Thermally driven winds

Viggo H. Hansteen
Insititute of Theoretical Astrophysics, University of Oslo

Introduction

e last decade has seen a large change in our understand
he solar wind, due both theoretical, computational, an
ervational advances

Recent models characterized by

- low electron temperature
- electric field is unimportant
- high proton and ion temperatures
- are able to achieve high velocity....

Overview

ogress largely due observations with instruments
board Ulysses and SOHO that have spawned a ne
derstanding of solar wind energetics, and the
nsideration of the chromosphere, corona and solar
nd as one unified system

- A pocket history
- The solar wind mass flux
- Energetics and the importance of including the chromosphere
- Hot ions and mass proportional temperatures

There are many ways to start the history of the solar wind...

...Kristian Birkeland (1896) suggested that the aurora borealis caused by electricall
charged particles

...in the 1930's Chapman gnetic storms explained by
cl sun

...in the late 1940's Forbus ty of cosmic rays was lowe

...in the early 1950's Bier pressure from the sun was
not sufficient to account are blown away from the

Edlén (1942) & Grotrian realized that emission lines observed in the corona
ie Fe X & Fe XIV implied a temperature of some MK.

$$\sqrt{kT/m} \simeq 100\ \mathrm{km/s} \ll u_\infty = \sqrt{2GM/R_S} = 618\ \mathrm{km}$$

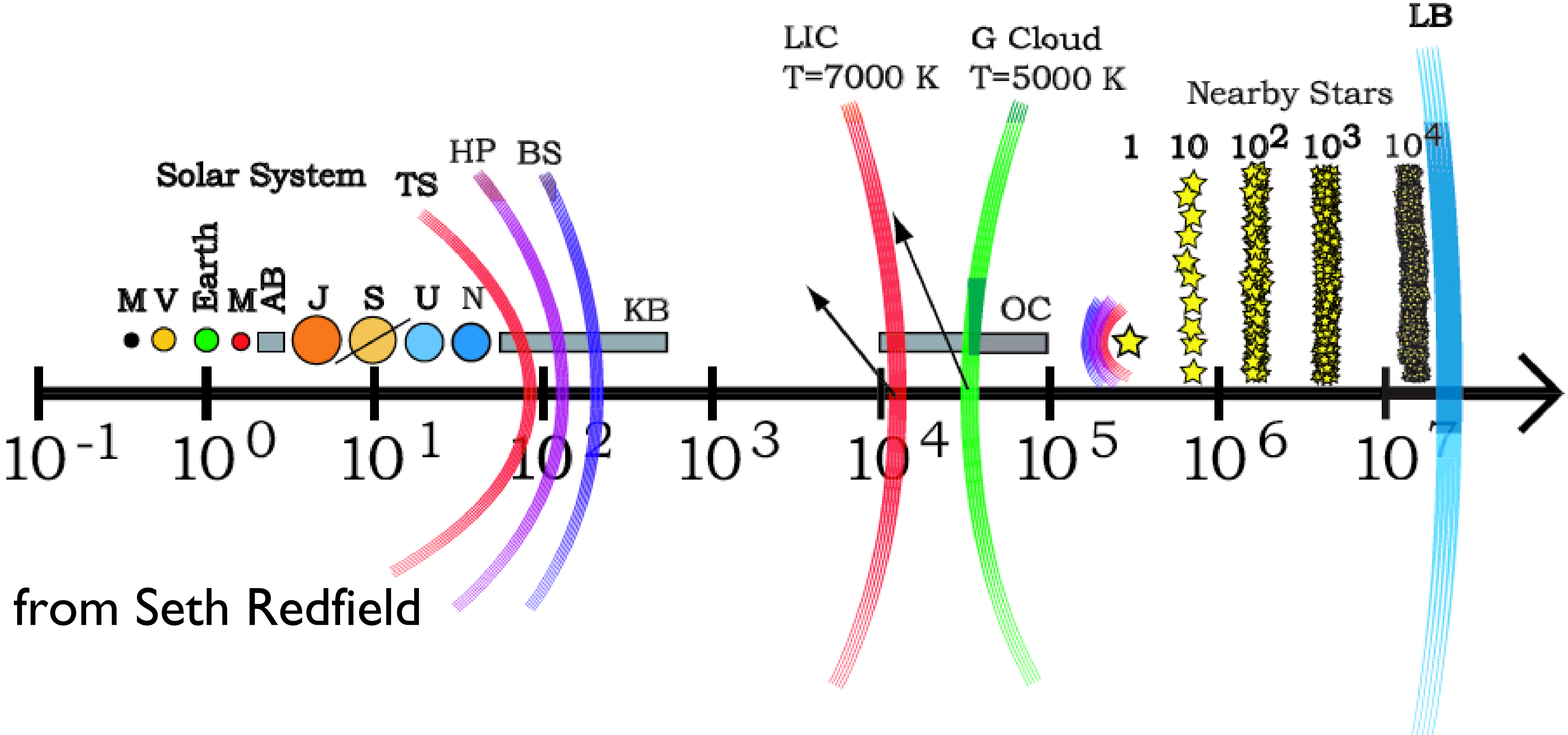

Figure from Seth Redfield

- with dimension 100pc (as close as 60pc as far as 250pc or unbound) T~10^6K, n~5×10^3m^{-3} contains some 10^5 stars

- Heliosphere immersed in warm cloud 'Local Interstellar Cloud', partially ionized

atmosphere

Chapman (1957) - and Alfvén (1941!) - showed that consequence of thermal conduction is that a hot corona is extended: that a hydrostatic solution to this temperature structure could be found to extend to infinity

$$
\begin{aligned}
\frac{d}{dr}(2nkT) &= -nm\frac{GM}{r^2} \\
n(r)T(r) &= n_0T_0 \exp\left[-\frac{GMm}{2k}\int_R^r \frac{dr}{r^2T(r)}\right] \\
\Rightarrow & \quad \lim_{r\to\infty} n(r)T(r) > 0
\end{aligned}
$$

Thus, if the temperature falls less rapidly than (1/r) we must expect a non-van
pressure at infinity.

In particular we find that this pressure is much larger than any conceivable inte
pressure, ~ 10^{17} for $n_0T_0 = 10^{14}\,m^{-3}\,10^6$ K and isothermal compared to ~ 10^9 meas

Mass, momentum, and energy conservation

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

$$\nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla \left(p + \frac{B^2}{2\mu_0} \right) + \frac{\mathbf{B}}{\mu_0} \cdot \nabla \mathbf{B} + \rho \mathbf{g}$$

$$\nabla \cdot [(\frac{5}{2}p + \frac{1}{2}\mathrm{u}^2)\mathbf{u} + \mathbf{q} + \mathbf{F}] = \rho \mathrm{u} \cdot \mathbf{g}$$

fluid, isothermal wind

Parker (1958) => Sub-supersonic wind: Assuming that thermal conduction is very efficient we may set up the equations of mass conservation and force balance to derive the "solar wind equation"

$$M = 4\pi\rho u r^2$$

$$u\frac{du}{dr} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{GM_S}{r^2}$$

with

$$p = \rho kT/m = 2nkT$$

give

$$\frac{1}{u}\frac{du}{dr}\{u^2 - 2kT/m_p\} = \{\frac{4kT}{m_p r} - \frac{GM_S}{r^2}\}$$

The solution we are interested in passes through a critical point

$$\frac{m_p G M_S}{\ldots} \qquad \sqrt{\frac{2kT}{\ldots}}$$

Solar wind

tegration of the force balance from the "coronal base" to the critical point to the tical point shows the density structure of the corona in the solar wind solution

$$\rho_c = \rho(r_c) = \rho_0 \exp\{-\frac{m_p G M_S}{2kTR_S} + \frac{3}{2}\}$$

Ve can find the resultant mass flux by examining the density and the velocity at the itical point

$$(nu)_E = n_c u_c \frac{r_c^2}{r_E^2}$$
$$\propto \rho_0 T^{-3/2} \exp\left[-\frac{C}{T}\right]$$

