1993

Energetic ions at comet Grigg–Skjellerup measured from the Giotto spacecraft

S. M. P. McKenna-Lawlor*, P. W. Daly†, E. Kirsch†, D. O'Sullivan§, A. Thompson§, K.-P. Wenzel‡ & V. Afonin¶

* Space Technology Ireland, St Patrick's College, Maynooth, Ireland
† Max Planck Institut für Aeronomie, D-3411 Katlenburg-Lindau, Germany
§ Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin, Ireland
‡ Space Science Department, ESA/ESTEC 2200 AG, Noordwijk, The Netherlands
¶ Space Research Institute, Profsoyuznaya 84/32, 117810 Moscow, GSP-7, Russia

On 10 July 1992, the Giotto spacecraft flew within about 200 km of the nucleus of comet Grigg–Skjellerup; this is only the third comet at which *in situ* measurements have been made, and the encounter constituted the closest approach so far of a spacecraft to a cometary nucleus. Here we report the detection by the EPONA instrument on Giotto of charged, energetic particles deep within the inner coma of Grigg–Skjellerup. In contrast to previous spacecraft encounters with comets Giacobini–Zinner (in 1985) and Halley (in 1986), well defined, periodic intensity variations recorded in the particle fluxes suggest that the ions close to the nucleus were strongly coupled to the ambient magnetic field. The present data indicate that Giotto flew on the nightside of the nucleus.

A comet nucleus is itself too small to be observed from the Earth, but as it approaches the Sun, mass is lost as an expanding atmosphere composed of dust, molecules, radicals and molecular ions is formed. The molecules undergo complicated chemical reactions in the inner regions of the cometary coma. Further

