Self-Consistent Hybrid Model: Applications to the Polar and Solar Winds

Sunny W. Y. Tam[1,2],
Fareed Yasseen[2] & Tom Chang[2]

1. Plasma and Space Science Center, National Cheng Kung University, Tainan, Taiwan
2. Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, U.S.A.

Outline

- Self-Consistent Hybrid Approach
  kinetic + fluid modeling
- Application to the Polar Wind
  photoelectron effects, observations & theory
  non-local kinetic collisional + fluid descriptions
- Application to the Fast Solar Wind
  kinetic wave-particle interaction

Hybrid Approach for Non-local Calculations

- ***Kinetic*** + ***Fluid*** calculations over the same modeling range
- Kinetic calculations to describe part of the particle species
- Fluid equations to describe the remaining part

Fluid Calculations

- Characterize the particle properties by a few **moment** quantities
- **Collision frequencies** are defined in order to characterize the **"average"** effects of collisions between particle species
- Most useful when the particle distributions are **thermal**, close to Maxwellian or bi-Maxwellian

Kinetic Calculations

- Describe the particle species using **distribution functions** (infinite number of moments)
- Collisional operator in equation is **nonlinear** due to self-collisions (non-linearity difficult to solve)
- Required when **non-thermal** features are significant

Self-Consistent Hybrid Approach [Tam et al., 1995b; 1998; Tam and Chang, 1999, 2001, 2002]

- Non-local kinetic collisional calculations for all ion species and suprathermal electrons
- Fluid calculations to determine the thermal electron properties and the electric field
- Iteration between kinetic and fluid calculations until results converge to ensure self-consistency

Application to the Polar Wind

- Experimental indications of photoelectron signature and effects in the polar wind
- Theory of ***photoelectron-driven polar wind***
- Model overview and results
- Formulation and modeling techniques

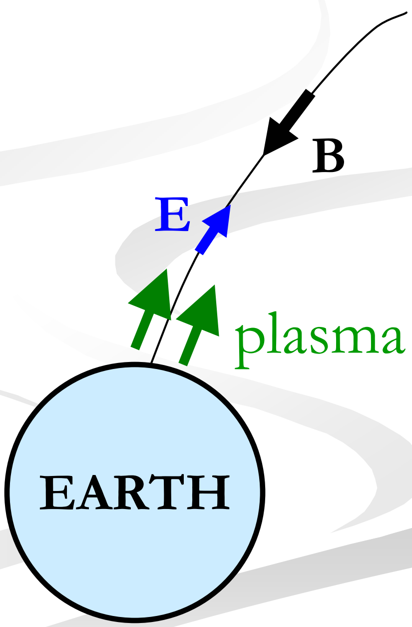
Classical Polar Wind:

Steady state, quasi-neutral, WPI negligible

Plasma Source: Ionospheric
thermal particle species

Transport and dynamics only
along magnetic field lines with
no electrical current

