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SPRING COLLEGE ON PLASMA PHYSICS

(25 May - 19 June 1987)

INTERACTION OF COMETS WITH THE SOLARWIND AND SOLAR RADIATION

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Interaction of Comets with the Solarwind and Solar Radiation

D. A. Mendis

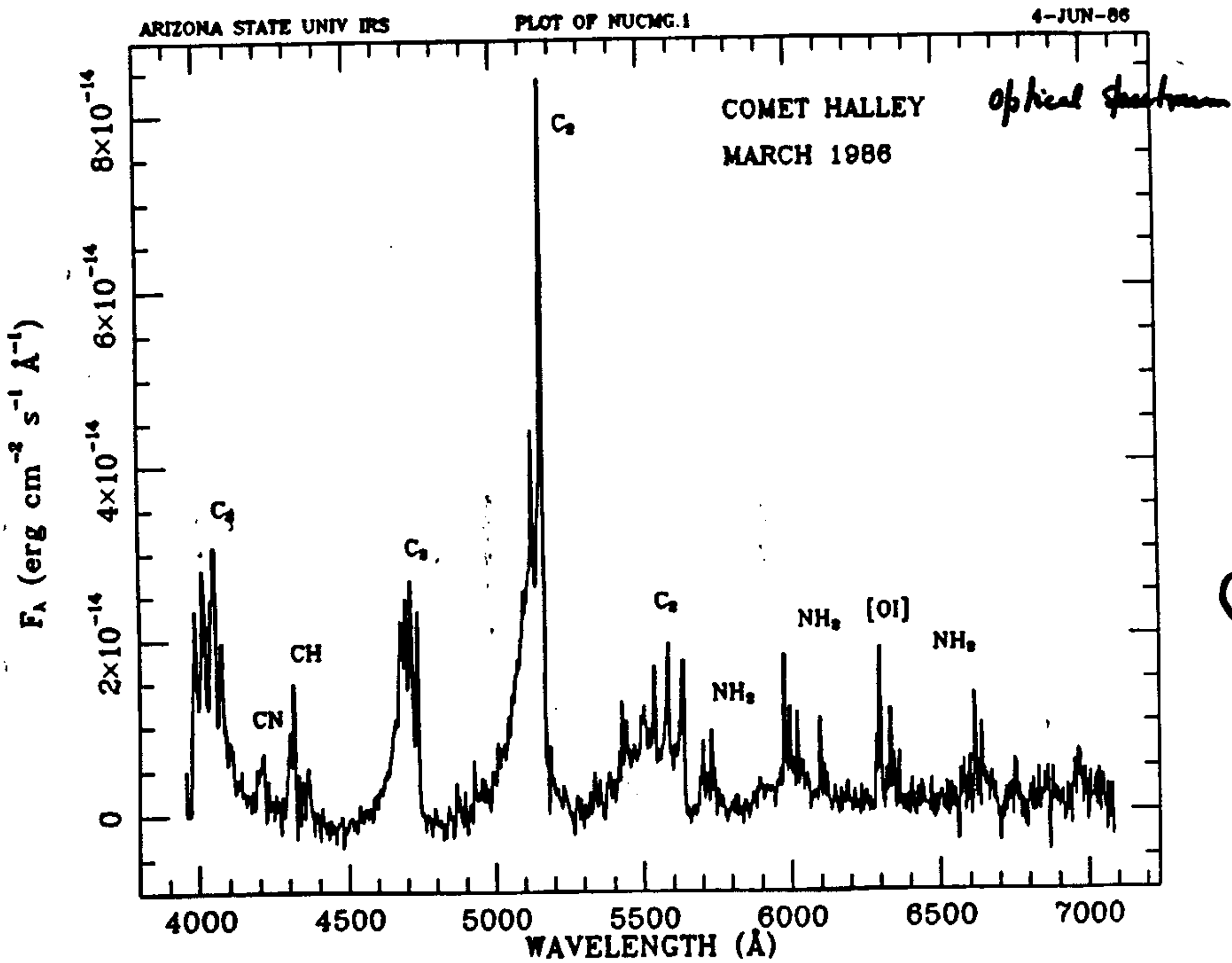
+ Cosmognic Significance.

+ Natural probes of the Interplanetary Medium

+ Cosmic Laboratories
  - Very low density gas
  - Plasma – neutral gas interaction
  - Plasma turbulence
  - Dust – plasma interaction etc.

+ Comparative Planetary atmospheres + Magnetospheres.

(3)



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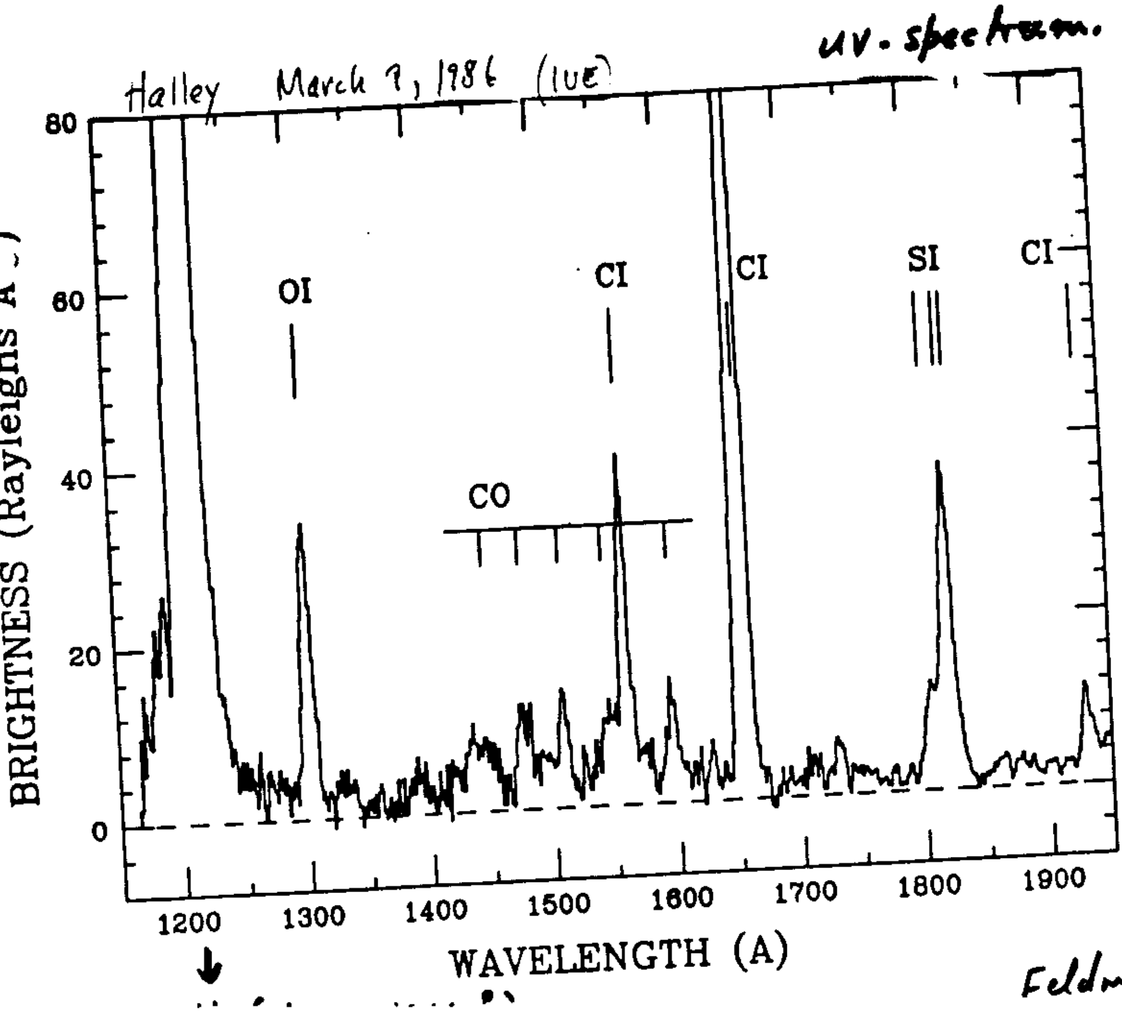


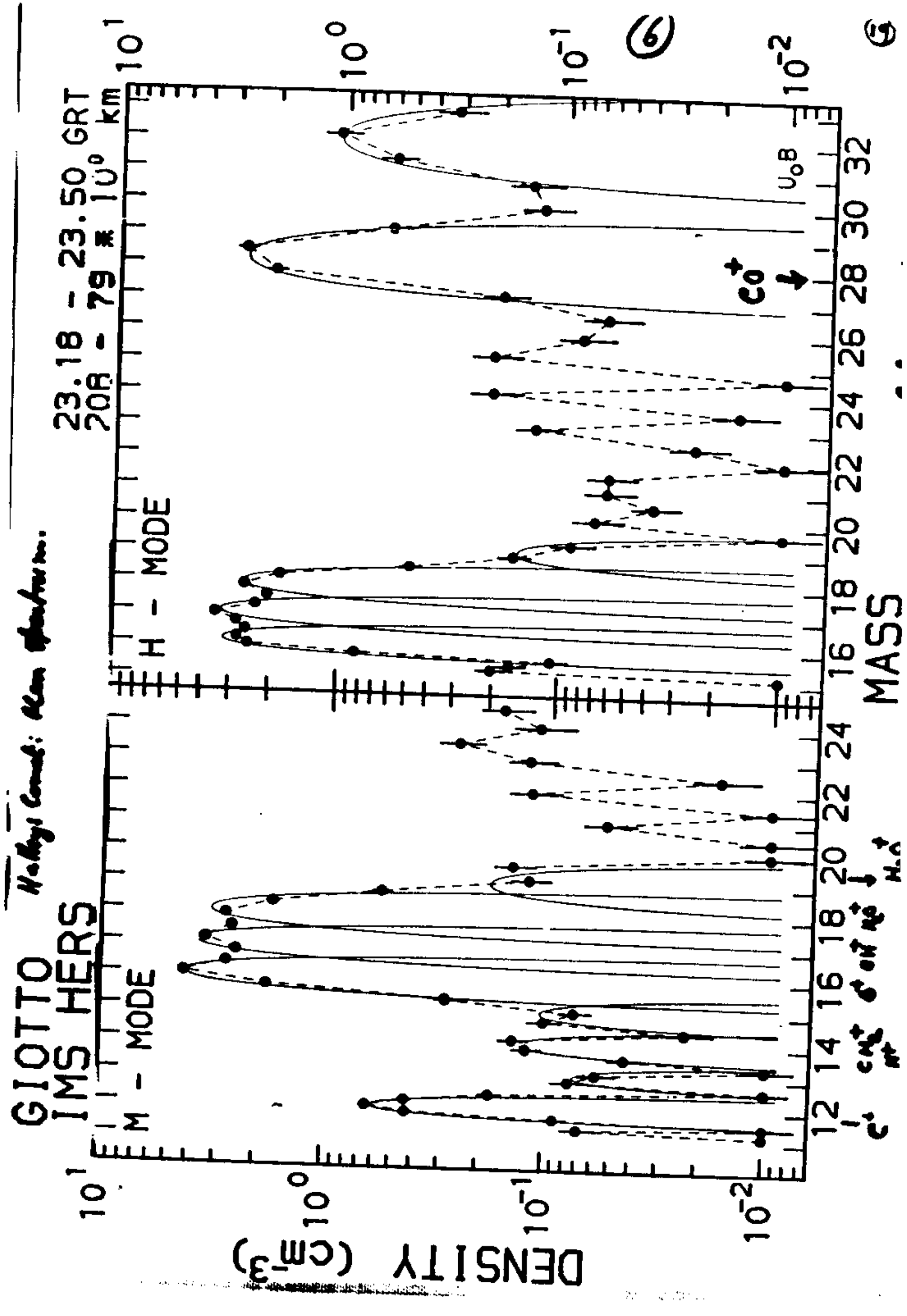
Feldman et al

Spectral Identifications. (5)

Elements	Neutral Molecules and Radicals	Ions.
H	C_2	C^+
O	$^{12}C^{13}C$	Ca^+
C	CH	CO^+
S	CN	CH^+
Na	CO	OH^+
K	CS	CN^+
Ca	NH	N_2^+
V	OH	CO_2^+
Mn	C_3	H_2O^+
Fe	NH_2	H_2S^+
Co	H_2O	
Ni	HCN	
Cu	CH_3CN	
Cr	S_2	Dust
	HCO	10 μm
	H_2CO (*)	18 - 20 μm
	NH_3	Silicate ?
	NH_4 (*)	Hydrocarbon polymer ?

(*) Tentative identification.

(6)



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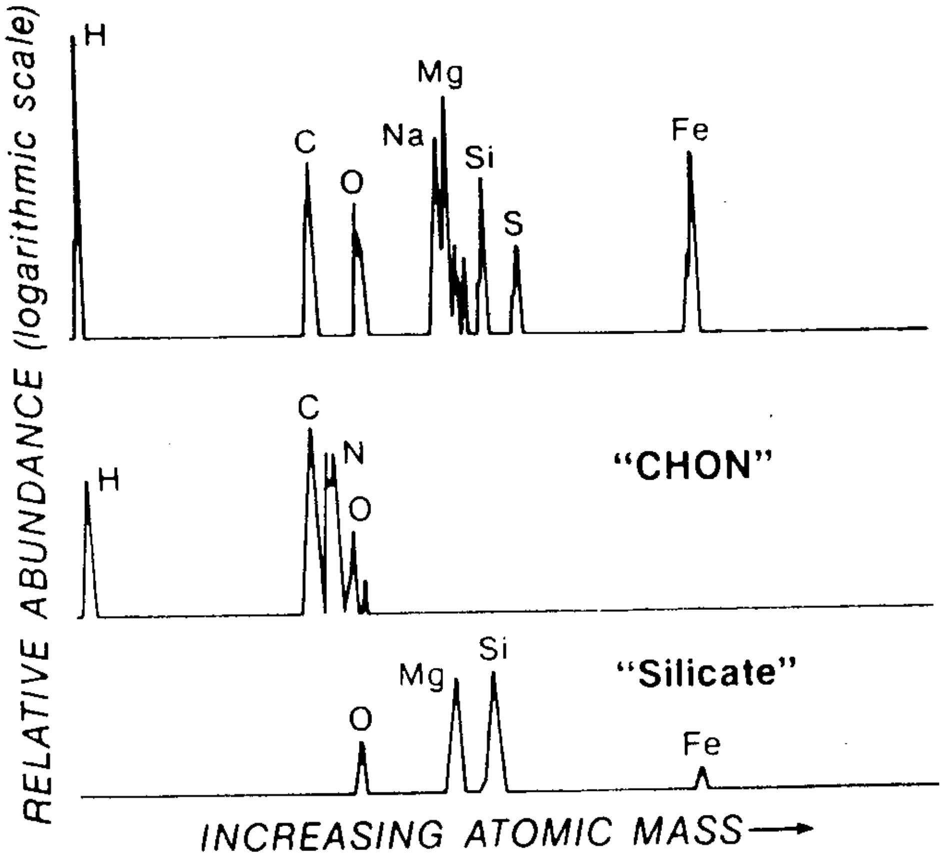
Halley Dust : Elemental Composition.

Kissel et al (MPK)



(8)

MAJOR DISCOVERIES

1. Nucleus
   - Surface very dark (Albedo ≤ 0.04) ≈ 0.2
   - Large (15 km x ≥ 8 km, 8 km), $M \approx 5\times10^{16} - 10^{17}$ g
   - Warm (330 ± 30°K) => Not evaporating surface; $\bar{\rho} \approx 0.2 - 1.0$ g cm^{-3}
   - ✔ Dust mantle (carbon?)
   - Dust jets => cracks in crust
   - Most material appears to come from the cracks
   - ✔ Nucleus darker than the surrounding dust; poor visibility
   - Spin period ~ 7.4 days? Precession period 2.2 days?

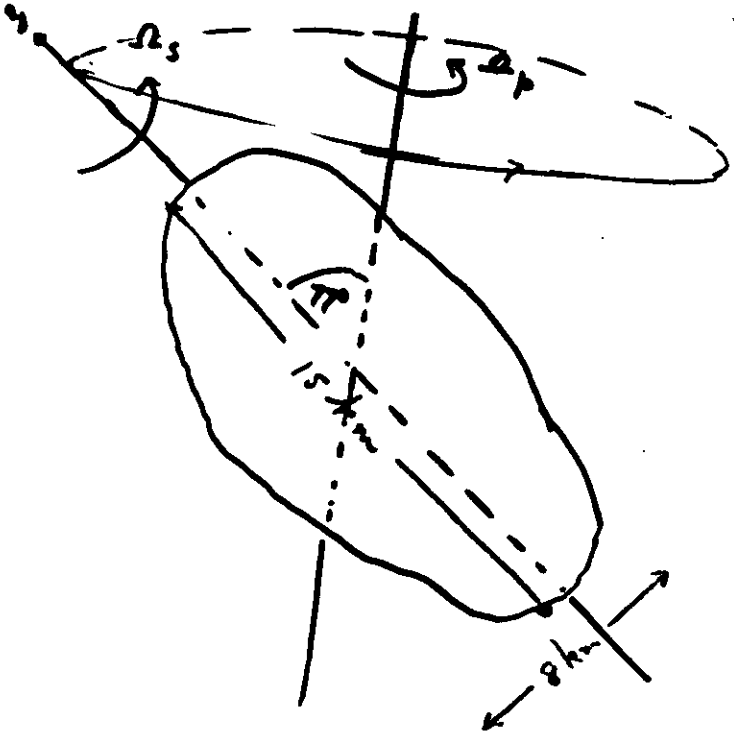
2. Dust
   - ✔ Smaller (10^{-15}-10^{-14}g) particles seen before larger (10^{12}g) particles; also at distances ≥ 200,000 km => electrical charging
   - ✔ No turnover of dust mass spectrum at ≈ 10^{-14}g (or ≤ 0.2 µm)
   - Minimum mass detected: 10^{-17}g
   - ✔ Dust elemental composition: mainly H, C, N, O (≤ 20 AMU); ≥ 80%
   - also some elements in the range 30-50 AMU (≤ 20%)

3. Atmosphere/Ionosphere
   - Neutrals: H_2O, CO_2, (C_2H_2), S_2; CN, C_2, OH, NH, NH_2, O, etc.
   - Ions: H_2O-group (H_2O^+, H_3O^+, OH^+, O^+)
     - CO-group (CO^+, HCO^+)
     - CO_2-group (CO_2^+; HCO_2^+, ...)
     - Fe-group (Fe^+, Ni^+, Co^+) ?
     - Hydrocarbons (?), S-group. S_2, CS_2/etc. H_2CO
   - Heavy ions up to ≈ 200 AMU (H_2O cluster ions?)

