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The Giotto Three-Dimensional Positive Ion Analyser

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Abstract

This instrument is designed to measure the three-dimensional energy distribution of positive ions in order to study the interaction between the solar wind and ionized cometary particles. The two sensors measure the distribution from 10 eV to 20 keV once per spacecraft spin and the distribution from 90 eV to 90 keV, with coarse mass discrimination, once every 32 spins.

1. Introduction

The plasma tail of a comet is arguably its most spectacular feature. Its filamentary structure, with waves, kinks and spirals can be seen stretching for as much as 10**8 km across the inner solar system for a large comet like Halley near perihelion.

Following the original proposal of Biermann (1951), it is now known that the plasma tail is the manifestation of the interaction between plasma from two distinct sources: ionized particles of cometary origin and the solar wind. Theoretical analyses of this interaction (Biermann et al., 1967; Wallis, 1973; Ip & Axford, 1982) have provided a model of the gross features of the plasma flow to be expected near the comet, but they do not yet give a detailed explanation of the formation of the visible tail. On the other hand, many of the features predicted by theory cannot be observed from the Earth. The gap between theoretical analysis of the solar-wind-comet interaction and ground-based observations of comet tails can only be filled by in-situ measurements of the plasma distributions within the visible coma of a comet. Theory says that the plasma should be divided into three main regimes separated by two surfaces - a contact surface and a bow shock. The contact surface encloses the region dominated by the cold, dense cometary plasma around the nucleus. Some of the neutral cometary particles are not bound by this contact surface and may travel well upstream into the solar wind before being ionized. The additional mass they then add to the solar-wind flow slows it down and eventually creates the second surface, a bow shock.
The objectives of the Johnstone Plasma Analyser (JPA) instrument can be concisely stated as:

- to look for the existence of a bow shock and a contact surface

- to observe the mass loading of the solar wind and the resultant deceleration and deflection of the flow
- to observe the distribution of implanted cometary ions and its stability
- to detect the principal ionization mechanisms.

The instrument is designed to achieve these objectives by measuring the three-dimensional velocity distribution of positive ions in the energy range from 10 eV to 90 keV. It includes two complementary sensors: the Fast Ion Sensor (FIS) measures the energy per charge distribution from 10 eV/q to 20 keV/q in all directions, except for a cone around the velocity vector, once every rotation (nominally 4 s) of the spacecraft; the Implanted Ion Sensor (IIS) measures the energy per charge distribution from 90 eV/q to 90 keV/q over a similar angular range, with discrimination into five mass groups, but takes 32 rotations to obtain a complete distribution.

The analysis is expected to be undertaken at several levels of processing. The existence of a bow shock, or contact surface, should be apparent even in raw telemetry data as a discontinuity. Studies of the mass loading of the flow require the derivation of such bulk plasma parameters as density, temperature, velocity, pressure and possibly higher order terms. To understand the stability of the cometary ions requires detailed analysis of the complete distribution.

2. Scientific Background

Neutral molecules and radicals emerge from the collision-dominated region close to the nucleus with an outward flow velocity V(i) which depends on the energy gained or lost in the complex photochemical reactions which take place there. The particles are ionized, it is believed, predominantly by photo-ionization or charge-exchange at a rate theta(i); which depends on the species, i. The ion production rate A(i) at a distance r from the nucleus is therefore given by

$$A(i) = \left(\frac{Q(i)\theta(i)}{4 \pi r^{2} V(i)}\right) \exp\left(-r\,\theta(i)/V(i)\right)$$

where Q(i) is the escape rate of the species i from the inner coma. The quantity (V(i)/theta(i)) has the character of a species-dependent scale length which determines the size of the coma of that particular species. In most theoretical studies a single species is assumed; in the real comet a number of important species will be encountered with different values of (V(i)/theta(i)). In Table 1 two species H^+ and CO^+, with very different scale lengths, are compared.

Once the ion has been implanted in the flow it is picked-up by the electric field in the solar wind and accelerated into a cycloidal orbit. Using the reference frame shown in Figure 1 with the magnetic field parallel to the y-axis and the solar-wind velocity in the yz-plane, the trajectory of the implanted ion is given by

$$V(x) = V(s) \sin(\phi) \sin(\omega(c)t)$$
$$V(z) = V(s) \sin(\phi) (1 - \cos(\omega(c)t))$$

Figure 1. The frame of reference used calculate ion pickup trajectories

The motion consists of a gyration about B with a velocity V(s) sin (phi) and a drift velocity V(s) sin (phi) perpendicular to B. The maximum velocity reached is 2 V(s) sin (phi); with typical values for the solar wind, V(s)=400 km/s, phi=45deg and B= 10 nT, one obtains the values given in Table 2 for ions of the same two sample species as in Table 1.

