min}) corresponding to cometary ion gyrofrequencies under the prevailing conditions.

Dissimilarities:
- Lower maximum particle energies ($\sim$100 keV) during Event II than during Event I ($\sim$260 keV)
- No related signature in other sectors during Event II^{+}
- The distance from BW to BS at P/Grigg-Skjellerup was $\sim 45 \times 10^3$ km whereas Event II was $\sim 9.2 \times 10^3$ km in extent
- No special B_T signature was associated with Event II whilst such a signature was associated with Event I

Note: The fluxes recorded in Channel 1 (T1, S1) during Event I were nearly a factor of 10 lower than those recorded in Channel 1 (T1, S3) and were yet less in other sectors.

If Events I and II are compared on the basis of similarity/dissimilarity it can be concluded that similarities prevail, and that the few dissimilarities can be explained on the basis of (a) a smaller size of Event II (by a few units) with a correspondingly lower gas production rate and (b) by a different geometry of the flyby (for example by a passage deep in the cometotail in the case of Event II because there was no pile-up in the magnetic field), and by a passage close to the nucleus in the case of Event I (since there was a pile-up of magnetic field). These topics are taken up again below, see in particular Sections 7.2. and 7.3.

7.1. Wave activity encompassing Events I and II

The quasiperiodicity of the peaks in countrates (close to 1^{min} and 2^{min} intervals) which correspond to cometary ion gyrofrequencies, is a particularly striking feature of Event II (as well as of Event I). Although Event II displayed wave related phenomena, this does not in itself prove that the Solar Wind had nothing to do with the observed waves—since the Solar Wind might have constituted the source triggering the waves and accelerating the cometary ions.

An investigation by Glassmeier and Neubauer (1993) of wave phenomenology in the P/Grigg-Skjellerup interaction region may be considered in this connection, and the results obtained by these authors are next, briefly, described. Table 3 summarises the characteristics of the various wave regions they identified close to the comet during the inbound and outbound passes of spacecraft Giotto. A feature of these observations is that the wave structures identified in a series of consecutive 'regions' on the inbound trajectory closely resembled those recorded in complementary 'regions' during the outbound pass. This similarity is reflected in the original paper of Glassmeier and Neubauer (1993), as well as in the present text, by the convention of labelling 'matching' regions inbound and outbound by upper case letters (A–G) and by lower case (g–a) letters respectively.

According to this convention, the first indication of pickup ion associated waves occurred in region A, at about 624×10^3 km from Closest Approach to P/Grigg Skjellerup (see Table 3). This marked the entry of Giotto into what was described as a 'Pickup Ion Contaminated Solar Wind Region', where waves of cometary origin occurred only sporadically as discrete wave packets. Closer to the comet, at a distance of about 258×10^3 km from CA (or from 10:12 SCET onwards), the wave activity became more continuous and the previously present wave packets vanished. This situation marked a transition into Region (B), described as the 'Inbound Outermost Upstream Region', where the presence of the comet started to dominate over temporal variations in the interplanetary magnetic field. At 12:39 SCET, at a distance of 134×10^3 km from CA, Giotto traversed a major directional discontinuity (see also Section 4, above) and entered region (C), where the wave activity became conspicuous and much less clearly pickup related than in region (B).

About 1 h later at a distance of 89.8×10^3 km from CA, Giotto entered what was called the 'Inbound Upstream Region Proper' (composed of subregions D1–D2) characterised by continuous large-amplitude fluctuations of the

Table 3
Wave regions characterizing the interaction region surrounding comet P/Grigg-Skjellerup, following Glassmeier and Neubauer (1993)

