Plasma Instabilities in the Earth's Ionosphere

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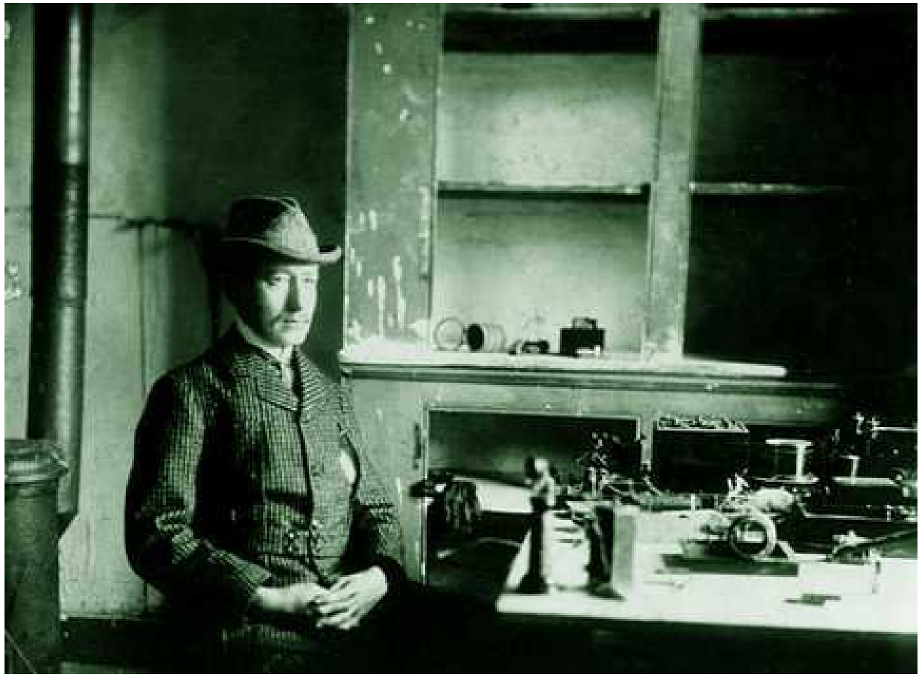
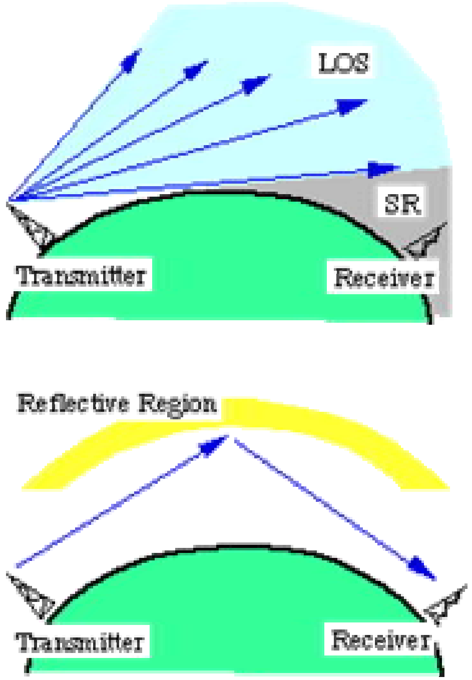
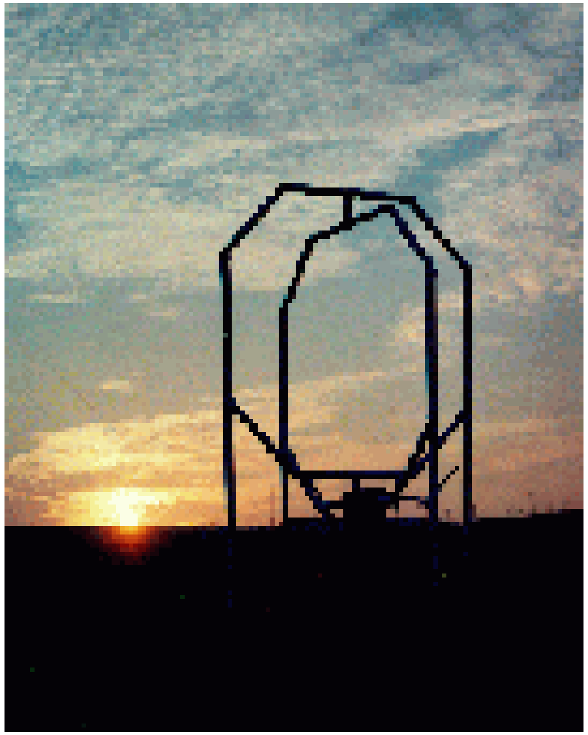
http:www.ep.sci.hokudai.ac.jp/~shw/Plasma.pdf

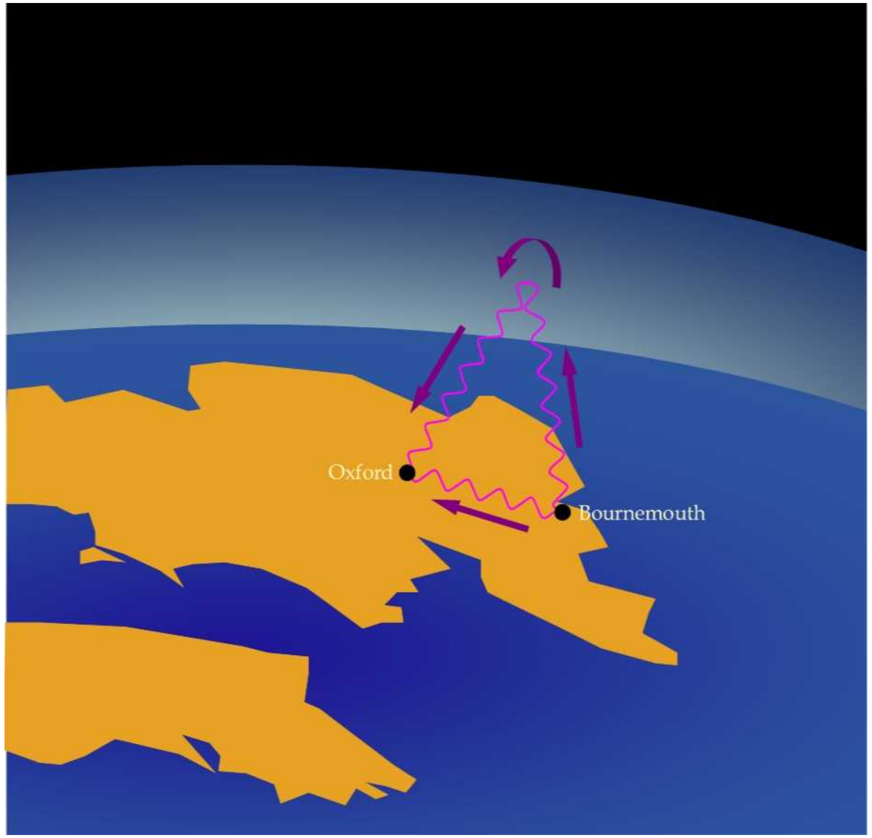
In December 12, 1901, Marconi demonstrated transatlantic communication by receiving a signal in St. John's Newfoundland that had been sent from Cornwall, England. Because of his pioneering work in the use of electromagnetic radiation for radio communications, Marconi was awarded the Nobel Prize in physics in 1909.





On the 12th of December 1924, Edward Appleton and his student Miles Barnett, started a series of pioneering experiments which proved the existence of an electrically charged layer in our atmosphere which is now known as the ionosphere.