4. Solar Wind Interaction
   - Weak bow shock R_s ~ 3-5x10^5 km
   - ✔ Magnetic barrier
   - ✔ Collisionopause R_c ~ 5x10^4 km
   - ✔ Ionopause R_i ≈ 5x10^3 km
   - ✔ Inner shock?
   - ✔ Ionosphere (Magnetic field-free cavity)
   - Strong wave activity near bow shock and inside.
   - Mass loading apparent at ≥ 5x10^6km
   - Field-aligned fluxes of energetic electrons at d ≥ 5x10^6km
   - ✔ keV ("auroral" electrons) near ionopause
   - Ring-beam distribution of pick-up ions.
   - Energetic pick-up ions (~0.4 MeV) → acc? process (wave-particle).

(9)

Rotation of Halley's Nucleus



$a \approx 15$ km

$b \approx c \approx 8$ km.

$T_s = \frac{2\pi}{\Omega_s} \approx 7.4$ days.

$T_p = \frac{2\pi}{\Omega_p} \approx 2.2$ days.

$\Omega_s = \Omega_p \left(I_0 / I_z - 1 \right) \cos\theta$

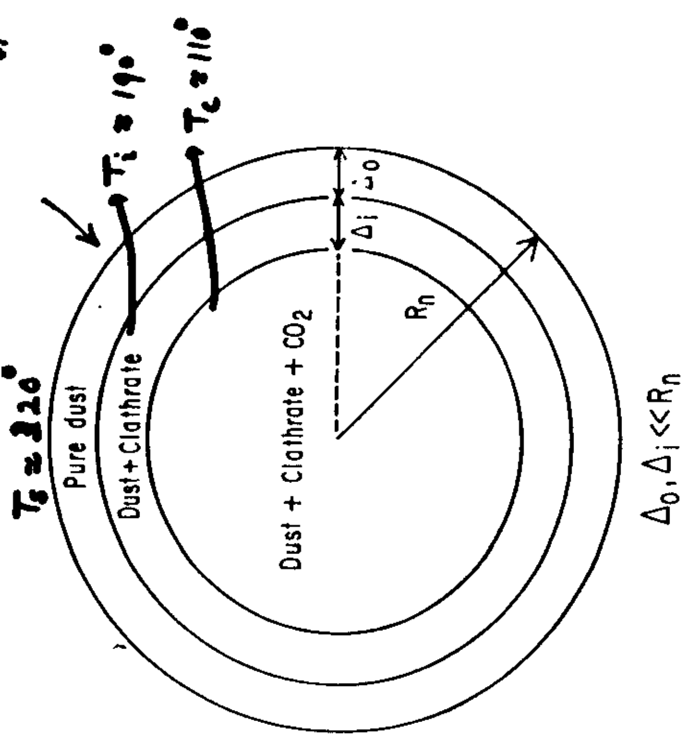
$\Rightarrow \theta \approx 77^\circ$

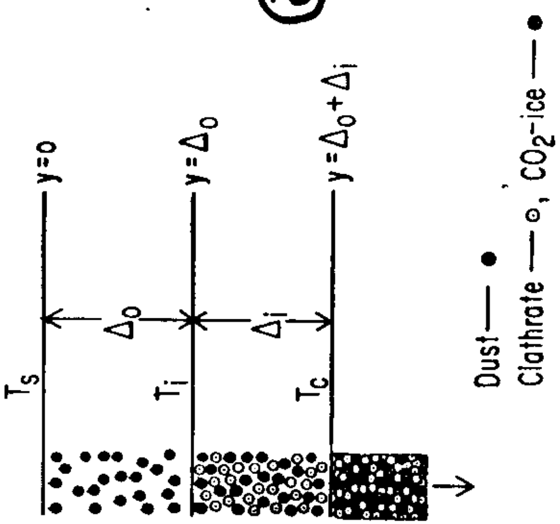
(Z. Sekanina)

(10)

Physical Structure : Dust Mantle (Whipple, 1950; Brin + Mendis, 1979; (3) Horanyi et al., 1984; Fanale + Salvail, 1984)

Chemical differentiation (Houpis, Ip and Mendis, 1985; Houpis and Gombosi, 1986)





$r = 0.89$ AU

Cometary Atmosphere / Ionosphere.

1. Multi-species
2. Two-phase (gas + dust).

(a) Chemistry. (photolysis + ion-mol.)

(b) Dynamics

(c) Thermodynamics

(d) Radiative transfer [UV; Vis + IR].

Sublimation of Surface or Sub-surface ices

Simplest case: (a) 'Bald' nucleus
no circumnuclear dust.
(quasi-steady state)

(1) $$F(1-A_B)\, r^{-2} \cos\theta \cos\phi = \epsilon_s \sigma T_s^4 + \frac{L_M}{N_A}\dot{Z}$$

"Rapidly rotating" nucleus → uniform temp.

$$\langle \cos\theta \cos\phi \rangle = \frac{1}{4}.$$

(2) $$\dot{Z} = n_s v_s = n_s \, . \, M_s \sqrt{\frac{\gamma k T_s}{m}}$$

Integrate Clapeyron - Clausius Eqn:

$$\frac{dP_s}{P_s} = \frac{L_M}{k N_A} \frac{dT_s}{T_s^2} \quad ; \quad L_M = m T_s + b$$

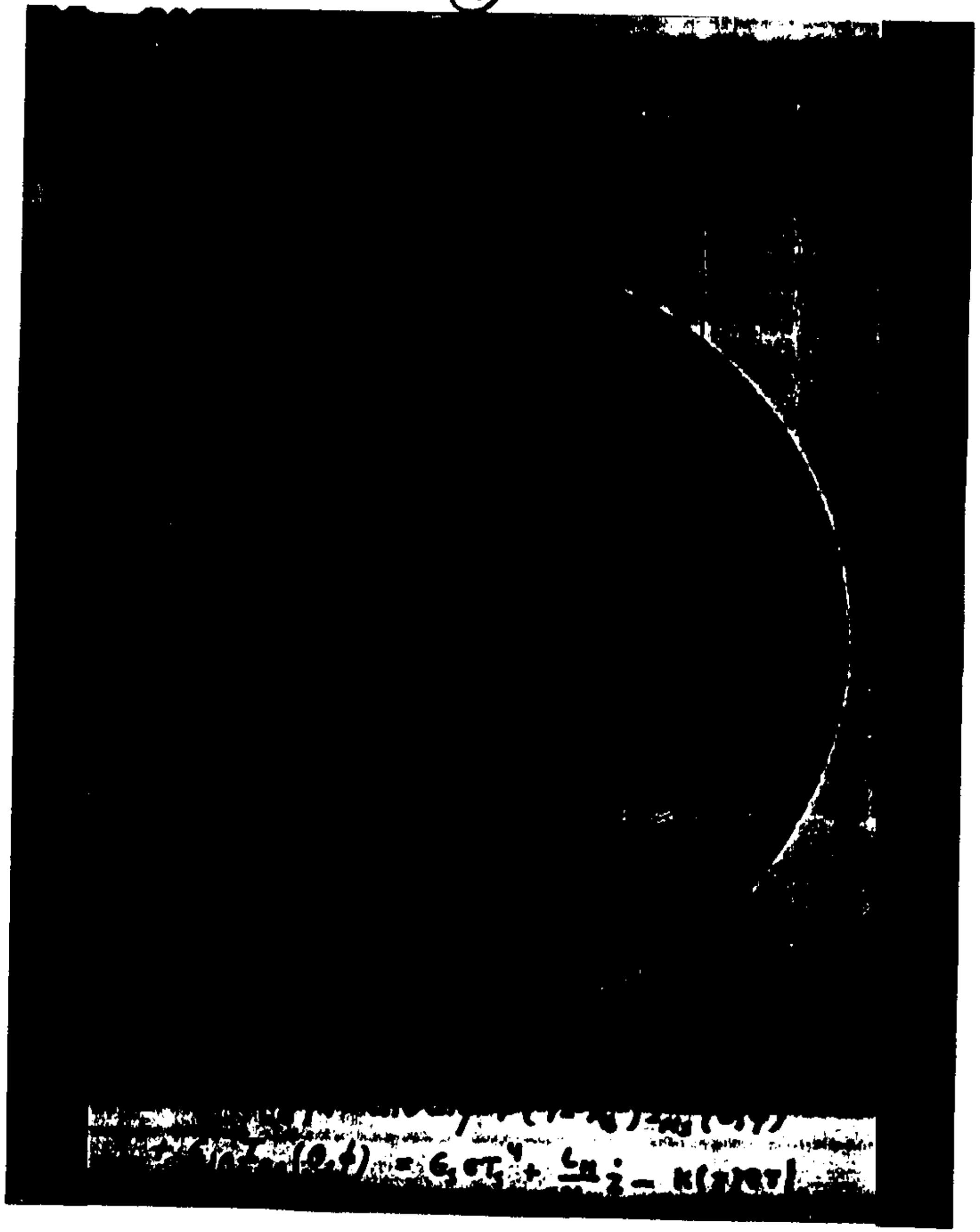
(3) ⇒ $$n = n_0 \left(\frac{T_0}{T_s}\right)^{(1 - m/kN_A)} \exp\left[\frac{b}{kN_A}\left(\frac{1}{T_0} - \frac{1}{T_s}\right)\right]$$

(b) Dust-mantle.

R.H.S of (1) $= \epsilon_s \sigma T_s^4 - K(T)\nabla T|_s$

Then $$K(T)\nabla T|_s = \frac{L_M}{N_A}\dot{Z}$$

(13)



a) Chemistry of an H_2O – dominated atmosphere. (14)

1. $H_2O + h\nu \rightarrow OH + H$ $\lambda < 1860Å$

2. $H_2O + h\nu \rightarrow H_2 + O(^1D)$ $\lambda < 1450Å$

3. $H_2O + h\nu \rightarrow H_2O^+ + e$ $\lambda < 984Å$

$OH + h\nu \rightarrow O + H$

$O + h\nu \rightarrow O^+ + e$

$H_2O + O(^1D) \rightarrow OH + OH$

$H_2O + H_2O^+ \rightarrow H_3O^+ + OH$

$H_2O + OH^+ \rightarrow H_3O^+ + O$

$H_2O + OH^+ \rightarrow H_2O^+ + OH$

$H_2O + H^+ \rightarrow H_2O^+ + H$

$H_2O + O^+ \rightarrow H_2O^+ + O$

$H_3O^+ + e \rightarrow OH + H_2$

$H_2O^+ \quad e \rightarrow OH + H$

Neutrals: H_2O, OH, H_2, O, H, H^*

Ions: H_2O^+, H_3O^+, OH^+, O^+, H^+, e

Dust: Grains of single size (a=0.5μm)

B) Continuity of #

$$\frac{1}{r^2}\frac{d}{dr}\left(n_i u_i r^2\right) = \sum \text{source} - \sum \text{sinks}$$

C) Continuity of momentum.

1. neutrals.
2. ions: $\rho_i u_i \frac{du_i}{dr} + \frac{dp_i}{dr} = -(\text{mom. tr}) + S_i(u_n - u_i) + \frac{e}{m}\rho_i E$
3. electrons: $\frac{dp_e}{dr} \approx -\frac{e}{m}\rho_e E$
4. dust.

D) Continuity of energy.

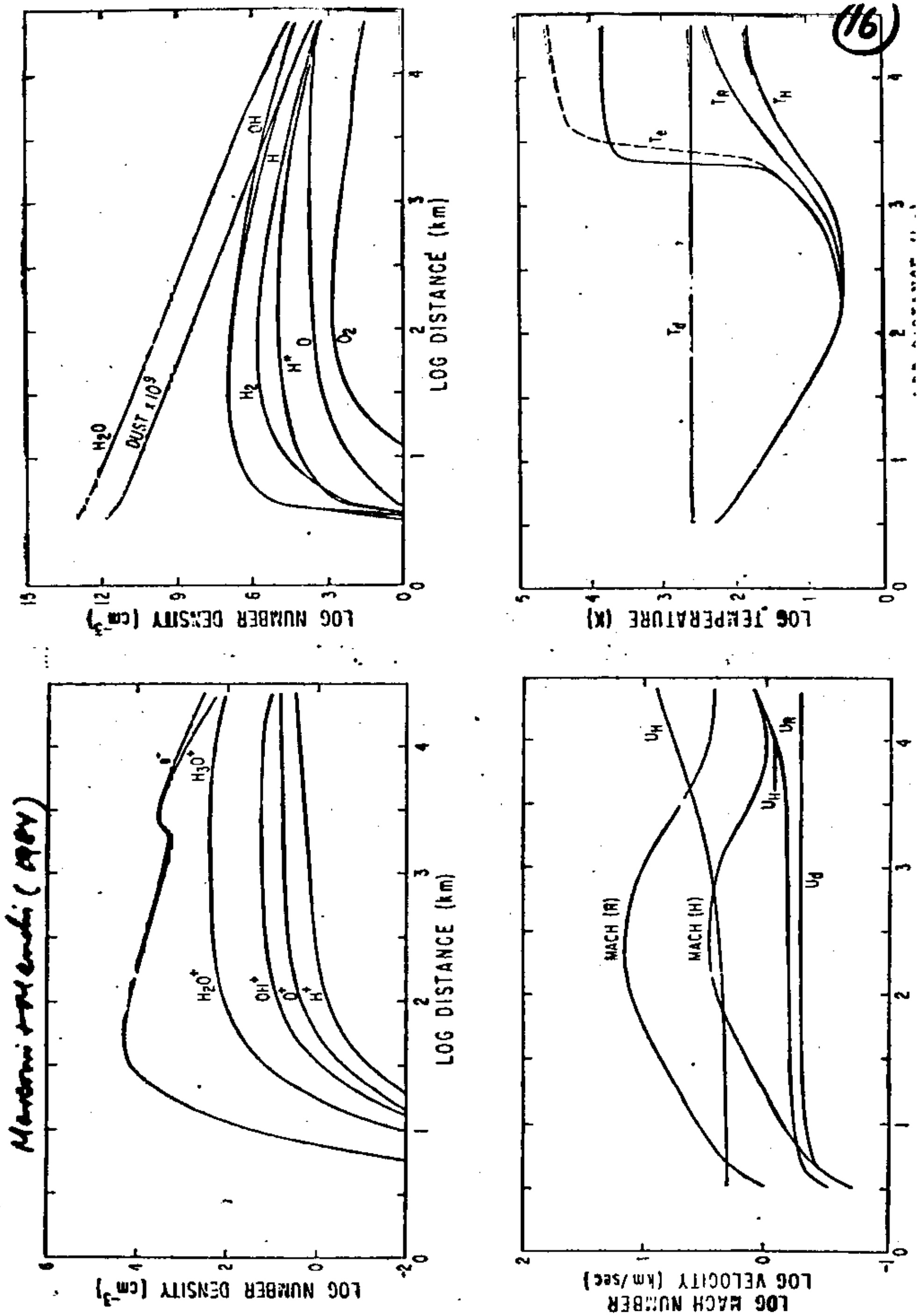
1. Neutrals
2. ions
3. Electrons: $\frac{1}{r^2}\frac{d}{dr}\left[r^2\rho_e u_e\left(h_e + \frac{1}{2}u_e^2\right) - r^2 k_e \frac{dT_e}{dr}\right] = \sum \text{source} - \sum \text{loss} - e n_e u_e E$.

E) Radiative transfer for J_1, J_2, J_3 + (J ...)

J_1: $1450 < \lambda < 1860$ A

J_2: $984 < \lambda < 1450$

J_3: $0 < \lambda < 984$



(17)

Recalculation of Neutral + ion temperature allowing for the heating of H_2O by dust, IR - radiation.