Field-aligned ambipolar
electric field influences the
outflow

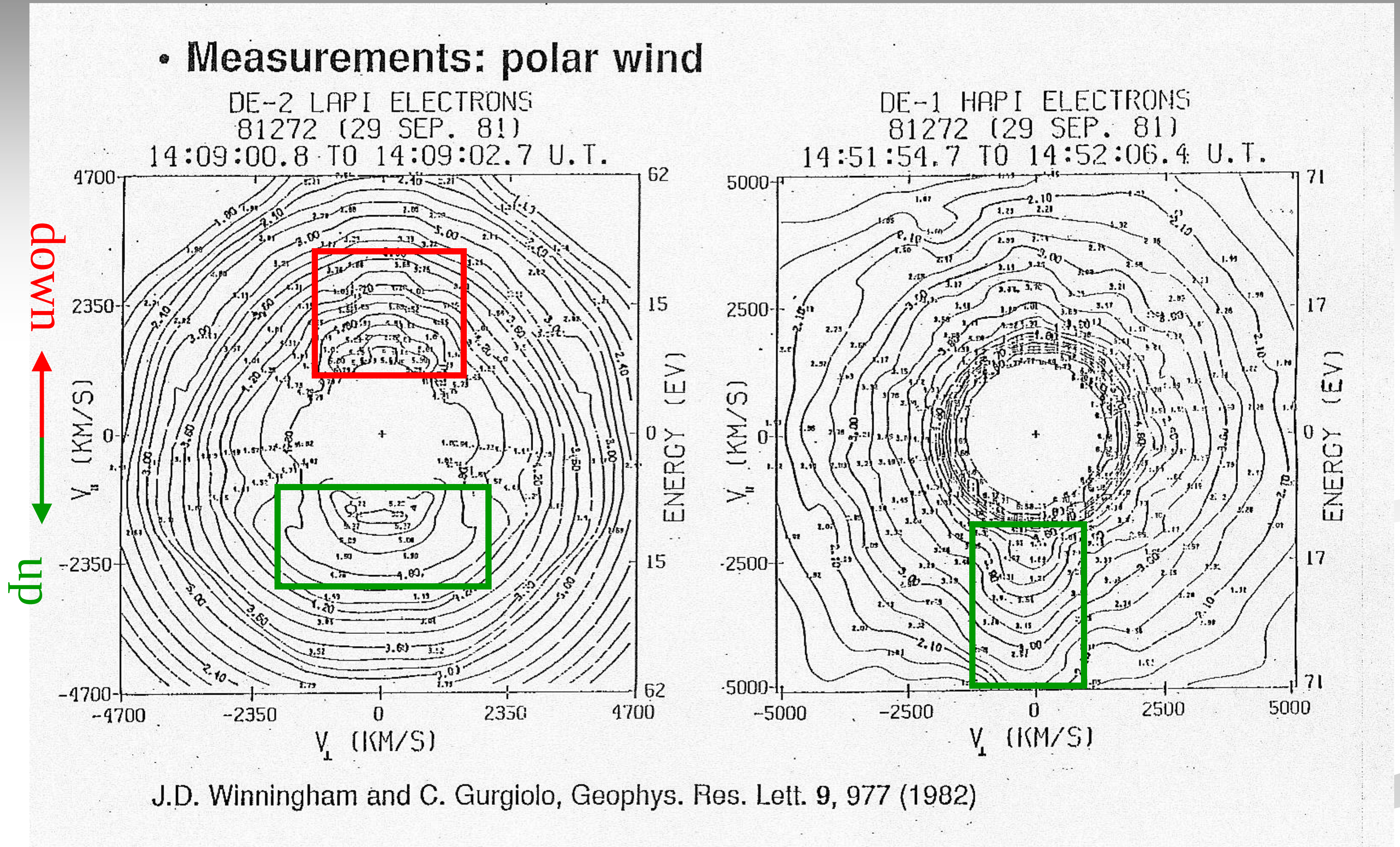


Photoelectrons in the Polar Wind: Experimental Indications

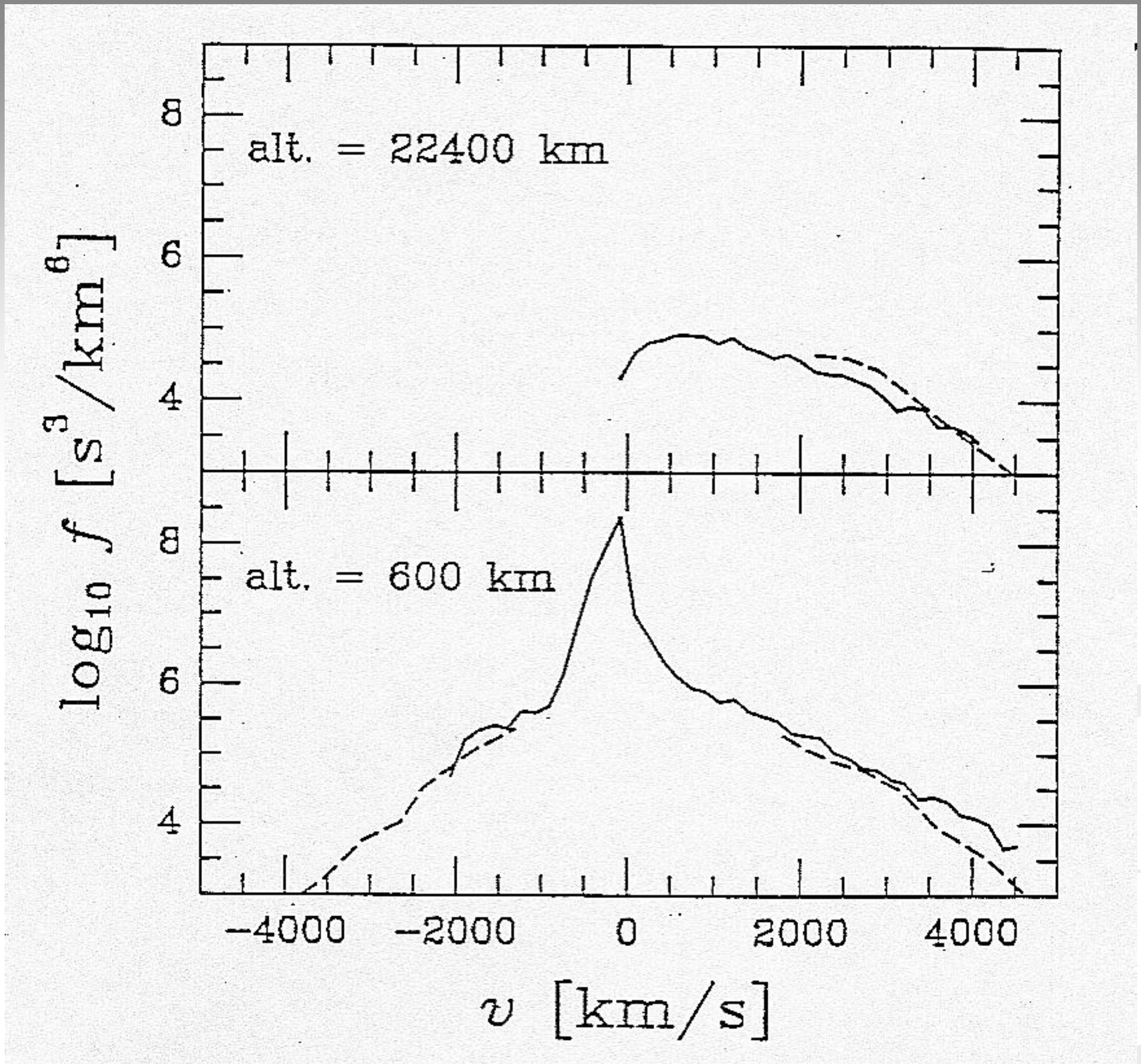
- Anomalous* field-aligned outward energy flux of suprathermal electrons (DE-1, -2 satellites)

  *cannot be explained by the idea of thermal conductivity and temperature gradient

DE-2 altitude: 600 km DE-1 altitude: 22400 km



Electric potential difference: 5 – 62 V (SZA dependent)



Solid: calculations

Dashed: observed e⁻ distributions

[Yasseen et al., 1989]

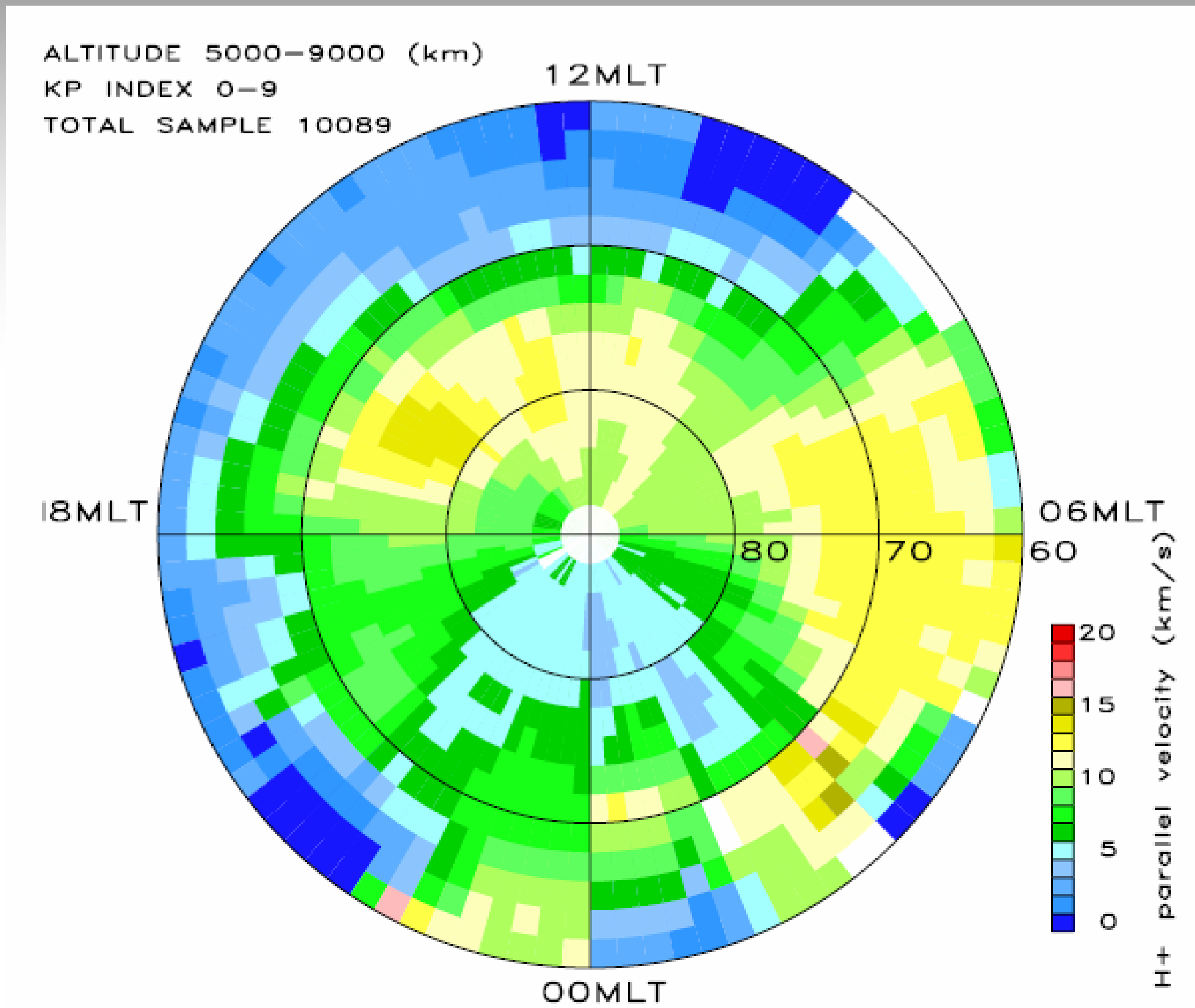
Photoelectrons in the Polar Wind: Experimental Indications