High-mass ions are therefore rapidly accelerated in a way that is strongly dependent on the direction of the magnetic field. In the relatively undisturbed solar wind, upstream from the bow shock, the field is normally at a large angle to the flow, and the ions can be accelerated to high energies. Near the nucleus, where the magnetic field lines draped around the comet lie nearly parallel to the flow, there will be little acceleration of the ions by this means. Again the ionic behaviour is strongly species-dependent. Hydrogen ions, created at large distances (see Table 1), are likely to follow cycloidal trajectories. Carbon-monoxide ions, created closer to the nucleus, have a gyro radius comparable to the size of their coma. Their motion is therefore going to be different in character from the hydrogen ions. It is worth noting in this respect that numerical models of the magnetohydrodynamic flow (Biermann et al., 1967; Schmidt & Wegmann, 1982) usually assume that the ions are immediately subsumed into the solar-wind flow, travelling at the solar-wind speed. This extreme case, which can be called the ’strong coupling case’, would result in the average energy <W> and momentum <p> being given by the equations

$$\langle W \rangle = \frac{1}{2} M V_s^2$$

$$\langle p \rangle = M V_s$$

At the other extreme, fully developed cycloidal trajectories give

$$\langle W \rangle = m V_s^2 (\sin \phi)^2$$

$$\langle p \rangle = m V_s (\sin \phi) \mathbf{k}$$

where k is a unit vector in the z-direction.

Table 1. Coma scale lengths

	theta(i)(s**-1)	V(i)(m/s)	V(i)/theta(i)(km)
H+	6.7x10**-7	8000	1.2x10**7
CO+	11.5x10**-7	700	6x10**5

Table 2. Cycloidal trajectory parameters

	Maximum energy (keV)	Gyro period (s)	Gyro radius (km)
H+	1.67	6.5	1850
CO+	50.1	183	50000

In the latter case the momentum is now perpendicular to the magnetic field and will cause a deflection as well as a deceleration of the solar wind. Again the nature of the interaction is strongly influenced by the direction of the magnetic field in interplanetary space, which can vary greatly even on short time scales. The strong-coupling case could become important if the ring distribution in velocity space created by the cycloidal trajectories was sufficiently unstable for the distribution to become rapidly isotropized (Ip & Axford, 1982). Recent calculations (Galeev, 1983) suggest that this is unlikely to occur rapidly enough to be important.

The solar-wind flow around the comet can be described by the full single fluid equations expressing conservation of mass, momentum, and energy. These equations have been solved numerically by several authors (Schmidt & Wegmann, 1982), albeit with many simplifying assumptions. An alternative approach is to use a quasi-one-dimensional formulation which can be treated analytically (Wallis, 1973; Wallis & Ong, 1975; Galeev et al., 1985):

$$\frac{d}{dx} [\rho u f(u,\mu)] = \frac{Q_i M_i \theta_i}{4 \pi V_i r^2} \delta\left(\mu - \frac{M_i u^2}{2B}\right)$$

$$\frac{d}{dx} (\rho u) = \frac{Q_i M_i \theta_i}{4 \pi V_i r^2}$$

$$\frac{d}{dx} \left(\rho u^2 + p_\perp + \frac{B^2}{2 \mu_0}\right) = 0$$

From these equations, for the case where B is perpendicular to the flow, it is possible to derive a solution for the cometary ion distribution function f(u,mu) in the region upstream from the shock. This is shown in Figure 2. In this distribution each value of magnetic moment corresponds to ionization occurring at a particular point upstream, with the highest magnetic moments being generated in the undisturbed solar wind. As the flow speed decreases, due to the mass-loading, the magnetic moment of the implanted ions also decreases. The particles with lowest magnetic moment in this distribution are created just upstream from the point of observation. Measuring this distribution therefore gives the possibility of sensing conditions upstream, including the unperturbed flow speed.

From these equations it is also possible to obtain the variation of mass flux as the flow approaches the nucleus. Continuous flow is only possible up to the point where (Galeev et al., 1985)

$$\rho u/\rho(\infty)u(\infty) = \gamma^2/(\gamma^2-1) = 4/3 \quad (\gamma=2)$$

where rho*u is the mass flux and the subscript "infinity" indicates the unperturbed upstream values and gamma is the ratio of specific heats.

In fact it is found that in numerical simulations the critical value for the formation of a shock is (rho*u/rho(infinity)u(infinity)) = 1.185.