Discovery of the Ionosphere

1819 Hans Christian Oersted discovers that electricity and magnetism are related

1864–73 James Clerk Maxwell describes theory of eletromagnetic radiation and predicts existence of radiowaves

1882 Balfour Stewart suggests winds drive electric currents in the upper atmosphere

1887 Heinrich Hertz proves existence of radiowaves

1901 Marconi transmits radio signal across Atlantic Ocean from Cornwall, England to St. John's, Newfoundland

1902 Oliver Heaviside; Arthur Kennelly propose existence of conducting layer in upper atmosphere

1909 Marconi awarded Nobel Prize

1924 Edward Appleton and others develop the ionosonde and begin ground-based soundings; prove existence of ionosphere

1925 Appleton discovers second layer (the F region)

1926 Robert Watson-Watt (later developer of radar) coins word "ionosphere"

1927 Sydney Chapman describes theory for formation of ionosphere

1947 Appleton awarded Nobel Prize

1948 Rocket probes begin

1950's Riometer (Relative Ionospheric Opacity Meter using Extra Terrestrial Electromagnetic Radiation) developed

1958 Incoherent Scatter Radar developed

1962 Alouette 1 satellite makes first topside soundings

Atmospheric atom and molecule are ionized by Extreme UltraViolet lights from the Sun.

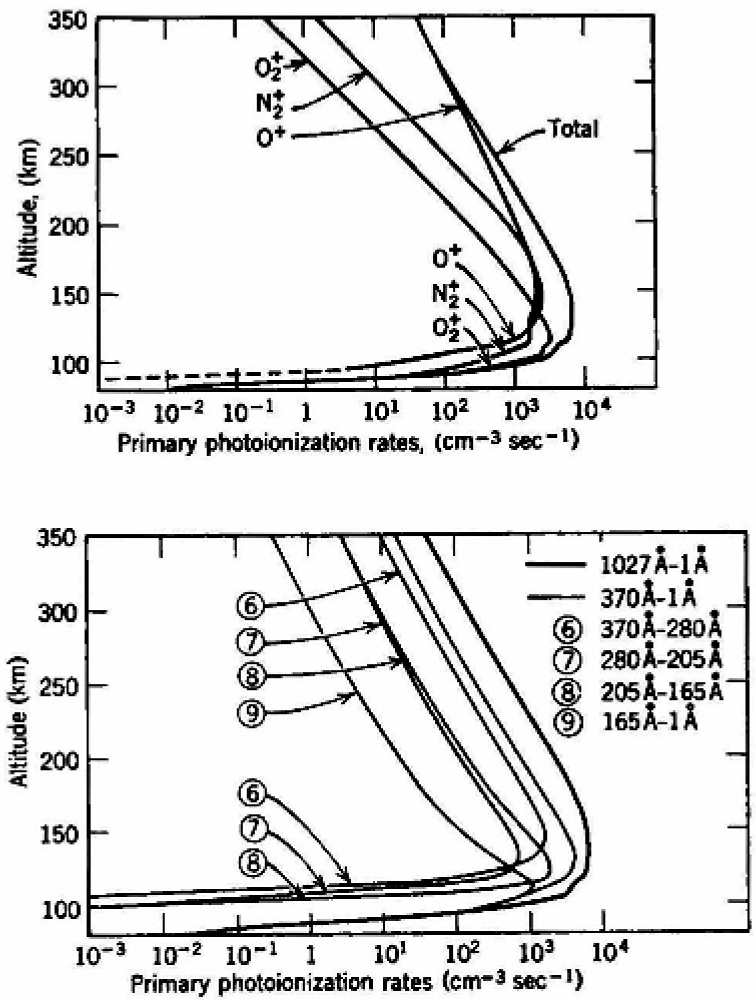


Fig. 5.18. Calculated ionization rates in the E- and F-regions. (From Hinteregger et al., 1965.)

Radiative recombination

$$O^+ + e \rightarrow O + h\nu \qquad 7.8\times10^{-14}(T/300)^{-0.5}\,m^3/s$$

Dissociative recombination

$$NO^+ + e \rightarrow N + O \qquad 2\times10^{-13}(T/300)^{-0.85}\,m^3/s$$

$$O_2^+ + e \rightarrow O + O \qquad 1.9\times10^{-13}(T/300)^{-0.5}\,m^3/s$$

$$N_2^+ + e \rightarrow N + N \qquad 1.8\times10^{-13}(T/300)^{-0.39}\,m^3/s$$

Charge exchange reaction

$$O^+ + N_2 \rightarrow NO^+ + N \qquad 2\times10^{-18}\,m^3/s$$

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad 2\times10^{-17}(T/300)^{-0.4}\,m^3/s$$

$$O_2^+ + N_2 \rightarrow NO^+ + NO \qquad 5\times10^{-22}\,m^3/s$$

$$N_2^+ + O \rightarrow NO^+ + NO \qquad 1.4\times10^{-16}(T/300)^{-0.44}\,m^3/s$$

$$N_2^+ + O_2 \rightarrow N_2 + O_2^+ \qquad 5\times10^{-17}(T/300)^{-0.8}\,m^3/s$$