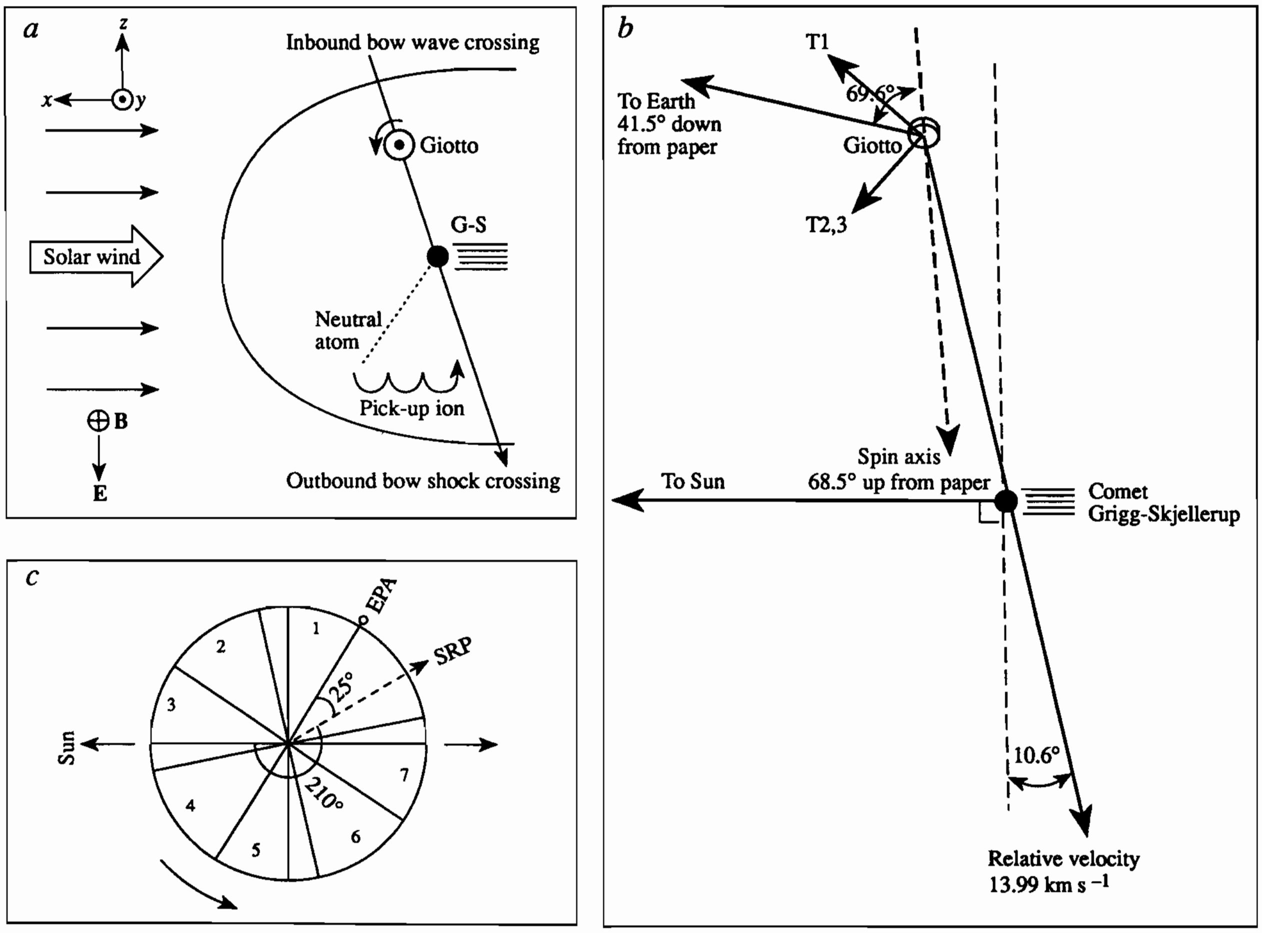


FIG. 1 *a* Schematic representation of the trajectory of the Giotto spacecraft through the reported[4] bow wave and bow shock (BW, BS) of comet Grigg–Skjellerup (G–S). A bow shock, defined as "a relatively steep change in the magnetic field vector components from outer to inner states that show little linear trend compared with the transition itself" was identified in ref. 4, outbound at 25 × 10^3 km from closest approach (CA). In the absence of a corresponding jump in the magnetic field vectors between two relatively uniform regions, or of a plasma shock without such a jump in the magnetic field data, it was inferred in ref. 4 that a cometary bow wave was traversed, inbound, at 20 × 10^3 km from CA. The coordinate system is such that x points towards the Sun and y lies in the ecliptic plane. Neutral atoms ejected from the comet move at low speeds through the solar wind ($\sim$1 km s^{-1}) until ionized by photon and/or electron fluxes. The resulting ions, being subject to the electric and magnetic fields that drive the solar wind ions, are compelled to move with them in cycloidal orbits. Hence they are said to be 'picked-up' by the solar wind. *b*, Encounter geometry and look directions of the three EPONA telescopes. T1 is oriented at 45°, and T2 and T3 both oriented at 135° to the spacecraft spin axis. T1 viewed in the backward hemisphere relative to the spacecraft's inbound flight path; T2 and T3 viewed in the forward hemisphere. The angle between the spacecraft spin axis and the relative velocity vector was 68.5° during the encounter. Measurements during the 4-s rotation period of the spacecraft were divided into eight sampling intervals (*c*), each of 0.5 s duration (S1–S8), T1, taking the odd-sector measurements and T2 and T3 the even-sector measurements (EPA represents the position of EPONA on the spacecraft, SRP denotes the Sun reference pulse).

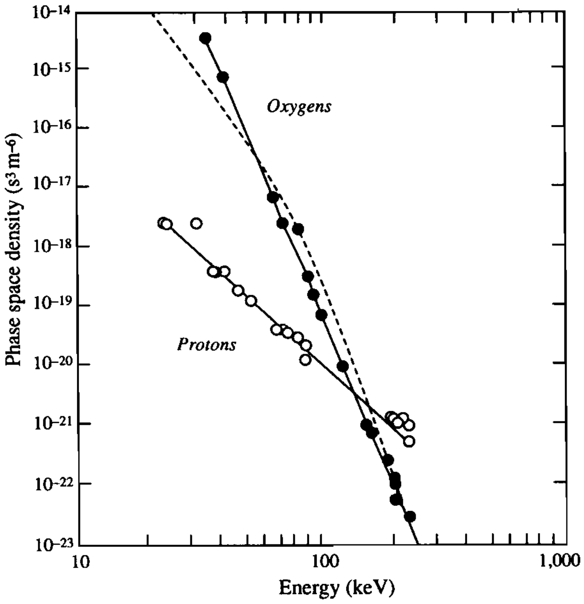


FIG. 2 Spectra fitting the counts recorded by EPONA, from 12.50–12.55 UT (1992 July 10), to a mixture of protons and oxygens. Species separation has been done by nonlinear least-squares fitting to two independent power-law spectra transformed into the solar wind frame (phase-space density is the number of ions per unit volume per unit velocity[3]). The solid lines are the resulting power-law spectra. The dotted line is a theoretical spectrum for second-order Fermi acceleration of oxygen ions[3], taking into account the effect of adiabatic compression in the cometary accretion flow and assuming that the mean free path corresponding to random scattering by ambient waves is of the order of 30 gyroradii.