Figure 2. The cometary ion distribution function in the unshocked solar wind as a function of the magnetic moment mu. It is calculated for a position just upstream from an M=2 shock where the velocity is 0.75 times the unperturbed solar wind velocity (Galeev et al., 1985)

Ions implanted inside the bow shock do not reach high energies because of field-line draping and because the turbulence is likely to prevent the full development of cycloidal trajectories, but those energetic ions created upstream are able to penetrate the shock, essentially unaffected, and could be detected in the inner region (Galeev et al., l985).

The objective of the JPA instrument is to obtain an in-situ evaluation of these theoretical ideas taking due account of the greater complexity of the real situation created by the presence of many different species and a variable magnetic-field direction.

3. Instrument Design

This is an exploratory mission and the JPA instrument will be the first to make three-dimensional ion measurements near a comet, so it is most important that it be able to cope with a wide range of possible circumstances and that it not be limited by pre-conceived ideas of what the ion distributions are like near a comet.

The instrument must cover as much of velocity space as possible, leaving no gaps in coverage for unsuspected distributions to slip through. This has implications for the ion optics of the analyzer design, as well as for the energy sweep rates and sampling patterns.

Structures have been observed near the head of a comet with thicknesses of the order of 1000 km. This upper limit is set by observational techniques and not by cometary physics. If experience in other space plasmas is any guide, spatial variations on much smaller scales are also likely. With a spacecraft speed relative to the comet of 68 km/s, a time resolution of 15 s is essential and a much faster time resolution is desirable.

The mass distribution as well as the complete angular distribution of the implanted ions must be measured if the characteristics of the flow are to be understood, because the behaviour is strongly species-dependent. It is not necessary to have the same mass resolution as for studies of the chemical constituents of the nucleus.

The JPA instrument is one of a group of complementary plasma sensors measuring ions on Giotto; the others are the IMS instrument (Balsiger et al., 1986), the PICCA sensor of the RPA (Reme et al., 1986), and the EPA instrument (McKenna-Lawlor et al., 1986). The JPA instrument is directed towards studies on the nature of the solar-wind interaction with the comet rather than the detailed chemical composition of the ions.

Figure 3. The flight units of the JPA instrument. From the left they are the Fast Ion Sensor, the Data Processing Unit and the Implanted Ion Sensor

The instrument consists of three separate packages: the Fast Ion Sensor, the Implanted Ion Sensor and the Data Processing Unit (Fig. 3).

The purpose of the Fast Ion Sensor is to provide a three-dimensional distribution over the energy range likely to include most of the ions near the comet as quickly as possible. It obtains the full azimuthal distribution once per rotation of the spacecraft.

It can measure the solar-wind distribution at its most anisotropic, giving the flow speed and direction, temperature and density. It follows the development of the solar plasma as it is thermalized, slowed down and deflected. It measures the ring distributions for the low-mass ions in the undisturbed solar wind (complete distributions up to mass 12), and for all ions once the angle between the flow direction and magnetic-field direction becomes smaller near the comet. Speed of response is achieved at the expense of mass discrimination, and by limiting the energy range to 10 eV to 20 kev.

Its geometric factor is determined by ensuring that the count rate in the most anisotropic and dense solar wind to be expected will not exceed the highest allowable count rate. Its wide dynamic range then ensures that weak secondary populations can also be detected, with the highest possible statistical significance.

It does not cover the distribution of energetic implanted ions (E> 20 keV), nor the cold cometary ions inside the contact surface. These ions will appear to be moving antiparallel to the spacecraft velocity vector.

There are several reasons for not covering this latter population. First, the fluxes are very much higher than any other fluxes encountered and if the sensitivity of the Fast Ion Sensor were to be reduced to cope with the cometary ions it would not have adequate sensitivity for other important populations. Secondly, to detect these ions would mean exposing the sensor to the flux of cometary dust and neutral particles past the spacecraft, which would create an undesirable background in the sensor for all of the measurements.

The task for the Implanted Ion Sensor is to search for massive cometary ions in the solar wind by extending the energy range of the measurements up to 90 keV, increasing the sensitivity so that very low densities can be measured and providing mass discrimination sufficient to separate the ions into the principal mass groups, enabling the ring distributions to be detected even when diffused by wave-particle interactions. The technique used to obtain the mass discrimination, namely time-of-flight analysis, has the additional property of having a very low background because it uses a coincidence technique. This means that extremely low count rates can be measured if sufficient integration times can be allowed. It achieves these properties at the expense of speed of response because it measures at one energy level each rotation of the spacecraft. With its high sensitivity, it is unable to measure the proton flux in the solar wind because the intense fluxes overload the time-of-flight analyzers.

The Data Processing Unit collects the data from the sensors and processes it for transmission to Earth.