- Anomalous* field-aligned outward energy flux of suprathermal electrons (DE-1, -2 satellites)

  *cannot be explained by the idea of thermal conductivity and temperature gradient

- Day-night asymmetries in ion outflow velocities (Akebono satellite)

Akebono H^+ velocity [Abe et al., 1993]



Theory of Photoelectron-Driven Polar Wind: Energy Flux Mechanism

Energy conservation (steady state, no cross collisions):

$$\frac{\partial}{\partial s}\left\{\frac{1}{B}\left[Q_w + nu\left(m\Phi_G + q\Phi_E\right)\right]\right\} = 0$$

where s ≡ distance along the field line

Φ_G ≡ gravitational potential

Φ_E ≡ electrostatic potential

and energy flux,

$$Q_w \equiv \int d\mathbf{v}\,\frac{1}{2} m v^2 v_{\parallel} f\left(s, \mathbf{v}\right)$$

$$\frac{\partial}{\partial s}\left\{\frac{1}{B}\left[Q_w + nu\left(m\Phi_G + q\Phi_E\right)\right]\right\} = 0$$

- Presence of photoelectrons introduces a large amount of upward electron energy flux ($Q_w > 0$)
- Q_w carried by photoelectrons tends to decrease with s to a great extent (due to collisions with thermal electrons)
- $q < 0$: Φ_E responds with a larger decrease with s
- ***Photoelectrons***

Energy flux ⟶ Electric field

Dayside ionosphere ⟶ Asymmetries

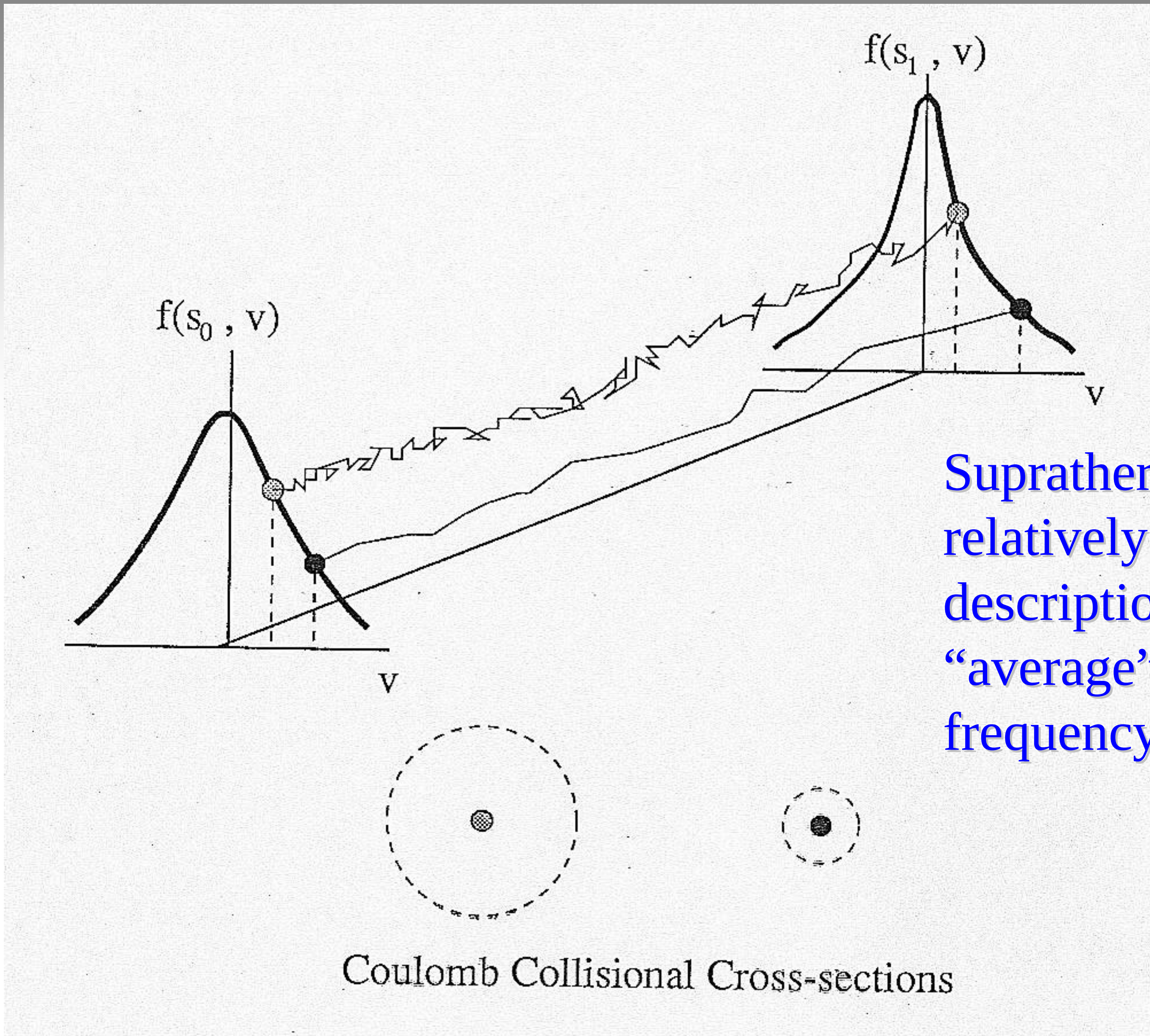
Theory of Photoelectron Effects in the Polar Wind [Lemaire and Scherer, 1972; Lemaire, 1972]

- Kinetic collisionless (exospheric) calculations
- Escaping photoelectron flux leads to enhancement in the ambipolar electric field and ion outflow velocities

How to model photoelectrons in the polar wind more precisely?

1. Collisional

   Coulomb collisions affect photoelectron energy flux and electric field



Suprathermal particles are relatively collisionless,; description based on “average” collisional frequency inadequate

- Classical heat conduction requires collision mean free path λ_{MFP} much shorter than the species scale length
- Coulomb collision frequency depends on the particle velocity

$$\nu_{coll} \sim |\mathbf{v}|^{-3}$$

$$\lambda_{MFP} = |\mathbf{v}| / \nu_{coll} \sim |\mathbf{v}|^{4}$$

- Some suprathermal particles violate the MFP requirement

How to model photoelectrons in the polar wind more precisely?

1. Collisional

   Coulomb collisions affect photoelectron energy flux and electric field

2. Kinetic

   collisional frequencies in fluid approach inadequate for suprathermal particles

3. Non-local

   Dependence of transition time on particle velocity; inhomogeneous background *n*, *E*, *B*, etc.

Self-Consistent Hybrid Model (Photoelectron-Driven Polar Wind) [Tam et al., 1995b; 1998]: Overview

- 1-D flux tube
- **Non-local kinetic collisional** (Monte Carlo) calculations for H^+, O^+ and photoelectrons
- Fluid calculations (along with quasi-neutrality and current-free conditions) to determine the thermal electron properties and the ambipolar electric field
- Iteration between kinetic and fluid calculations until results converge to ensure self-consistency

Akebono PW Observations [Abe et al., 1993; Yau et al., 1995] **addressed by the model**

- Ion qualitative features (5000 – 9000 km alt.)