this ties together to a very successful model which was confirmed by the Mariner

The Parker Spiral

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Fast wind, slow wind, CME

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Corona and Coronal Holes

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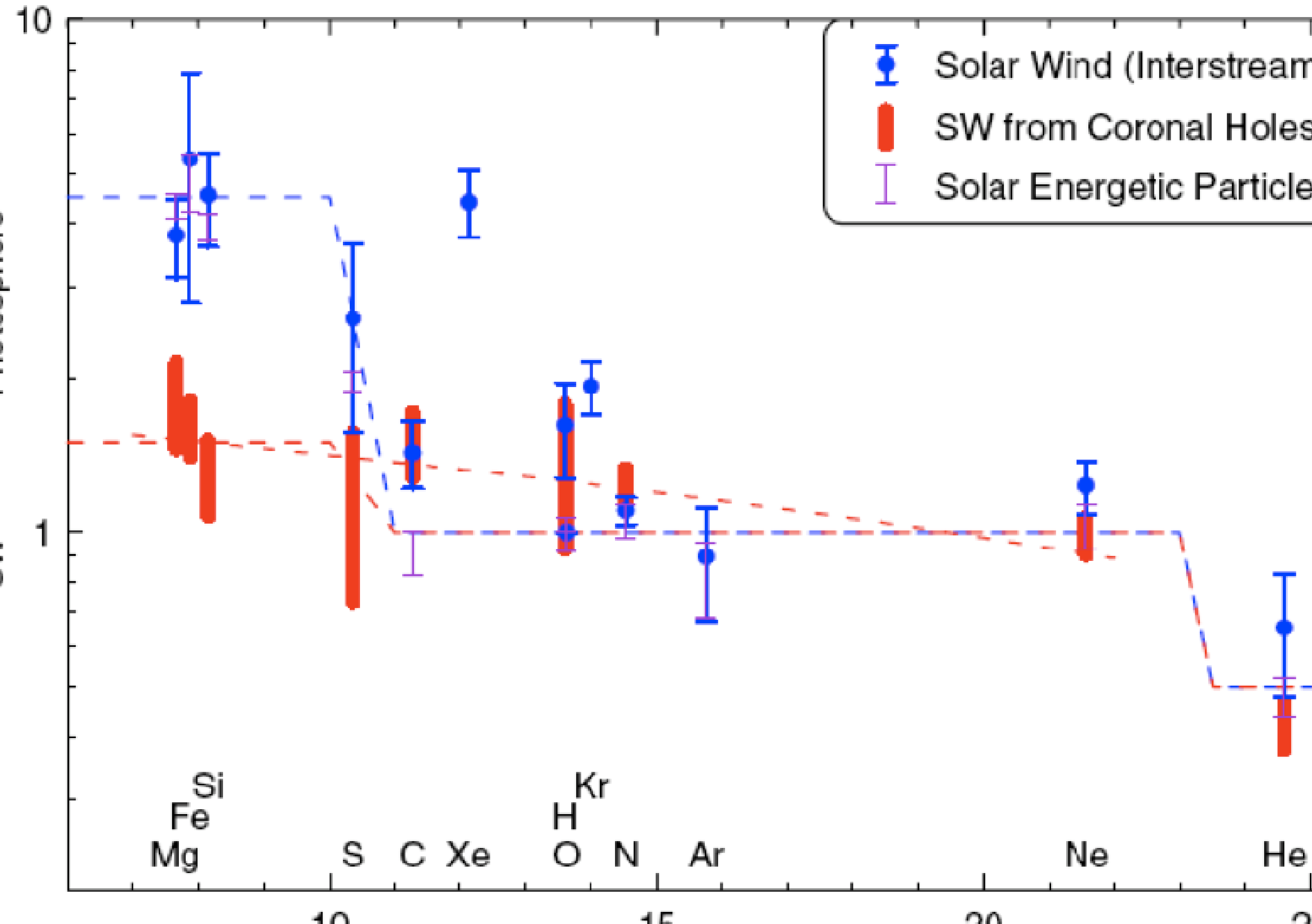
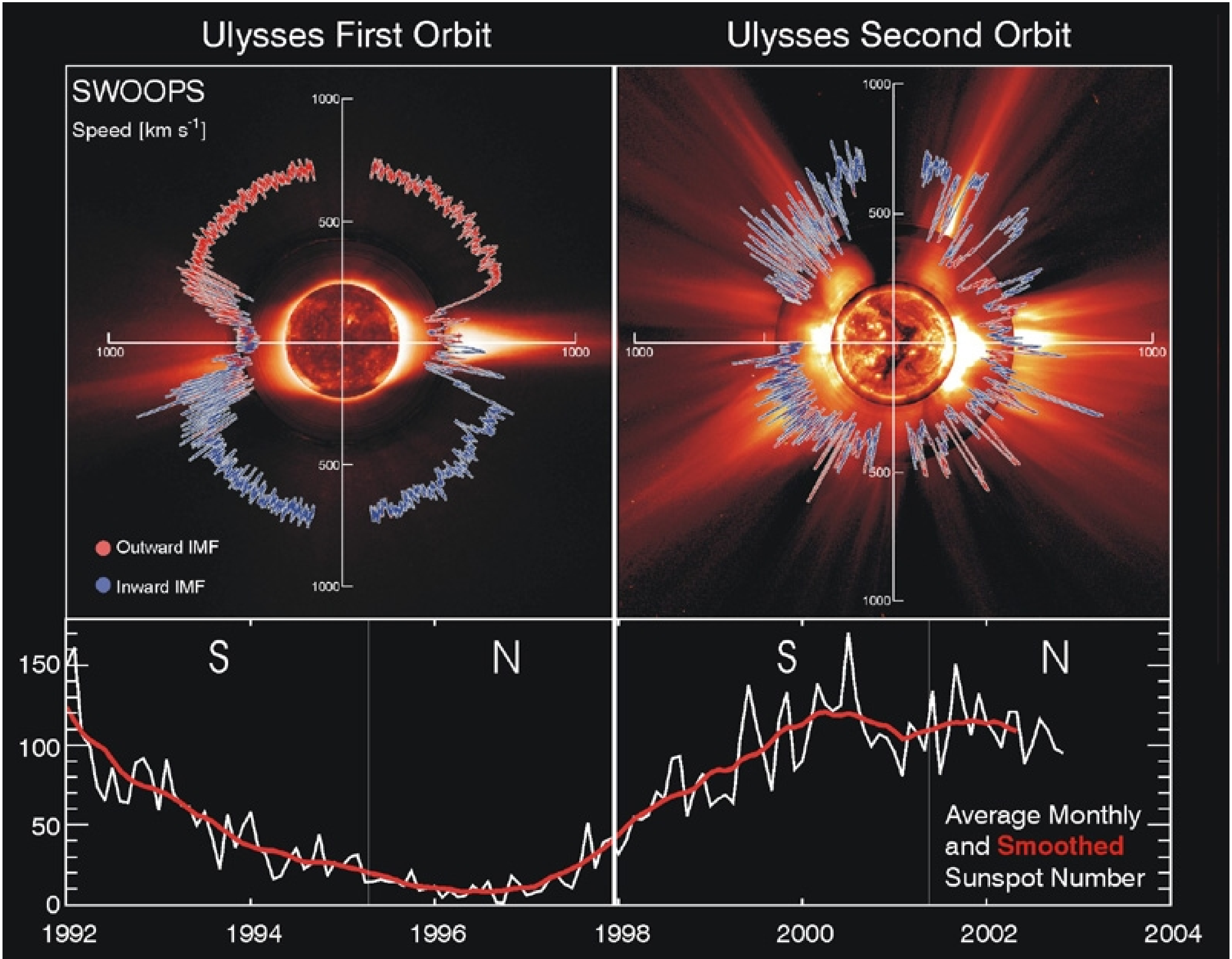
(some) solar wind properties



d model - to simplify & illustrat

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

So far so good, but...



...a pocket history continued

Measurements of high speed streams show that u > 700 km/s

This is difficult to achieve without adding energy beyond the coronal base (Parker 1965).

Leer & Holzer (1980) showed that this energy must be added beyond the critical point in order to combine a low mass flux with a large asymptotic flow speed.

Energy (or forces) added inside the critical point will increase the scale height and thus the mass flux

... this may actually result in a reduced asymptotic flow speed.

The second "problem" is that the proton flux in this type of model is extrem
sensitive to the coronal temperature.

An interlude with Alfvén waves

(with thanks to J. Hollweg)

ALFVÉN WAVES IN A TWO-FLUID MODEL OF THE SOLAR WIND

JOSEPH V. HOLLWEG*
Department of Physics, California Institute of Technology; and
Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, Federal Republic of Germany

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ABSTRACT

We present a two-fluid model for the solar wind which includes the presence of Alfvén waves which originate at the Sun. The effective pressure of the Alfvén waves is included, as well as a model representation for proton heating via nonlinear damping of the Alfvén waves. The effects of rotation in the solar equatorial plane are self-consistently included. Our principal results are summarized as follows:

1) Our calculations reproduce the T_p-v correlation at 1 a.u. quite well for $v \lesssim 450$ km s^{-1}. This supports the idea that Alfvén waves of solar origin are responsible for the high-speed streams.

2) An Alfvénic energy flux of 6000 ergs cm^{-2} s^{-1} at the Sun yields values for T_p, v, and n at 1 a.u. which agree well with the data.

3) Wave pressure tends to produce a positive n-v correlation at 1 a.u., contrary to the observed negative correlation. This suggests that the cross-section of the high-speed streams may increase more rapidly than r^2.