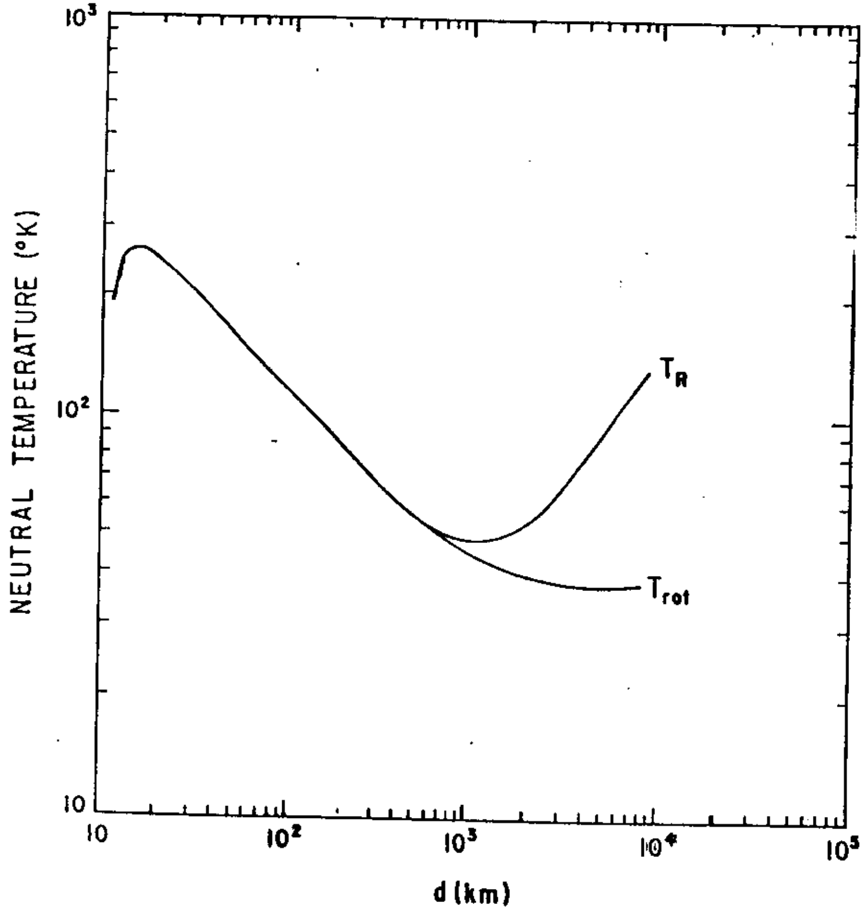
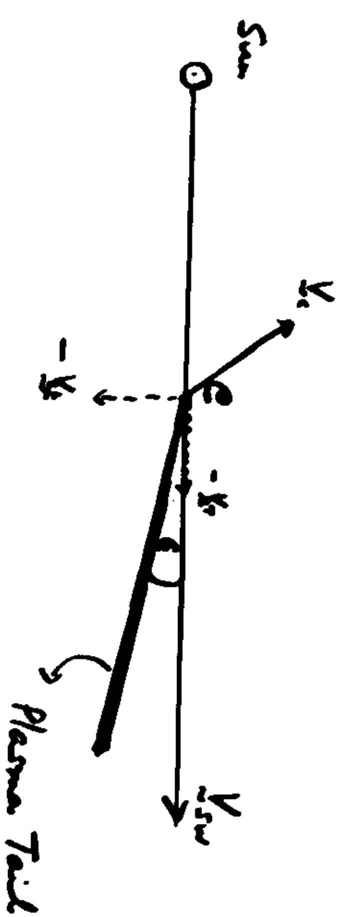


Fig. 3

(18)

1943 : Hoffmeister $\quad V_t \propto \epsilon$

1951 : Biermann

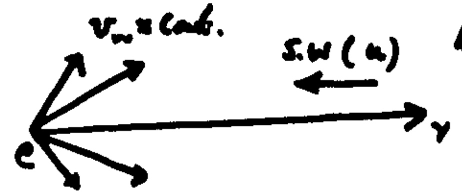


$$\epsilon \approx \tan \epsilon = \frac{V_{ct}}{V_{sw} + V_{cr}} \approx \frac{V_{ct}}{V_{sw}}$$

$$\therefore V_{sw} = \frac{V_t}{\epsilon} \sim \frac{20 \text{ km/sec.}}{0.05 \text{ rad}} \approx 400 \text{ km/sec.}$$

Solarwind mass loading : 1-D steady state model.

Biermann et al 1967



Neutrals: $\frac{1}{r^2}\frac{d}{dr}(r^2 n v_n) = -\frac{n}{\tau_i}$; $v_n \approx$ const

$$\Rightarrow n = \frac{\dot Q_n}{4\pi r^2 v_n} e^{-r/v_n\tau_i} \approx \frac{\dot Q_n}{4\pi r^2 v_n} \quad \text{— (1)}$$

$$\dot Q_n = 4\pi r_0^2 n_0 v_n$$

Ions:

$$-\frac{d}{dr}(\rho u) = m_i \frac{n}{\tau_i} \quad \text{— (2)}$$

$$-\frac{d}{dr}\left(\rho u^2 + p + \frac{B^2}{8\pi}\right) = \dot S_m \quad \text{— (3)}$$

$$-\frac{d}{dr}\left[u\left(\frac{1}{2}\rho u^2 + \frac{\gamma}{\gamma-1}p + \frac{B^2}{4\pi}\right)\right] = \dot S_E \quad \text{— (4)}$$

Neg. $\dot S_m$, $\dot S_E$, $B^2/8\pi$; $x = \rho u$, $x_\infty = \rho_\infty u_\infty$

(1) + (2) $\Rightarrow$ $\hat x = \frac{\rho u}{\rho_\infty u_\infty} = 1 + \frac{\dot Q_n m_i}{4\pi v_n \tau_i \rho_\infty u_\infty}\cdot\frac{1}{r}$ — (5)

Int. (3) and (4), taking $p_\infty = 0$ $\Rightarrow$

$$p + ux = u_\infty x_\infty \quad \text{— (6)}$$

$$x u^2 + \frac{2\gamma}{\gamma-1} p u = x_\infty u_\infty^2$$

El. p bet. (6) and (7)

$$\hat x \hat u^2 - \frac{2\gamma}{\gamma+1}\hat u + \frac{\gamma-1}{\gamma+1} = 0 \; ; \quad \hat u = \frac{u}{u_\infty}$$

$$\therefore \hat u = \frac{1}{\hat x}\frac{\gamma}{\gamma+1}\left[1 \pm \sqrt{1-\frac{\gamma^2-1}{\gamma^2}\hat x}\right] \quad \text{— (8)}$$

+ = supersonic branch

− = sub-sonic branch.

$\hat x \le \frac{\gamma^2}{\gamma^2-1}$ eg $\gamma = 2$, $\frac{\rho u}{\rho_\infty u_\infty} \le \frac{4}{3}$

$c^2 = \gamma\frac{p}{\rho}$, $M^2 = \frac{u^2}{c^2}$

$$\therefore M^2 = \frac{1+\sqrt{1-\frac{\gamma^2-1}{\gamma^2}\hat x}}{1-\gamma\sqrt{1-\frac{\gamma^2-1}{\gamma^2}\hat x}}$$

(or) $$\hat x = \frac{\gamma^2}{\gamma-1}\cdot\frac{M^2\left[M^2(\gamma-1)+2\right]}{(\gamma M^2+1)^2} \quad \text{— (9)}$$

when $M = 1$ $\hat x = \frac{\gamma^2}{\gamma^2-1}$ $\left(= \frac{4}{3}, \gamma = 2\right)$

when $M = 2$ $\hat x = \frac{32}{27}$ $(\gamma = 2)$

* cf. Galeev, 1985.

MHD: models Schmidt + Wegmann, Fedder, Ogino et al.

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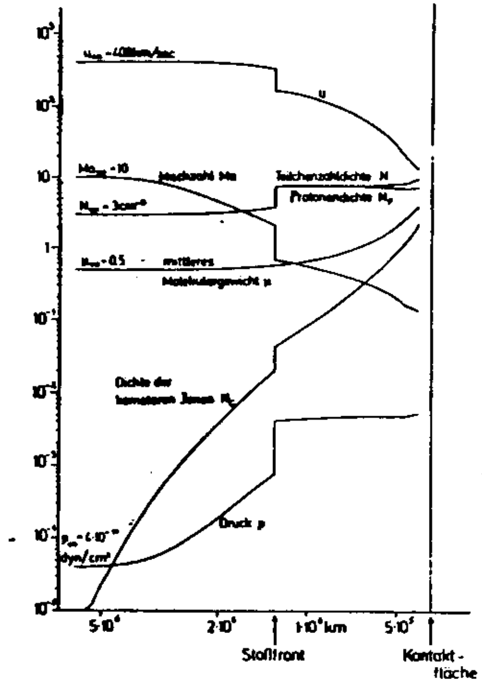

FIGURE B36 The 2-D hydrodynamic model of the cometary atmosphere-solar wind interaction. Solution along the comet-sun line. (From Brosowski and Wegmann, 1972)

2-D Hydrodynamic model.

$\dot{Q}_m \approx 10^{30}\ s^{-1}$.

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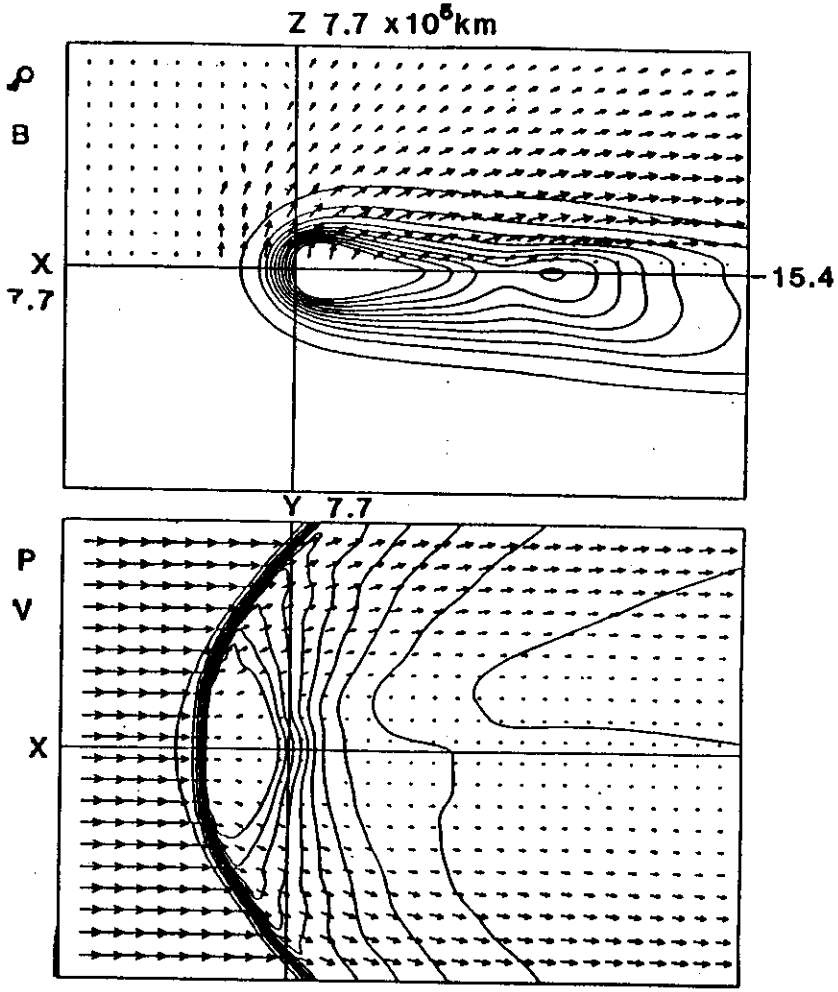
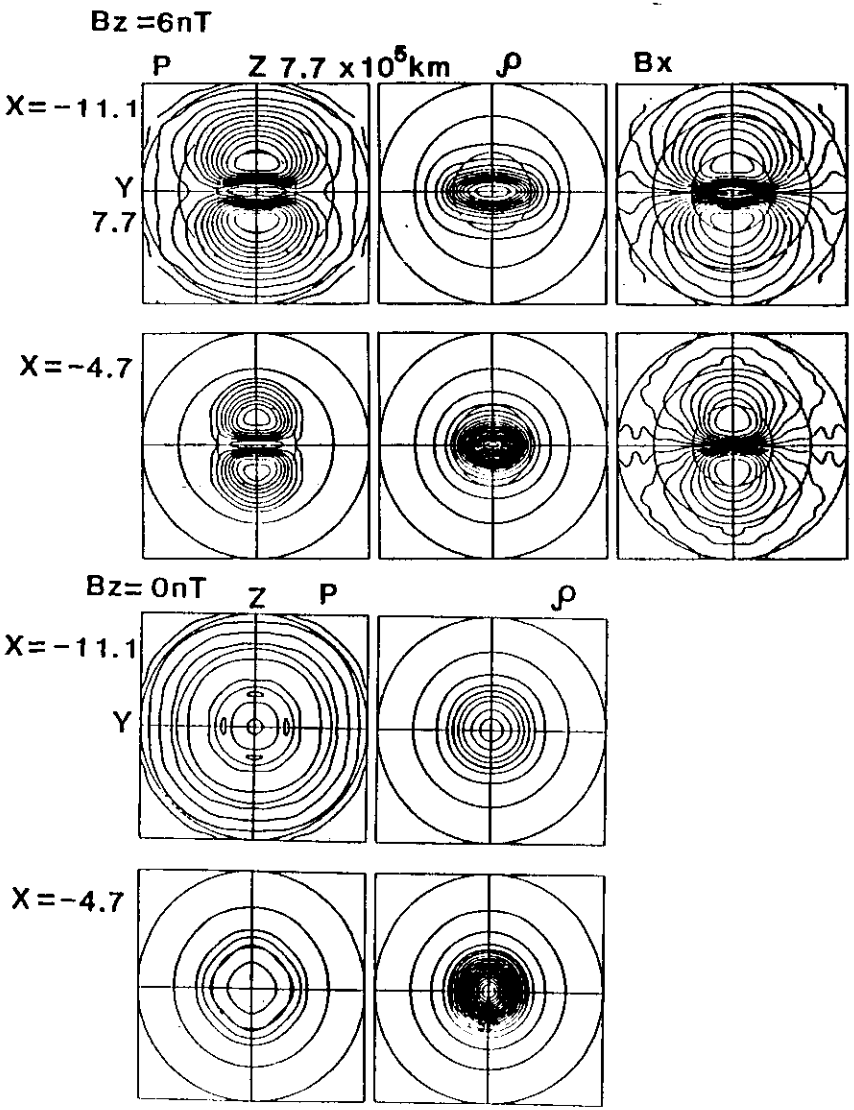


Ogino et al, 1987.

Fig. 3

3-Dim MHD

(23)

