INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

H4-SMR 393/6

SPRING COLLEGE ON PLASMA PHYSICS

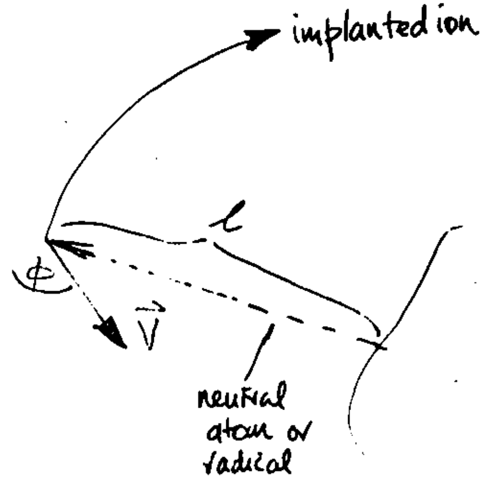
15 May - 9 June 1989

ALFVENIC TURBULENCE IN BEAM-PLASMA SYSTEMS (I)

A. Johnstone

Mullard Space Science Laboratory
University College London
Holmbury St. Mary
Surrey, RH5 6NT
Dorking
U. K.

THE FUNDAMENTAL COMETARY PLASMA PROCESS.



$P(\ell) = e^{-\ell/L}$

$L = \frac{V_e}{\nu}$ $\frac{\text{expansion velocity}}{\text{ionisation rate}}$ $\frac{\sim 1\,\text{km/s}}{\sim 10^{-6}\,\text{s}^{-1}}$ $\approx 10^6\,\text{km}$

neutral density

$$n(\ell) = \frac{Q}{4\pi V_e \ell^2} \exp\left[-\frac{\nu \ell}{V_e}\right]$$

FLUID EQUATIONS FOR COMETARY FLOW

[illegible] et al. [illegible] 1, [illegible], 1987

Conservation of

number $\quad \frac{\partial n}{\partial t} + \nabla . n\vec{u} = A$

mass $\quad \frac{\partial \rho}{\partial t} + \nabla . \rho\vec{u} = B$

momentum $\quad \frac{\partial}{\partial t}\rho\vec{u} + (\vec{u}.\nabla)\rho\vec{u} + \rho\vec{u}(\nabla.\vec{u}) + \nabla p = C$

energy $\quad \frac{\partial}{\partial t}\left(\rho\frac{\vec{u}^2}{2} + \frac{p}{\gamma-1}\right) + \nabla.\vec{u}\left(\rho\frac{\vec{u}^2}{2} + \frac{\gamma p}{\gamma-1}\right) = D$

Source Terms

- A local ionisation rate
- B ionisation rate x mass difference
- C loss of momentum by charge exch
- D loss of energy by charge exchange

Assumption

Instantaneous assimilation into solar wind flow of cometary ions.

COMETARY ION SOURCE

Assumptions

(a) constant gas production rate Q moles/s $\sim 10^{30}$

(b) radially symmetric outflow at constant velocity $V_e \sim 1$ km/s

(c) constant ionisation rate $\nu \sim 10^{-6}$ s

Neutral density n_c

$$n_c = \frac{Q}{4\pi V_e r^2} \exp\left(-\frac{\nu r}{V_e}\right)$$

Ionisation rate

$$\frac{\partial n_i}{\partial t} = \frac{Q\nu}{4\pi V_e r^3} \exp\left(-\frac{\nu r}{V_e}\right)$$

Ion flux

$$n_i u_i = \int_{x_0 y_0}^{\infty} \frac{Q\nu}{4\pi V_e r^2} \exp\left(-\frac{\nu r}{V_e}\right) dS$$

Define scale length $L = V_e/\nu \sim 10^6$ km

$$n_i v_i = \frac{Q}{4\pi L^2} \int_{x_0}^{\infty} \frac{1}{(x^2+y_0^2)} \exp\left[-(x^2+y_0^2)^{\frac{1}{2}}\right] dx$$