4) Including the spiral magnetic field in the electron energy equation worsens the disagreement between observed and calculated values of T_e at 1 a.u., if the electron heat conductivity is given by the collisional value. More work on the electron energy equation is needed.

5) Peripheral to our main theme, we present (*a*) general derivation of the conservation equations in the presence of Alfvén waves; (*b*) a simple, new derivation for the properties of Alfvén waves in a spiral field; and (*c*) a new power series for the electron temperature near $r = \infty$, in the presence

Time average conservation equations

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla \left(p + \frac{\langle \delta B^2 \rangle}{2\mu_0} \right) + \rho \mathbf{g}$$

$$\nabla \frac{3p}{2\rho} + p\nabla \cdot \mathbf{u} = -\nabla \cdot [\mathbf{q} + \mathbf{S} + \frac{1}{2}\rho \langle \delta \mathrm{u}^2 \rangle \mathbf{u}] + \mathbf{u} \cdot \nabla (\langle \delta B^2 \rangle /$$

$$\mathbf{S} = (\langle \delta B^2 \rangle / \mu_0)(\mathbf{u} \pm \mathbf{v}_A) \qquad \mathbf{v}_A = \mathbf{B}(\mu_0 \rho)^{-1/2}$$

$$\langle \delta B^2 \rangle$$

Wave pressure variation with distance from the Sun

$$Q = -\frac{1}{r^2}\frac{d}{dr}[r^2(S_r + \frac{1}{2}\rho \mathrm{u}\langle \delta \mathrm{u}^2\rangle)] + \frac{\mathrm{u}}{2\mu_0}\frac{d}{dr}\langle \delta B^2\rangle = 0$$

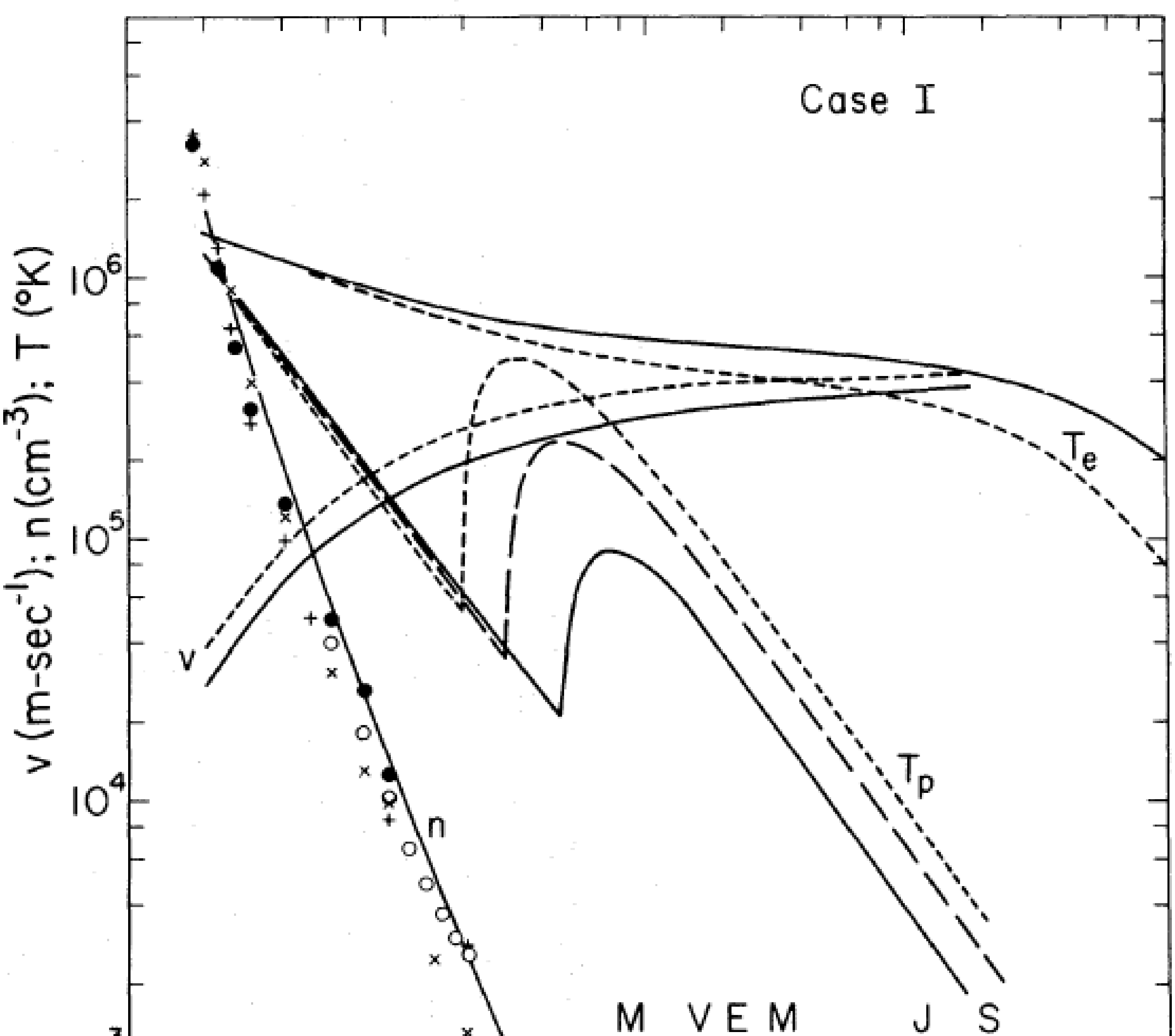
$$S_r = \frac{\langle \delta B^2\rangle}{\mu_0}(\mathrm{u} + \mathrm{v}_{Ar}) \qquad \frac{1}{2}\langle \delta \mathrm{u}^2\rangle = \frac{\langle \delta B^2\rangle}{2\mu_0}$$

$$-\frac{d}{dr}[\langle \delta B^2\rangle(3\mathrm{u}r^2 + 2\mathrm{v}_{Ar}r^2)] + \mathrm{u}r^2\frac{d\langle \delta B^2\rangle}{dr} = 0.$$

$$\mathrm{u}r^2 - a/\rho, \qquad \mathrm{v}_{Ar}r^2 - b/\rho^{1/2}$$

$$B^2\rangle^{-1}\frac{d\langle \delta B^2\rangle}{dr} - \frac{3}{2\rho}\frac{d\rho}{dr} + 2\left(1 + \frac{\mathrm{v}_{Ar}}{\mathrm{u}}\right)^{-1}\frac{d}{dr}\left(1 + \frac{\mathrm{v}_{Ar}}{\mathrm{u}}\right) =$$

Wave pressure variation with distance from the Sun II



The coronal He abundance and the proton flux

$$[\frac{\partial u_s}{\partial t} + (u_s \frac{\partial}{\partial r}) u_s] + \frac{\partial p_s}{\partial r} - eZ_s n_s E + \rho_s \frac{GM_S}{r^2} = \frac{\delta M_s}{\delta t} + \rho_s D_s$$

$$\frac{\delta M_s}{\delta t} = -\sum_t (n_s \nu_{st} + n_t \gamma_{ts}) m_s (u_s - u_t) + \sum_t \nu_{st} z_{st} (\mu_{st}/kT_{st}) [q_s - \frac{\rho_s}{\rho_t} q_t],$$

$$eE = -\frac{1}{\ldots} \frac{dp_e}{\ldots} - \frac{15}{\ldots} \frac{\nu_{ep} + \nu_{e\alpha}}{\ldots} k \frac{dT_e}{\ldots}$$

Wind from a helium dominated corona

Assume that the corona contains a significant He abundance

It turns out that if the helium abundance is greater than some 20-30% the proton and helium scale heights are roughly the same and the balance of forces on protons are determined by the (inward) gravity, friction and the (outward) electric field

In this case Helium acts as a 'governor' for the proton flux through
a) increased frictional coupling when the temperature is high
b) an increased electric polarization field when the temperature is low

$$(n_{\mathrm{p}} u_{\mathrm{p}}) \approx \frac{G M_{\mathrm{S}}}{r_{\mathrm{E}}^2} \left(\frac{n_{\mathrm{p}}}{\nu_{\alpha \mathrm{p}}} \right) \frac{5}{4(3 A_{\mathrm{He}} + 2)}$$

$$\nu_{st} = 1.7 \left(\frac{\ln \Lambda}{\;} \right) \left(\frac{m_p}{\;} \right) \left(\frac{\mu_{st}}{\;} \right)^{1/2} n_t T_{st}^{-3/2} Z_s^2 Z_t^2$$

Why helium rich corona?

- Difficult to pull “heavy” helium out of corona
- Thermal force brings ions up transition region temperature gradient and prevents gravitational settling down towards chromosphere
- Combination of these two effects very easily results in He abundance of > 30%...
- ...perhaps in accordance with slow wind

What is the thermal force?