Earth's Ionosphere/Thermosphere

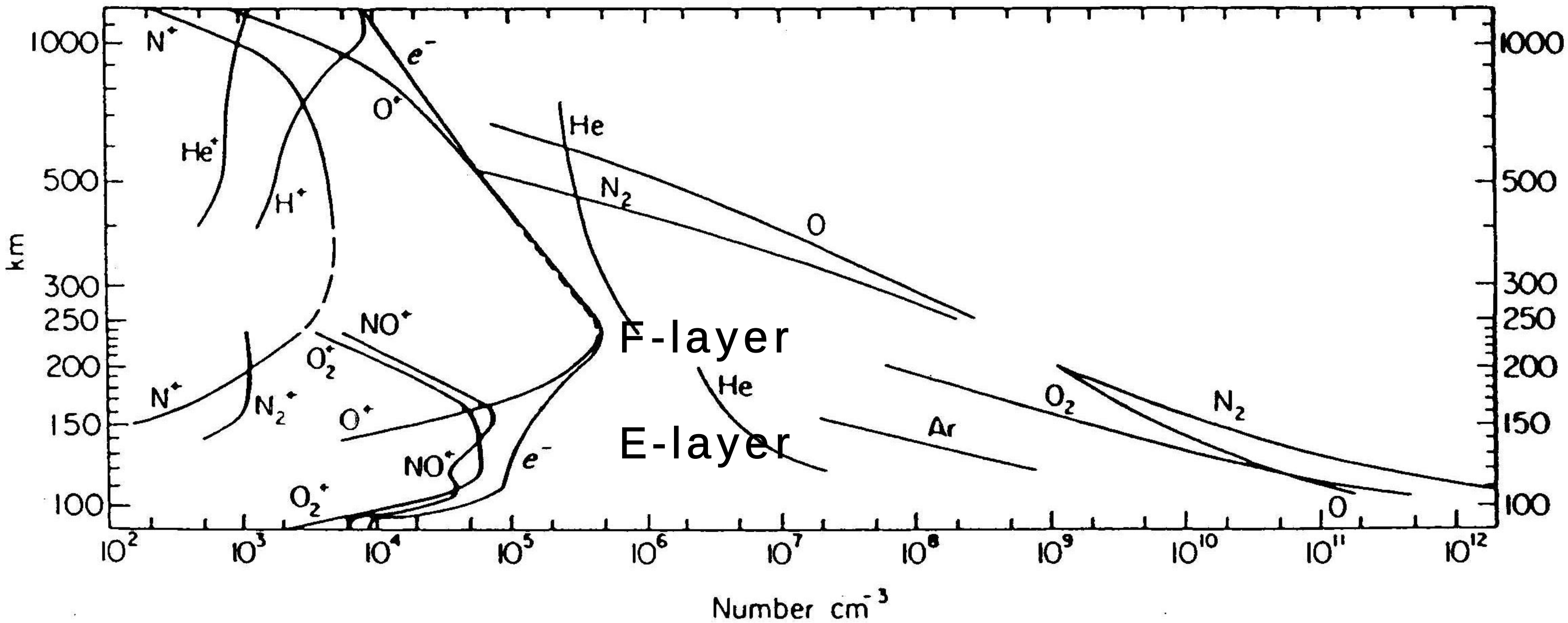


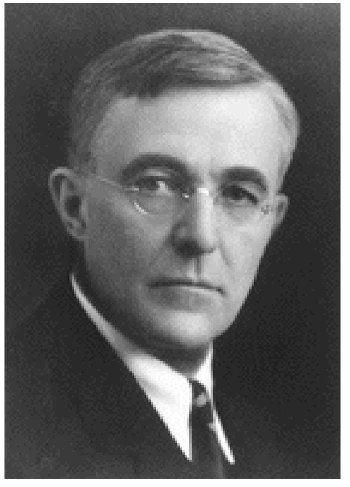
Fig. 1.2. International Quiet Solar Year (IQSY) daytime atmospheric composition, based on mass spectrometer measurements above White Sands, New Mexico (32°N, 106°W). The helium distribution is from a nighttime measurement. Distributions above 250 km are from the Elektron II satellite results of Istomin (1966) and Explorer XVII results of Reber and Nicolet (1965). [C. Y. Johnson, U.S. Naval Research Laboratory, Washington, D.C. Reprinted from Johnson (1969) by permission of the MIT Press, Cambridge, Massachusetts. Copyright 1969 by MIT.]

Plasma

- Langmuir (1928)

’We shall use the name plasma to describe this region containing balanced charges of ions and electrons’.

- >99.9% of material in space are Plasma.



Lorentz force $F = q(E + v \times B)$

Equation of motion $m\frac{dv}{dt} = q(E + v \times B)$

when $E = 0$

$$m\frac{dv}{dt} = q(v \times B)$$

$$mv\frac{dv}{dt} = qv(v \times B)$$

derivation

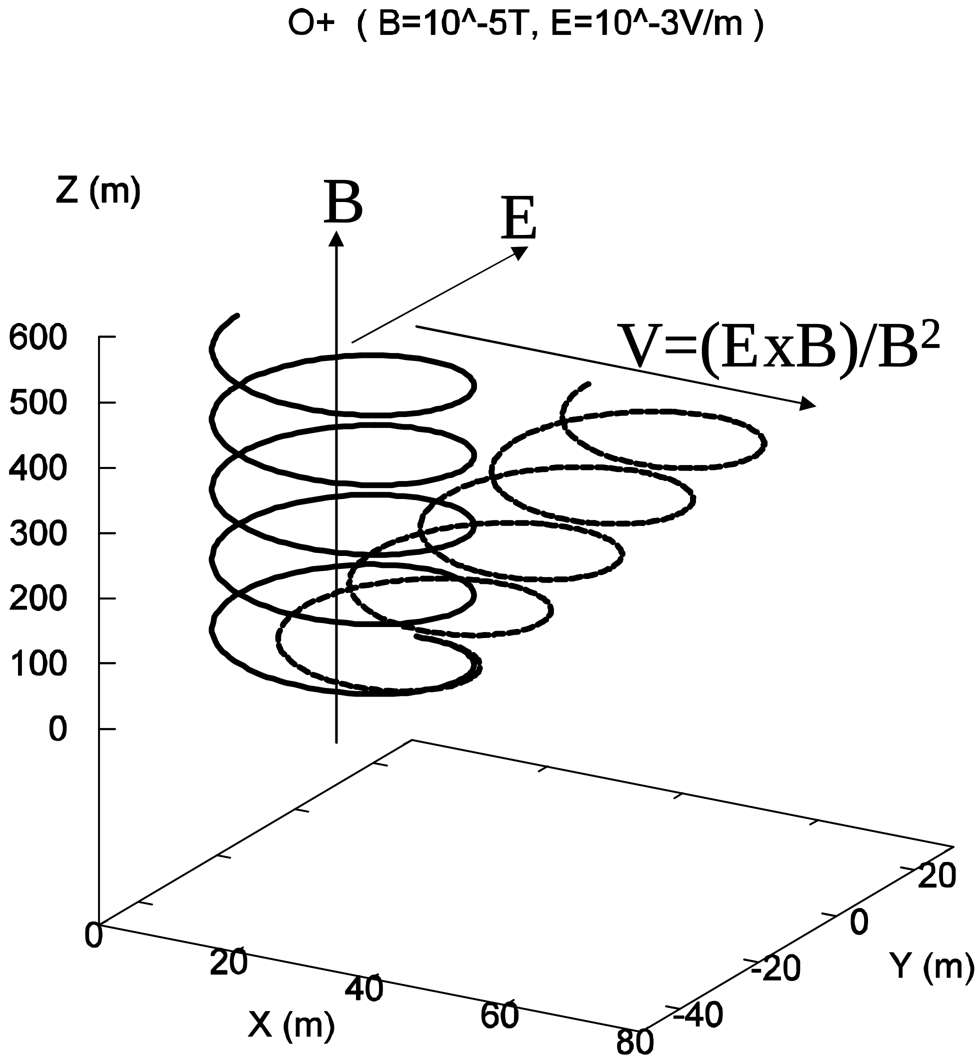
Conservation of energy $\frac{d}{dt}\left(\frac{mv^2}{2}\right) = 0$

simple harmonic oscillation $\frac{d^2v}{dt^2} = -\left(\frac{qB}{m}\right)^2 v$

Cyclotron frequency $\omega = \frac{qB}{m}$

$$\frac{dv_{//}}{dt} = 0$$

Charged particle does helical motion around magnetic field line.



$$v = r_L \omega_C$$

r_L Larmor radius

ω_C cyclotron frequency

	v_{th}	r_L	ω_C
O^+	10^3m/s	17m	60rad/s
e	1.7×10^5m/s	0.1m	1.7×10^6rad/s

T＝1000K

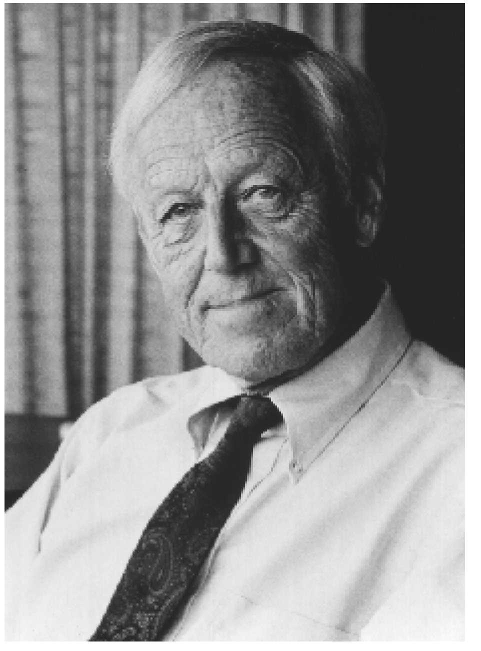
Magnetohydrodynamic Equations: MHD Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0$$

$$\rho \frac{\partial V}{\partial t} + \rho (V \cdot \nabla) V = -\nabla p + (J \times B)$$

$$\frac{\partial B}{\partial t} = \nabla \times (V \times B) + \frac{1}{\mu \sigma} \Delta B$$

$$\nabla \times B = \mu J$$



Alfven: The Nobel Prize in Physics 1970 for fundamental work and discoveries in magneto-hydrodynamics with fruitful applications in different parts of plasma physics.