Time (SCET)	Distance from CA to P/G-S ($km \times 10^3$)	Regime	Comment
02:57–10:12	624–258	A	Waves of cometary origin occurred only sporadically as discrete wave packets
10:12–12:39	258–134	B	Wave activity became continuous, wave packet character vanished
12:39–13:32	134–89.8	C	Major directional discontinuity at 12:39 SCET. Wave activity becomes, thereafter, conspicuous
13:32–14:55	89.8–19.9	D1–D2	Inbound Upstream Region Proper. Large amplitude magnetic field fluctuations
Inbound Bow Wave/Pileup Region/Outbound Bow Shock/Foreshock			
16:04–16:48	37.9– 75.4	d2–d1	Outbound Upstream Region Proper. Fluctuations as in D1–D2
16:48–17:04	75.4– 87.96	c	Pickup associated waves barely visible. Magnetic discontinuity associated with Event II at 17:04 SCET
17:04–20:22	87.96–254.5	b	Outbound Outermost Upstream Region. Pickup waves continuously observed
20:22–23:45	254.5–424.0	a	Upstream waves of cometary origin occur only sporadically and as discrete wave packets

magnetic field. This latter region was terminated by the inbound Bow Wave (traversed at a distance of about 19.9×10^3 km from CA).

Outbound, between 16:04–16:48 SCET subregions (d2–d1) displayed essentially the same characteristics found in regions D1–D2. In the interval 16:48–17:04 SCET spanning Region c (which was located between 75:4 and $87:9 \times 10^3$ km from CA), Glassmeier and Neubauer (1993) noted that 'pickup' associated upstream waves were 'barely visible'. This 'Outbound Intermediate Region' was terminated by what was termed 'A Major Directional Discontinuity'—which corresponds with the magnetic aspect of Event II (described above in Sections 5.2. and 6.5.). After traversal by the spacecraft of this discontinuity, pickup waves were continuously observed throughout Region b (which was styled the 'Outbound Outermost Upstream Region') and endured until about 20:22 SCET (at 254×10^3 km from CA), a time beyond which upstream waves of cometary origin occurred only sporadically and as discrete wave packets. The last wave event of cometary origin was recorded at 23:45 SCET (at 424×10^3 km from CA) in the outbound 'Pickup Contaminated Solar Wind Region', designated by the letter (a).

A detailed study of the characteristics of the waves described indicates that current linear instability analyses of pickup ions of cometary origin can explain many of their observed properties (Glassmeier et al., 1997) and it can be inferred that the Solar Wind was not the source triggering local wave activity in the immediate Event I/Event II environment. It is noted that Neubauer et al. (1993b) concluded from studies of power spectra, polarization observations and the Alfven Mach number (M_{Ar})—see also Section 1—that, from 16:02 to 17:00 SCET, LH^+ but not LH^- waves were possible. Thereafter, LH^+ and LH^- waves could be excited, and a change in direction at 17:02 SCET could have resulted in two left-hand mode waves crossing each other. However, no direct observational proof of the wave propagation direction is available (Glassmeier et al., 1997). The surprisingly regular character of those waves close to, but upstream of, the Bow Wave and Bow Shock at comet P/Grigg-Skjellerup was interpreted by Neubauer et al. (1993) to be due to the effects of nongyrotropy and/or nonlinear dispersive effects (see also Hada et al., 1989; Coates et al., 1993a).

It is noted that the relationship between gyrophase bunched ions and wave fields was considered in connection with the Earth's Bow Shock and Foreshock by Gurgiolo et al. (1981; 1993) and by Hoppe et al. (1981). Some initial steps towards developing a stability theory of nongyrotropic distributions have already been taken by Brinca et al. (1992) and by Motschmann and Glassmeier (1993). However, further theoretical work is still needed in this area.

If it is assumed that Event II was somehow produced by a change in wave activity due to the observed magnetic field change at 17:03–17:14 SCET, then we would expect that the overall pattern of Event II in energetic particles should follow the described magnetic changes (i.e. it should follow the large scale transition between two quasi-stable states (1) and (2) described in Section 6.5. However, (see Fig. 3 and also Section 7.3.) the energetic particle event was observed when the second quasi-stable state of the background magnetic field was already established. The (inbound) change in B_y and B_z, meanwhile, took place during the major transition between the two quasi-stable magnetic states. The structure in energetic particles of Event II does not reflect the background asymmetry of the magnetic field and the generally symmetrical pattern it displayed may be ascribed to a local effect (suggested in Section 7.2 to be, as in the case of Event I, a gas production source). Also, it is noted that no further particle event was recorded in region (b) where, according to Glassmeier and Neubauer, 1993, 'pickup waves were continuously observed'.