- The thermal force results from the net effect of Coulomb collisions when heavy and light ions collide; heavy ions will collide with a 'skewed' distribution of light particles in a steep temperature gradient colliding more frequently with cool particles from below than with hot particles from above.
- This results in a net force on heavy ions up the temperature gradient...
- ...but is dependent on a correct descriptio

Construction of transport equations including collision terms

Multiply Boltzmann equation by moments of the velocity integrate over velocity space

Close system by assuming particle distribution function f_s

$$f_s = f_{s0}(1 - \phi)$$

A new description of the particle distribution function

$$\phi = \frac{m_s}{kT_s p_s}\left(1 - \frac{m_s c_s^2}{5kT_s}\right)\mathbf{q}_s \cdot \mathbf{c}_s$$

replaced by

$$\phi = \frac{m_s^2 c_s^2}{5k^2 T_s^2 p_s}\left(1 - \frac{m_s c_s^2}{7kT_s}\right)\mathbf{q}_s \cdot \mathbf{c}_s$$

al force reduced by ~ factor 4, but significant c

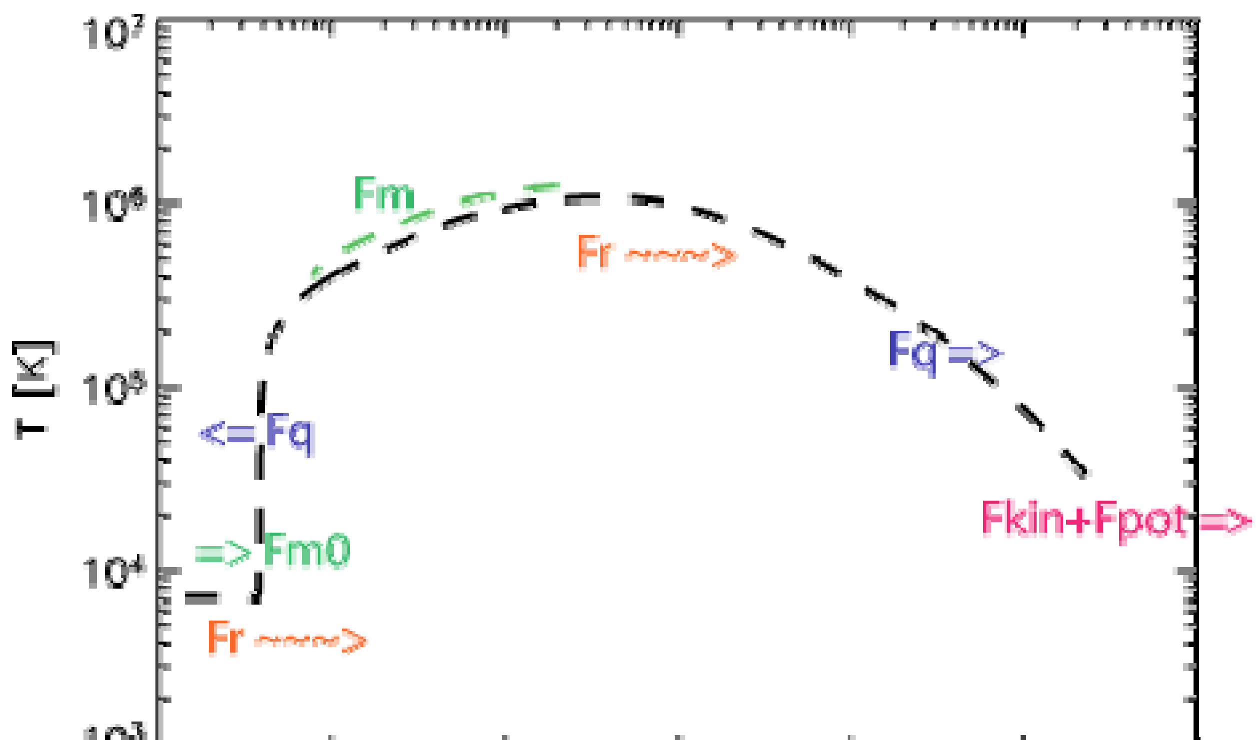
The energy budget

$$F_{m0} + F_{q0} + M(-\frac{1}{2}v_g^2 + \frac{1}{2}u_0^2 + \frac{\gamma}{\gamma - 1}\frac{p_0}{\rho_0})$$

$$= F_m + F_q + M(-\frac{GM_S}{r} + \frac{1}{2}u^2 + \frac{\gamma}{\gamma - 1}\frac{p}{\rho}) + F_r$$

where

$$F_r = \int_{r0}^{r} A n_e n_H f[T] dr$$



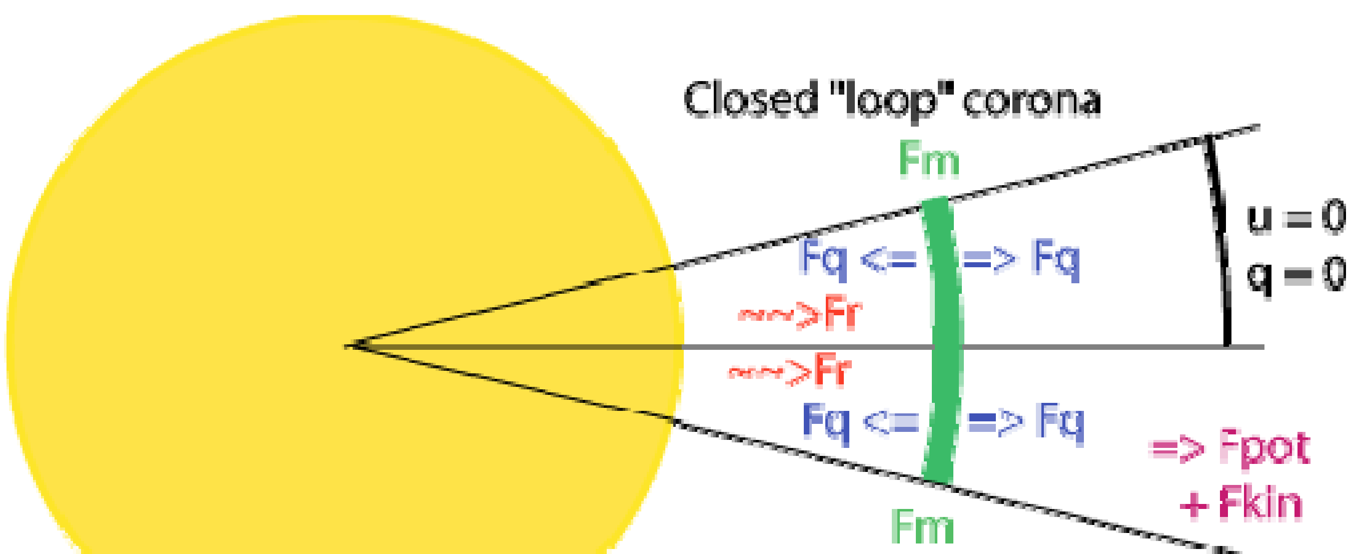
A simple example

Let us consider a case where we "turn off" the wind: this makes the energy budget very simple