Maxwell's equation

$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}}$$ Faraday’s law

$$\nabla \times \mathrm{B} = \mu \mathrm{J}$$ Ampere’s law

Ohm's law

$$\mathrm{J} = \sigma\left(\mathrm{E} + \mathrm{V} \times \mathrm{B}\right)$$

Induction equation

$$\frac{\partial \mathrm{B}}{\partial \mathrm{t}} = \nabla \times \left(\mathrm{V} \times \mathrm{B}\right) + \frac{1}{\mu\sigma}\Delta \mathrm{B}$$

Basic equations of plasma atmosphere

Equation of continuity

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{v}_i) = P_i - L_i$$

Equation of motion

$$\frac{\partial \mathbf{v}_i}{\partial t} + (\mathbf{v}_i \cdot \nabla)\mathbf{v}_i = -\frac{1}{\rho_i}\nabla p_i + \mathbf{g} + \frac{q}{m_i}(\mathrm{E} + \mathbf{v}_i \times \mathrm{B}) - \sum_k \nu_{ik}(\mathbf{v}_i - \mathbf{u}_k)$$

State equation (perfect gas)

$$p_i = n_i k T_i$$

Equation of motion

$$\cancel{\frac{\partial \mathbf{v}_i}{\partial t} + (\mathbf{v}_i \cdot \nabla)\mathbf{v}_i} = -\frac{1}{\rho_i}\nabla p_i + \mathbf{g} + \frac{q}{m_i}(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \sum_k \nu_{ik}(\mathbf{v}_i - \mathbf{u}_k)$$

$$\mathbf{v}_i = \frac{\nu_{in}\Omega_i}{\nu_{in}^2 + \Omega_i^2}\left(\frac{\mathbf{E}}{B} - \frac{\nabla p_i}{n m_i \Omega_i} + \frac{\mathbf{g}}{\Omega_i} + \frac{\nu_{in}\mathbf{u}_n}{\Omega_i}\right) + \frac{\Omega_i^2}{\nu_{in}^2 + \Omega_i^2}\left(\frac{\mathbf{E}}{B} - \frac{\nabla p_i}{n m_i \Omega_i} + \frac{\mathbf{g}}{\Omega_i} + \frac{\nu_{in}\mathbf{u}_n}{\Omega_i}\right) \times \frac{\mathbf{B}}{B}$$

$$\mathbf{v}_e = -\frac{\nu_{en}\Omega_e}{\nu_{en}^2 + \Omega_e^2}\left(\frac{\mathbf{E}}{B} + \frac{\nabla p_e}{n m_e \Omega_e} - \frac{\mathbf{g}}{\Omega_e} - \frac{\nu_{en}\mathbf{u}_n}{\Omega_e}\right) + \frac{\Omega_e^2}{\nu_{en}^2 + \Omega_e^2}\left(\frac{\mathbf{E}}{B} + \frac{\nabla p_e}{n m_e \Omega_e} - \frac{\mathbf{g}}{\Omega_e} - \frac{\nu_{en}\mathbf{u}_n}{\Omega_e}\right) \times \frac{\mathbf{B}}{B}$$

In the ionospheric F region,

$$\Omega_i >> \nu_{in}, \qquad \Omega_e >> \nu_{en}$$

$$\mathbf{v}_i = \left(\frac{\mathbf{E}}{B} - \frac{\nabla p_i}{n m_i \Omega_i} + \frac{\mathbf{g}}{\Omega_i} + \frac{\nu_{in}\mathbf{u}_n}{\Omega_i}\right) \times \frac{\mathbf{B}}{B}$$

$$\mathbf{v}_e = \left(\frac{\mathbf{E}}{B} + \frac{\nabla p_e}{n m_e \Omega_e} - \frac{\mathbf{g}}{\Omega_e} - \frac{\nu_{en}\mathbf{u}_n}{\Omega_e}\right) \times \frac{\mathbf{B}}{B}$$

$$\approx \frac{V_{th}^2}{\Omega L} = \frac{V_{th} r_L}{L}$$

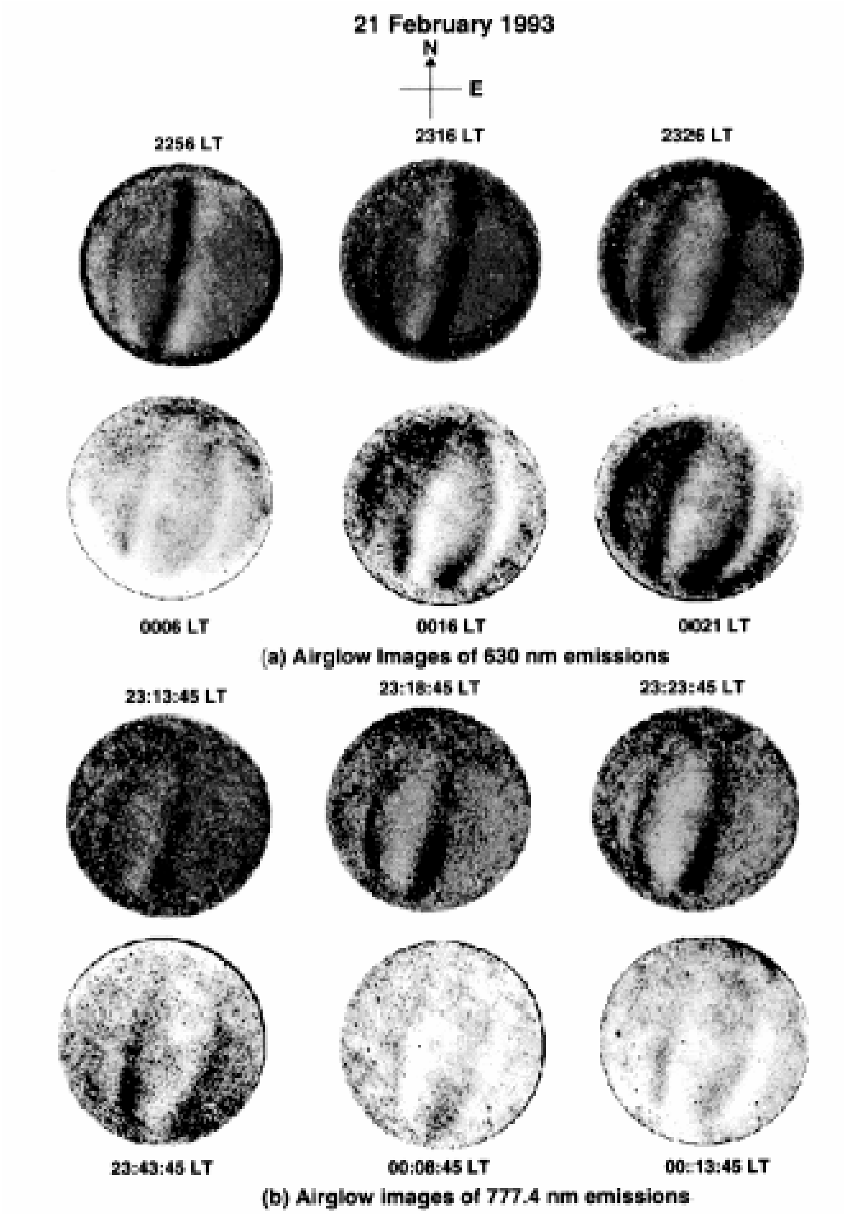


Fig. 4. Sequence of airglow images taken on the night of 21 February, 1993 over SHAR (a) 630 nm images at 2256, 2316, 2326, 0006, 0016 and 0021 LT and (b) 777.4 nm images at 23:13:45, 23:18:45, 23:23:45, 23:43:45, 00:08:45 and 00:13:45 LT. The arrow points towards geomagnetic north.