Ion Pickup Trajectories

Coordinate system

B along z

$\vec{V}_s$ in x-z plane at angle α to $\vec{B}$

Pickup trajectories

$$x = V_\perp \left[t - \frac{1}{\Omega_i} \sin(\Omega_i t + \epsilon) \right] + x'$$

$$y = -\frac{V_\perp}{\Omega_i} \cos(\Omega_i t + \epsilon) + y'$$

$$z = V_\parallel t + z' \approx z'$$

$$\Omega_i = eB/m_i$$

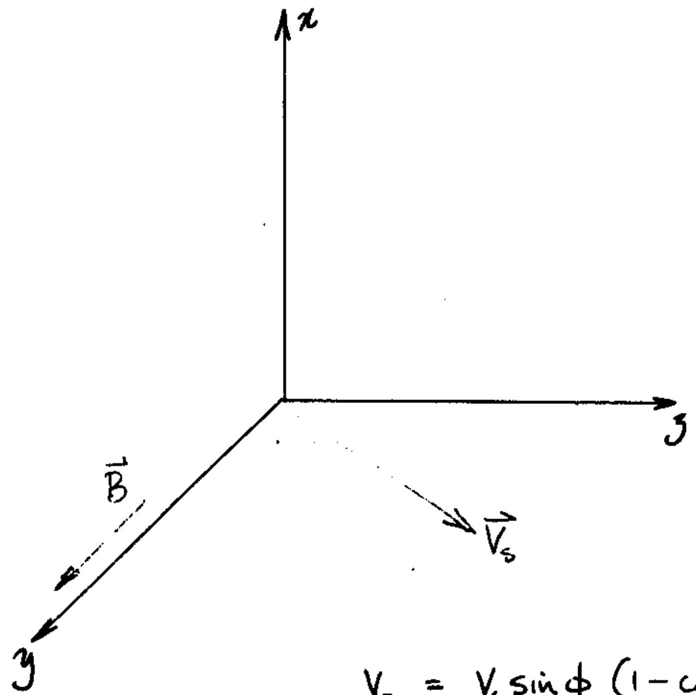
$$V_\perp = V_s \sin\alpha$$

$$V_\parallel \approx V_e \approx 0$$

Motion is (gyration at $V_\perp$) + (drift at $V_\perp$)

all perpendicular to B

Ion pickup perpendicular to B



$$V_z = V_s \sin\phi \,(1 - \cos\omega_c t)$$
$$V_y = 0$$
$$V_x = V_s \sin\phi \,\sin\omega_c t$$