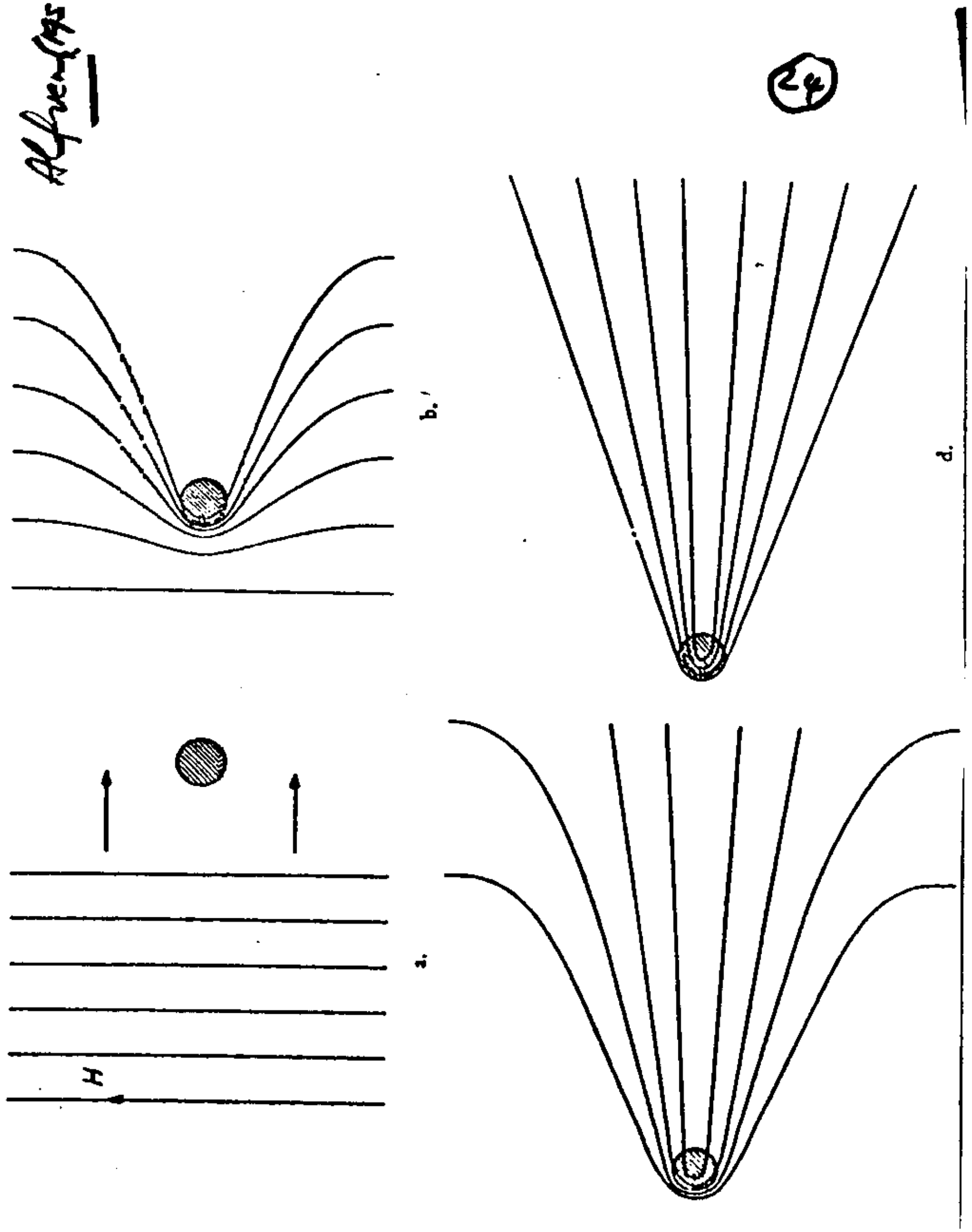


Tail Structure

Ogino et al, 1997

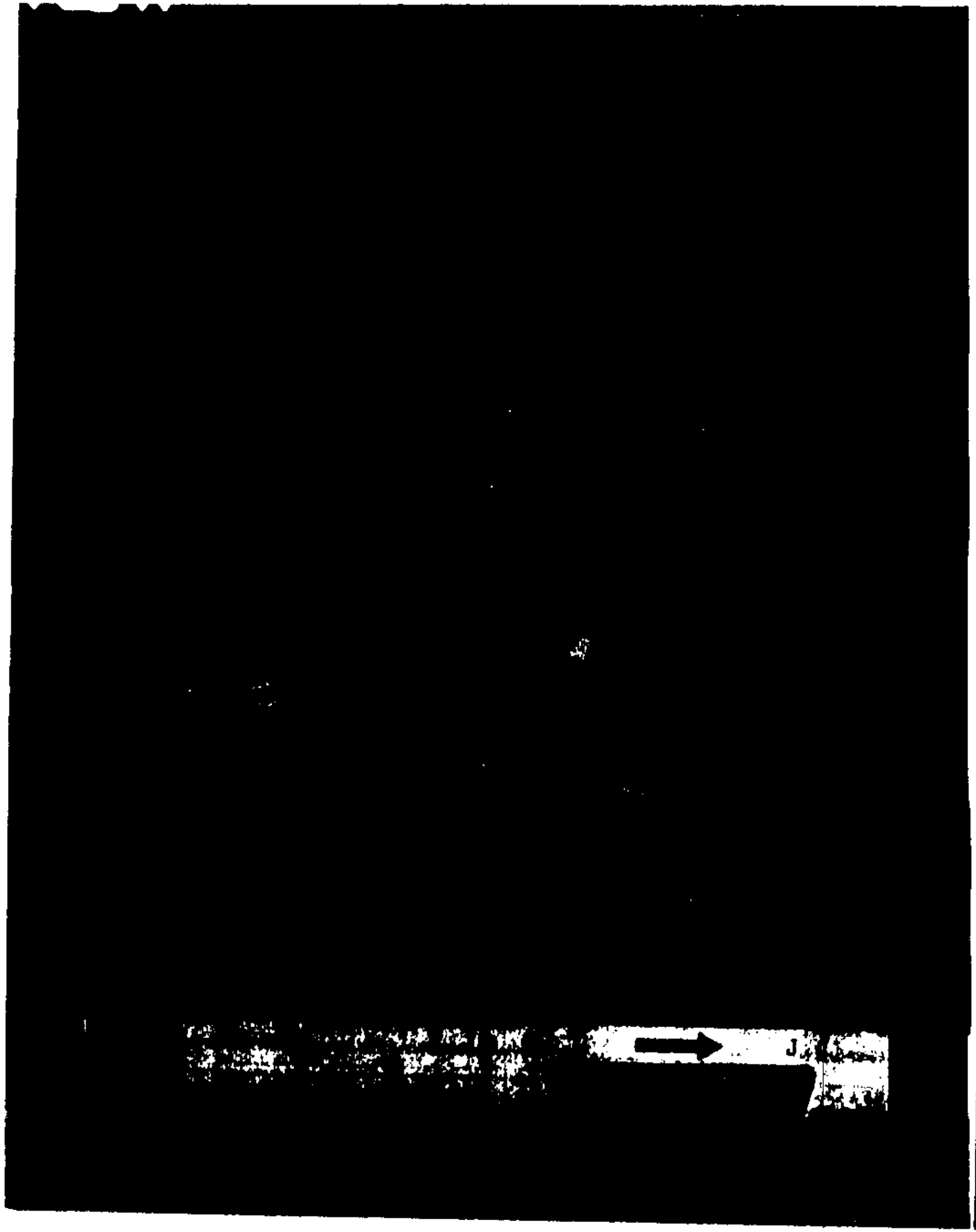
Fig. 7

(24)



(25)

Induced cometary magnetosphere.



(26)

Nose : Dynamo region. ($\underline{E} \cdot \underline{j} < 0$)

$$\underline{u}_\perp = \frac{c}{eB^2} \underline{f}_i \times \underline{B}$$

$$\underline{f}_i = - m_i \frac{d\underline{u}}{dt}$$

$$I_i \approx h\, m_i\, c \int_{r_i}^{r_s} \frac{n_i}{B}\, u\, \frac{d\underline{u}}{dr} \cdot d\underline{r}$$

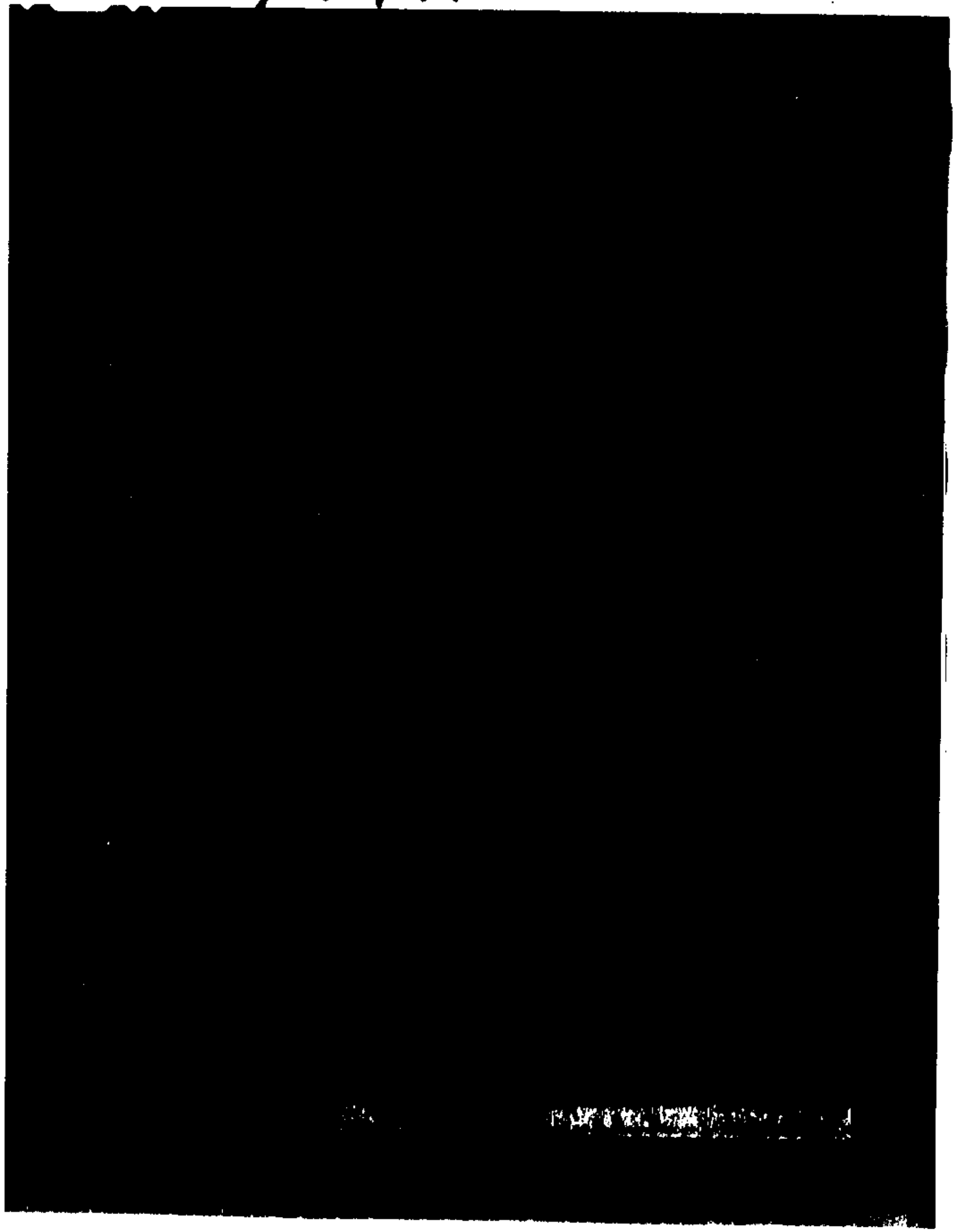
$$h \approx r_i \quad \Rightarrow I_i \approx 5 \times 10^8 \, A$$

$$I_t \approx \frac{B_t \cdot c\, l}{2\pi}$$

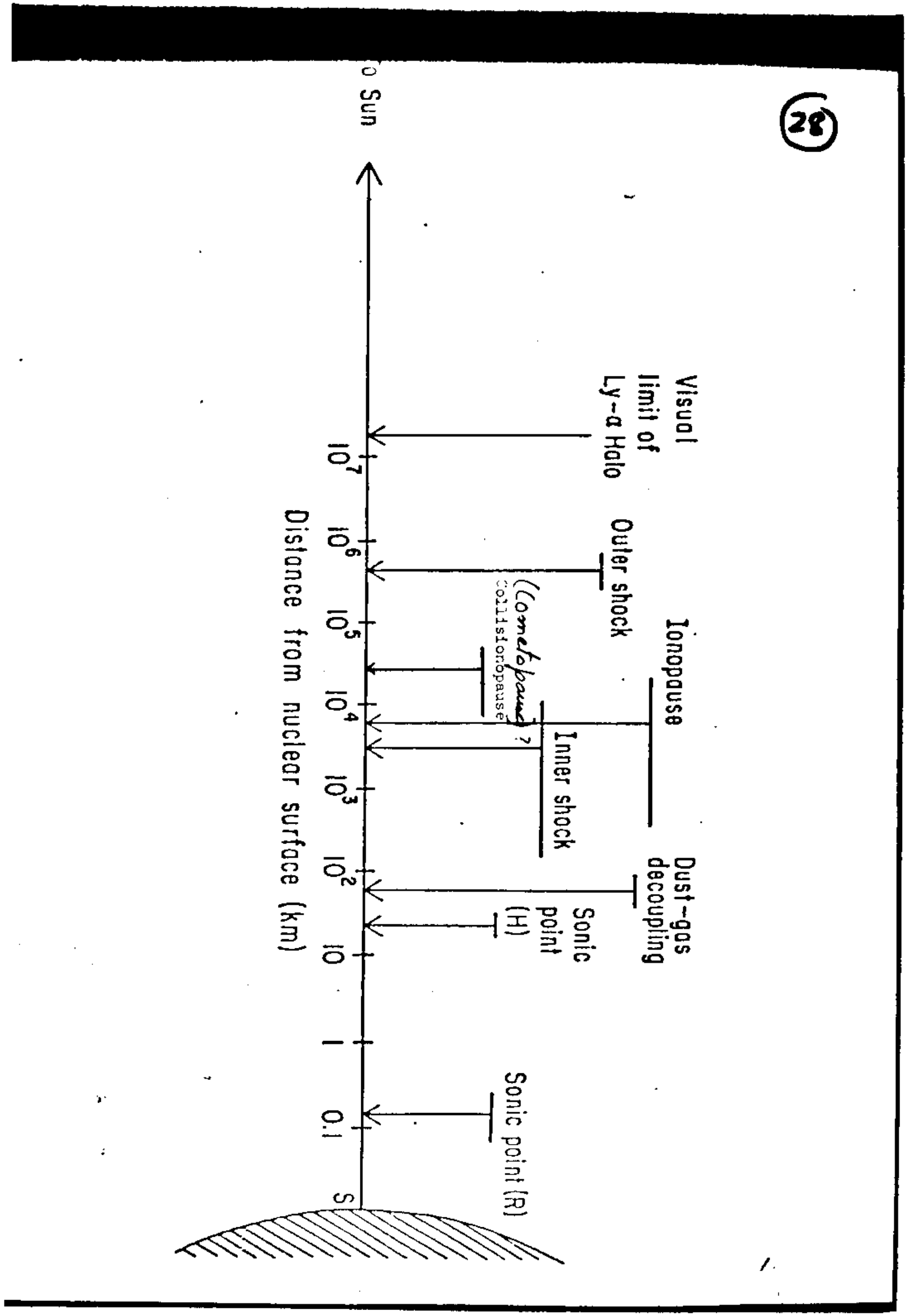
$$l \approx 10^7 \, km \, ; \; B_t \approx 10\gamma$$

$$\Rightarrow I_t \approx 4 \times 10^8 \, A$$

Overview of the S-W int. with the cometary atmosphere. (27)



(28)



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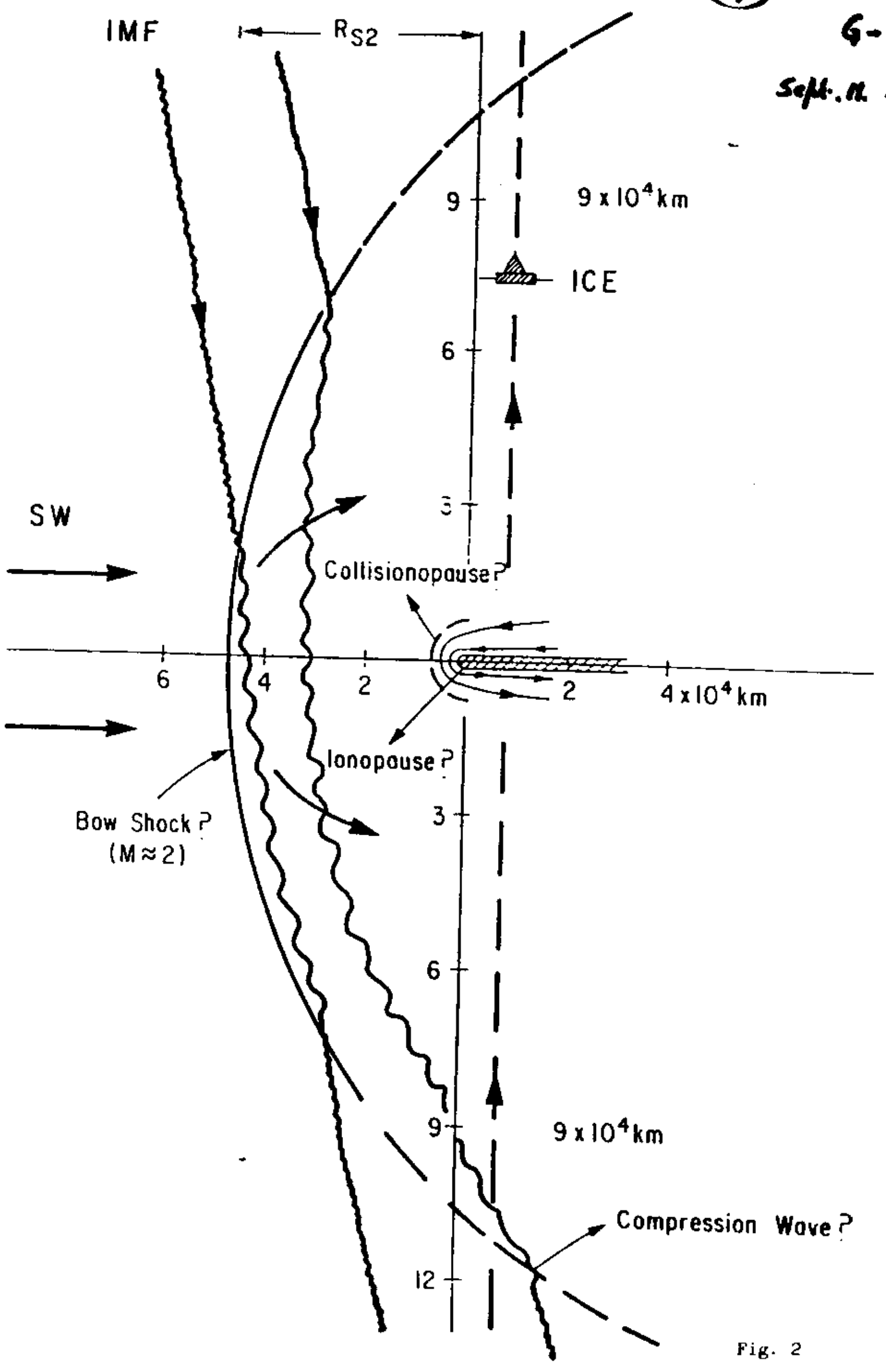