Plasma Bubbles at Magnetic Equator

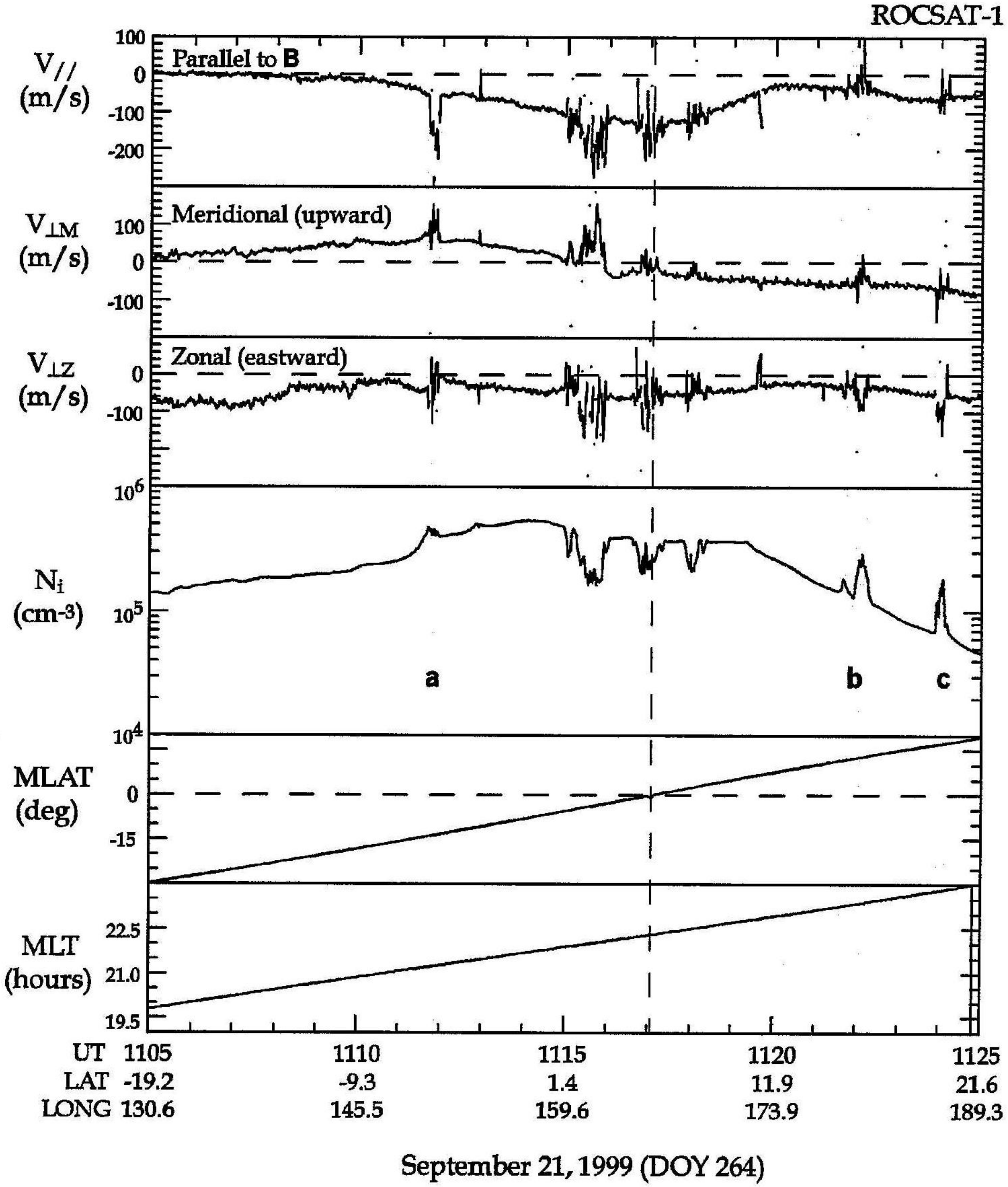
630nm

777.4nm

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

$$O_2^{+} + e \rightarrow O + O + h\nu$$

Plasma Bubbles observed by ROCSAT Satellite



Jicamarca Radar Observation of Plasma Density Irregularities associated with Plasma Bubbles

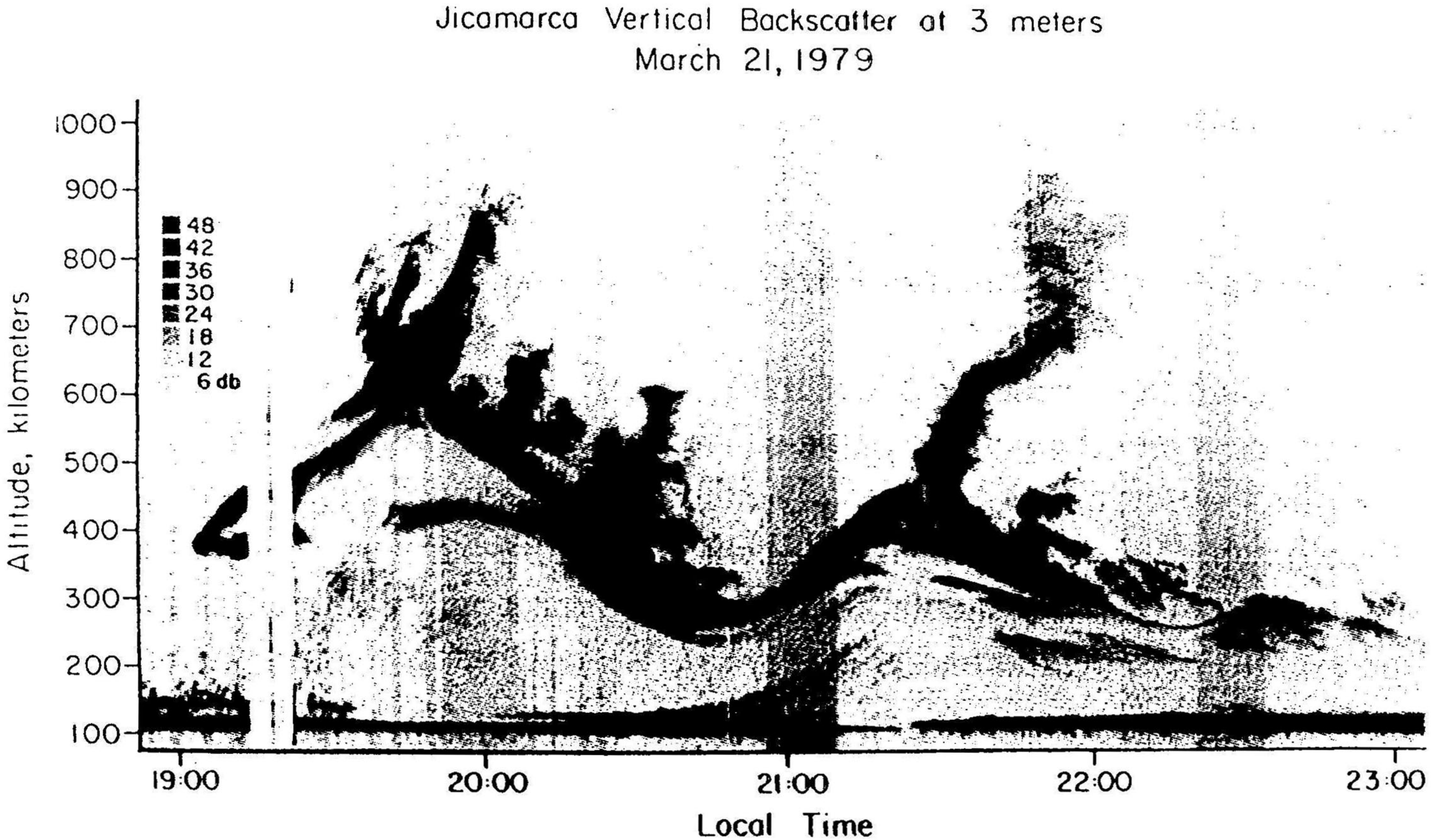
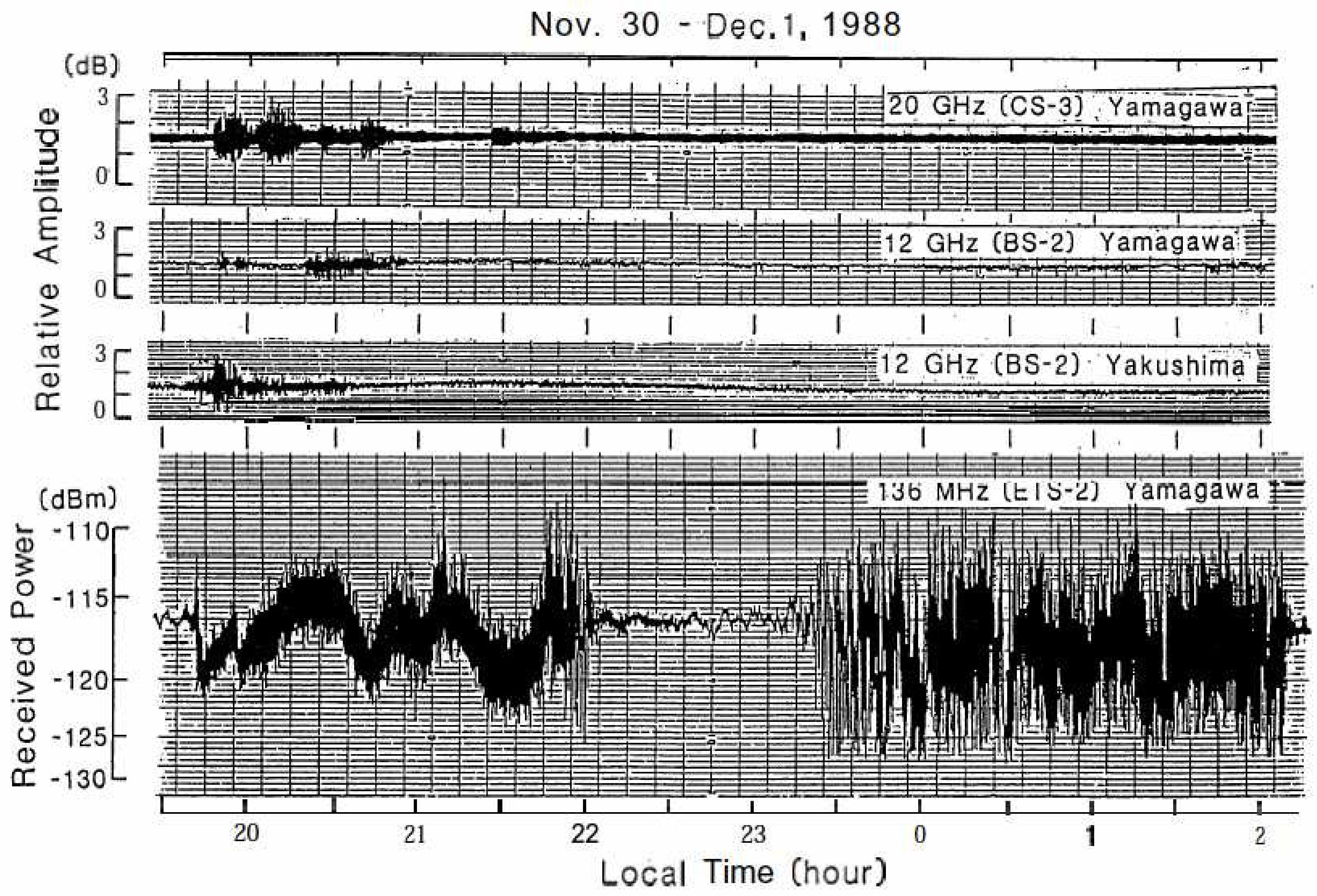