7.2. Cometary characteristics in energetic particles of Events I and II

The uniqueness of the comet–Solar Wind interaction is of assistance in seeking to determine the nature of Events I and II. Comets interact with the Solar Wind through the processes of ion pickup and mass loading (see Section 1). The incorporation of newly born cometary ions into the Solar Wind requires the transfer of momentum and energy to these particles. Large-amplitude electromagnetic wave fields and turbulence generated due to the relative streaming of newborn ions of cometary origin and Solar Wind ions, leads to diffusion in velocity space and, thereby, accommodates the required momentum and energy transfer. In addition to microscopic wave-particle interactions, the activity of the comet (its Q value) and the pertaining Solar Wind conditions determine the overall macroscopic structure of the interaction region, as well as the key properties of the ambient waves

Under the prevailing interplanetary conditions on 10 July 1992, heavy pickup ions accelerated above the maximum available pickup energy so as to achieve registration in Telescope 1, could in principle be recorded by EPONA in the Event I/Event II environment (see Sections 1.0, 2.0, 3.2, 3.3 and 6.1). The look direction of T1, S3—opening angle 30°, inclined at 45° to the spin axis of the spacecraft, which was nearly parallel to the magnetic field direction throughout both events—was, however, inappropriate at Event I to record cometary ions from a local source until sufficient pitch angle scattering had occurred to bring such particles into the field of view of the instrument (i.e. at a location close to the inbound P/Grigg-Skjellerup Bow Wave).

In Events I and II, the first significant enhancements in energetic particles were recorded by EPONA deeper inside the structure than the reported magnetic field boundaries—both inbound and outbound. Comparisons show that the quasiperiodic particle increases in Event II (and also in Event I) were not especially modulated by fluctuations in the magnetic field associated with cyclotron wave activity. At times, some degree of anticorrelation was present between variations in the particles and fields data, but this was not a requirement at either object for the observation of particle quasiperiodicity.

The quasiperiodicity of the peaks in count rates at both locations (corresponding to cometary ion gyrofrequencies under the prevailing interplanetary conditions), suggests that ions with masses in the range $M = 16$–18 amu and $M = 28$–32 amu were present in Events I and II. Inbound at Event II, the quasiperiodicity of the ion counts indicates that only heavy ions were recorded. As reported by Glassmeier and Neubauer (1993), pickup associated upstream waves were 'barely visible' outbound between 75.4 and 87.9×10^3 km from P/Grigg-Skjellerup. See also the report of Coates et al. (1993b) of the presence of one sided pitch angle distributions to a distance of about 85×10^3 km outbound. It is noted that, although Event I showed a minor enhancement in (T1, S1)—less by a factor of ~ 10 than that in (T1, S3) and miniscule enhancements in some other Sectors—Event II was a feature of (T1, S3) only, suggesting that a lower level of scattering pertained at this object. The maximum particle energy attained was also lower in Event II ($E \sim 100$ keV) than in Event I ($E \sim 260$ keV).

Since there was outbound in Event II some degree of anti-correlation between the particle data and variations in the magnetic field, it can be surmised that, at this juncture, an enhanced level of coupling between particle and field phenomena was present, and it is recalled that pickup waves were found to be continuously present between $\sim 85 \times 10^3$ and 254×10^3 km outbound from the location of Closest Approach to Event I (Glassmeier and Neubauer, 1993). The waves immediately encompassing Events I and II were generated by gyroresonant pickup ions (not triggered by disturbances in the Solar Wind) and they were, in general, notable for their high, regular, amplitudes (Coates et al., 1993a).

The fact that Events I and II each displayed wave-type signatures at the typical cyclotron frequency of water group ions, might only be due to the fact that the medium in which these waves propagated was the same. However, the 'stratification' of water group and heavy ions in Events I and II, coupled with the identification of many similarities between the gross and fine structure elements defining this pair of twin peaked enhancements with their well defined boundaries, suggests that these objects individually exhibited internal spatial structure, in addition to displaying characteristic wave profiles.