Fig. 2

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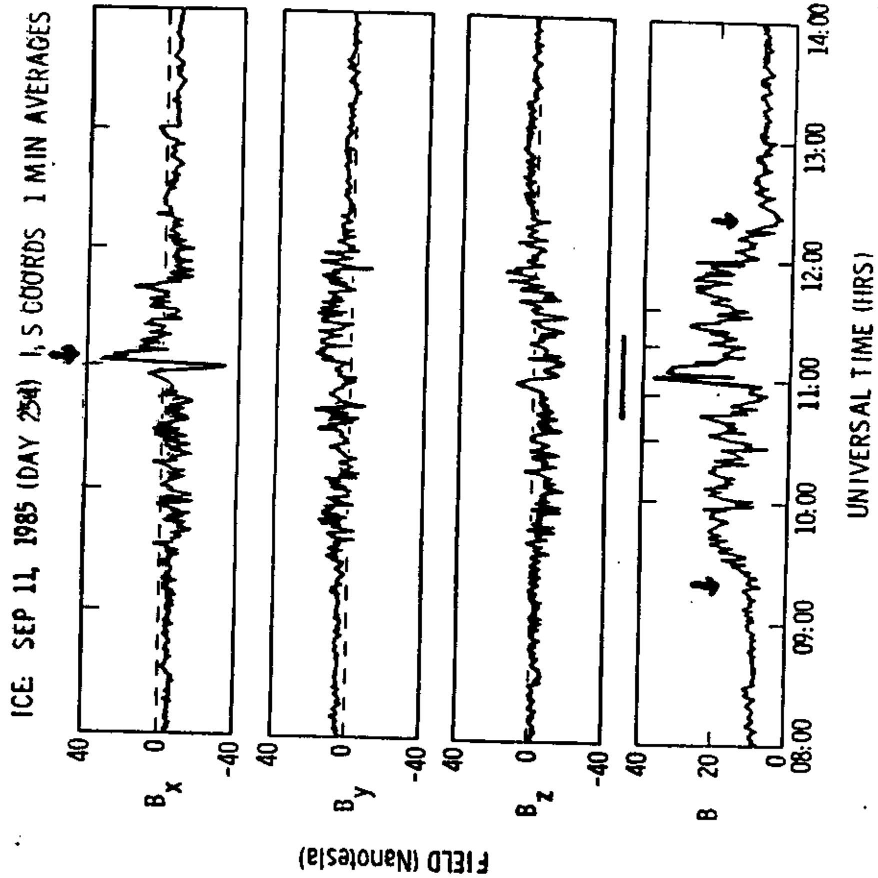


(31)

Smith et al., 1985

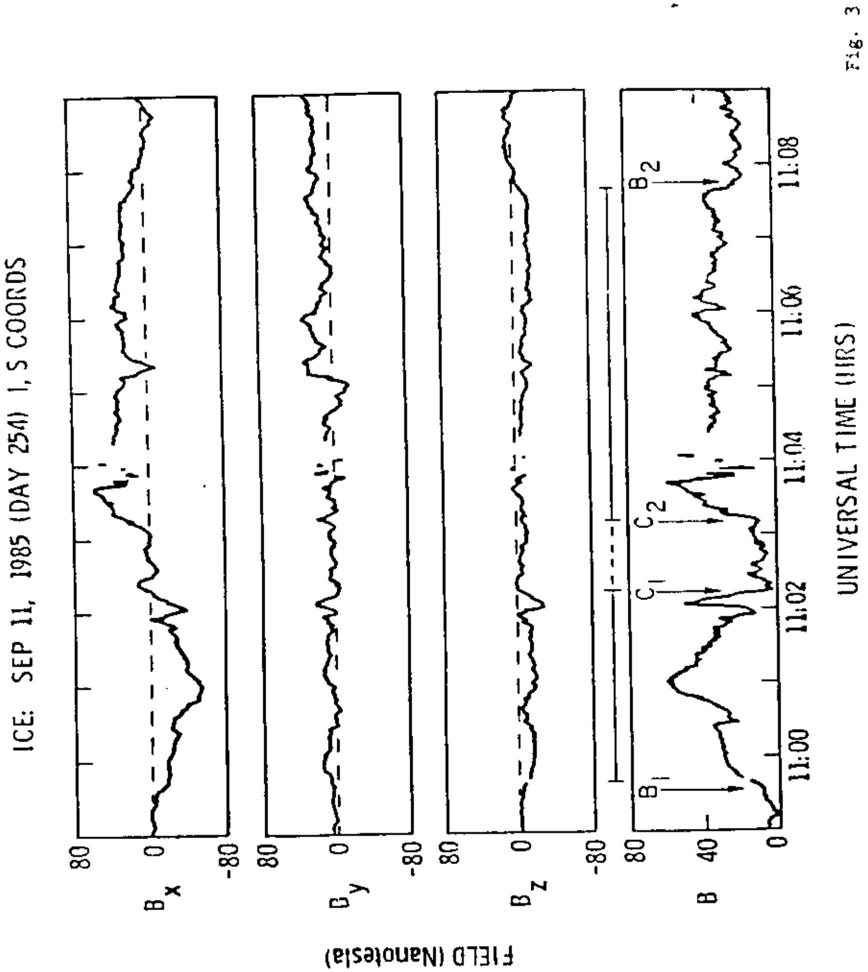


Fig. 3

(32)

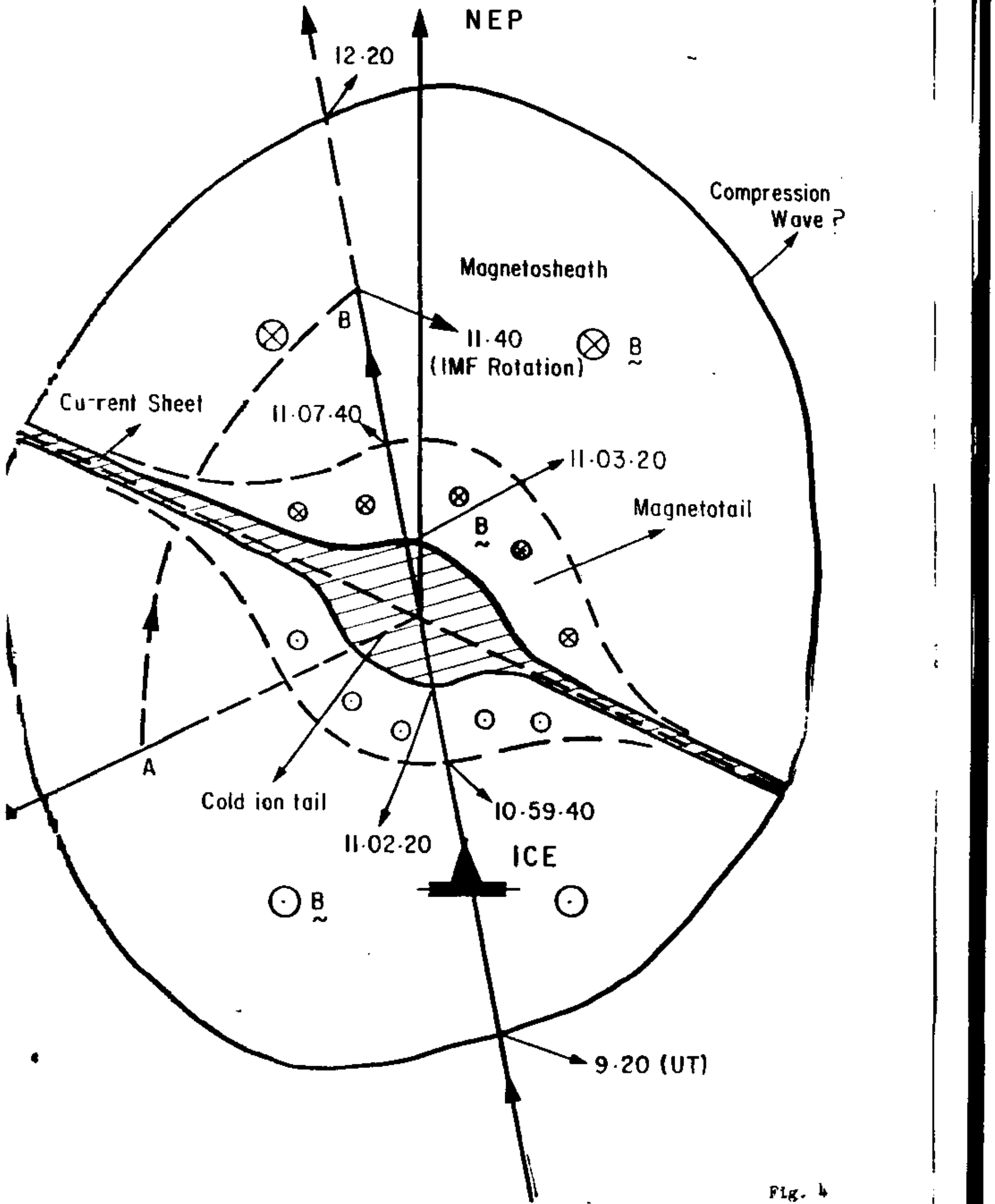


Fig. 4

(33)

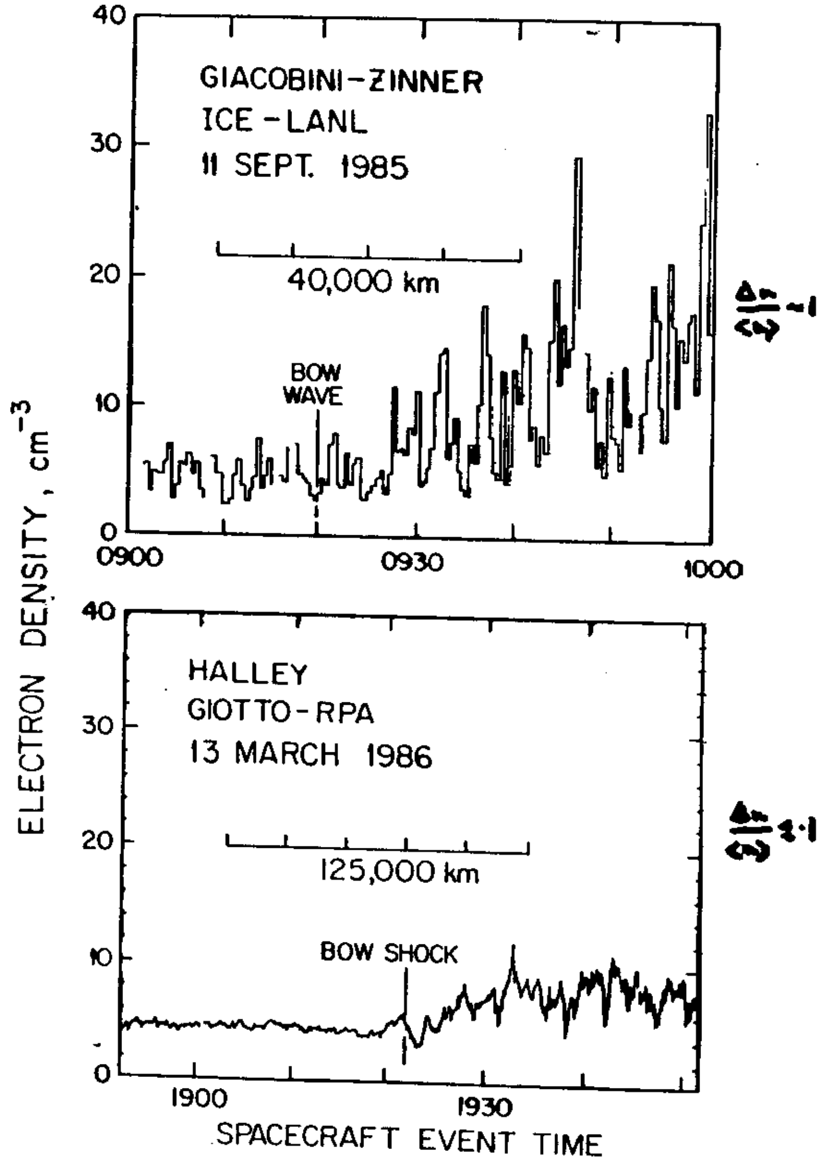
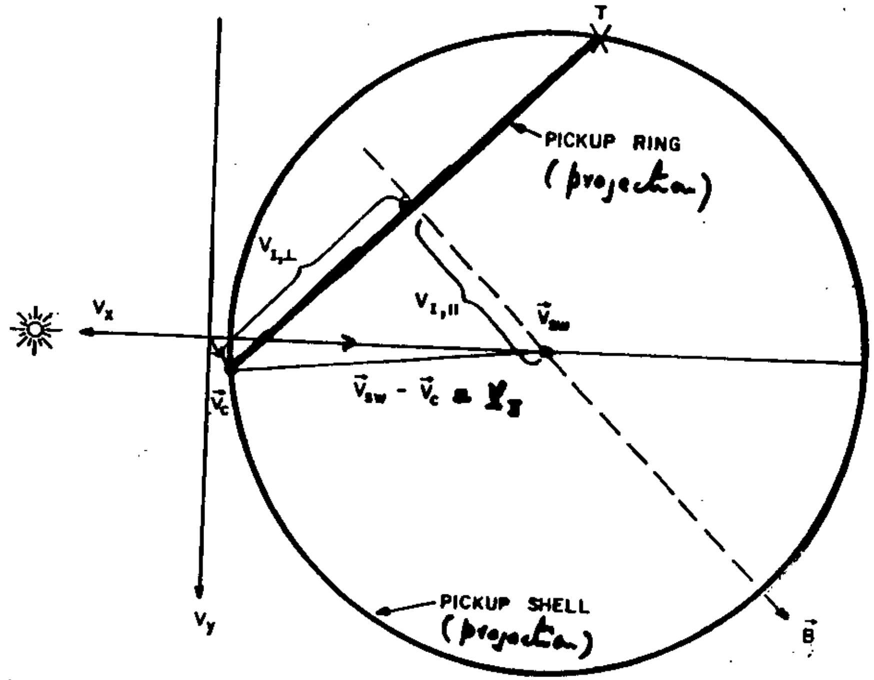


Fig. 1

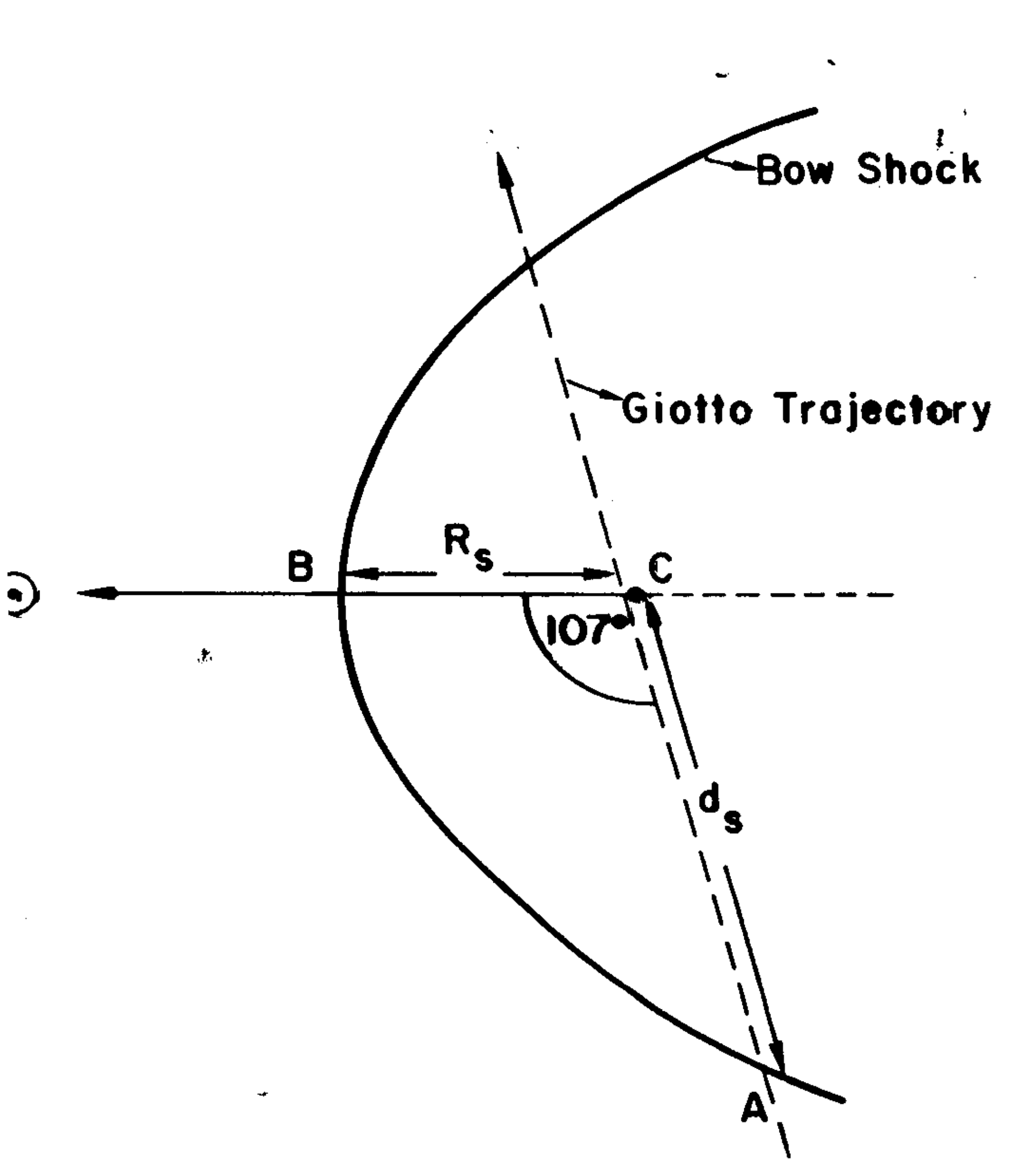
(34)