4. Fast Ion Sensor

The principal design aims of this sensor are: (a(a) high sensitivity, i.e. a large geometric factor, (b) wide dynamic range, i.e. high maximum count rates and low background, (c) complete and continuous coverage of a wide solid angle, in the energy range from 10 eV to 20 keV for positive ions, and (d) angular and energy resolution good enough to resolve the supersonic flow in the solar wind. The coverage in solid angle is achieved by having a wide angle of acceptance (160deg) for the analyzer in a plane containing the spin axis of the spacecraft. Then, as the spacecraft rotates, the detectors sweep through the full 4 pi solid angle apart from the 20deg cone around the velocity vector.

The Fast Ion Sensor (FIS) consists of four principal elements (Fig. 4), a hemispherical electrostatic energy analyzer, a quadrispherical angular dispersion sector, a microchannel plate detector, and a discrete-anode, position-sensitive readout system (Johnstone et al., 1985).

After entering the aperture, ions pass through a hemispherical energy analyzer, which selects a narrow band in energy per charge (delta(E)/E=4.7%). After an intermediate aperture, the selected ions enter an 80deg angular dispersion sector, which disperses them to emerge around a 160deg annular sector according to the angle of incidence at the input aperture. They are then accelerated onto the front face of a microchannel plate detector, which produces a cloud of electrons for each ion striking the input. Finally, the electrons are collected and form a charge pulse on one of a series of eight metal anodes behind the microchannel plate. Each of the anodes has a defined angular range (Table 3) and is connected to a charge-sensitive pulse amplifier mounted within the sensor which produces a logic level pulse output for each electron cloud striking the anode. The arrangement provides continuous coverage over the sensor field of view.

The energy of the detected ion is known from the analysis voltage applied to the spherical deflection plates. The plate voltages are applied in a fixed ratio V(inner)/V(outer) = -1.18, to give the zero potential surface exactly half way between the spherical plates. The ’gain’ of the analyzer (i.e. the ratio of the energy selected to the plate potential difference) is 3.55. The polar angle is known from the anode which registers the count. Azimuthal angle is measured by timing with respect to the spacecraft Sun pulse.

The detector consists of two double-thickness microchannel plates in a chevron configuration, specially cut to cover the 160deg arc of the output aperture of the analyzer. The combination produces a saturated pulse distribution, with full-width-half-maximum of 70% at a gain of 2 X 10**6. The saturated distribution enables reliable operation in a pulse-counting mode, with little dependence of the overall detection efficiency on the amplifier gain or threshold. Achieving the saturation at a low gain enables the plate to operate at high count rates and thus maximizes the dynamic range. The maximum pulse rate the channel plate can deliver per anode sector is of the order of 2 X 10**6 pulses/s. In principle, such count rates could occur simultaneously in all sectors. The discrete anode, with individual pulse counters, is the only type of position sensitive readout presently capable of handling such count rates.

Figure 4. Diagram of the operation of the Fast Ion Sensor

Table 3. Fast Ion Sensor analyzer characteristics

E/q range (keV/q)	0.01-20
Acceptance angles:	
azimuthal	5deg
polar	160deg
Outer plate radius r(1) (mm)	38
Inner plate radius r(2) (mm)	33
Centre radius r (mm)	35.5
Analyser gain [=r/2(r(1)-r(2))]	3.55
Aperture diameter (mm)	2.25
Aperture area (mm**2)	4
Plate voltage splitting (V(2)/V(i))	-1.18
Energy resolution (delta(E)/E)	4.7%
Geometric factor (mm**2 sr eV)	4.7 x 10**-3 E (eV)
(26deg anode at normal incidence)	

The energy passband of the analyzer is swept continuously, along an exponential decay curve from the maximum energy of 20 keV down to l0 eV in one sixteenth of a spin. The sweep is synchronized to the spin by using the spacecraft Spin Segment

Clock Pulse to control the sweep.

Since the angle of acceptance in the spin plane is 5 deg, there are gaps in the azimuthal coverage between successive sweeps which are 22.5deg apart. This is important in the solar wind where the undisturbed solar wind may be confined within an angular range of 5 deg. In order to provide contiguous azimuthal coverage, an energy sweep covering one quarter of the energy range (a factor of 6.7 in energy) is used four times as often in the 45deg angular sector centred on the solar direction. The solar-wind mode is used on alternate spins giving a time resolution for solar-wind measurements of 8 s. The starting energy for the reduced sweep (Table 4) is adjusted automatically on-board (Section 6) to ensure that the proton and alpha-particle distributions in the solar wind are always covered.