The source of the cometary ions composing Event II was not associated with debris or jets arriving from Event I (Sections 6.3. and 6.4.). Also, these ions were not transferred from Event I to Event II via the magnetic field (Section 6.5). The overall extent of Event II (9.2×10^3 km) along the Giotto trajectory was roughly equal to the gyroradius of a 100 keV water group ion (9.6×10^3 km) in the prevailing magnetic field. The distance from Bow Wave to Bow Shock at P/Grigg-Skjellerup was $\sim 45 \times 10^3$ km. Overall, the data are in accord with the interpretation that Event II constituted a comet-like body that was three to four times smaller than P/Grigg-Skjellerup. The Q value of Event I (even if scaled to include an accompanying, inferred, Event II), does not fall within the category of weakly outgassing objects described by Bogdanov et al. (1996).

7.3. Model of the magnetic data recorded at the location of Event II

Figure 5 provides a simplified schematic diagram to explain the main features of the small scale magnetic changes in B_x, B_y, B_z that occurred at the location of Event II—variations which were, (see Section 6.5.), superposed on a large scale transition between two quasistable states (these particular local changes are also shown 'highlighted' in the appropriate panels of Fig. 3 by hatching). Figure 5 is drawn in CSE co-ordinates for the viewpoint of an observer sighting along the $-X$-axis (sun-spacecraft line); 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. It is noted that the interplanetary magnetic field lines were predominantly directed along the Y-axis during Event II. Oppositely directed variations in the direction of the magnetic field components B_y and B_z (designated in the bottom panels of Fig. 5 by ΔB_y and ΔB_z) mark the inbound traversal by the spacecraft of what is, for convenience, called a Magnetic Transition Region. This is represented in Fig. 5 (top) by a ring shaped structure (not to scale). In the inner core of this structure a general increment in ΔB_x—compare Fig. 5 with panel 10 of Fig. 3—remained at what was effectively a constant level while, also, there was practically no change in B_y. On the other hand, two oppositely directed peaks were recorded in the center of the core in B_z. It can be inferred from these (simplified) representations that

(1) The observed increase in ΔB_x requires the existence of a current on the surface of the core (shown by arrows Js on the drawing).
(2) The variations in the center of the core in B_z require the presence of a sheet of current (JTW) flowing along the X-axis in a plane perpendicular to the Y-axis.

Overall, the observations indicate that the spacecraft crossed a magnetic structure suggestive of a cometary tail. If this interpretation is correct, then the two currents