Maximum Velocity $\quad 2V_s \sin\phi$

Maximum Energy $\quad 4E\sin^2\phi$

where $\quad E = \frac{1}{2} m V_s^2$

Mean momentum $\quad m V_s \sin\phi$ along Z

Mean energy $\quad$ [illegible] $\sin^2\phi$

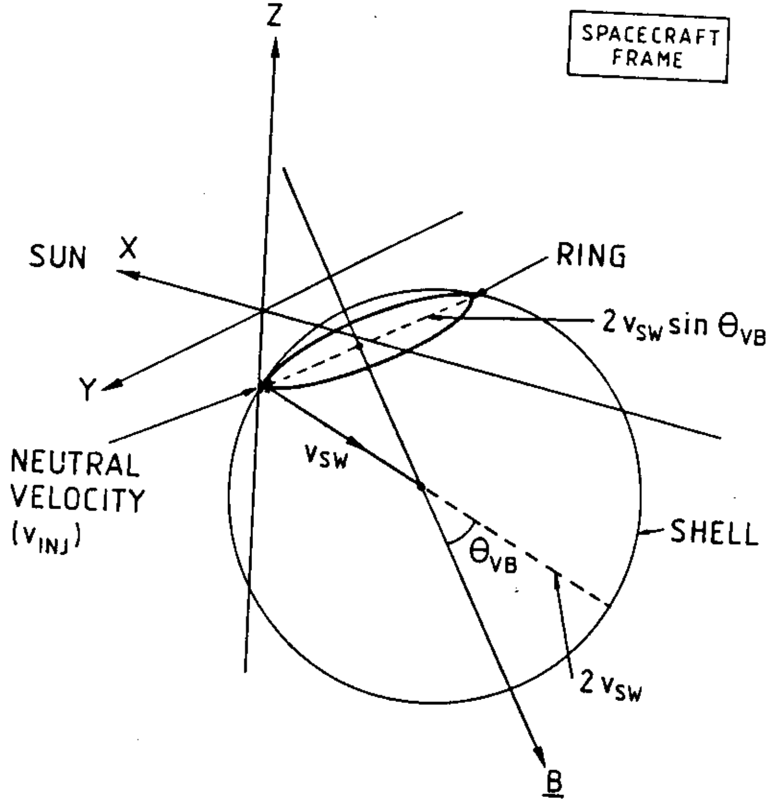


Figure 1 - Ion pickup velocity space geometry in the spacecraft frame, for an arbitrary orientation of the magnetic field **B**. Neutral particles are injected at the point indicated by the star ($\underline{v}_{inj} \simeq (0, 0.15, -68.4)$km/s in this frame) and their initial trajectory is in a ring around **B**. Later they scatter onto a shell centred on the solar wind speed to a first approximation.

ION VELOCITY DISTRIBUTION

Distribution a ring of radius $V_s \sin\alpha$ in velocity space centred on the solar wind speed

maximum energy in ring $4 \frac{m_i}{m_p} E_p \sin^2\alpha$

E_p energy of solar wind proton

If scattered into shell

maximum energy $4 \frac{m_i}{m_p} E_p$

For instant assimilation we require

either $\alpha = 90°$

or rapid scattering over the shell

One dimensional equations

Wallis + Ong Plan. Sp. Sci 23, 715, 1975
Galeev et al ApJ 289, 807, 1985

Coordinate system
x parallel to flow
z parallel to B

Conservation equations

$$\frac{d}{dx}\{\rho_i u f(\mu, u)] = \frac{m_i Q \nu}{4\pi V_e r^2} \exp\left(-\frac{\nu r}{V_e}\right) \delta\left(\mu - \frac{m_i u^2}{2B}\right)$$

$$\frac{d}{dx}(\rho u) = \frac{m_i Q \nu}{4\pi V_e r^2} \exp\left(-\frac{\nu r}{V_e}\right)$$

$$\frac{d}{dx}\left(\rho u^2 + p_\perp + \frac{B^2}{8\pi}\right) = 0$$

Solution

$$\frac{U_\infty}{U} = 2 - \left[4 - 3\left(\frac{\rho u}{\rho_\infty u_\infty}\right)\right]^{1/2}$$

∞ refers to upstream, undisturbed values

reversal when $\frac{\rho u}{\rho_\infty u_\infty} = \frac{4}{3}$

Shock must form.

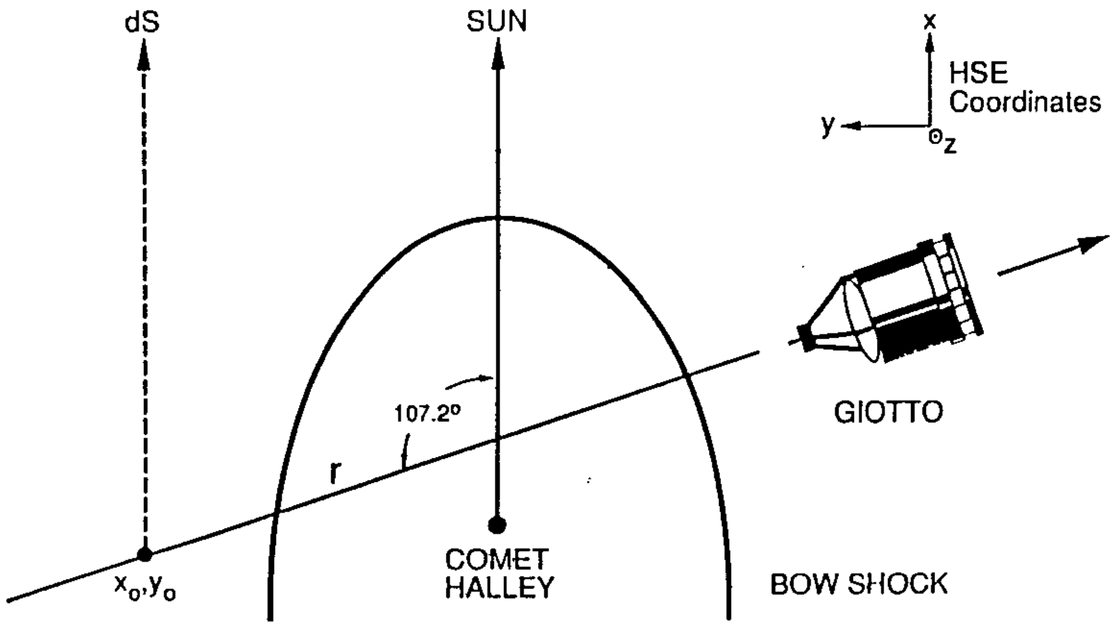


Figure 1 - Schematic representation of the Giotto fly-by geometry in Halley-centred Solar Ecliptic (HSE) coordinates, showing the integration path, dS, for estimation of the implanted cometary ion flux at a spacecraft position (x_0, y_0).