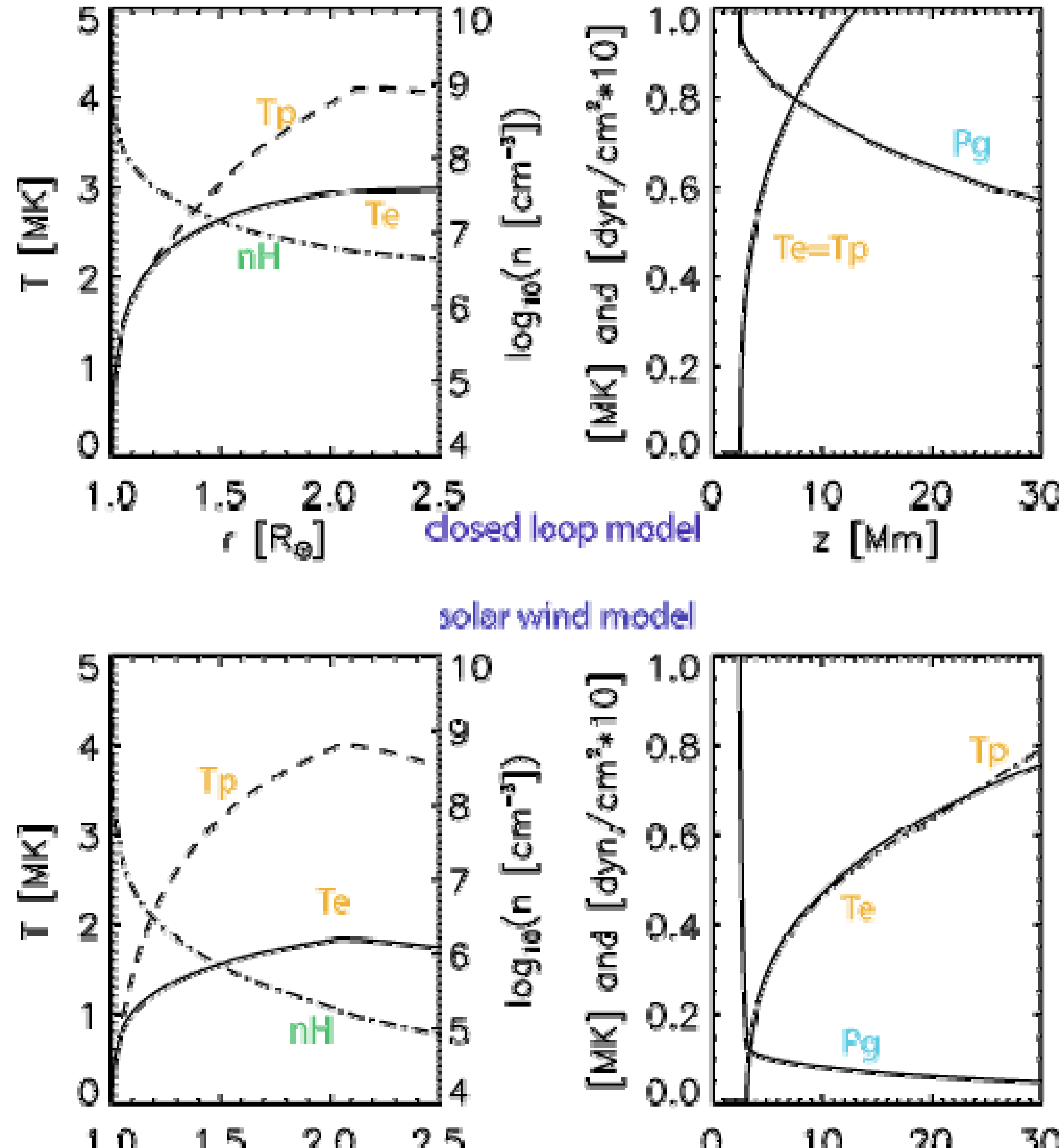
$$F_{m0} = F_m + F_q + F_r = F_{r\infty}$$

ve insert a "mechanical" heating energy flux that is dissipated at some sition, the energy balance is between radiation and thermal conduction.

us contrast this solution, similar to the Rosner, Tucker, Vaiana (1978) dels, with a solution that has identical heating but where the plasma is owed to flow into interplanetary space.



A simple example II



The mass flux

We can obtain an expression for the mass flux (also) by manipulating the integral energy equation:

$$(mnuA) = \frac{F_{m0} + F_{q0} - F_{q\infty} - F_{r\infty}}{\frac{1}{2}(v_g^2 - u_\infty^2)}$$

The question we can ask is:

What portion of the energy deposited in the outer solar atmosphere goes into driving the wind?

the chromosphere

der to answer our question we strive to solve for coronal heating and solar wind
eration as a coupled problem: i.e. no “coronal base”.

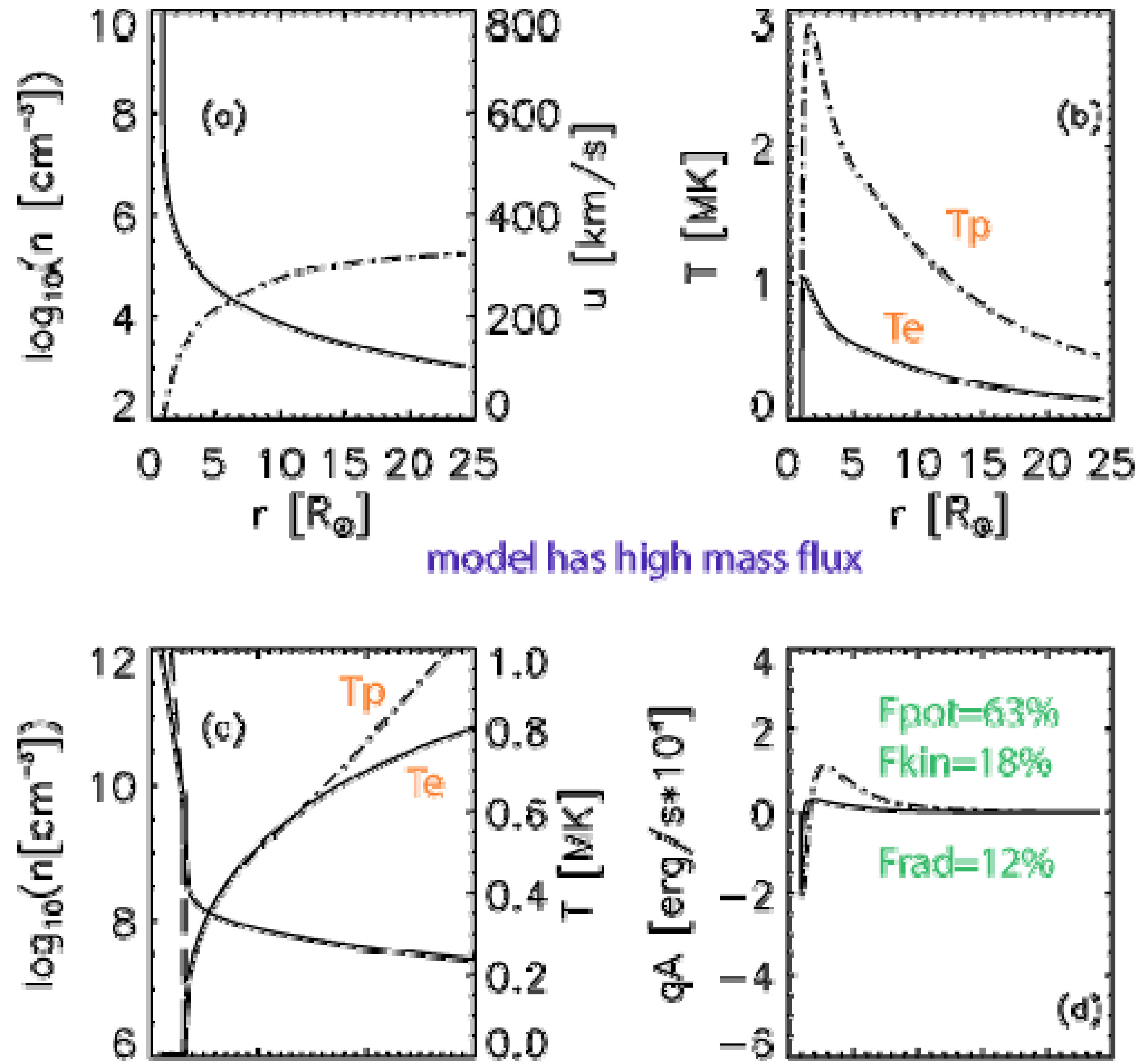
$$F_{\mathrm{m}} = F_{\mathrm{m0}} \exp\left[-(r - r_{\mathrm{m}})/H_{\mathrm{m}}\right]$$