Sagdeev, Shapiro + Shevchenko, (1986)



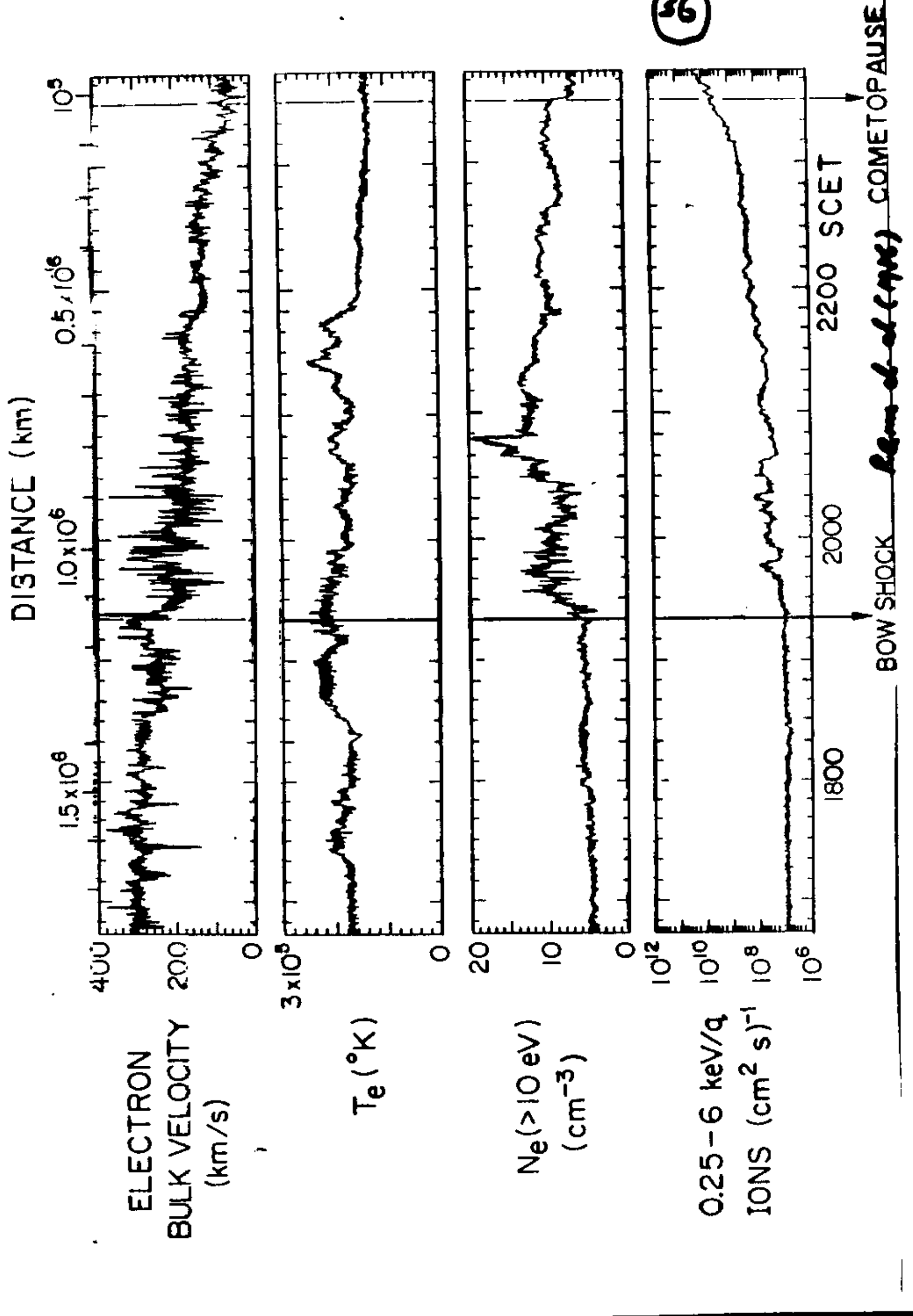
Velocity space distribution of pick-up ions in solar wind frame of reference. (proj.)

(35)

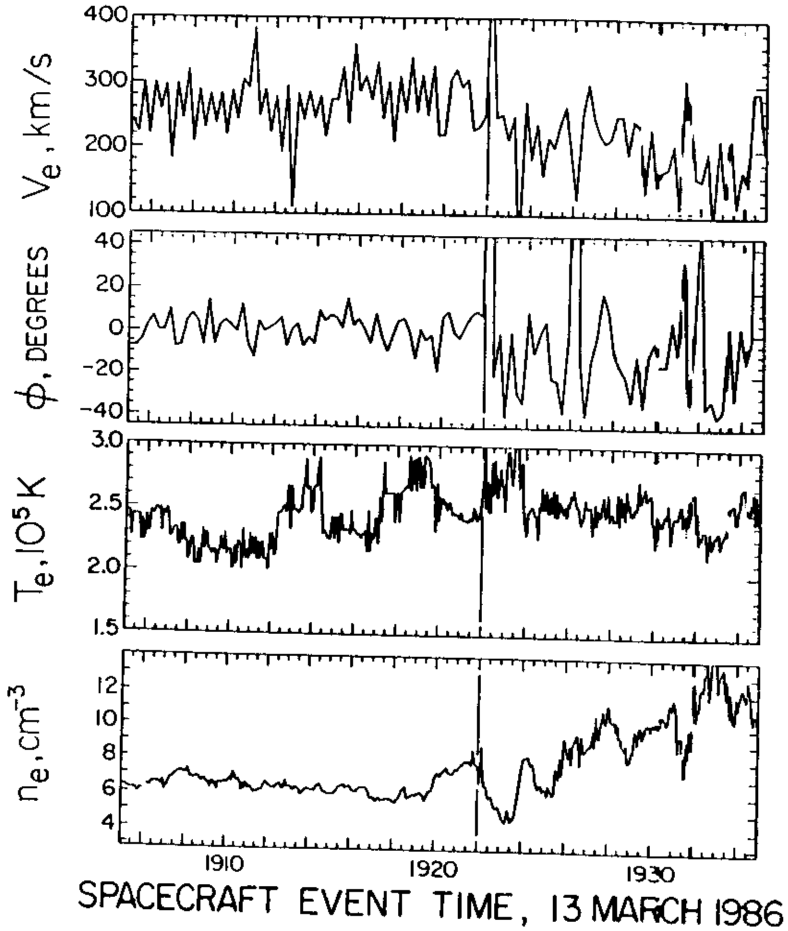


Bow Shock
Giotto Trajectory
B
R_s
C
107°
d_s
A

(36)



DISTANCE (km)
ELECTRON BULK VELOCITY (km/s)
T_e (°K)
N_e (>10 eV) (cm^-3)
0.25 – 6 keV/q IONS (cm^2 s)^-1
BOW SHOCK
COMETOPAUSE
SCET



Reme et al (198x)

Halley

Flare-ratio (α) ≈ 2

$\theta \approx 107°$

$r \approx 1.15 \times 10^6$ km

$\Rightarrow R_s \approx 4.0 \times 10^5$ km

Just outside shock — ($r = 1.15 \times 10^6$ km)

$n_e k T_e \approx 200$ eV cm^{-3}

$n_p k T_p \approx 50$ eV cm^{-3}

$n_i k T_i \approx 250$ eV cm^{-3}

} Coates et al, 1987

$U_{sw} \approx 300$ kms^{-1} ($\Rightarrow U_\infty \approx 325$ kms^{-1})

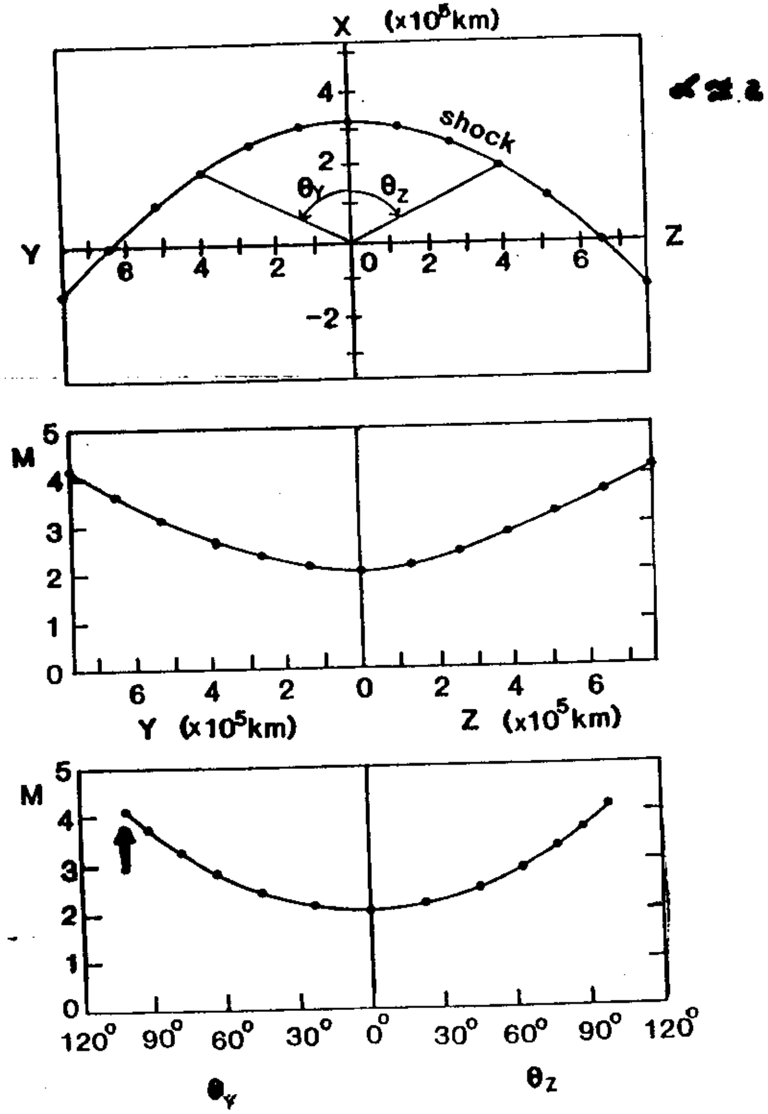
$\therefore M_0 \approx 4.3 \sim 2.6$ (without pickup ions)

$M_0 \approx 4.3 \rightarrow M_s \approx 1.9 \rightarrow \dot{Q}_m \approx 3 \times 10^{29} s^{-1}$

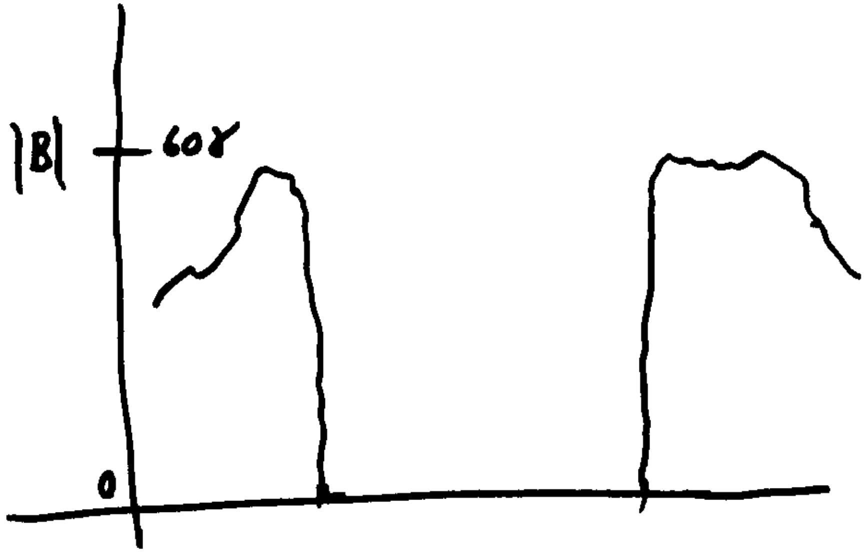
$M_0 \approx 2.6 \rightarrow M_s \approx 1.4 \rightarrow \dot{Q}_m \approx 5 \times 10^{29} s^{-1}$

(using adiabatic model)

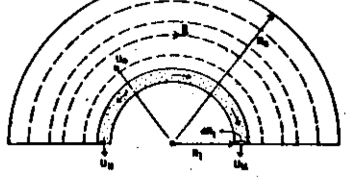
$\dot{Q}_m$ (obs) $\sim 6.9 \times 10^{29} s^{-1} \pm 50\%$.



Agarwal et al., 1987



Obs. of variation of B-field near closest approach; Halley's comet (Giotto) — Neubauer et al (1986



Ionopause (TD)

$$\underset{\sim}{F}_D = \text{neutral drag on ions} \approx k_D n_i n_n m_i (u_n - u_i)\,\hat{r} \quad (1)$$

$$\underset{\sim}{F}_E = \frac{\underset{\sim}{j} \times \underset{\sim}{B}}{c} = -\frac{1}{4\pi} B \frac{dB}{dr}\,\hat{r} - \underbrace{\frac{1}{4\pi}\frac{B_i^2}{R_i}\,\hat{r}}_{\text{dominant term}} \quad (2)$$

Ip + Axford (1982)

$$n_n = n_{no}\frac{R_n^2}{r^2} \quad (3)$$

$$\pi h R_i dR_i \frac{n_n}{\tau_i} = \pi h R_i dR_i k_R n_i^2 + 2h\, dR_i n_i u_{\parallel} \quad (4)$$

Subst. for n_n and n_i from (3) and (4) in (1) and taking $\underset{\sim}{F}_D + \underset{\sim}{F}_E = 0$

$$\Rightarrow R_i^2 = \frac{4\pi k_D u_n n_{no} R_n^2}{B_i^2}\left(-\frac{u_{no}}{\pi k_R} + \sqrt{\frac{u_{\parallel}^2}{\pi^2 k_R^2} + \frac{n_{no} R_n^2}{k_R \tau_i}}\right) \quad (5)$$

Flammer et al (1986)

Taking $\dot{Q}_n (= 4\pi R_n^2 n_{no} u_{no}) \approx$ [illegible] $\times 10^{29}\,s^{-1}$; $k_R = 5 \times 10^{-7}\,cm^3 s^{-1}$

$B_i \approx 50\gamma$; $u_{\parallel} \approx 1\,km\,s^{-1}$, $k_D (= \sigma_D v_{rel}) \approx$ [illegible] $\approx 10^{9}\,cm^{-3}$ [illegible]

we obtain $R_i \approx 4500\,km$

Halley

Ip + Axford (1986)
Cravens (1986)
Mendis et al (1986)

G-Z

Mendis et al (1986a)

Stability (Ershkovich, Flammer, Mendis, 1986)

Stability of the cometary Ionopause

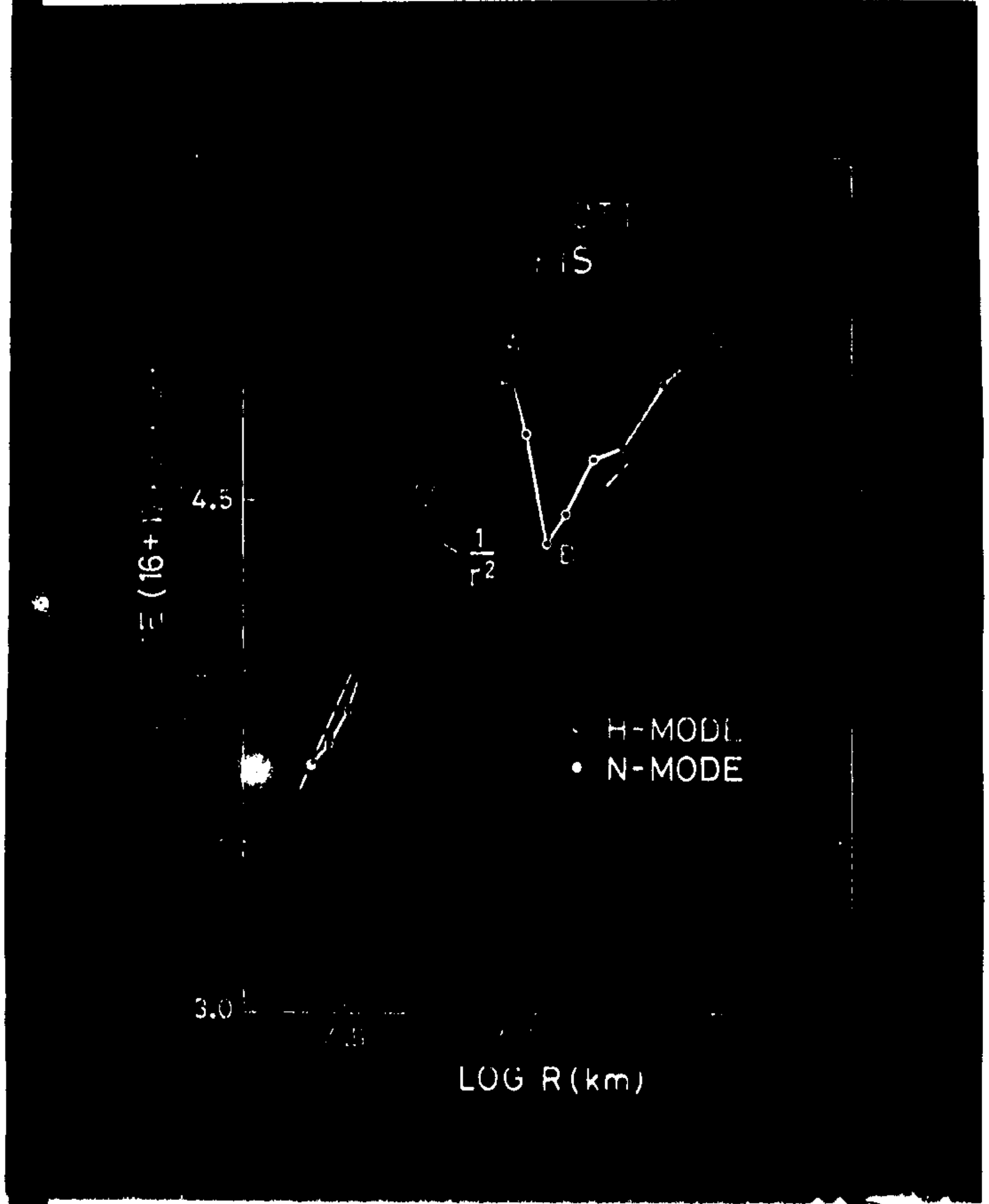
- "Flute" :- Ip & Mendis (1976)
- K-H. :- Ershkovich + Mendis (1983)
  Galeev + Lipatov (198?)
  (effect of particles, wave damping)
- "Drag" :- Ershkovich & Mendis (1986)
- Effects of drag, sources, compressibility, finite thickness etc. - Also of the partial penetration of the IMF into the ionosphere (restabilization)
  Ershkovich, Flammer & Mendis (1986)
- Non-linear effects: Ershkovich + Flammer (198?)
  ([illegible] large amplitude waves)