The intrinsic energy passband of the analyzer has delta(E)/E=4.7%. At the sweep rate, this energy range is covered in 1 ms. If the accumulation time of the counters is increased, the energy passband of the measurement is increased correspondingly. Thus during solar wind sweeps 2 ms accumulation times will be used, giving delta(E)/E=0.096. For the High Angular Resolution Distribution mode (Section 6), 8 ms accumulation times given delta(E)/E=0.3 and for the Fast Time Resolution with 16 ms accumulation time delta(E)/E ~ 0.6.

The FIS electronics has two functions: to accumulate the pulses from the anodes, and to provide the high bias voltages to operate the analyzer and the detector. The outputs of the eight amplifiers are routed through mode-switching logic, where they are combined in two different accumulator modes (wide energy and solar wind) before being counted by a series of six, 16-bit accumulators. The polar-angle ranges selected in the six accumulators for the wide energy and solar wind accumulator modes are shown in Table 5. The solar-wind mode has been arranged to provide high angular resolution measurements around the solar direction and is used simultaneously with the solar-wind sweeps described above.

Table 4. Start and stop energy levels for FIS solar-wind sweeps

Solar wind sweep preset	Start energy (eV/q)	Proton velocity (km/s)	Stop energy (eV/q)	Proton velocity (km/s)
7	19963	1962	4161	895
6	15956	1754	2494	693
5	9562	1358	1494	536
4	5730	1051	896	4l5
3	3434	813	537	321
2	2058	630	322	249
1	1233	487	193	192
0	739	377	115	149

Table 5. Fast Ion Sensor Polar angles sampled by the accumulators

Accumulator	Polar angles sampled in wide-energy mode	measured from z axis* in solar-wind mode
1	98-124	98-150
2	124-150	46-98
3	46-72	46-59
4	72-98	59-72
5	20-6	72-85
6	150-180	85-98

* Directed along comet-spacecraft relative velocity vector.

The high-voltage unit produces two types of high-voltage output. The first is a negative high-voltage bias for the microchannel plate, which has four possible settings selectable by ground command. The three operating voltages are provided in case of gain degradation in the microchannel plate during the mission. The second type of output is the programmable positive and negative deflection voltages for the outer and inner electrostatic deflection plates. The output of these units has maximum values of 2600 and -3060 V, respectively, corresponding to selecting ions with energy 20 keV, Each of the three high-voltage outputs is monitored by spacecraft analogue housekeeping telemetry.

Figure 5. Results of the calibration of the Fast Ion Sensor. The azimuth degrees correspond to polar angle in the spacecraft relative to the spin axis i.e. -80deg azimuth is 0deg polar angle; +80deg azimuth is 160deg polar angle. The numbers are the discrete anodes of the position-sensitive detector

The Fast Ion Sensor was calibrated using an ion beam with low angular and energy spreads at various fixed energies, at Southwest Research Institute (Johnstone et al., 1985). In all, approximately 60000 individual data points were collected per run in (energy, angle) space, covering the complete angular and energy response of the analyzer. The individual measurements were integrated to give the overall response of the sensor. The results are shown in Figures 5 and 6. Although the aim was to achieve a polar angle coverage of 160deg, the response (as expected) falls off at large

Figure 6. Results of the calibration of the Fast Ion Sensor. The plot shows the energy angles of response of one anode integrated over all angles

incidence such that the practical limit of a measurable response is a range of 150deg. This leaves a small hole (~5deg cone) in the coverage of the sensor in the direction of the spin axis, as well as around the velocity vector (~25deg cone).

5. Implanted Ion Sensor

The Implanted Ion Sensor (IIS) is an ion spectrometer (Fig. 7) which combines electrostatic analysis with a time-of-flight measurement. An electrostatic analyzer selects positive ions of a given energy per charge, E/Q. The ions are then accelerated by a potential difference, V, before the time T to travel a path length D is determined. The measured quantities E/Q and the time-of-flight T can be combined to yield the mass-to-charge ratio, M/Q, according to the following equation:

$$M/Q = 2WT^{2}/QD^{2}$$

where W, the total energy after post-acceleration, is given by

$$W = Q[V + (E/Q)]$$

Since the cometary particles are ionized by photons or charge-exchange, their charge state is predominately Q=1 and the ion mass can then be easily determined. In the solar wind there are ions with higher charge states, such as alpha particles (Q=2) and high charge states of oxygen (O^{6+}).

The instrument contains five sensors, each consisting of a spherical electrostatic energy analyzer and a time-of-flight (TOF) analyzer (Fig. 7). The five sensors are arranged as an angular array to cover the range l5 deg to 165 deg, in five equally spaced sectors 10deg wide relative to the spin axis of the spacecraft. As the spacecraft rotates, the angular distribution of the ions is obtained as with the Fast Ion Sensor.