with

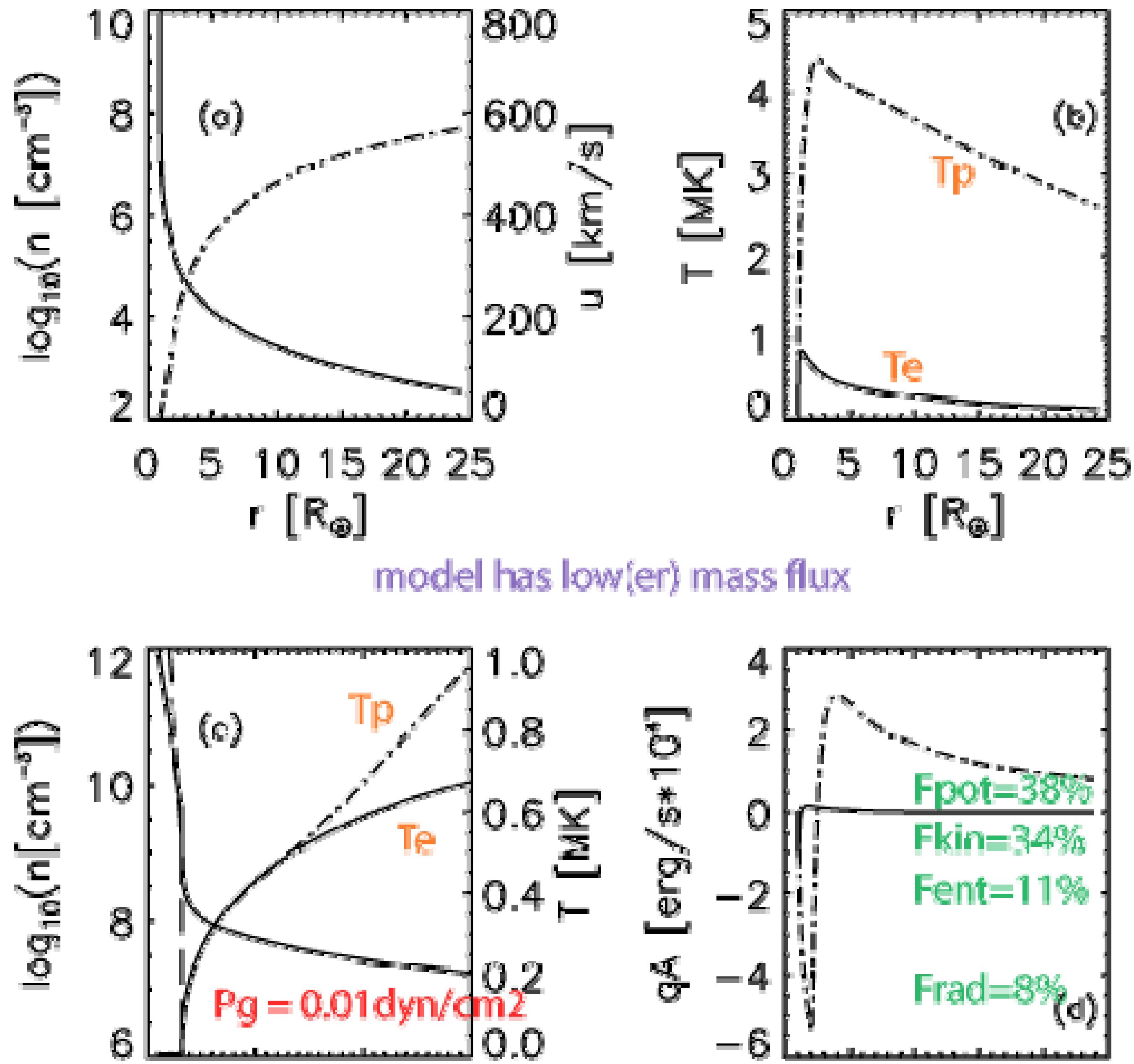
$$F_{\mathrm{m0}} = 100\,\mathrm{W/m^2}, \quad H_{\mathrm{m}} = 0.5\,R_{\mathrm{S}}$$

Let us vary r_m, % of energy into protons/electrons, include He, ...

region

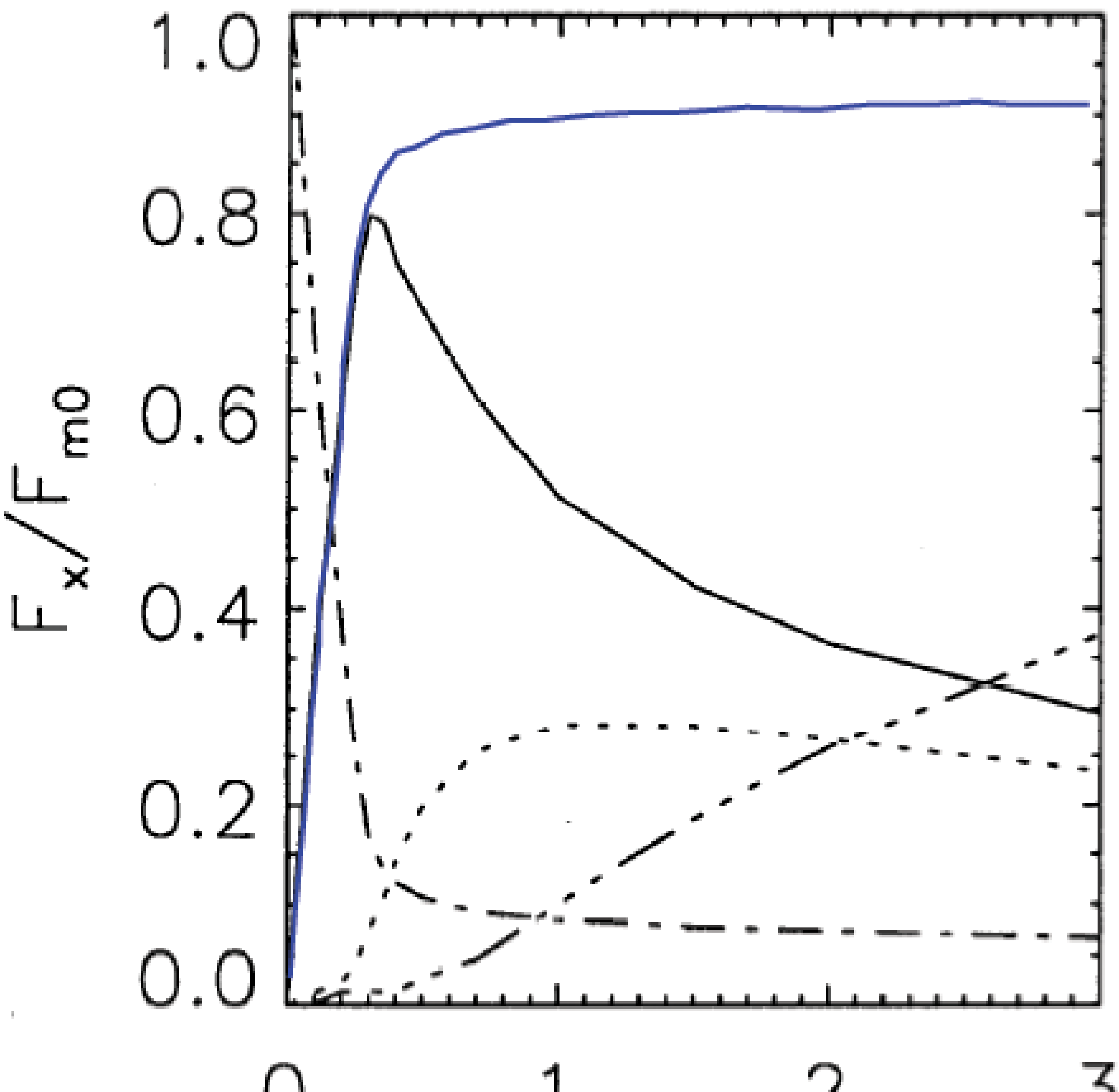

(a)
log10(n [cm-3])
u [km/s]
r [R⊙]
(b)
T [MK]
Tp
Te
r [R⊙]
model has high mass flux
(c)
log10(n[cm-3])
T [MK]
Tp
Te
(d)
qA [erg/s*10^4]
Fpot=63%
Fkin=18%
Frad=12%