Criterion for instability:

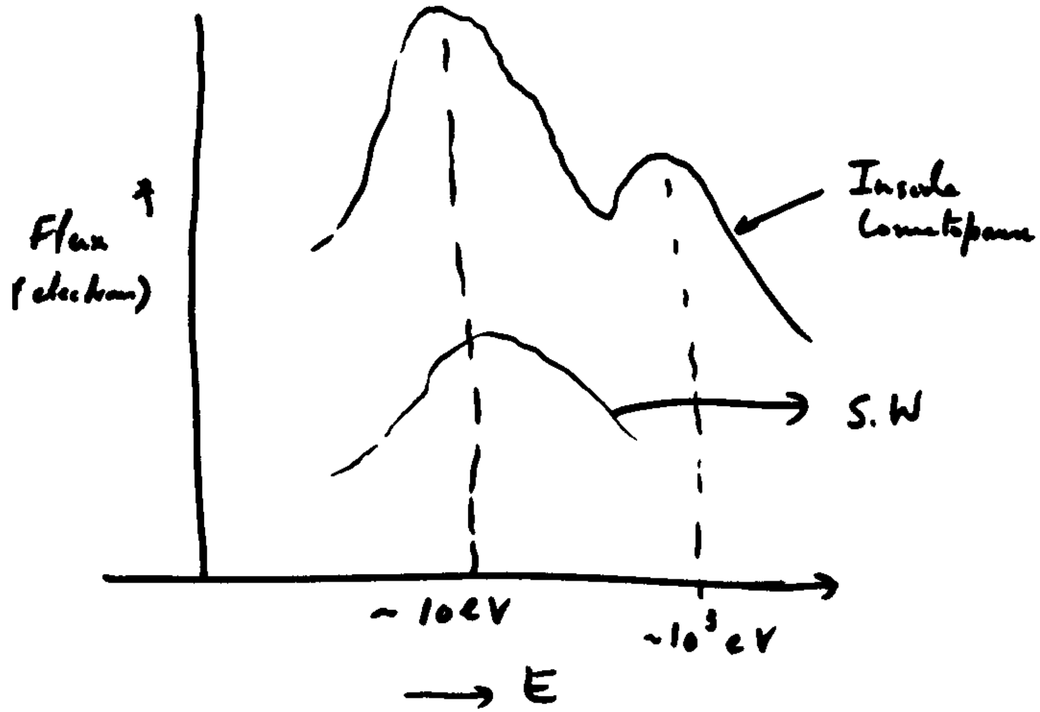
$$\tau_{growth} < \tau_{convection} \left(\approx \frac{\pi R}{2V_g};\ V_g = Re\left(\frac{d\omega}{dk}\right)\right)$$

G-Z Vs. Halley.

Halley : Ion " Pile up" region $r \simeq 12 \times 10^{8}$ km

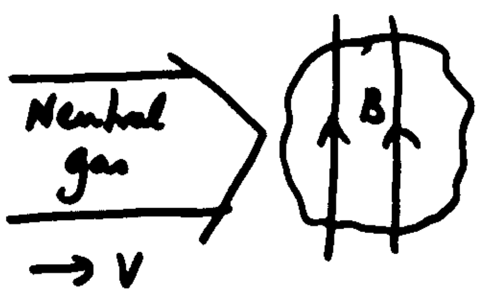


Observation of enhanced fluxes of suprathermal electrons (keV).



Gringauz et al. (1986)

Critical Vel. ionization Mech.



$\lambda_{in} >> L$

Rapid ionization + breaking when $\frac{1}{2} m_n V^2 \geq e\phi_i$.

$$V_c = \sqrt{\frac{2e\phi_i}{m_n}}.$$

1. Possible if ion K.E is first transferred in electron K.E.

- How are electrons energized. ?

A. Cross-streaming of newly produced ions + primary plasma ions → Lower hybrid wave → electron heating.
(Sherman, 1969, Raadu, 1975, ...)

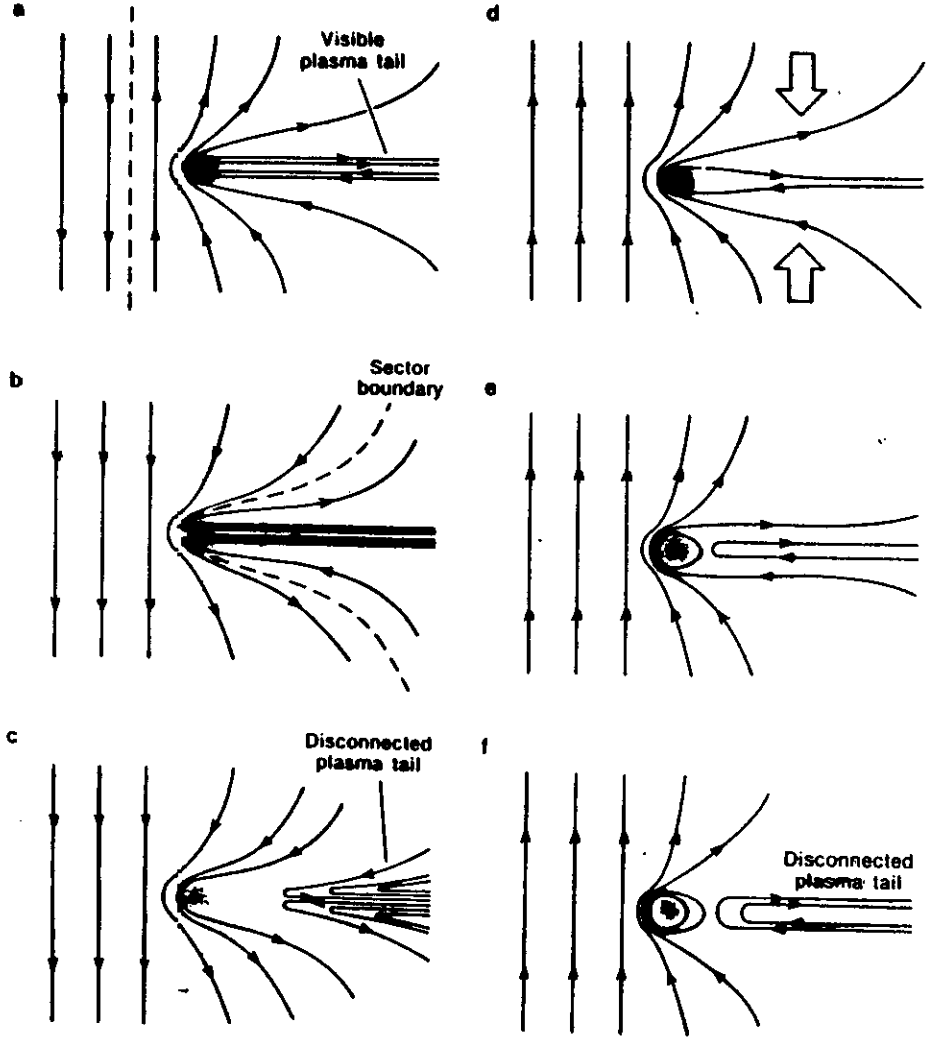
Formisano_Septem Townsend Criterion:

$$\tau_{ion} + \tau_{rc} < T_L \approx L/v_e$$

Formisano, Galeev + Sagdeev (1982)....
FG ⇒ [illegible]

Tail disconnection – theories.

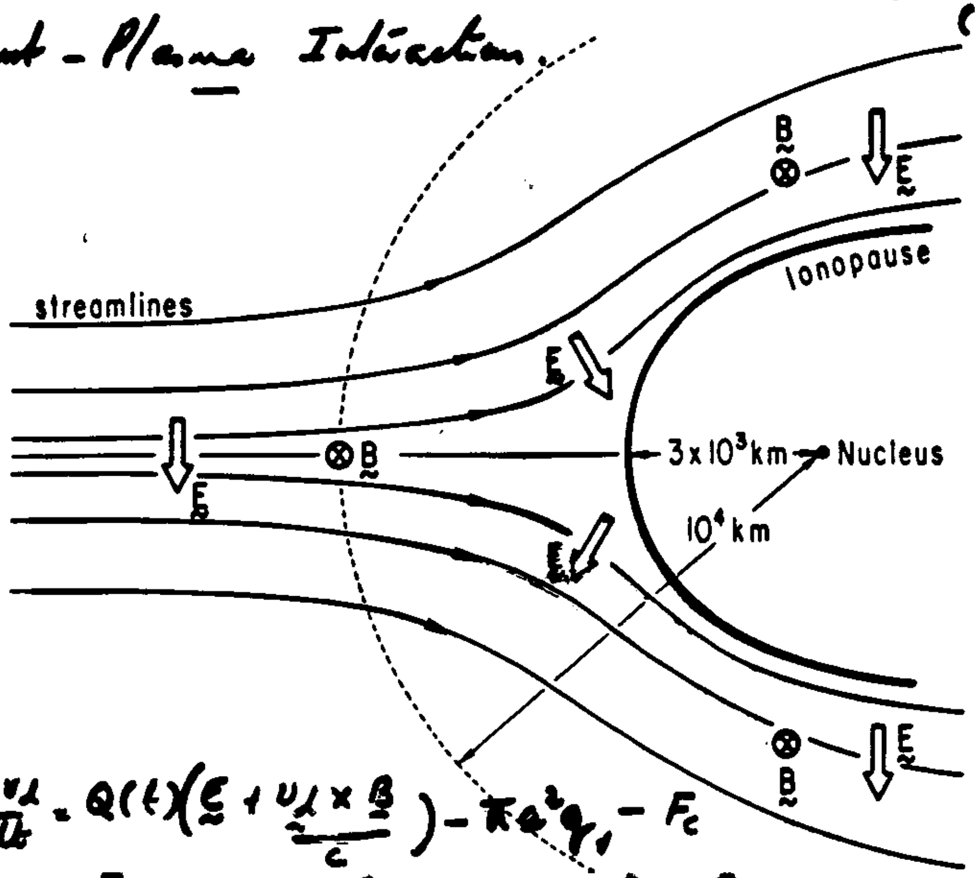
Also : Flute instability at nose of ionopause



Niedner + Brandt (1979)

(1985, 1986 ....).

Dust - Plasma Interaction.

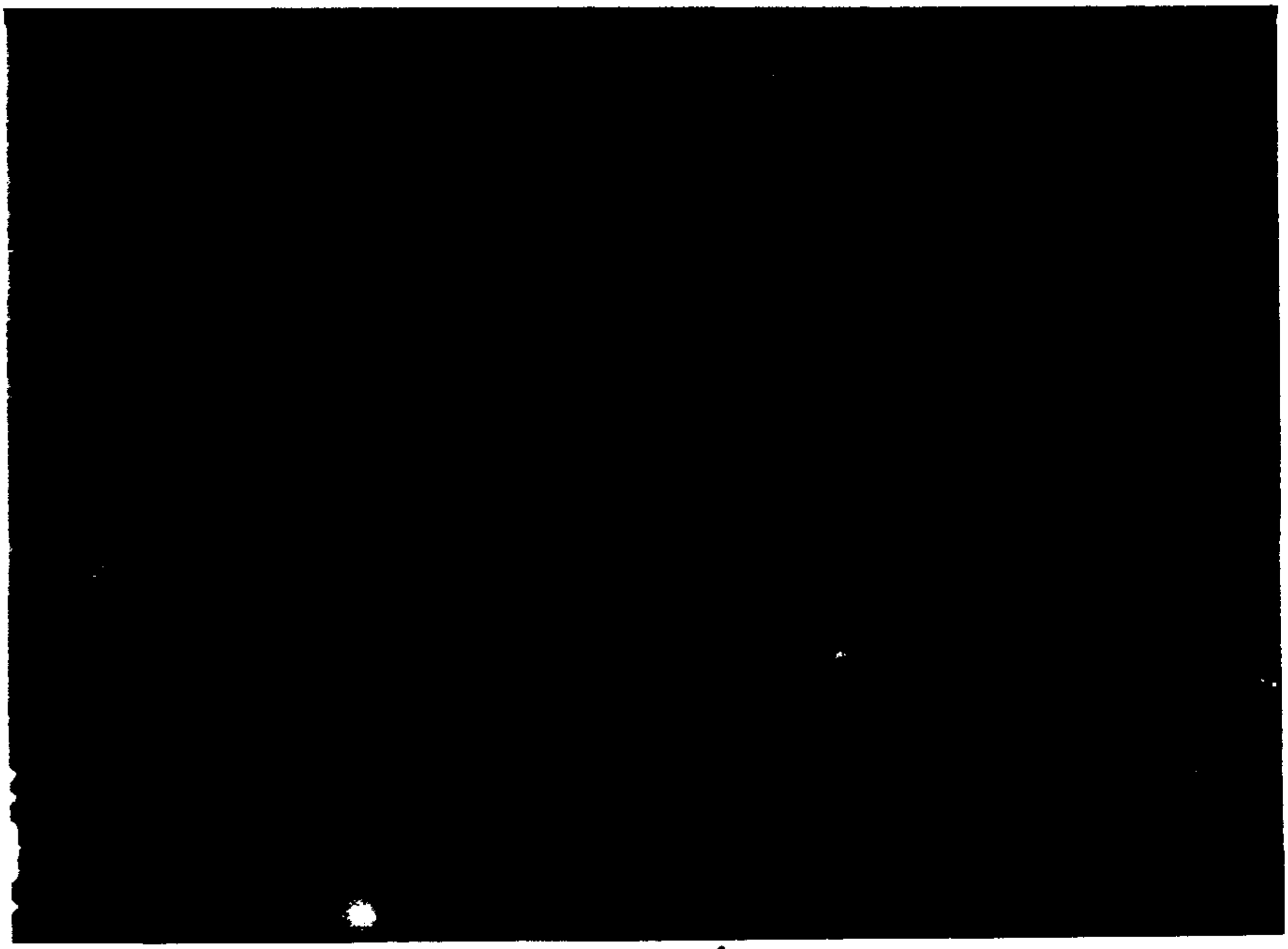


$$m_d \frac{dv_d}{dt} = Q(t)\left(E + \frac{v_d \times B}{c}\right) - \pi a^2 q_r - F_c$$

$$E = -\frac{v \times B}{c}, \quad q_r = \frac{Q_{pr} S_\odot}{c\, d^2}, \quad F_c = f(v_d - v).$$

$$\frac{dQ}{dt} = 4\pi a^2 \frac{d\sigma}{dt} = \sum I = I_{pe} - I_e + I_i + I_s$$