The spherical-plate electrostatic analyzer has a mean radius of 50 mm and a plate spacing of 3 mm, giving an analyzer gain factor (energy measured/voltage applied) of 8.3. A voltage V(0) of up to = -11 kV is applied to the inner plate of the analyzer, while the outer plate is kept at 0 V. Thus the ions are effectively accelerated by (V(0)/2) on entering the analyzer, and the effective gain factor is 7.8. The energy bandwidth, defined as the full width at half maximum, is delta(E)/E= 10%. The energy

Figure 7. Diagram showing the layout of the Implanted Ion Sensor. The five electrostatic analyzers with time-of-flight analyzers are shown as an array viewing through the single aperture. Electronic boards for signal processing are mounted behind, with the high-voltage power supply underneath them

range from 90 eV to 90 keV is covered in 32 steps, equally spaced logarithmically by a factor 1.25. The level is changed once per spin and steps up on the odd-numbered steps (1, 3, 5, etc.) and down on the even steps (30, 28, 26, etc.).

As the ions leave the electrostatic analyzer (Fig. 8) they are accelerated by 10 kV before striking a thin (5 micro g/cm**2), grid-supported carbon foil at the entrance to the time-of-flight analyzer.

Ions passing through the carbon foil transfer a small fraction of their energy to secondary electrons. Those secondaries that escape from the foil are accelerated by 0.7 kV and deflected towards the microchannel plates. The fast output pulses of the microchannel plate (typical rise time of ~0.9 ns) result in an accurate timing pulse for the ’START’ signal. Essentially the same principle is used in the ’STOP’ detector, except that the secondary electrons are generated in the surface layer of an aluminium absorber. Although the ions enter the time-of-flight system on approximately parallel trajectories, Coulomb interaction with the atoms in the carbon foil will result in strong angular scattering. The resulting variations in the flight path are limited to +/-5% by using a spherical concave converter surface for the ’STOP’ detector.

Figure 8. Cross-section of one of the five individual sensors in the Implanted Ion Sensor

The output signal from the five ’START’ microchannel plates are added together by one fast summing amplifier, and the outputs from the five ’STOP’ microchannel plates in another. A time-to-amplitude converter converts the time interval between the pulses into a proportional pulse amplitude. The pulses are stretched in a sample-and-hold circuit and then digitized to give an 8 bit value proportional to the time interval.

The maximum time interval is set at 80 ns. Unless a ’STOP’ signal is received within the 80 ns following a ’START’ signal, the event is not converted.

The time required to process the signals from a single event is 25 micro s. Within this processing period, further ’START’ pulses and valid ’START-STOP’ combinations are recorded but cannot be processed.

Two separate count rates are monitored:

(a) the number of ’START’ pulses
(b) the number of valid ’START-STOP’ combinations (TAC pulse).

The requirement of a valid ’START-STOP’ combination gives a high rejection of background signals from penetrating radiation and detector noise and enables very low counting rates to be reliably measured.

Monitoring the number of ’START’ pulses enables the amount of dead time in the instrument to be estimated. For example, it cannot record accurately (and was not intended to do so) the high flux of protons in the solar wind. The ’START’ count indicates the number of events that could not be processed.

The TOF value is used in two ways. Together with the step number of the high-voltage sweep, it addresses a look-up table where the mass of the ion responsible for the event is assigned.

The events are separated into five contiguous mass groups based on the time-of-flight and the energy level of the analyzer. The mass groups correspond to the atomic mass number unit given in Table 6 below.

The angular and energy distribution of each of the five mass groups is recorded. Secondly, a TOF spectrum is accumulated for a complete spin while the energy is constant at one level, by combining the outputs from all five sensors.

Angular information is derived from two sources. The azimuthal angle comes from the timing in the spin relative to the Sun reference pulse; the polar angle comes from the identification of the sensor responsible for the event. The identification can itself be achieved in two ways: in the 'FIND' mode, each event is associated with the 3 bit number of the sensor; in the 'SCAN' mode, each sensor is enabled alone for one-fifth of the time in each azimuthal angle sector. The usual mode used is the 'FIND' mode, but if the intensity in one sector overwhelms that in the other sectors, the 'SCAN' mode can be used to allow the other sectors to register. It reduces the overall sensitivity by a factor of five. Alternatively, each sensor can be enabled or disabled individually by command.

Three types of distribution are telemetered from the sensor. The 256-level TOF spectrum is integrated over all angles for each spin; the 4D distribution comprising five mass groups, five polar angle zones, eight or l6 azimuthal sectors and 32 energy levels, and the 'START' and 'TAC' totals in 16 sectors each spin. The complete distribution requires 32 spins, or approximately 128 s to accumulate. The detector characteristics are summarized in Table 7.