out, ions are created from cometary neutrals through photoionization and other mechanisms.

These newly formed ions are created essentially at rest (velocity ~1 km s^{-1}) in the comet's rest frame, where they undergo cycloidal motion in the crossed electric and magnetic fields of the solar wind (the pick-up process). Their peak energy is then $E_{max}=4A\sin^2\theta E_{sw}$ (where A is ion mass in atomic mass units, θ is the angle between the solar wind velocity vector and the magnetic field direction, and E_{sw} is the energy of a proton travelling at the solar wind bulk speed).

In the rest frame of the solar wind, the ions are created with a speed equal to the solar wind speed in the comet's rest frame, and form a ring distribution in velocity space as they gyrate about the magnetic field lines. Such a distribution is highly unstable and gives rise to resonant ion-cyclotron waves, making the magnetic field turbulent. Wave scattering in this turbulent field acts to make the ion distribution isotropic, by producing a shell-like distribution of particles (pitch angle scattering) within a few gyroperiods. Further shells of lower energies are similarly progressively formed. If efficient pitch angle scattering occurs in the flow rest frame, then the peak energy (E_{max}) of the ions is $4AE_{sw}$, independent of the magnetic field direction, and the mean direction of motion depends only on the direction of the solar wind flow.

The energy and momentum imparted to the ions thus picked up comes from the solar wind which, as momentum is conserved, is decelerated by ever-increasing amounts as the comet nucleus is approached (mass loading effect). When the number density of the pick-up ions approaches ~1% of the number density of the solar wind, a weak shock forms and the frozen-in interplanetary magnetic field starts to drape around the comet to form an elongated, induced magnetotail[1].

Here we present energetic ion measurements made by the EPONA instrument on board Giotto during the encounter with comet Grigg–Skjellerup (Fig. 1) on 10 July 1992. EPONA features three semiconductor telescopes (T1, 2 and 3), each with geometric factor 2.0×10^{-2} cm^2 sr. We will only describe the data from T1 and T3. Ionized particle energies are determined by measuring their energy loss in the solid-state detectors in various energy intervals[2]. The (calibrated) energy thresholds in channels 1–4 of T1 and T3 are 29, 44, 78 and 217 keV for protons and 60, 97, 144 and 260 keV for H_2O^+ ions. Details of the encounter geometry, the telescope look directions and the sectors into which data are divided are shown in Fig. 1.

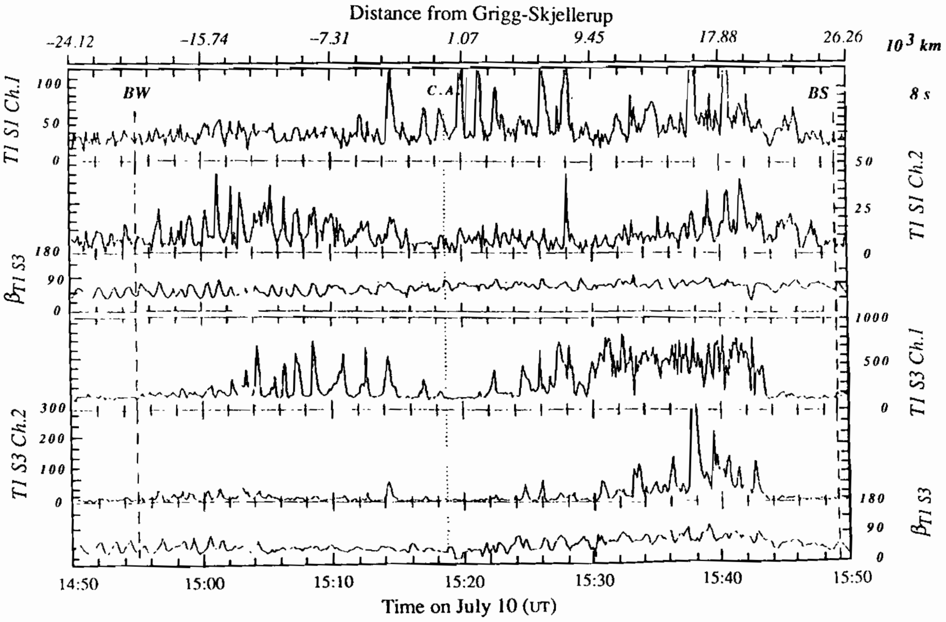
All the observations at the comet are expressed in spacecraft event time. The first small signature of cometary ions (not illustrated) was detected from ~03:10 UT on 10 July in T1, sector S5 channels 1–4 (distance from closest approach ~6×10^5 km), and gradually increased. In general, during the encounter, the fluxes recorded were higher by a factor of 3–10 in sector S3 of T1 than in sectors S1, 5 and 7. The flux before encounter was also anisotropic, showing that there was a Sun-related contribution in T1, S3. Cometary ions (outbound) faded at ~20:50 UT in T1, S3 channels 1–4 (distance from closest approach ~6×10^6 km).