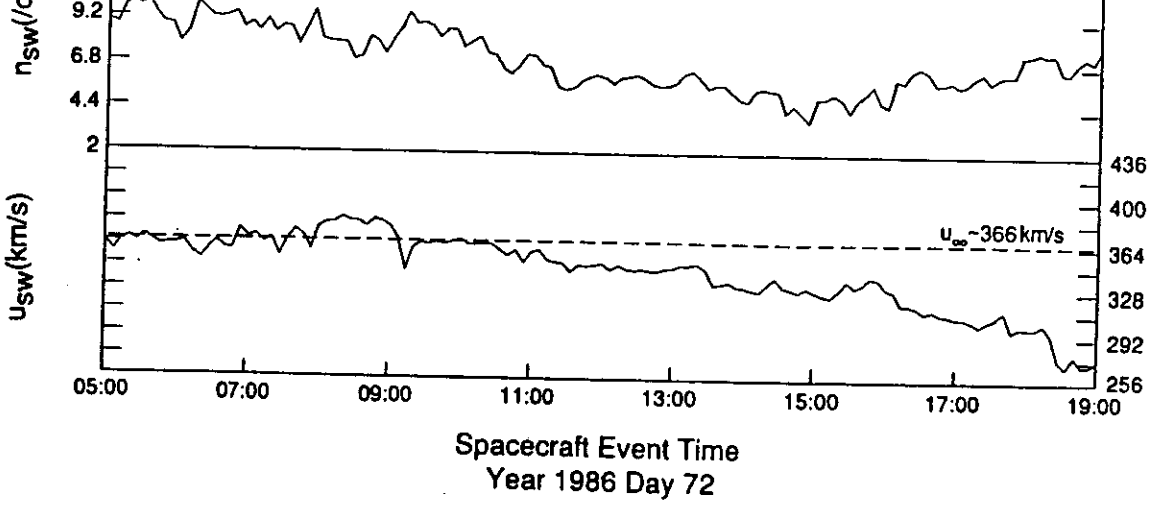


Figure 3 - Smoothed solar wind proton density and velocity profiles for the same period as in Figure 2. An upstream velocity of $u_\infty \sim 366$ km s^{-1} is overlayed.