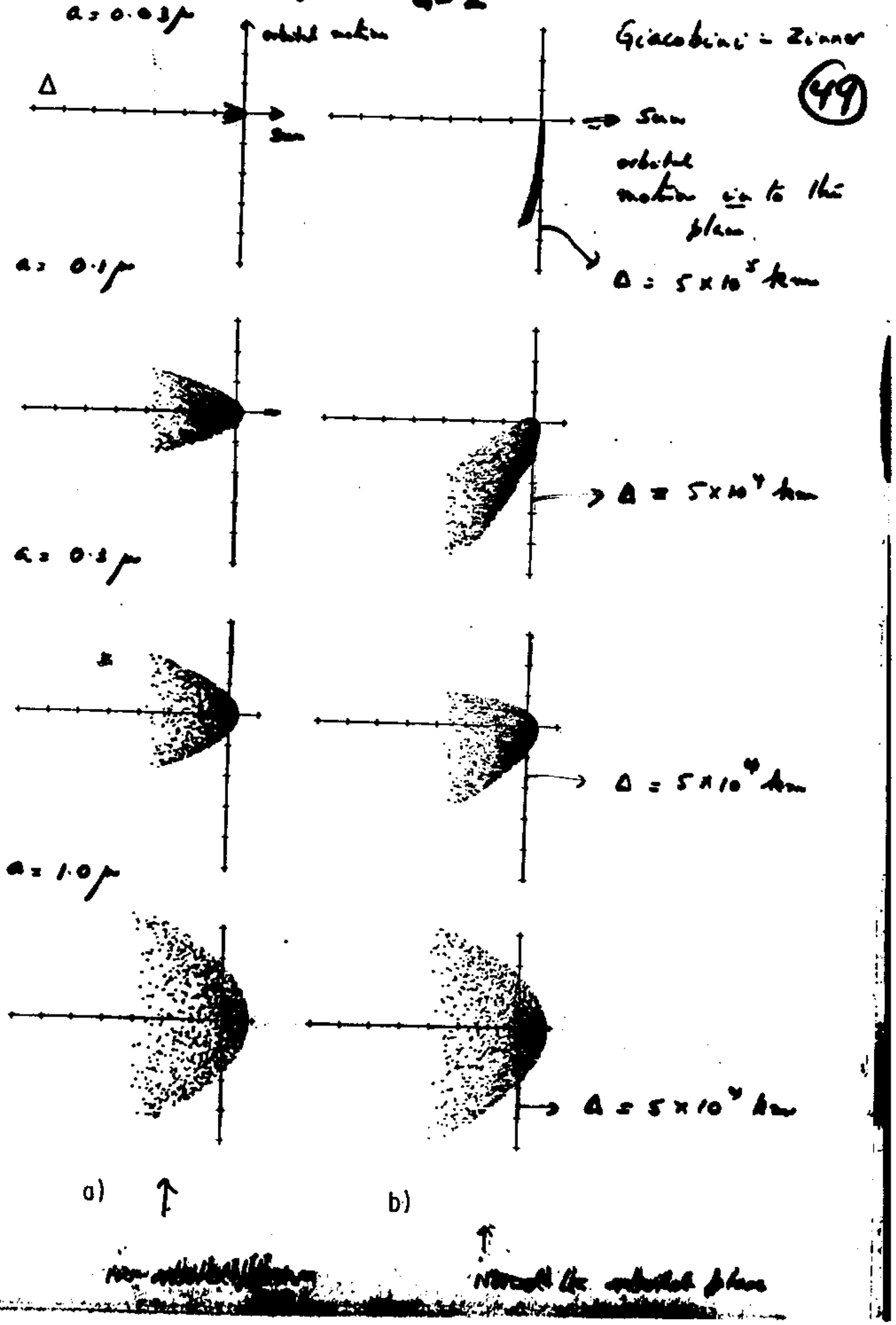
(47)

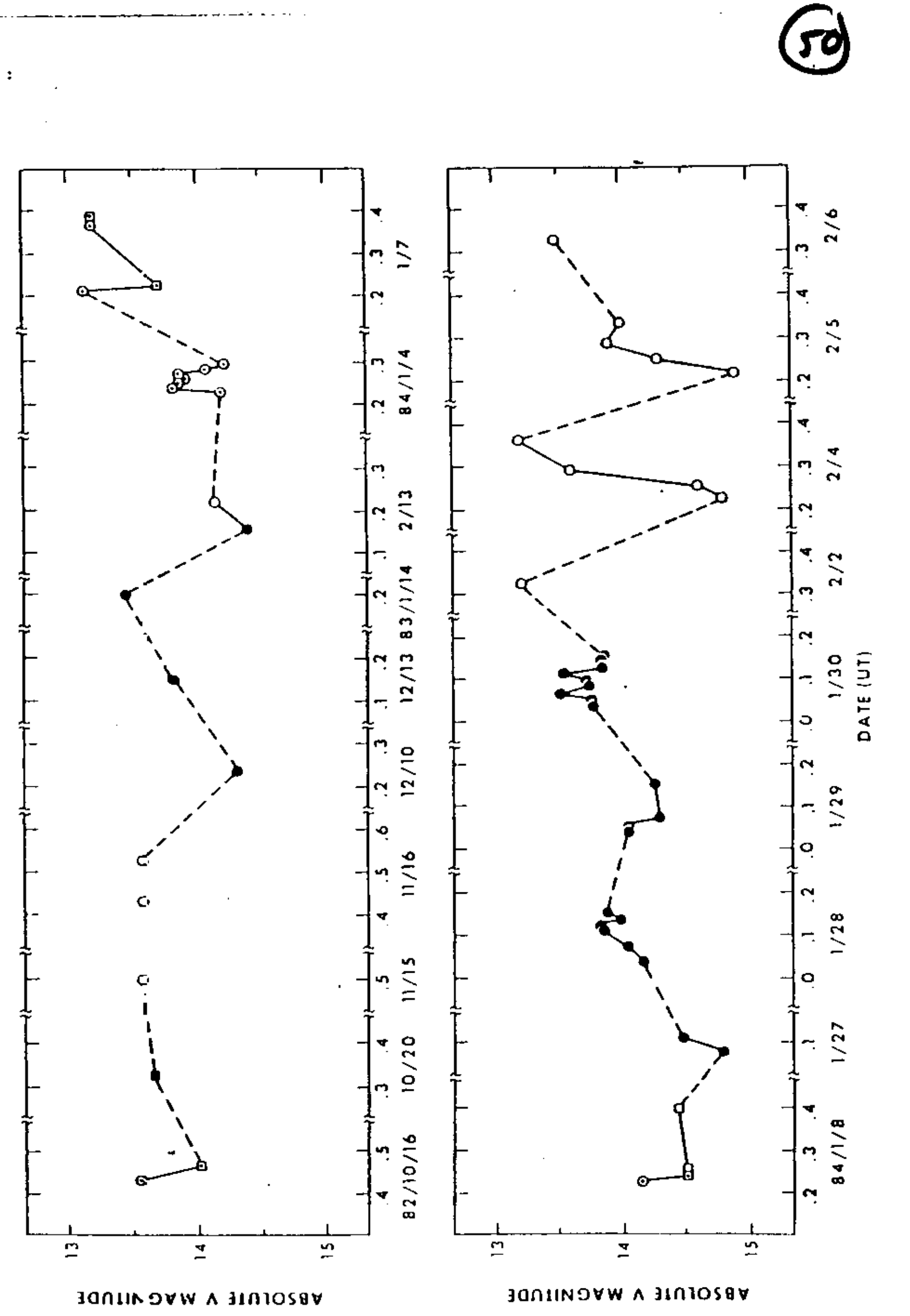


(48)

Schematic of charged dust grain orbit.

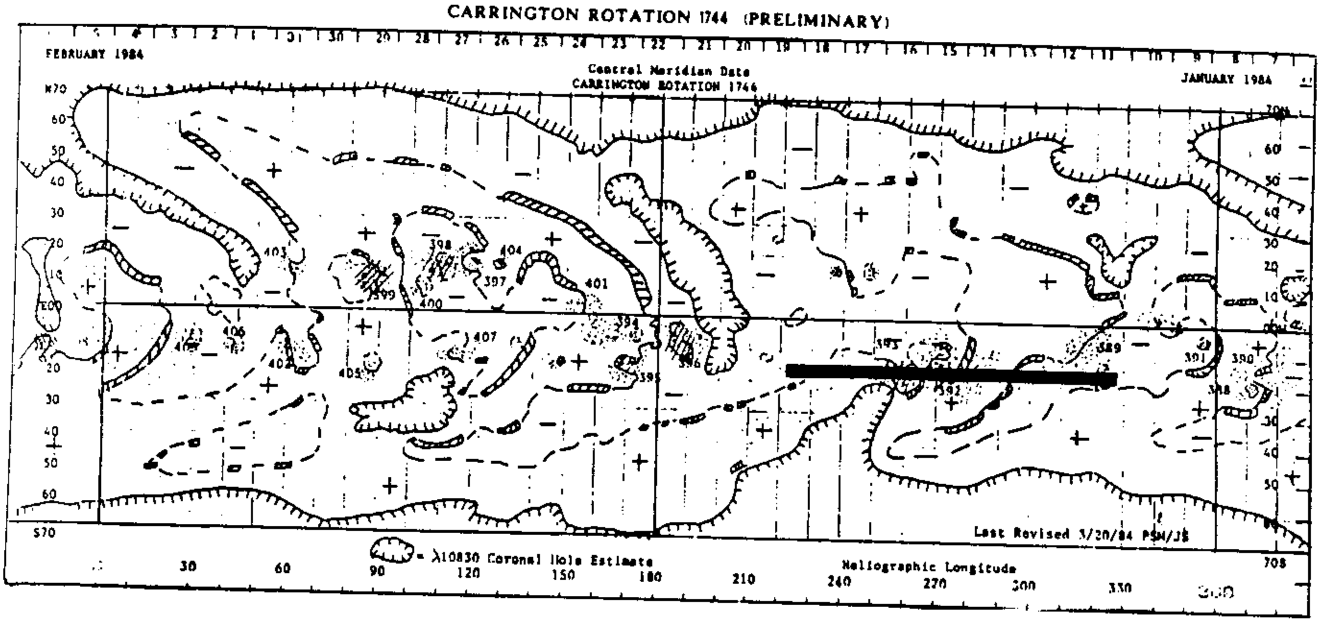
charged dust distribution at comet G-Z



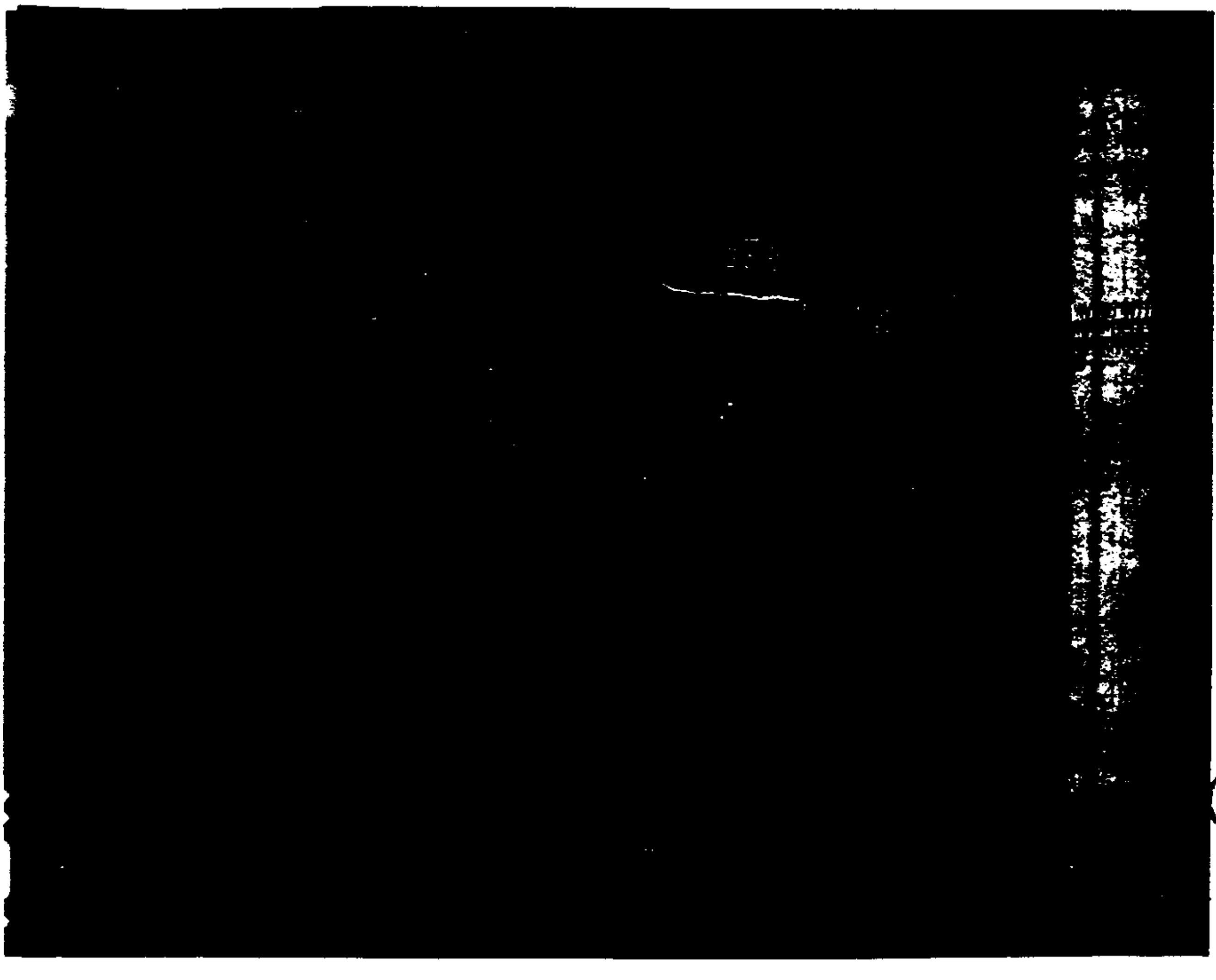


Hα SYNOPTIC CHART

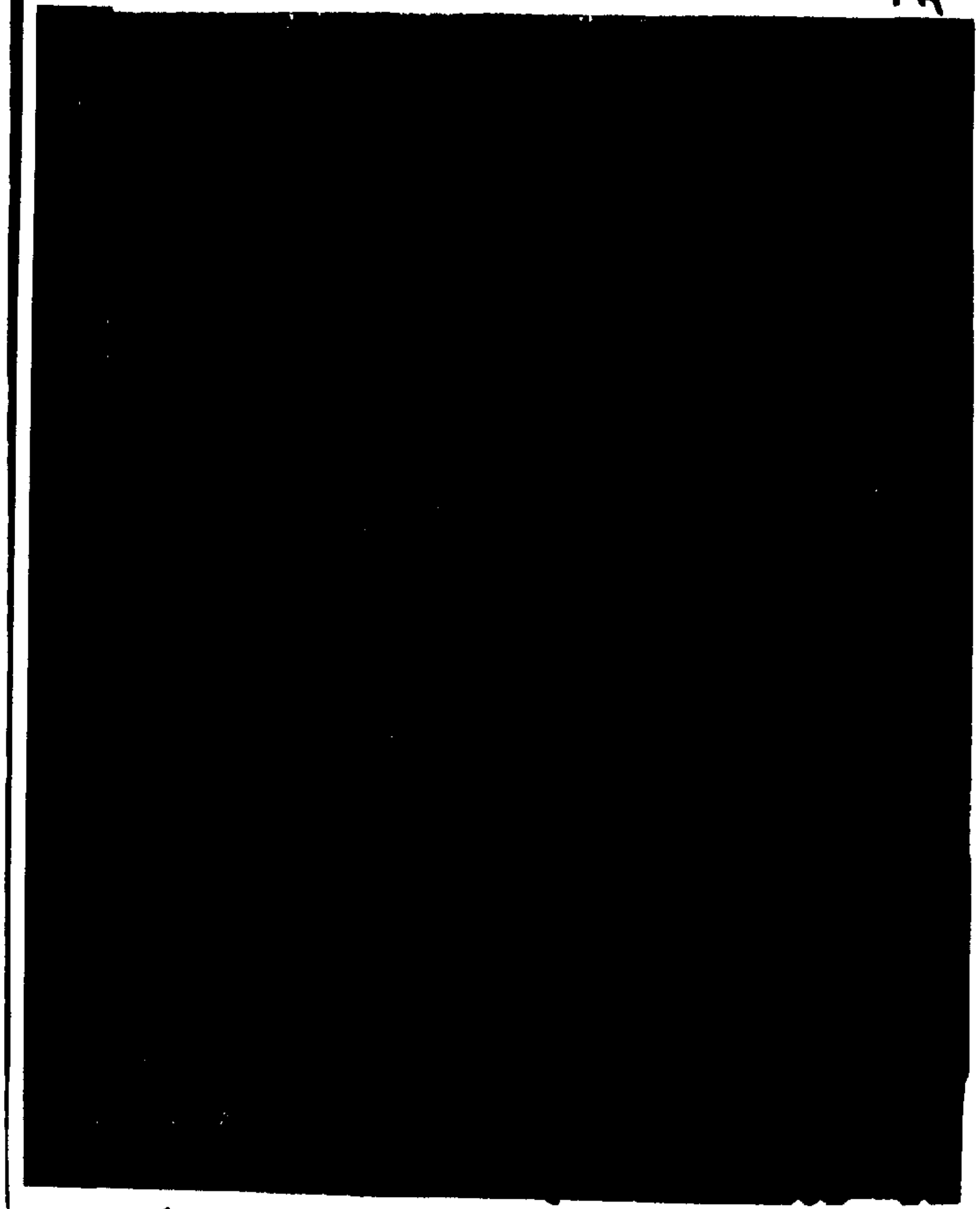
CARRINGTON ROTATION 1744 (PRELIMINARY)



(51)



(52)



Variation of Shock + Ionopause dist. with d (Table 2)

E-H response of the nucleus to direct interaction with the S-W.