Fig. 4.1. Range–time–intensity map displaying the backscatter power at 3-m wavelengths measured at Jicamarca, Peru. The gray scale is decibels above the thermal noise level. [After Kelley *et al.* (1981). Reproduced with permission of the American Geophysical Union.]

Signals from Geosynchronous Satellite



Stability of Equatorial Ionosphere

Continuity equation, Current conservation

$$\frac{\partial n}{\partial t} + \nabla(nv) = 0, \quad \nabla \cdot J = 0$$

= equilibrium state + perturbed state

$$n = n_0 + n', \quad v = v_0 + v', \quad J = J_0 + J'$$

$$v_0 = \frac{g}{\Omega_i} \times \frac{B}{B}, \quad v' = \frac{E' \times B}{B^2}, \quad J_0 = 0, \quad J' = en' \frac{g}{\Omega_i} \times \frac{B}{B}$$

Equations are linearized with respect to the perturbed quantities.

$$\frac{\partial n'}{\partial t} + n_0 \nabla(v') + v' \nabla(n_0) + v_0 \nabla(n') = 0$$

$$\nabla \cdot J' = 0$$

$$n', v' \propto e^{-i(\omega t - kx)}$$ Plane wave solutions are assumed.

Continuity equation

$$-i\omega n' + ikn_0 \frac{E'}{B} + \frac{E'}{B}\frac{\partial n_0}{\partial z} + ik\frac{g}{\Omega_i} n' = 0$$

Current conservation

$$ik\frac{en_0}{B}\frac{\nu_{in}}{\Omega_i}E' + ike\frac{g}{\Omega_i}n' = 0 \quad \rightarrow \quad \frac{E'}{B} = -\frac{g}{\nu_{in}}\frac{n'}{n_0}$$