  -- O^+ dominance over H^+ ions

  -- monotonically increasing ion outflow velocities

  -- supersonic H^+ and O^+ outflow

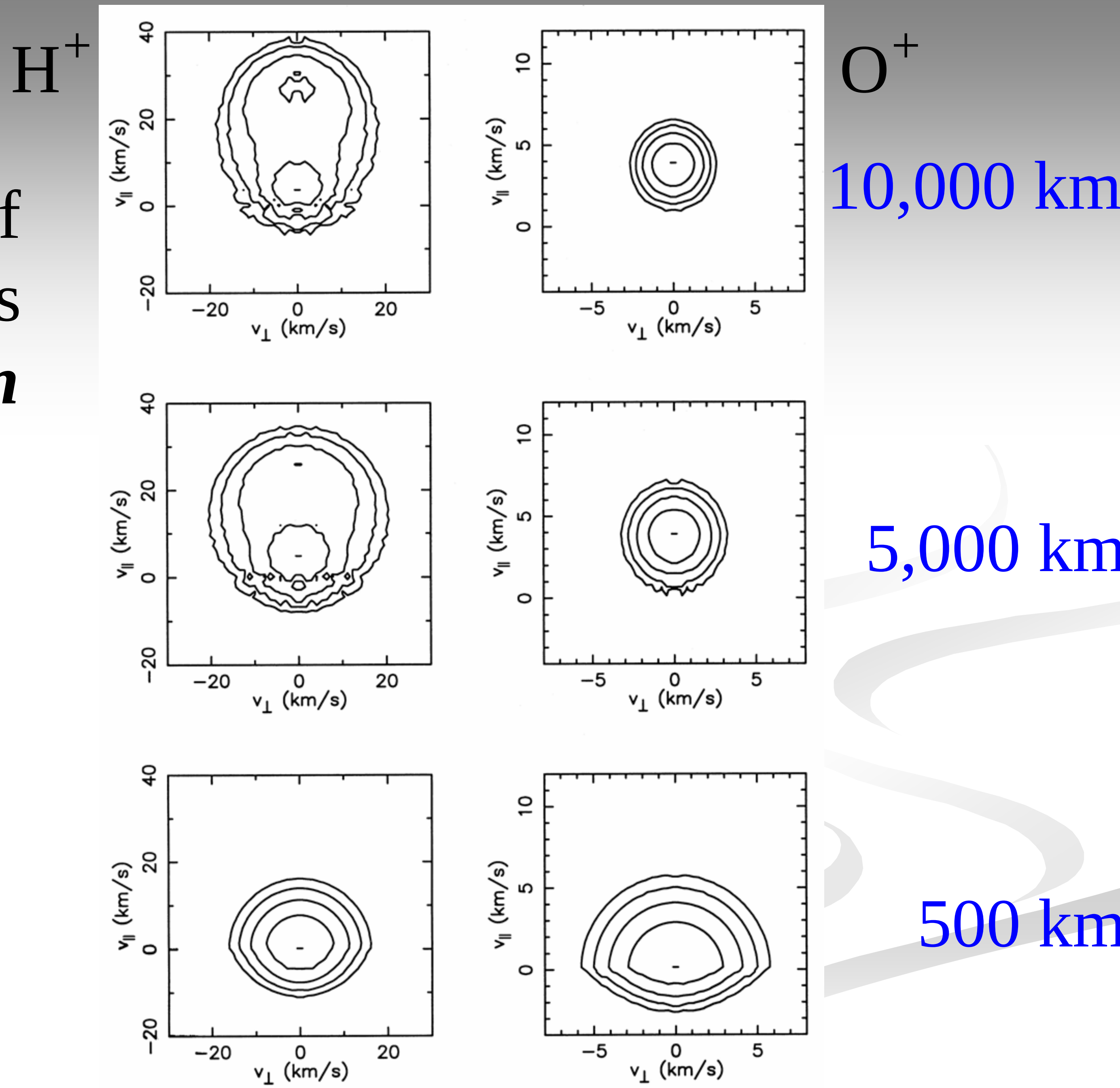
- Electron qualitative features ($\approx$ 1700 km alt.)

  -- anisotropy between upward and downward moving electron populations:

  $$T_{e,\,up} > T_{e,\,down}$$

  -- upward total electron heat flux

Formation of double peaks starts at ***high altitude*** due to **self-collisions**



Day-Night Transition [Tam et al., 1998]

- Four cases with different boundary photoelectron to thermal electron density ratio:

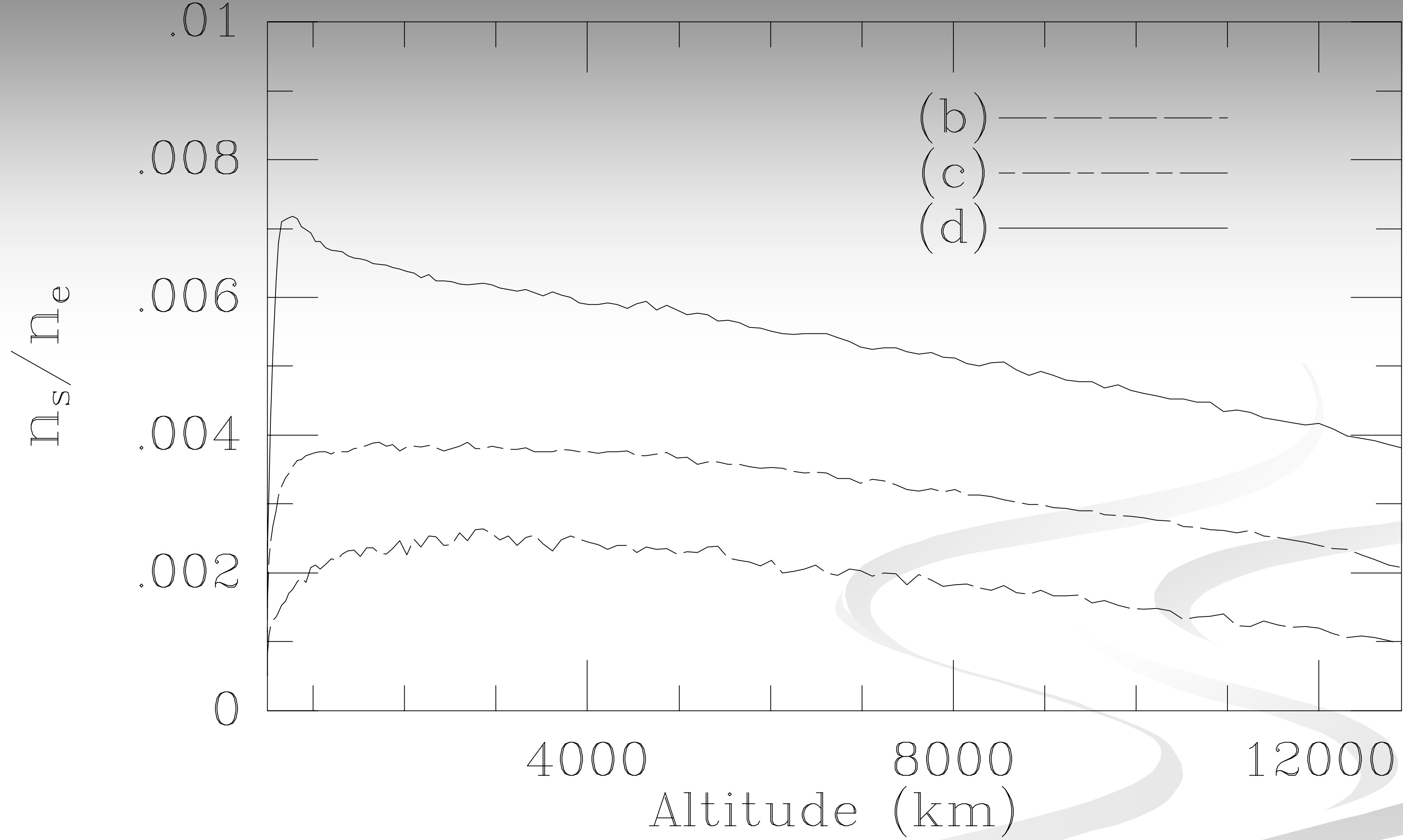
  (a) $n_s/n_e = 0$

  (b) $n_s/n_e = 5\times10^{-4}$

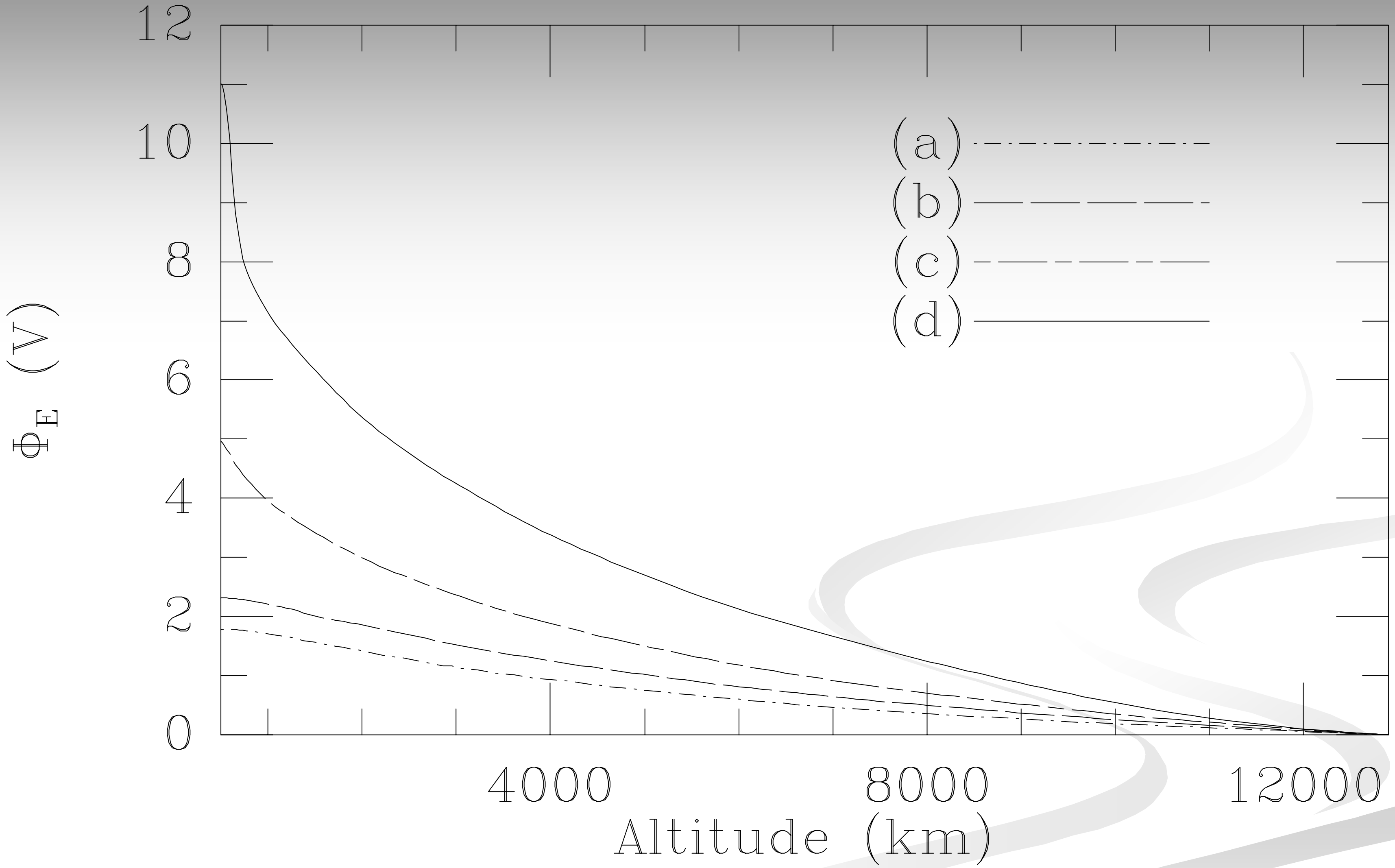
  (c) $n_s/n_e = 10^{-3}$

  (d) $n_s/n_e = 1.5\times10^{-3}$

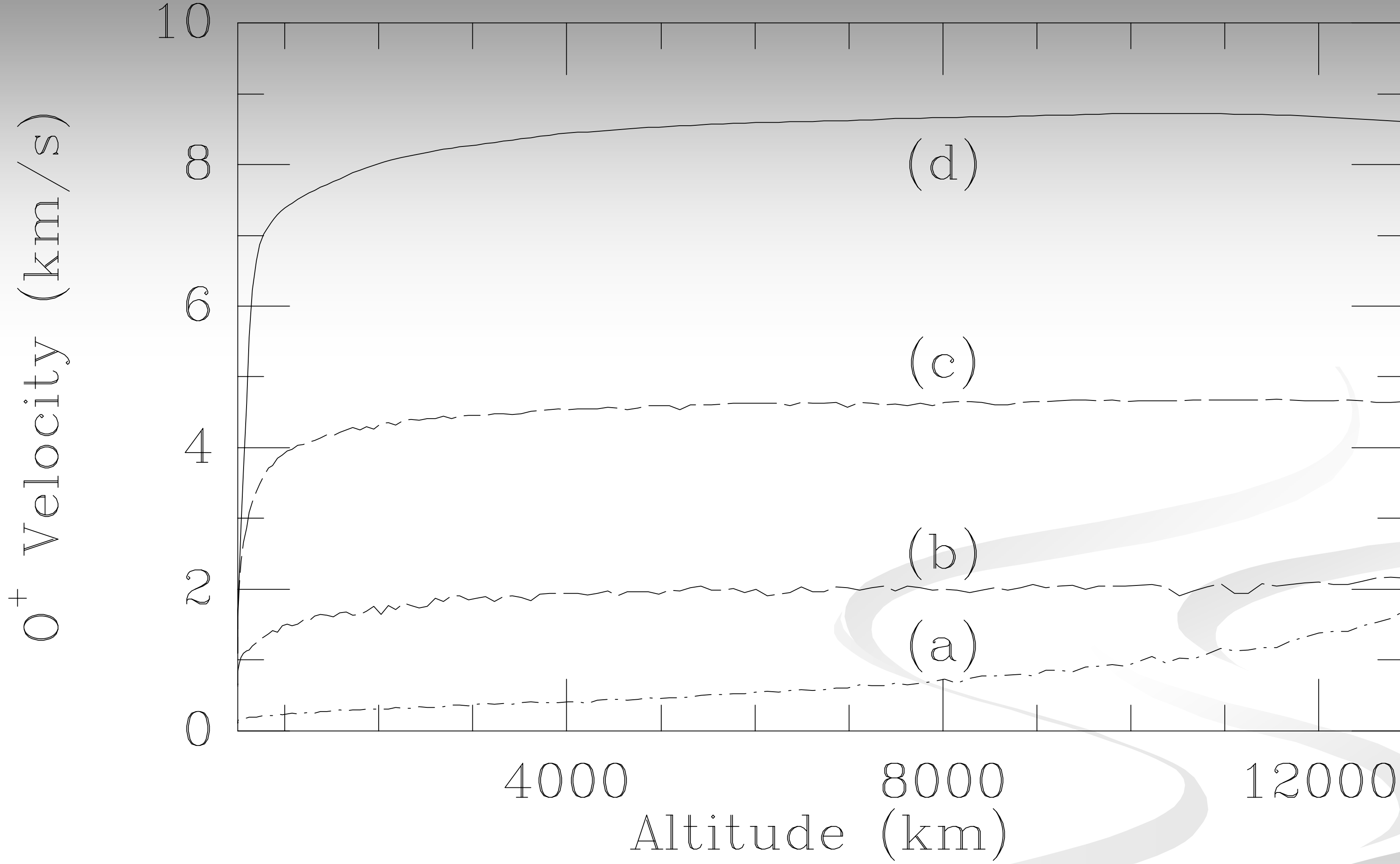
  Other boundary parameters identical for all cases
- (a) to (d): gradual transition from night-time to daytime