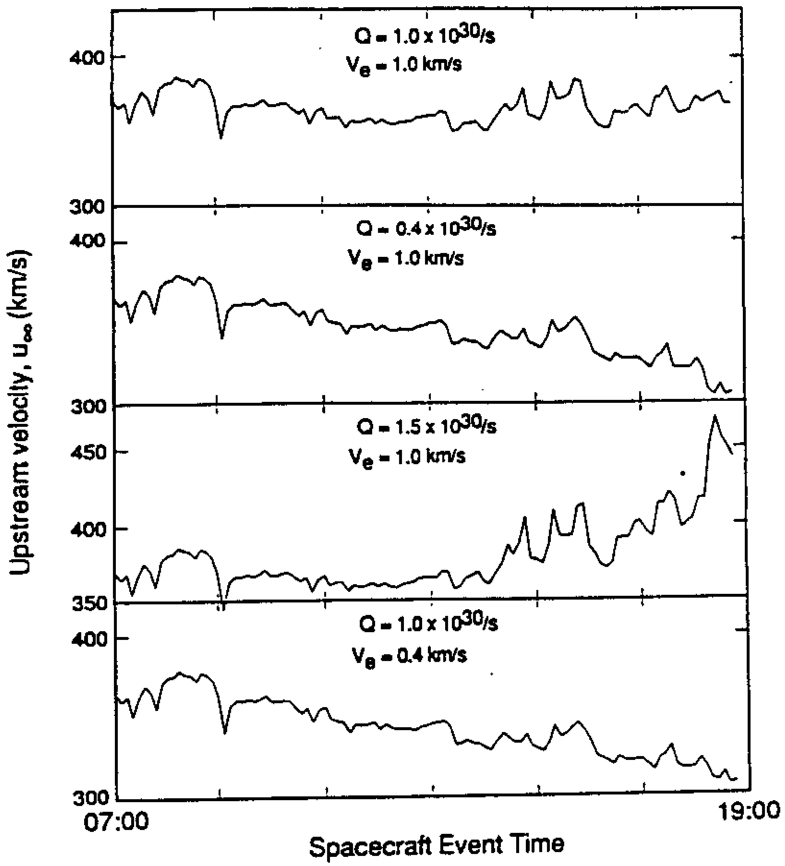


Figure 5 - Effects of differing gas emission values on the u_∞ profiles inferred.

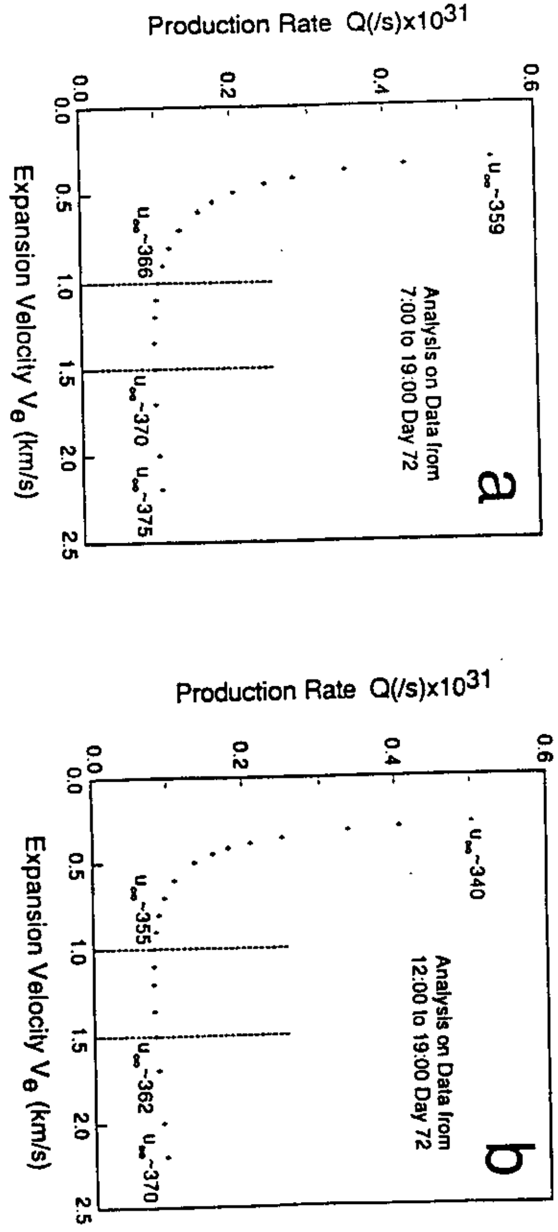
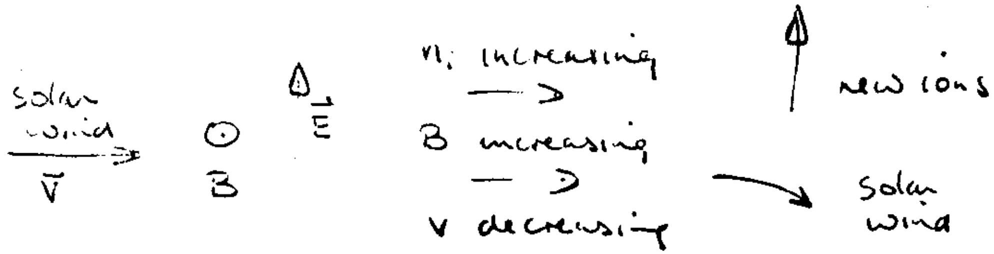


Figure 7 - Set of possible solutions resulting from analysis on the data periods (*a*) 07:00-19:00 hrs, and (*b*) 12:00-19:00 hrs.