$$\omega = \omega_r + i\gamma$$

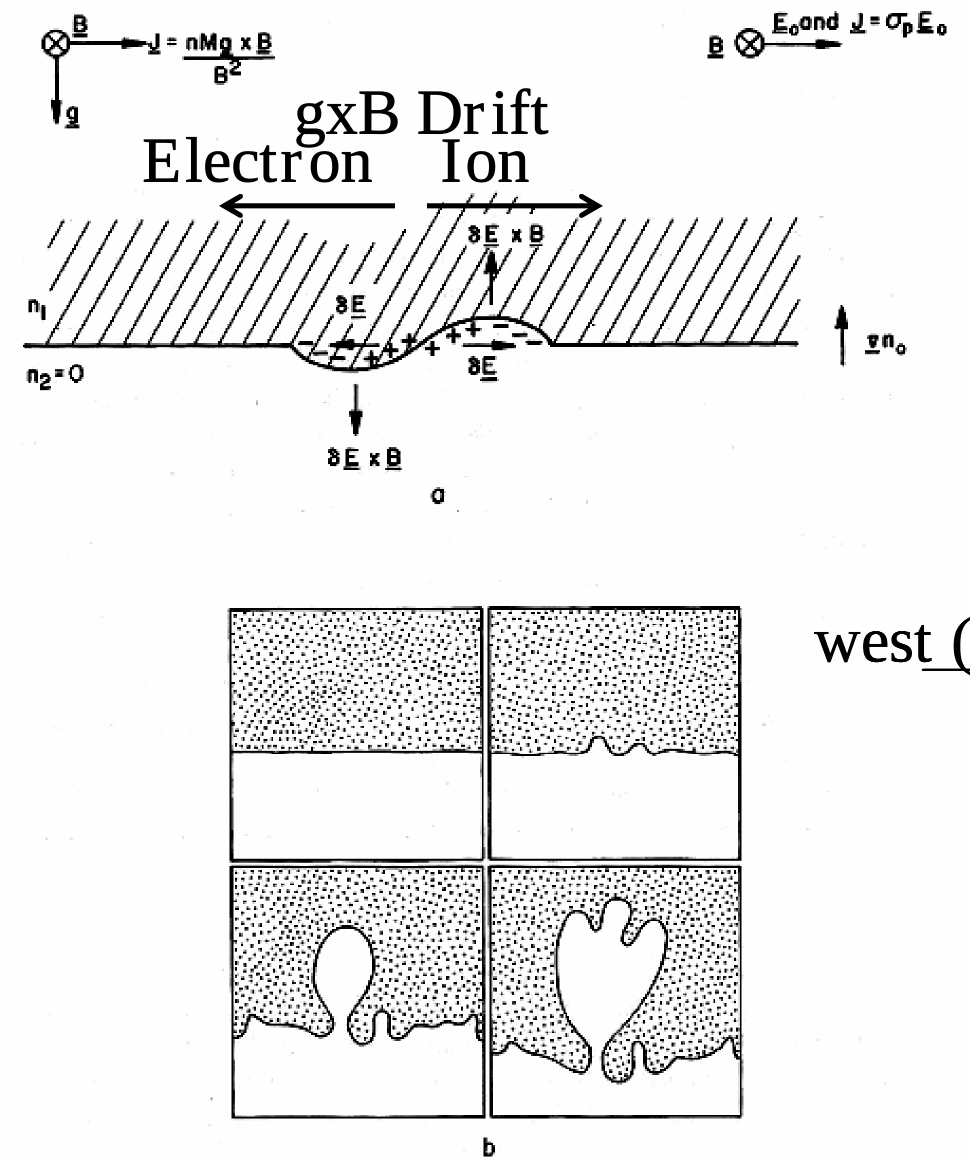
Growth rate Rayleigh-Tayler Instability

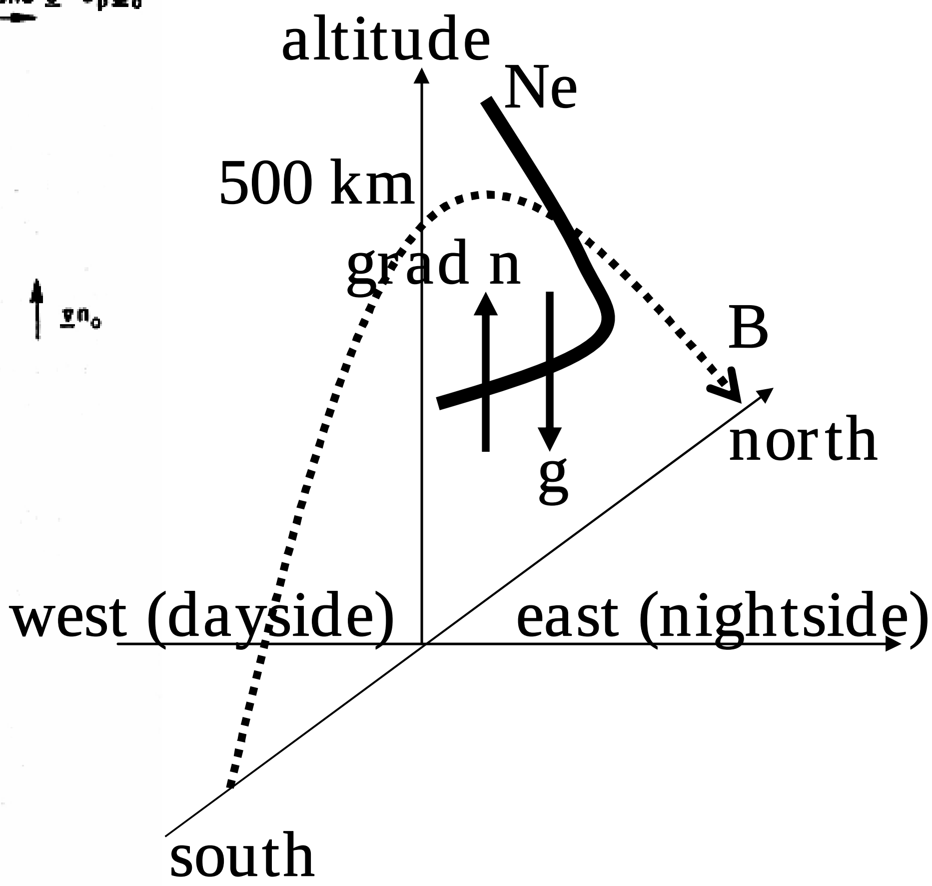
$$\gamma = \frac{g}{\nu_{in}}\frac{1}{n_0}\frac{\partial n_0}{\partial z}$$

Generalized Rayleigh-Tayler Instability

$$\gamma = \left(\frac{g}{\nu_{in}} + \frac{E_x}{B} + \frac{\nu_{in} u_{nx}}{\Omega_i}\right)\frac{1}{n_0}\frac{\partial n_0}{\partial z}$$