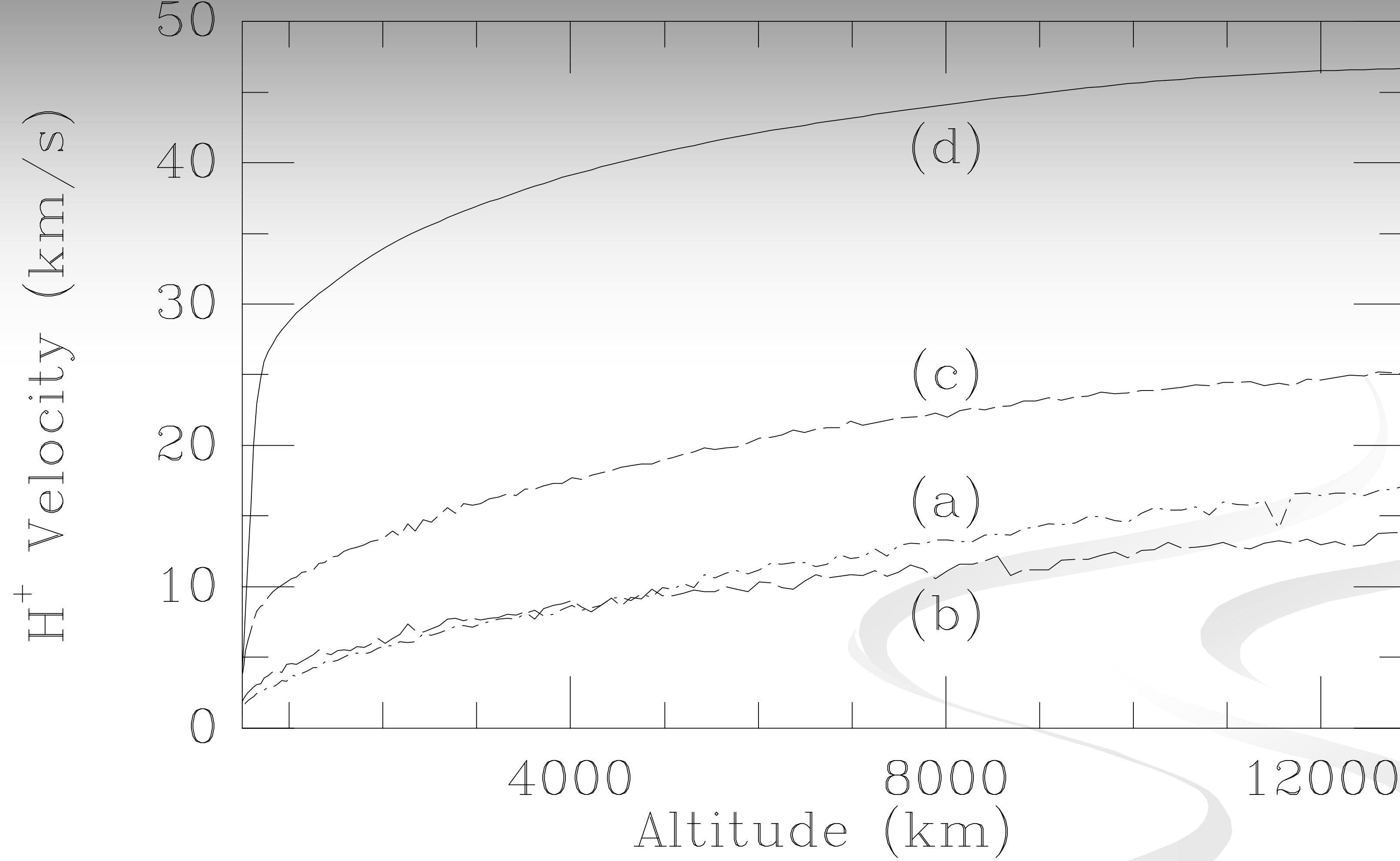


.01
.008
.006
.004
.002
0
n_s/n_e
4000
8000
12000
Altitude (km)
(b)
(c)
(d)