PERPENDICULAR PICKUP MECHANISM



⊛ Momentum balance perpendicular to flow between new ions and solar wind

⊛ solar wind decelerated by electric field

⊛ $E \neq -\vec{V}_s \times \vec{B}$

Is the ring distribution stable?

Wu + Davidson JGR 77, 5399, 1972
Lee + Ip JGR 92, 11041, 1987

Dispersion relation for electromagnetic waves propagating parallel to the magnetic field

$$k^2c^2 = \omega^2 + 4\pi^2\omega \sum_j \frac{q_j^2}{m_j} \int dv_\parallel \, dv_\perp \, v_\perp^2 \, \frac{G F_j}{\omega - kv_\parallel + \Omega_j}$$

$$G \equiv \frac{\partial}{\partial v_\perp} + \frac{k}{\omega}\left(v_\perp \frac{\partial}{\partial v_\parallel} - v_\parallel \frac{\partial}{\partial v_\perp}\right)$$

⊛ work in the solar wind frame

⊛ cold sw electrons
cold sw protons
ring beam of cometary ions

⊛ assume $\omega - kv_\parallel + \Omega_i$ more sharply peaked than F_i

Then $$\omega_r^2 = k^2 V_A^2$$

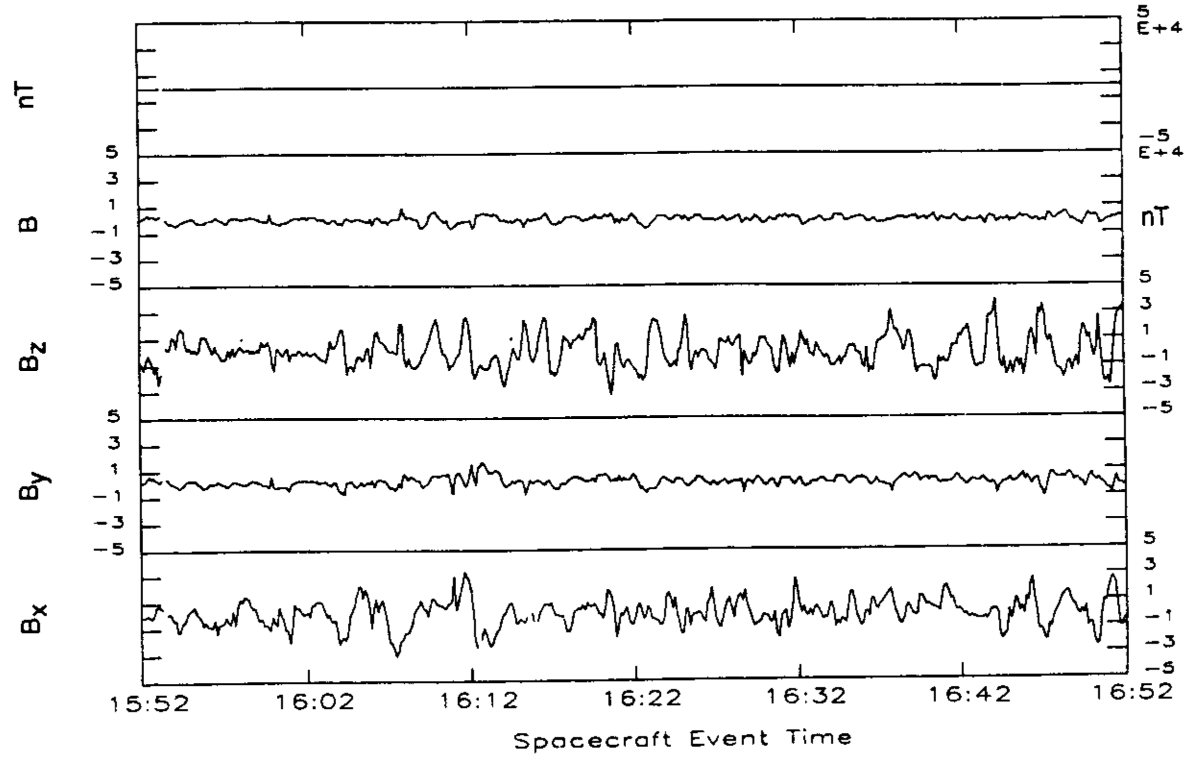
$$\gamma = \frac{\pi^2}{2} \frac{V_A^2}{c^2} \frac{\omega_i^2}{n_i} \int dv_\parallel \, dv_\perp \, v_\perp^2 \, \delta(\omega_r - kv_\parallel + \Omega_i)\, G$$