Three high-voltage units are required to operate the sensor. The microchannel plate supply has eight commandable levels between 1000 V and 3100 V to allow the bias to be set at the correct level for the gain required. The variable voltage supply provides the voltage for the electrostatic analyzer and may be set to step through the sequence described above or to remain fixed on any one of the 32 levels. The acceleration voltage can be set to 5 kV or 10 kV.

During ground testing and the launch phase the aperture is closed by a spring-loaded cover held in place by a small pellet of biphenol (C12H10). Once in the vacuum of space, the biphenol sublimates, the cover is released and the aperture opened. This should occur within 50 h of launch. The cover's status could not be checked in orbit for two months, but it was then found to be open.

Table 6. IIS mass groups

Group	Mass/charge
1	1
2	2-11
3	12-22
4	23-33
5	34-45

Table 7. Implanted Ion Sensor characteristics

E/q range (keV/q)	0.090-90
Acceptance angles (each sensor)	
azimuthal	6deg
polar	10deg
Outer plate radius (mm)	51.5
Inner plate radius (mm)	48.5
Analyser gain	8.3
Plate voltage splitting	
inner	-11 V to -11 kV
outer	0
Aperture area (mm**2)	42

Energy resolution (delta(E)/E)	10%
Time-of-flight path length (mm)	22
Geometric factor (mm**2 sr eV)	7.6x10**-2 E (eV)

6. Data Processing Unit

The Data Processing Unit (DPU) performs the following functions:

(a) It is the interface between the sensors and the spacecraft for power, telemetry and commands.

(b) It controls the measurement sequence of the instrument and synchronizes it to the spacecraft rotation. Two standard signals from the spacecraft are used to achieve the synchronization: the Sun Reference Pulse (SRP) and the Spin-Segment Clock Pulse (SSCP). The latter divides the period between successive SRPs by 16384. The Fast Ion Sensor sequence has a duration of two spins beginning 22.5deg before the sensor's field-of-view fan crosses the solar direction. Each spin is divided into eight sectors of 45 deg. During the first sector the sensor operates in the solar-wind mode, making eight short energy sweeps. In the remaining seven sectors of the first spin, and for all eight sectors of the second spin, the sensor operates in the wide-energy mode, making two full energy sweeps in each sector. The Implanted Ion Sensor sequence has a duration of 32 spins, holding each of its energy levels for one complete spin. All the measurements are synchronized to the rotation, so that each value received at the ground is already associated with its direction without needing reference to the spacecraft attitude solution.

(c) The DPU collects the accumulated counts from registers in the sensors at the conclusion of each sampling period timed with reference to the SSCP. For the Fast Ion Sensor the sampling period is eight cycles (~2 ms) in solar-wind mode and 32 cycles (~8 ms) in wide-energy mode. For the Implanted Ion Sensor, it is 1024 cycles (~250 ms).
The data are acquired from the sensors each spin in the form of an array of up to third order counts [energy (or mass), polar angle, azimuthal angle]. The array is produced with the intrinsic resolution of the sensor. For the FIS in wide-angle mode, this is 30 energies, six polar angle zones (the detector anodes) and 16 azimuthal sectors (corresponding to energy sweeps).
The size of this array is greater than can be accommodated by the telemetry allocation and so the array is compressed by combining adjacent elements. This is done in more than one way for a particular array so that different aspects of the data are covered. The transmitted arrays are listed in Tables 8 and 9.

Table 8. Fast Ion Sensor transmitted Distribution

	Polar** zones (deg)	Azimuthal res. (deg)	Energy spectrum	Time resolution
Wide-energy mode	20-72	45	15 contiguous	One spin
	72-124	45	bands	
	124-180	45		
PTR distribution			delta(E)/E=0.6	
			10 eV to 20 keV	
Wide-energy mode	20-46	45	30 contiguous	Three spins
	46-72	45	bands	
	72-98	22.5		
HAR distribution	98-124	22.5	delta(E)/E=0.3	
	124-150	45	10 eV to 20 keV	
	150-180	45		

Solar-wind mode	46-98	5.6	30 contiguous	Two spins
			bands	
SWA distribution			delta(E)/E=0.096	
			E* to 6.7E*	

Solar-wind mode	46-59	45	30 contiguous	Two spins
	59-72	45	bands	
SWP distribution	72-85	45	delta(E)/E=0.096	
	85-98	45	E* to 6.7 E*	
	98-150	45	E* set by	
			command or	
			on board	
			processing	

FTR = Fast Time Resolution; HAR = High Angular Resolution; SWA = Solar-Wind Azimuthal; SWP = Solar
** Measured from z-axis