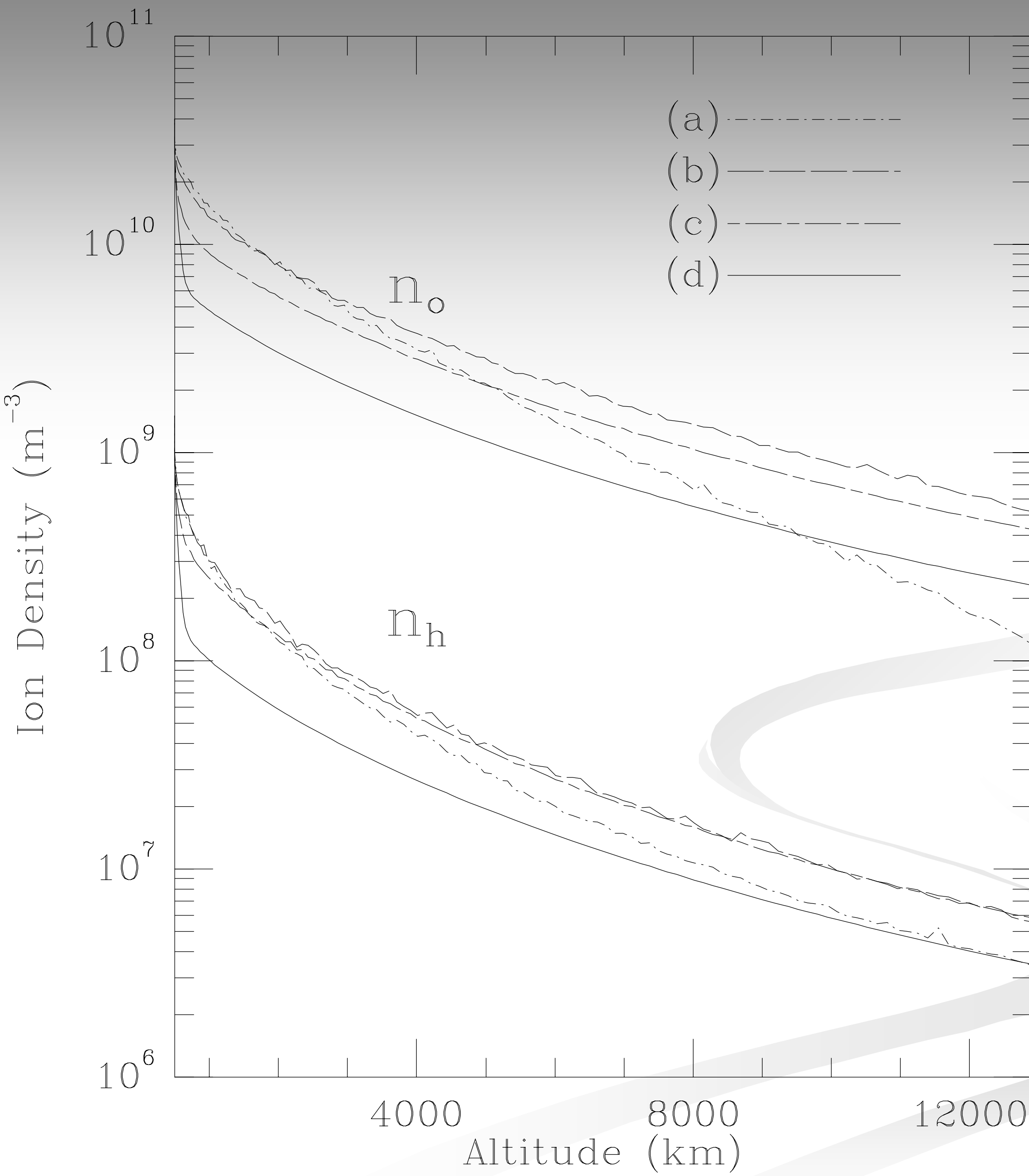


12
10
8
6
4
2
0
Φ_E (V)
(a)
(b)
(c)
(d)
4000
8000
12000
Altitude (km)


10
8
6
4
2
0
(d)
(c)
(b)
(a)
4000
8000
12000
Altitude (km)
O+ Velocity (km/s)



50
40
30
20
10
0
H+ Velocity (km/s)
(d)
(c)
(a)
(b)
4000
8000
12000
Altitude (km)



10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
Ion Density (m^{-3})
4000
8000
12000
Altitude (km)
(a)
(b)
(c)
(d)
n_o
n_h

Non-Local Kinetic Collisional Polar Wind Formulation

- 1-D flow along field line: distance *s*
- Gyrotropic approximation: $\mathbf{v}_\perp \rightarrow v_\perp$
- Steady-state kinetic equation for species *j*:

$$\left[v_\parallel \frac{\partial}{\partial s} - \left(g - \frac{q_j}{m_j} E_\parallel \right) \frac{\partial}{\partial v_\parallel} - v_\perp^2 \frac{B'}{2B} \left(\frac{\partial}{\partial v_\parallel} - \frac{v_\parallel}{v_\perp} \frac{\partial}{\partial v_\perp} \right) \right] f_j = \sum_i \left(\frac{\delta f_j}{\delta t} \right)_i$$

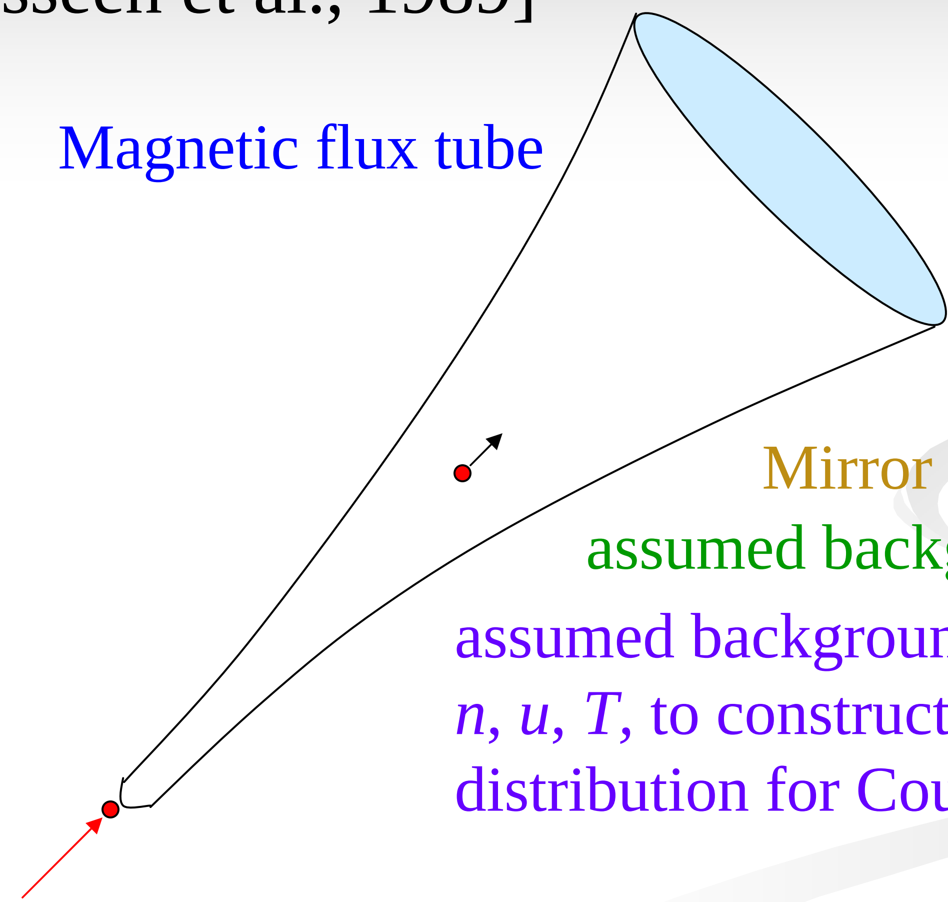
$f_j = f_j(s, v_\parallel, v_\perp)$; $B' \equiv dB/ds$;

$(\delta f_j / \delta t)_i$: collisional term due to Coulomb interactions with species *i*

Difficulty: $\left(\delta f_j / \delta t\right)_j$ is **nonlinear** in f_j

Non-Local Kinetic Collisional Test-Particle Model [Tam et al., 1995a]

- Monte Carlo calculations [Retterer et al., 1983; Yasseen et al., 1989]



Magnetic flux tube

Obtain $f(v_{\parallel}, v_{\perp})$ at all grid points s to find $f(s, v_{\parallel}, v_{\perp})$

Mirror force

assumed background E field profile

assumed background thermal particle profiles, *n*, *u*, *T*, to construct drifting Maxwellian distribution for Coulomb interactions

Test particles (H^{+}, O^{+}, and photoelectrons)

Non-Local Kinetic Collisional Test-Particle Model

- Approximation in formulation:

$$\left[v_{\|}\frac{\partial}{\partial s} - \left(g - \frac{q_j}{m_j}\tilde{E}_{\|} \right)\frac{\partial}{\partial v_{\|}} - v_{\perp}^2 \frac{B'}{2B}\left(\frac{\partial}{\partial v_{\|}} - \frac{v_{\|}}{v_{\perp}}\frac{\partial}{\partial v_{\perp}} \right) \right] f_j = \sum_i L_{coll,FP,i}(\tilde{f}_i)\, f_j$$

where $L_{coll,FP}$ is the linearized Fokker-Planck Coulomb collision operator, and $\tilde{E}_{\|}$ and $\tilde{f}_i$ are assumed background