Figure 2 presents a pair of typical spectra for the period 12.50–12.55 UT. Protons and oxygen ions have been separated out by a nonlinear least-squares fitting method that reproduces the measured count rates from the sum of two independent power-law spectra transformed into the solar wind frame. Although it is not possible to separate protons of cometary origin from those in the solar wind, we expect the latter to dominate. The oxygens are interpreted to be pick-up ions of cometary origin, as the corresponding solar wind component is likely to be small.

The maximum pick-up energy at the prevailing solar wind speed during encounter (about 400 km s^{-1} as reported by the Johnstone Plasma Analyzer Experimenters, personal communication) was 3.32 keV for a proton and 52 keV for a water group ion. Such particles would fall below the EPONA detection threshold. As the particles recorded by EPONA showed energies of ⩾ 260 keV, some additional accelerating mechanism(s) must have been operating. Wave scattering can result in energy diffusion through second-order Fermi acceleration. This is caused by stochastic ion scattering in the presence of strong wave turbulence. The dotted line in Fig. 2 is a theoretical spectrum for second-order Fermi acceleration of oxygen ions[3] and provides a reasonable qualitative fit to the experimental data.

Figure 3 shows the count rates recorded by EPONA in T1 sector S1 and T1 sector S3 (channels 1, 2) between the times that Giotto crossed the reported[4] bow wave (inbound) and bow shock (outbound) of the comet[4]. Plotted against the count rates in Fig. 3 are the corresponding instantaneous pitch angles, β, between the velocity vector of the ion and the magnetic field direction. Oscillations in the magnetic field vector, reflected in the pitch angle variations, have a period of about 1 minute, indicating the presence of oxygen cyclotron waves (singly charged oxygen ions in a field of 20 nT have a cyclotron

FIG. 3 Count rates measured by EPONA in T1, S1 and T1, S3, energy channels 1 and 2, predominantly between the inbound bow wave (BW) and outbound bow shock (BS) crossings, with corresponding instantaneous pitch angles (β) plotted against time (β is the angle between the velocity vector of the ion and the magnetic field direction). The time of closest approach to the comet (CA) is indicated.