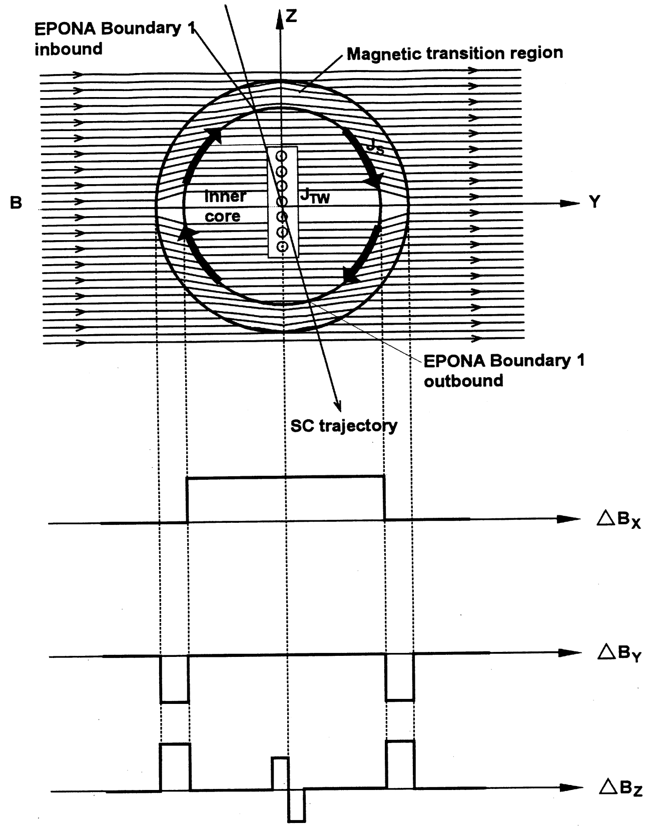

Fig. 5. (Top) provides a simplified schematic model of the magnetic variations in B_x, B_y and B_z at the location of Event II during spacecraft traversal. This model, which comprises a ring shaped structure (not to scale) is drawn as viewed along the $-X$-axis (sun-spacecraft line); the $+Y$-axis (East) 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. The interplanetary magnetic field lines were predominantly directed along the Y-axis during Event II. Surface currents (see the text) are indicated by Js, and a current sheet flowing along the X-axis in a plane perpendicular to the Y-axis is indicated by J_{TW}. The inbound and outbound boundaries of Event II in energetic particles are each indicated on the diagram and it is seen that the particles were confined to the inner core of the magnetic structure. Figure 5 (bottom 3 panels) provides a simplified representation of the major changes (ΔB_x, ΔB_y, ΔB_z) in the B_x, B_y, B_z components of the magnetic record at the location of Event II. The recorded variations are highlighted in Fig. 3 (panels 9–11) by shading.

shown in the model imply the existence, at the location concerned, of a more complicated, but finite, three dimensional current and magnetic field structure. It is noted particularly that all of the energetic particle fluxes recorded by EPONA at the location of Event II were confined to the inner core of the structure described (compare the locations of EPONA Boundaries B1–E, inbound and outbound, in Fig. 3 with the corresponding magnetic data).

A flyby through the tail of a comet would not be characterized by the observation of a pileup region and, indeed, no special peak in B_T was observed during Event II, see panel five of Fig. 3. In the case of Event I, this comet was traversed in a direction from west to east and from north to south either to sunward or to tailward of the nucleus, this is not yet fully decided, see Section 1. However, a drop in particle counts recorded in EPONA data during flyby in the data of (T3, S4) can be interpreted to indicate that Giotto flew on the nightside of the nucleus (McKenna-Lawlor et al., 1993). The best available estimate of the flyby distance (provided by the ESOC tracking center) is > 120 km. At this distance the spacecraft should not have crossed the contact surface, see the theoretical calculation of Huddleston et al. (1992b). This latter result is supported by the observational fact that the peak magnetic field strength at P/Grigg-Skjellerup was recorded at Closest Approach, and that its ratio to the Solar Wind stagnation pressure was smaller than was the case at the peak of the magnetic pileup region at P/Halley—implying that the spacecraft did not traverse the maximum pileup point.

8. Genesis of Event II

On the premise that Event II was cometary, it can be argued either that Events I and II constituted a pair of cometary bodies having a separate genesis or, as is more probable, that the nucleus of II split off from Comet P/Grigg-Skjellerup). The splitting of cometary nuclei is a well known phenomenon (cadence about once per hundred years per comet), and can occur even at large distances from the Sun (Chen and Jewitt, 1994). Conducive to splitting is tidal breakup; rotational breakup and, for new comets approaching the Sun, failure to withstand heat shock and the differential expansion caused by a non uniform distribution of incident solar radiation. Further, pressure driven subsurface flows of volatiles can penetrate cracks produced through processes of recondensation and recrystallisation, thereby leading, even in an originally homogeneous comet to splitting.

P/Grigg-Skjellerup has an aphelion distance of 4.94 AU and belongs to the Jupiter class of comets. Three times this century its motion was significantly perturbed by close approaches to the planet. The last and closest such encounter occurred on 17 March 1964 when this comet passed within only 0.33 AU of Jupiter. The cumulative effect of these perturbations was to increase the orbital period from 4.8 to 5.1 years. Also, the inclination relative to the ecliptic was increased from 8° to 21°, and the perihelion distance increased from 0.75 to 0.99 AU. Perihelion at the time of the Giotto encounter (10 July 1992) was just inside the Earth's orbit.

Efforts were made to determine if splitting of P/Grigg-Skjellerup might have been recorded optically during its 1992 apparition using the 3.5 m telescope at Calar Alto Observatory. No such effect was, however, identified and it was estimated by the observers that a double nucleus of more than 1 arcsec separation was not seen up to a brightness difference of about two magnitudes (B. Marsden, Private Communication).