Fluid Equations for the entire (thermal + suprathermal) electron populations

Momentum equation

$$B\frac{\partial}{\partial s}\left(\frac{n_e T_e + n_e m_e u_e^2 + n_s T_{s\parallel} + n_s m_e u_s^2}{B}\right) + (n_e + n_s)\left(m_e \frac{\partial \Phi_G}{\partial s} - e\frac{\partial \Phi_E}{\partial s}\right) + \frac{B'}{B}\left(n_e T_e + n_s T_{s\perp}\right) = \frac{\delta M_e}{\delta t} + \frac{\delta M_s}{\delta t}$$

Energy equation

$$B\frac{\partial}{\partial s}\left[\frac{n_e u_e}{B}\left(\frac{5}{2}T_e + \frac{m_e u_e^2}{2}\right) + \frac{Q_{ws}}{B} + \left(\frac{n_e u_e}{B} + \frac{n_s u_s}{B}\right)\left(m_e \Phi_G - e\Phi_E\right)\right] = \frac{\delta \mathcal{E}_e}{\delta t} + \frac{\delta \mathcal{E}_s}{\delta t}$$

Closure assumption: thermal electron heat flux, $Q_e = 0$

- Collisional time scales for thermal electrons extremely short compared with those for other particle species → **fluid treatment**

- Collisional transfer of momentum and energy in fluid equations for thermal electrons, $\delta M_e / \delta t$ and $\delta E_e / \delta t$, determined from kinetic calculations (conservation laws)

Key procedure: Iteration between kinetic and fluid calculations

Convergence of Results → a self-consistent background

- A self-consistent background for $L_{coll,FP}$
- Self-consistent $\delta M_e/\delta t$ and $\delta E_e/\delta t$
- Self-consistent ambipolar electric field

Fast Solar Wind

- Proton core anisotropy: perpendicular temperature higher than parallel temperature

  Indication of ion perpendicular heating
- Preferential acceleration of the alpha particles over the protons
- Double-peaked proton velocity distribution
- Kinetic ion cyclotron resonance (?)

Application to the Fast Solar Wind

- Modification from the polar wind model:

  1. $H^{+}, O^{+} \rightarrow H^{+}, He^{2+}$

  2. suprathermal electrons: anti-sunward tail of the Maxwellian electron distribution at the lower boundary (corona)

- New: kinetic wave-particle interactions (ion cyclotron resonance)

Effects of Ion Cyclotron Resonant Heating

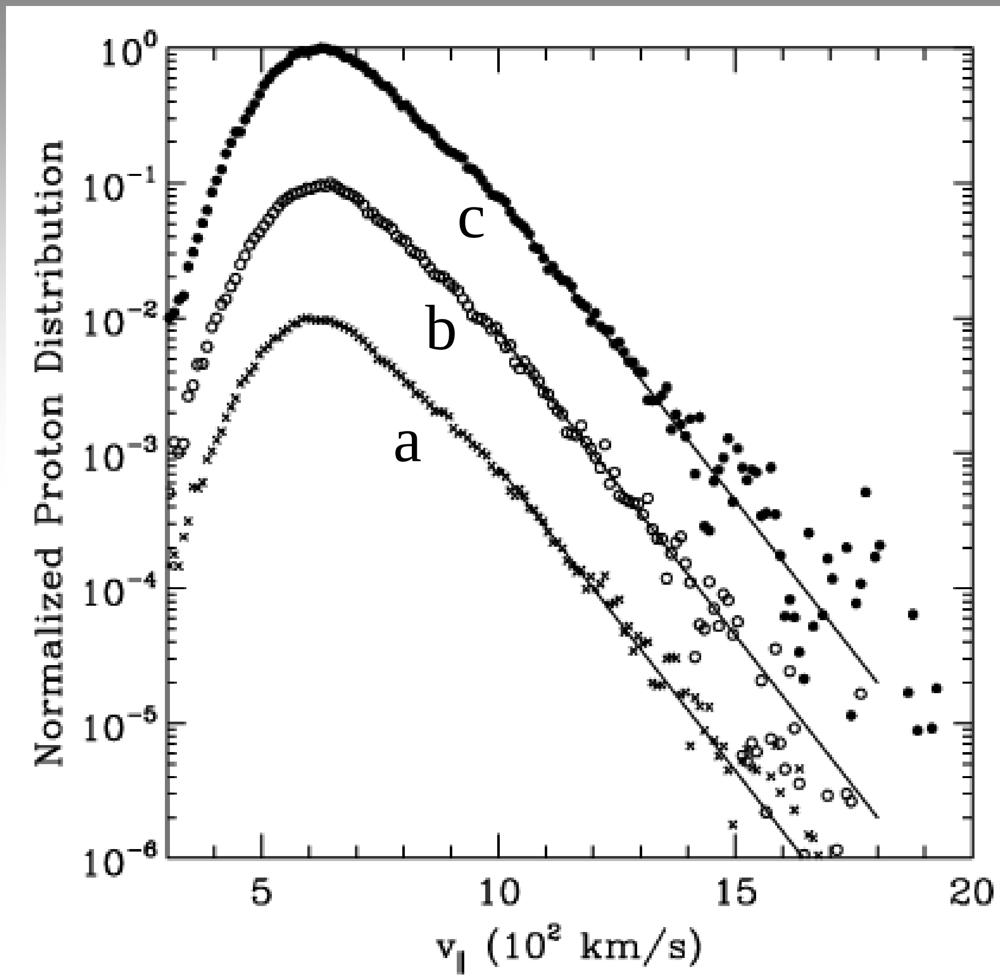
- Diffusion:

$$\left[v_{\parallel}\frac{\partial}{\partial s} - \left(g - \frac{q_j}{m_j}E_{\parallel} \right)\frac{\partial}{\partial v_{\parallel}} - v_{\perp}^2 \frac{B'}{2B}\left(\frac{\partial}{\partial v_{\parallel}} - \frac{v_{\parallel}}{v_{\perp}}\frac{\partial}{\partial v_{\perp}} \right) \right] f_j = \sum_i \left(\frac{\delta f_j}{\delta t} \right)_i + D_j f_j$$

where $D_j = \frac{\partial}{\partial v_{\parallel}} D_{j\parallel} \frac{\partial}{\partial v_{\parallel}} + \frac{1}{v_{\perp}}\frac{\partial}{\partial v_{\perp}}\left(v_{\perp} D_{j\perp}\frac{\partial}{\partial v_{\perp}} \right)$

$D_{j\parallel}$ *and* $D_{j\perp}$ *depends on s and* $v_{\parallel}$, but not f_j

- Diffusion term rewritten in Fokker-Planck form, incorporated into Monte Carlo calculations



Formation of **double-peaked** proton velocity distribution (due to the presence of sunward propagating waves)

[Tam and Chang, 2002]

a to c: increasing sunward propagating waves

Summary

- Self-consistent hybrid model: kinetic + fluid calculations over the same altitude range
- Kinetic: all the ions and suprathermal electrons (Reason: non-thermal and/or kinetic effects, including velocity filtration effect due to collisions)
- Fluid: thermal electrons (Reason: extremely short collisional time scales)
- Key of Model: Iteration for self-consistency