Put $$F_i = \frac{n_i}{2\pi^{3/2} v_\perp \sigma} \, \delta(v_\perp - v_{\perp 0}) \exp\left(-\frac{(v_\parallel - v_{\parallel 0})^2}{\sigma^2}\right)$$

Obtain maximum $\gamma = \underline{1} \, / \underline{2\pi})^{1/2} \, \underline{V_A} \, \underline{\omega_i^2} \, V_{\perp 0}^2 \, V_{\parallel 0}$

Giotto MAG Magnetic Field Fluctuations

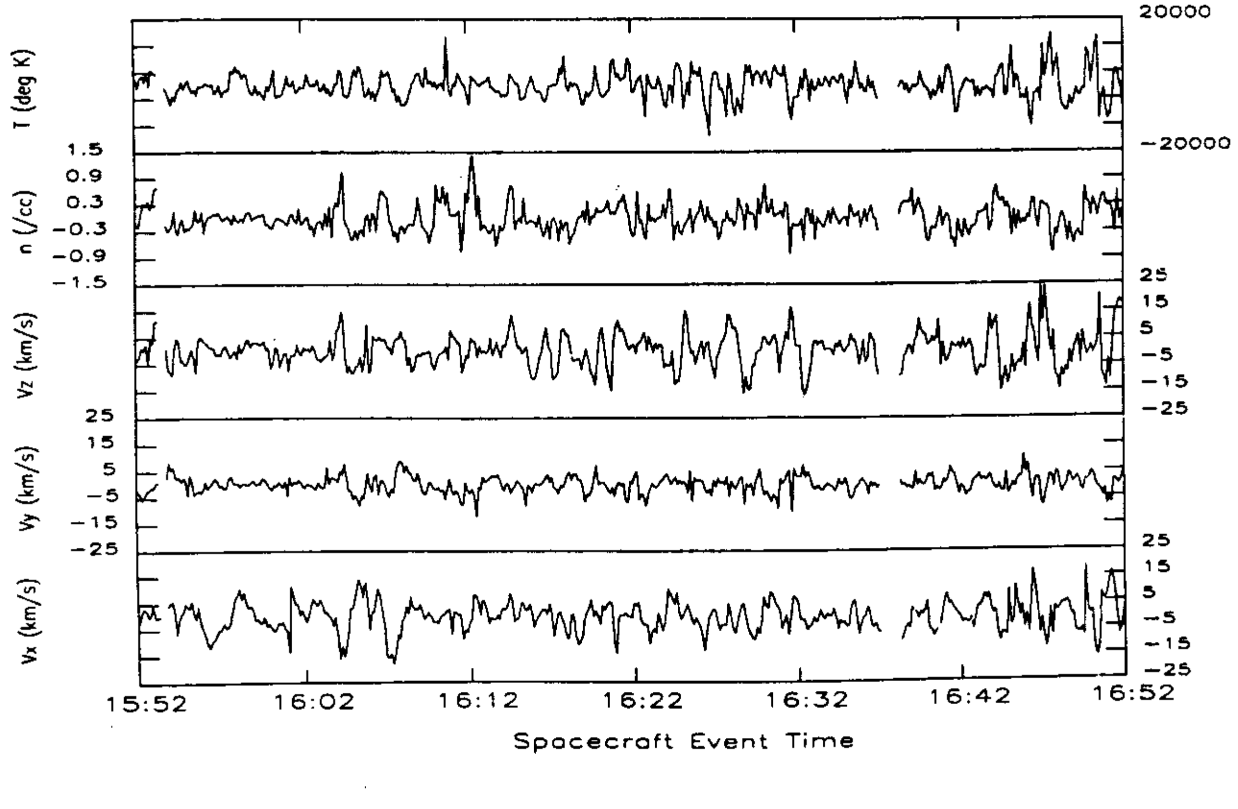
Year 1986 Day 72 FLD coordinates