It is noted that the optical observations were performed between September 14 and 17 1993 (considerably after the Giotto flyby). Fragments detached from cometary nuclei, however, often decay within days (Sekanina, 1982). In this regard it was suggested by Keller, (1990b) that a more volatile substance (such as CO) may be responsible for the activity of newly formed fragments or, alternatively, that the activity of such objects decays as the fresh surface exposed becomes progressively depleted of water ice. Sekanina (1982) derived the velocity of separation of the members of several well observed split cometary nuclei and demonstrated that the values measured varied between 2 and 0.3 m s^{-1} (being larger at smaller heliocentric distances).

9. Conclusions

A significant flux enhancement in energetic particles ($E > 60$ keV) of extent $\sim 45 \times 10^3$ km was recorded during P/Grigg-Skjellerup flyby by the EPONA instrument on Giotto (Event I) in the data of T1, S3. Corresponding signatures in other sectors were either very minor or absent. In general, the same cometary boundaries (Bow Wave, Bow Shock, Mystery Boundary Transitions) were sensed in energetic particles at this comet as were reported by the other onboard particles and fields instruments. Elevated fluxes of energetic particles interpreted to be ions of species $M = 16$–18 amu were identified in the P/Grigg-Skjellerup cometosheath, and it was inferred that heavy ions of species $M = 28$–33 were present in the innermost region of this comet (as viewed in the sunward direction).

A further flux enhancement (Event II) was recorded by EPONA ($E > 60$ keV) about 90×10^3 km beyond P/Grigg-Skjellerup along the Giotto trajectory in the data of T1, S3. Event II showed generally similar internal structure to that displayed by Event I and, again, peaks in the countrates at 1–2 min periods corresponding to cometary ion gyrofrequencies under the prevailing magnetic conditions were observed.

The possible identity and origin of Event II was considered and it was demonstrated that the increased ion density recorded at this location was not associated with emanations from Event I or with ion transfer via the local magnetic field.

Pickup ion related wave signatures suffused the Event I/Event II environment. The plasma wave activity was notable for the simple, regular and high amplitude wave forms recorded in the data of the various particle and fields instruments on Giotto and this observation was probably a consequence of nongyrotropy in the ion distributions, an effect which can induce coupling of the gyrotropic eigen modes.

The particle fluxes observed were not, in either case, especially modulated by fluctuations in the magnetic field associated with cyclotron waves and the energetic particles recorded in Events I and II are interpreted, on the basis of the available data, to be heavy gyrophase-bunched ions.

The overall extent of Event II (9.2×10^3 km) was roughly equal to the gyroradius of a 100 keV water group ion in the prevailing magnetic field and an interpretation in accord with the data is that Event II constituted a comet three to four times smaller than P/Grigg-Skjellerup, with a correspondingly lower gas production rate. The particles recorded in association with Event II attained slightly lower maximum energies and were somewhat less scattered than those recorded in association with Event I.

At Event I there is a suggestion that the spacecraft flew at about 120 km from the comet nucleus on the night side, and although there is a well defined signature in B_{Total}, it can be inferred that the spacecraft did not quite reach the maximum pileup point. There was no special B_{Total} signature associated with Event II (compare Figs 1 and 3). The Event II observation may be explained by the passage of the spacecraft deep in the tail of a comet-like object showing magnetic boundaries. The Event II energetic particles were recorded inside these boundaries. Two more or less stable regimes of the background interplanetary magnetic field (IMF) were situated on either side of Event II. The energetic particles of Event II were recorded when the second stable background state of the IMF had already been reached.

Events I and II might, according to the above scenario, have constituted a pair of autonomous comets from the beginning of their existence. It is more probable, however, that the nucleus inferred to pertain to Event II split off from P/Grigg-Skjellerup—possibly in consequence of earlier weakening due to a gravitational encounter with Jupiter.

A more detailed analysis is presently planned to determine the nature of the boundaries and regimes characterizing Event II, and to consider in depth differences and similarities between these data and the records not only of various particles and fields instruments at P/Grigg-Skjellerup, but also of complementary data recorded in situ at P/Halley and at P/Giacobini-Zinner.

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