Table 9. Implanted Ion Sensor transmitted distribution

	Polar** zones (deg)	Azimuthal res. (deg)	Energy spectrum	Time resolution	M
4DF distribution	15-25	22.5	32 levels	32 spins	5
	50-60	22.5	delta(E)/E=0.1		
	85-95	22.5	90 eV to		1
	120-130	22.5	90 keV		2
	155-165	22.5			1
					2
					3
4DH distribution	15-25	45	32 levels	32 spins	5
	50-60	45	delta(E)/E=0.1		1
	85-95	45	90 eV to		2
	120-130	45	90keV		1
	155-165	45			2
					3
TOF distribution	15-165	360	32 levels	32 spins	2
	(all polar		delta(E)/E=0.1		f
	zones combined)		90 eV to 90 keV		
START	15-165	22.5	32 levels	32 spins	N
TAC	15-165	22.5	32 levels	32 spins	N

4DF = 4-Dimensional Full Resolution; 4DH = 4-Dimensional Half Resolution; TOF = Time-of-Flight Spe
TAC = Timing processed pulses.
** Measured from z-axis

(d) The accumulation is carried out in 16 bit registers which the DPU compresses to 8 bits in a quasi-logarithmic way. The first four bits, effectively the exponent, denote the position of the first non-zero bit in the number, and the remaining four transmitted bits contain the next four bits of the original number, the mantissa. The maximum error from the truncation is therefore 3.1%. This scheme is capable of compressing from 19 bits to 8 bits so there are some exponents (the hexadecimal values D, E and F) which do not occur in real data and can be used for other purposes.

(e) The instrument is spin-synchronized and produces a fixed number of data words each rotation. The spin period can vary with respect to the telemetry-format duration, so that there must be a means of allowing for a variation in the number of words transmitted. This has been achieved by devising an instrument telemetry format that is spin-synchronized and has a basic length corresponding to a rotation of 45deg. The JPA format ’floats’ within the spacecraft telemetry format and is identified by three format sync. words. These words begin with the three hexadecimal numbers not obtained from the data compression, i.e. D, E and F. The second half of each sync. word contains further information about the sequence and the instrument status. The telemetry output is double-buffered. 1n one side, a table of values is compiled from the data currently being acquired, while values acquired during the previous sector are read out to the telemetry from the other side. If the table of values has not been completely read out by the telemetry by the end of a 45deg sector then the remaining values are lost when the buffers are interchanged. The order in which the data are compiled in the table is obviously important and has been prioritized. Figure 9 shows how the table is constructed in each telemetry format and the possible variation in the number of values transmitted in each sector. Each type of distribution, e.g. 4DF or FTR (see Tables 8 and 9), is transmitted completely before the next is started. Where a distribution may be only partially transmitted, the order in which the values are listed is also designed to minimize the loss of information. For exampie, alternative energy levels through the spectrum are transmitted first and then the intermediate values are sent. This ensures that a coarse spectrum over the full range is transmitted first.

The main cause of the variation in samples per sector is not the possible change in the spin period, but the nonuniform spacing of the JPA words in the telemetry format. This effect is most severe in Format 3 where, on some occasions, no data are transmitted in a sector. This is not a disadvantage because more distributions can be transmitted than if the sampling were uniform. The time resolution is reduced because data from two spins must sometimes be combined to obtain one complete distribution.

(f) The final function of the DPU is to set the energy range for the solar-wind mode. There are eight possible starting points for the sweep in the upper half of the full sweep range. The range can be set by ground control or can be automatically tracked. The DPU scans through the solar-wind spectrum and searches for the peak count. If that peak count does not exceed 64, then the range is stepped to the next lower one. If no count greater than 64 has been recorded by the time it reaches the bottom level, then it recycles to the top and continues. If a peak with more than 64 counts is found, the starting point of the sweep is changed until its energy level lies between two preset limits in the 30-level spectrum. These limits are calculated to ensure that the alpha-particle peak is included as well as the proton peak.

7. In-flight Performance

The instrument was first turned on on 8 September 1985. The performance throughout all testing was nominal. At the time the spacecraft was more than 10 million kilometres from the Earth in the solar wind. The only population that could be identified so far is the solar wind. The Fast Ion Sensor has been able to follow the solar-wind variations with its auto-ranging capability. The Implanted Ion Sensor has been able to identify higher mass ions such as O^{6+} and O^{5+} in the solar wind. The instrument has been operated since then whenever spacecraft operations allow.

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Figure 9. The structure of the JPA spin-synchronized floating format in the three spacecraft formats. The cross-hatched bar beside each column shows the range of variation in the number of samples transmitted in each sector. The distributions (FTR,4D, etc.) are defined in Tables 8 and 9.

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