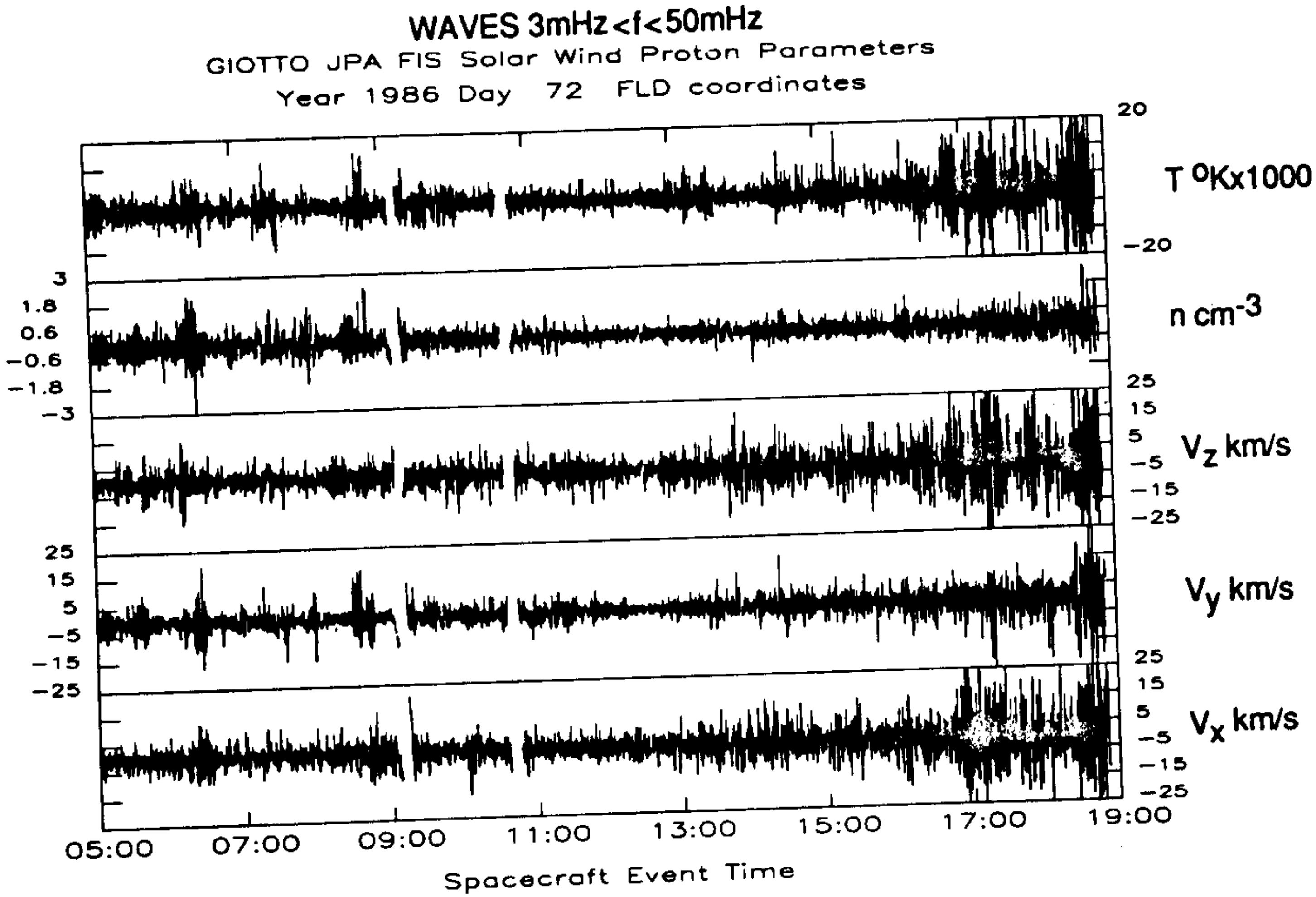


Fluctuations

GIOTTO JPA FIS Solar Wind Proton Parameters

Year 1986 Day 72 FLD coordinates




WAVES 3mHz<f<50mHz
GIOTTO JPA FIS Solar Wind Proton Parameters
Year 1986 Day 72 FLD coordinates
T °Kx1000
n cm-3
Vz km/s
Vy km/s
Vx km/s
20
-20
3
1.8
0.6
-0.6
-1.8
-3
25
15
5
-5
-15
-25
05:00
07:00
09:00
11:00
13:00
15:00
17:00
19:00
Spacecraft Event Time