Generation Process of Plasma Bubble in the Bottomside of equatorial F region

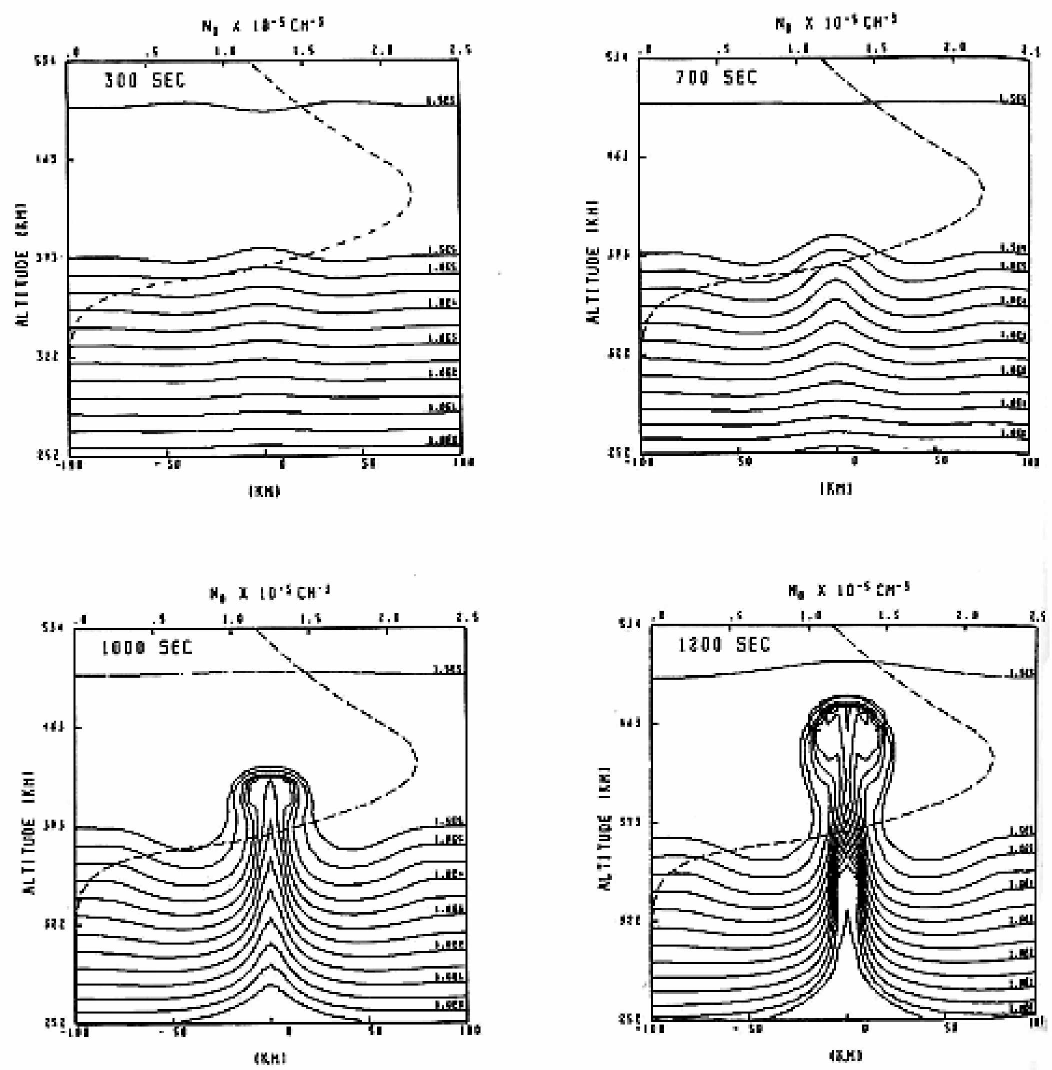




Evolution of Plasma Bubbles

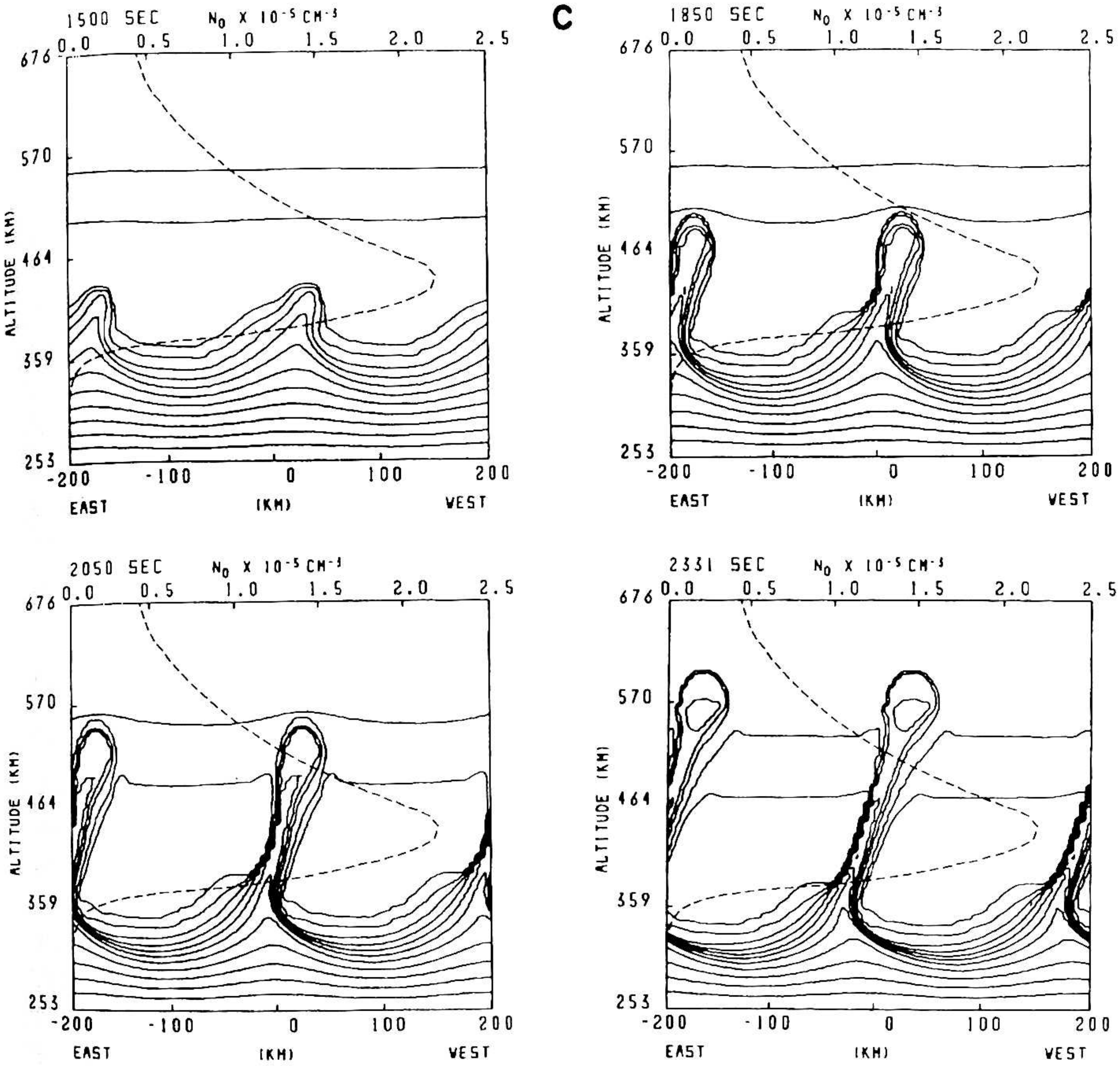
Continuity equation,   Current conservation

$$\frac{\partial n}{\partial t} + \nabla(nv) = 0, \quad \nabla \cdot J = 0$$

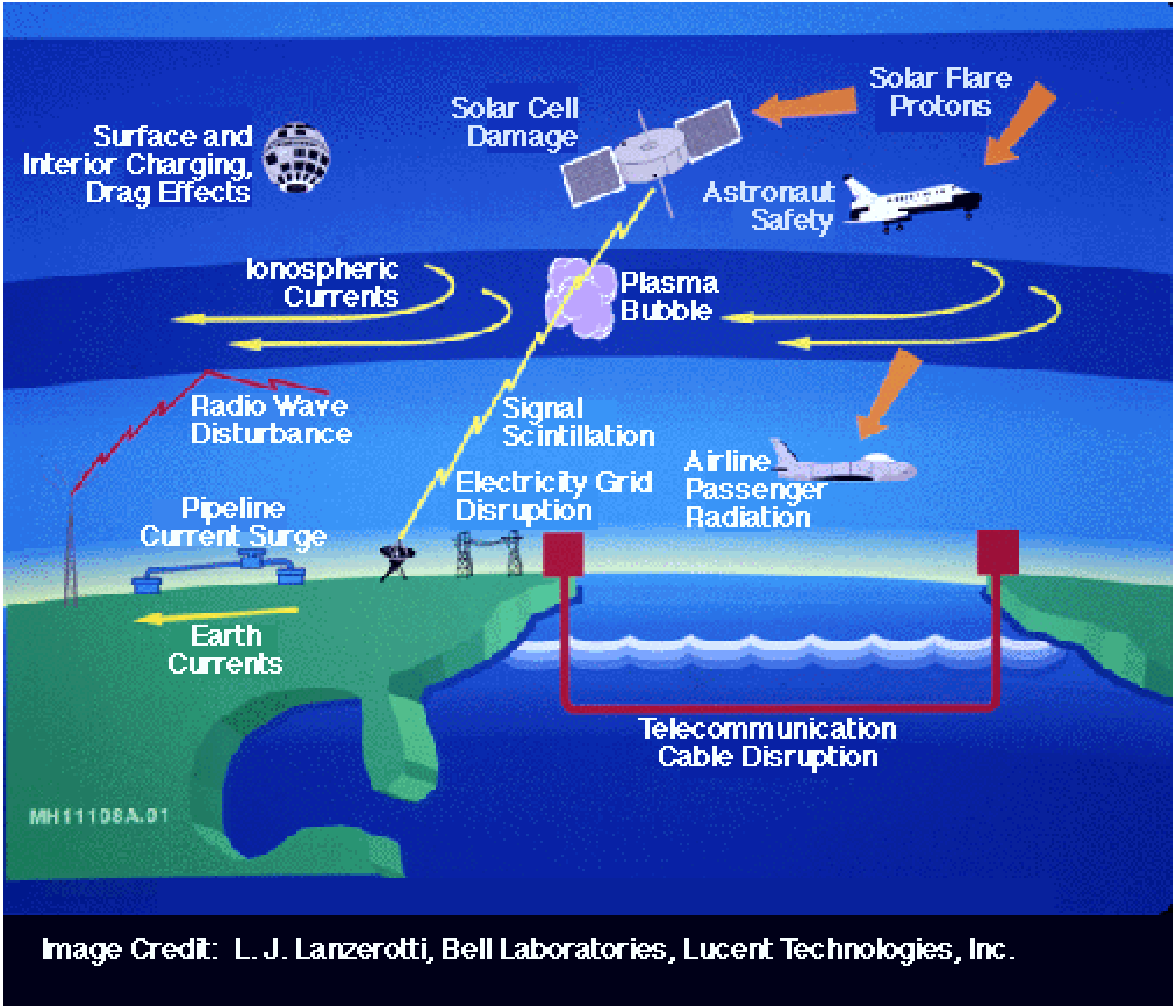


Evolution of Plasma Bubbles

with Neutral Wind



Space Weather



Plasma Bubble is One of the Important Research Themes for Space Weather Program.

However,

We don’t understand

* 3D structure and dynamics of plasma bubble,
* Generation mechanism of small scale irregularity,
* Seed mechanism,
* Effect of penetrating electric field from polar ionosphere.