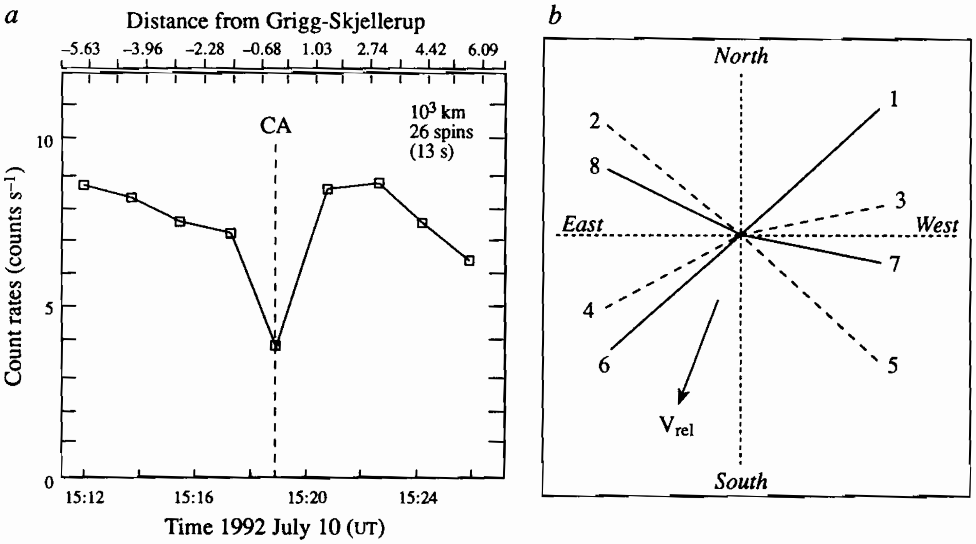
frequency of 52 s). The particle count rates were highest when the measuring sector was almost perpendicular to the magnetic field (β = 90°). Oscillations in the particle intensities are interpreted as being due to the stable pitch angle distribution moving with the magnetic field periodically through the view direction of the T1 detector.

Figure 4*a* shows particle counts from T3 sector S4, channel 2, averaged over 26 spins (13 s accumulation time per point) spanning closest approach. The number of counts in the central point is 48, and on either side 94 and 107. The drop in counts (observed only in T3, S4) represents 5 standard deviations. If the reduction in flux was caused by absorption along the particle's path, then the occulting obstacle was east-southeast and sunward of the spacecraft (the look direction of sector 4; see Fig. 4*b*). As the estimated closest distance to the comet nucleus (200 km, ESOC tracking data) is much less than the 2,000 km gyroradius of the oxygen ions, gyrocurvature may be neglected in determining the direction of the obstacle. The size of the particle data gap is ~1,500 km (100 s times the 14 km s^{-1} flyby speed). The distorted magnetic field around the comet nucleus could have constituted the 'occulting object'.

Grigg–Skjellerup, with a nuclear gas production rate of $Q = 6 \times 10^{27}$ s^{-1}, is only the third comet at which *in situ* energetic particle measurements have been made[5] — the others were the highly active Halley ($Q = 6.9 \times 10^{29}$ s^{-1}) and less active Giacobini–Zinner ($Q = 2 \times 10^{28}$ s^{-1}). The Giotto encounters with Grigg–Skjellerup and Halley, and the encounter of the International Cometary Explorer (ICE) with Giacobini–Zinner, occurred at roughly the same Sun/comet separation, so the effects of radial variations in the solar wind and solar radiation can essentially be disregarded when comparing these data. The closest approach of Giotto to comet Halley and of ICE to Giacobini–Zinner occurred, respectively, at 600 km to sunward and at 7,800 km to tailward of the nucleus concerned. The EPONA observations suggest that Giotto flew on the nightside of the nucleus of Grigg–Skjellerup (targeted miss distance 200 km).

In all three cases, large fluxes of pick-up ions were recorded

FIG. 4 *a*, Count rates measured by EPONA in T3, channel 2, S4 averaged over 26 spins (accumulation time per point 13 s). The scale at the top of the figure gives the distance in 10^3 km before and after closest approach (CA). *b*, Geometry of the flyby in a plane perpendicular to the ecliptic (the east–west axis) and the comet–Sun line, looking towards the Sun. $\mathbf{V}_{rel}$ is the direction of the velocity of Giotto relative to Grigg–Skjellerup. The numbered lines represent the projection of the ?! EPONA look directions onto the page for the corresponding sector: solid lines looking out of the page, dashed lines into it. The shorter the line, the further the look direction is away from the plane of the page.



far upstream of the bowshock, streaming predominantly away from the Sun[6,7]. The fluxes measured by EPONA at Grigg–Skjellerup were almost a factor of 100 lower than those at Halley[7]. However, the particle energies at all three comets were similar ($\geqslant$ 260 keV) and always significantly exceeded the maximum energy attainable by the pick-up process alone.

The energetic particle profiles recorded at Grigg-Skjellerup were markedly different from those detected during previous encounters. In particular, the variations in fluxes at the oxygen ion cyclotron frequency recorded close to the nucleus have not been seen before. □

Received 2 October 1992; accepted 6 April 1993.

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