Heating TRs from the photosphere

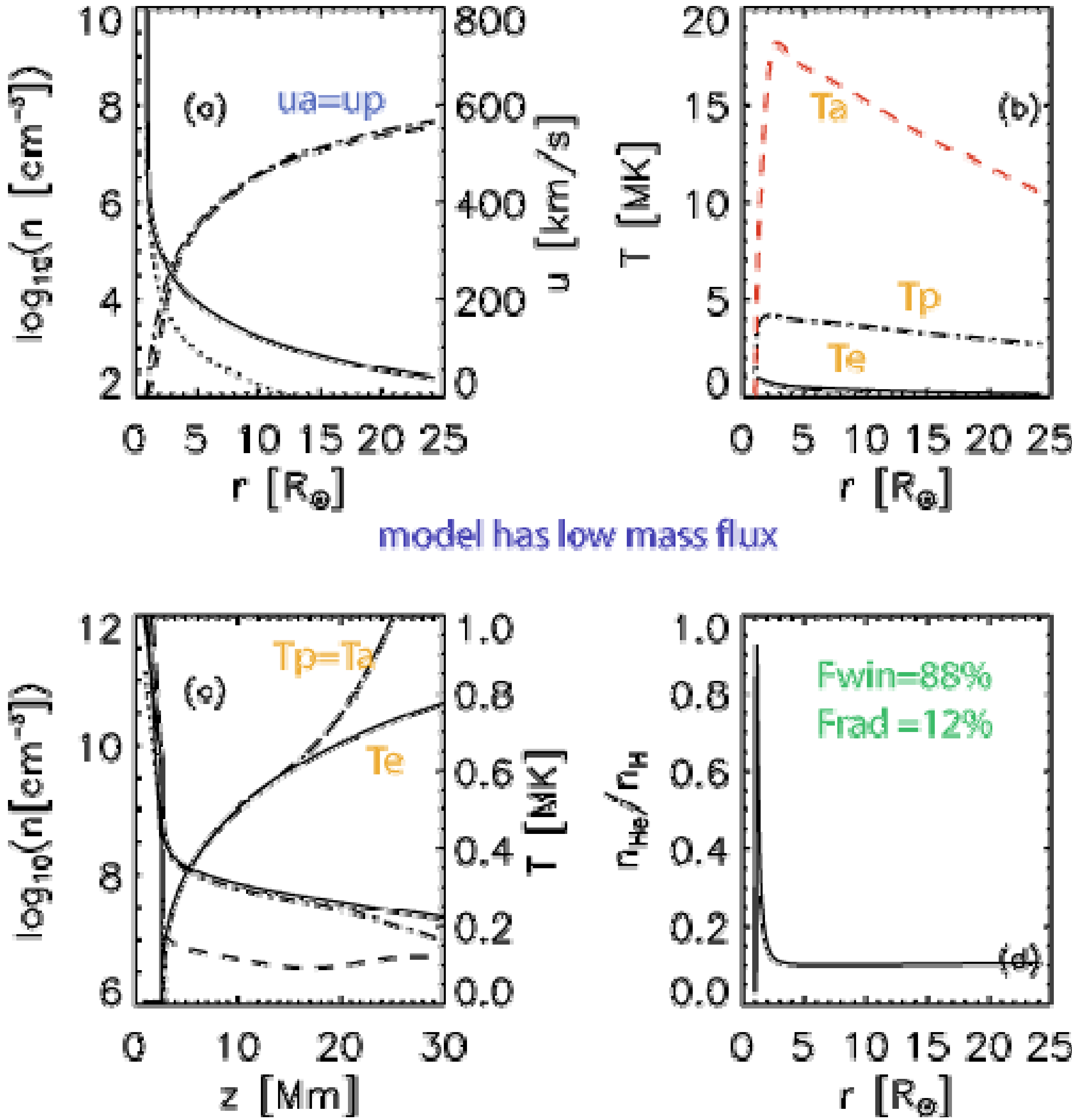


Radiation vs solar wind

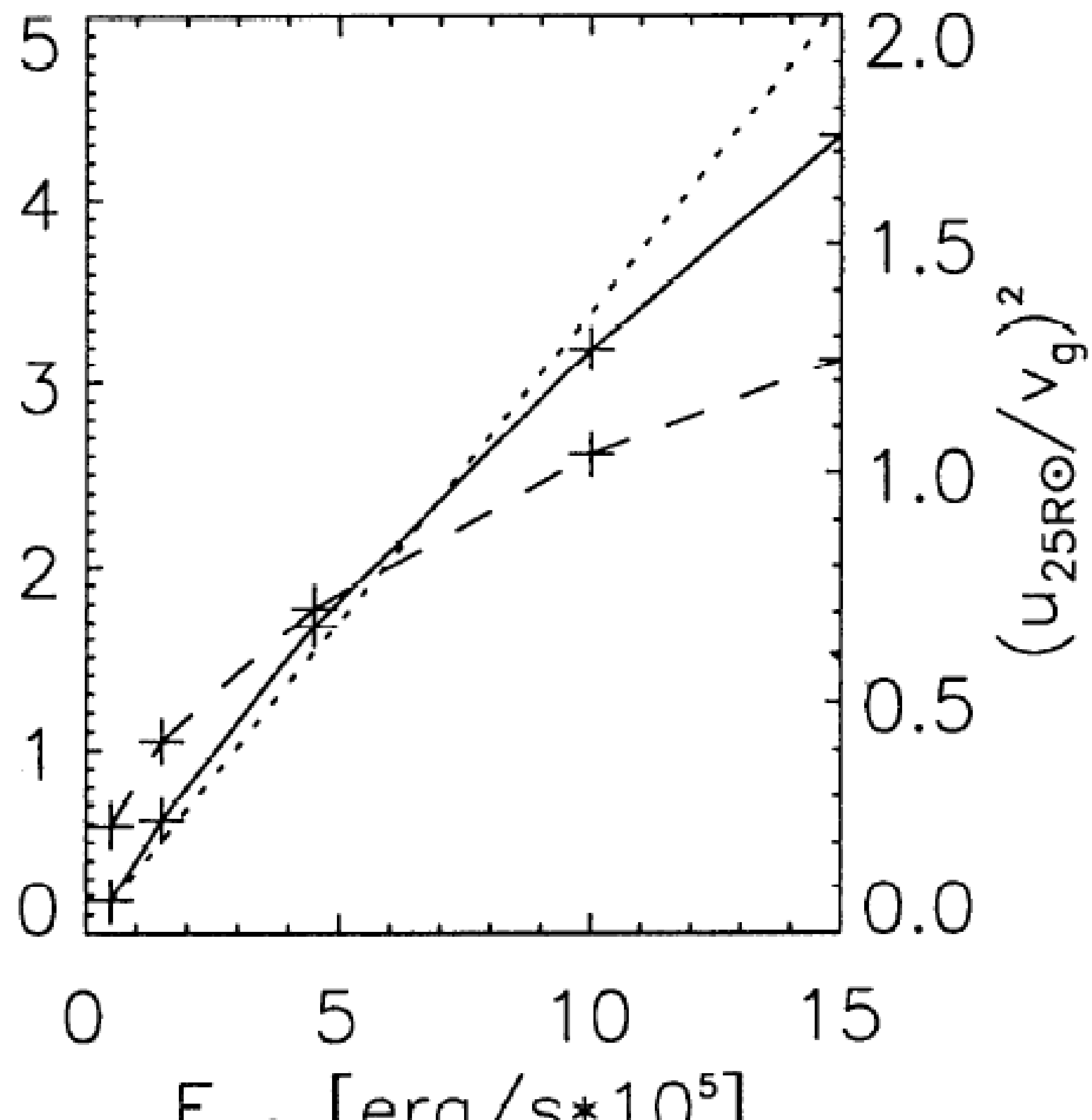
$$(mnuA) \approx \frac{F_{m0} + F_r}{\frac{1}{2}(v_g^2 + u_\infty^2)}$$



The effect of Helium



mechanical energy flux



$$(mnuA) \approx \frac{F_{m0}}{\frac{1}{2}(v_g^2 + u^2 \ldots}$$

$$A) \approx \frac{F\, mU}{\frac{1}{2}(v_g^2 + u_\infty^2)}$$

So far so good but

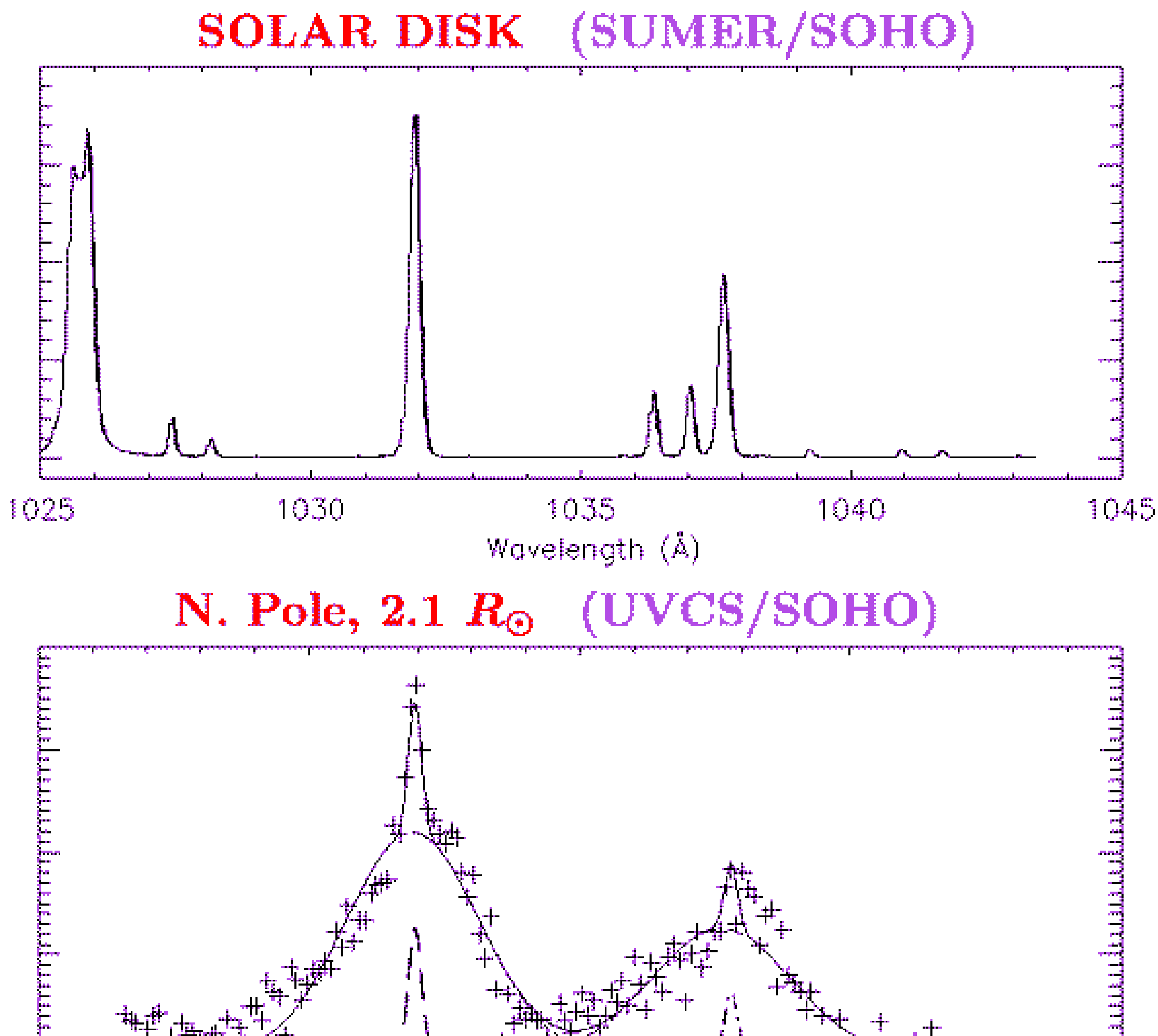
onstant mass flux implies a constant heat input int the corona

problem seem to naturally explain/predict:

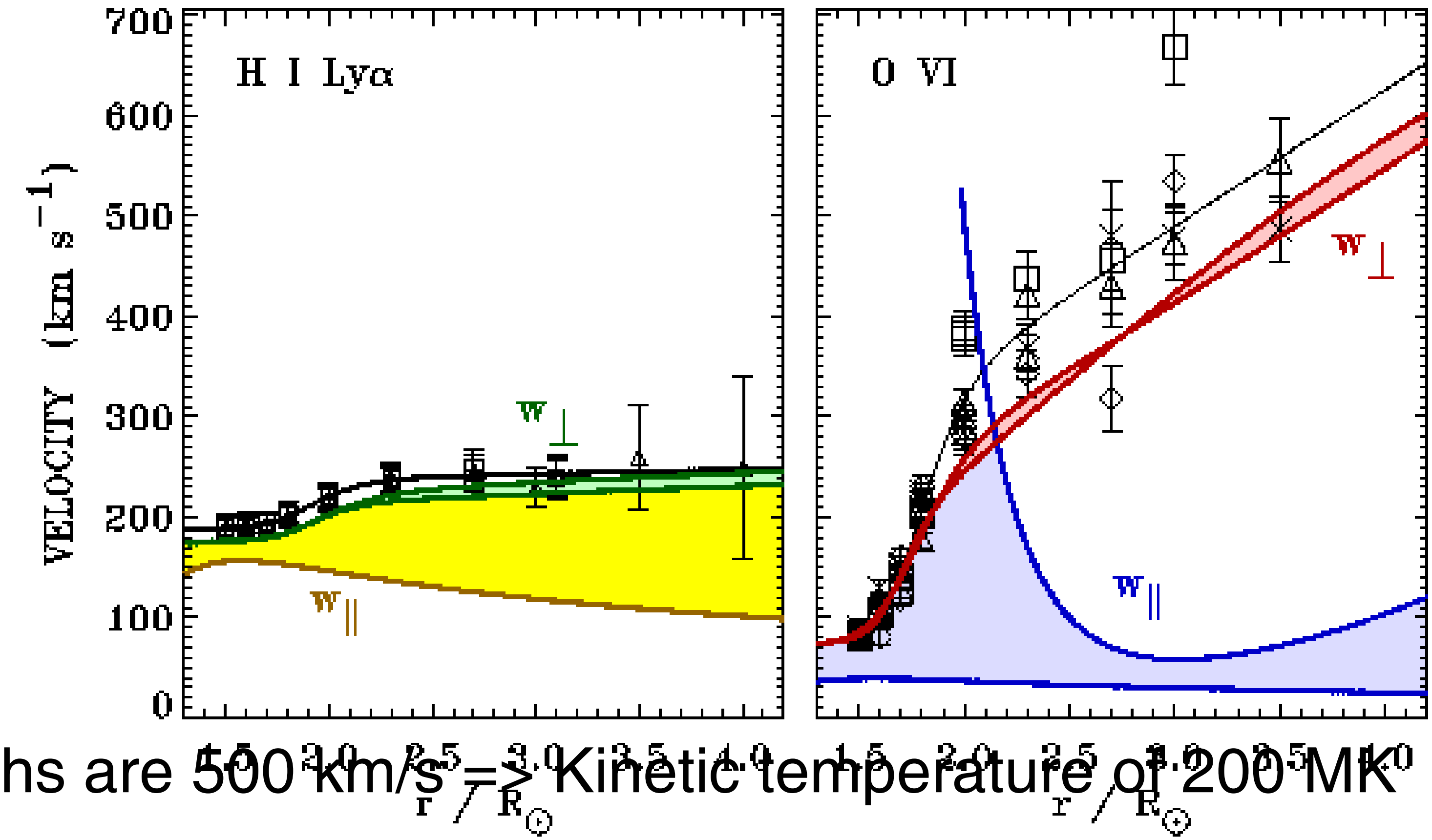
- high T_p and T_{ion}
- little collisional coupling between species
- are able to achieve both ‘fairly’ high asymptotic speed...
- ...and low mass flux

- Treatment of conduction important, as conduction is responsible for supplying corona with enough particles
- What about thermal force?

SOHO/UVCS observations; line widths



asymmetric $T_{\parallel}/T_{\perp}$



- Widths are 500 km/s => Kinetic temperature of 200 MK

- H speeds parallel to the radial magnetic field (yellow) may be as larg as the speeds in the perpendicular direction (green).

What do high ion temperatures actually imply?

UVCS observations have been taken as evidence for "preferential" ion heating.

But what should we expect if only energy loss mechanism given ions is expansion into interplanetary space in the form of a supersonic wind?

In which case ions must attain velocity equal to escape velocity at some height *r*, giving an estimated temperature

$$T_s \simeq m_s \frac{2GM_{\mathrm{S}}}{kr}.$$

Continuity equation

$$\frac{\partial n}{\partial t} = -\frac{1}{A}\frac{\partial}{\partial r}(nuA) \tag{1}$$

Momentum equation

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial r} - \frac{k}{m}\left(\frac{\partial T_{e\|}}{\partial r} + \frac{\partial T_{p\|}}{\partial r}\right) - \frac{k(T_{e\|}+T_{p\|})}{nm}\frac{\partial n}{\partial r} - \frac{1}{A}\frac{dA}{dr}\frac{k}{m}[(T_{e\|}-T_{e\perp})+(T_{p\|}-T_{p\perp})]$$
$$-\frac{GM_s}{r^2} - \frac{1}{nm}\frac{\partial p_w}{\partial r} + \frac{1}{nm}\left(\frac{\delta M_e}{\delta t} + \frac{\delta M_p}{\delta t}\right) \tag{2}$$

where the thermal forces on electrons and protons add up to zero; $\frac{\delta M_e}{\delta t} + \frac{\delta M_p}{\delta t} = 0$. Electron parallel energy equation

$$\frac{\partial T_{e\|}}{\partial t} = -u\frac{\partial T_{e\|}}{\partial r} - 2T_{e\|}\frac{\partial u}{\partial r} - \frac{1}{nk}\frac{\partial q_{e\|}}{\partial r} - \frac{1}{A}\frac{dA}{dr}\frac{q_{e\|}}{nk} + \frac{2}{A}\frac{dA}{dr}\frac{q_{e\perp}}{nk} + \frac{1}{nk}Q_{me\|} + \frac{1}{nk}\frac{\delta E_{e\|}}{\delta t} \tag{3}$$

Electron perpendicular energy equation

$$\frac{\partial T_{e\perp}}{\partial t} = -u\frac{\partial T_{e\perp}}{\partial r} - \frac{1}{A}\frac{dA}{dr}uT_{e\perp} - \frac{1}{nk}\frac{\partial q_{e\perp}}{\partial r} - \frac{2}{A}\frac{dA}{dr}\frac{q_{e\perp}}{nk} + \frac{1}{nk}Q_{me\perp} + \frac{1}{nk}\frac{\delta E_{e\perp}}{\delta t} \tag{4}$$

Heat flow equation for parallel energy in the electrons

$$\frac{\partial q_{e\|}}{\partial t} = -u\frac{\partial q_{e\|}}{\partial r} - 4q_{e\|}\frac{\partial u}{\partial r} - uq_{e\|}\frac{1}{A}\frac{dA}{dr} - 3\frac{k^2 nT_{e\|}}{m_e}\frac{\partial T_{e\|}}{\partial r} + \left[\frac{\delta q_{e\|}}{\delta t}\right]' \tag{5}$$

Heat flow equation for perpendicular energy in the electrons

$$\frac{\partial q_{e\perp}}{\partial t} = -u\frac{\partial q_{e\perp}}{\partial r} - 2q_{e\perp}\frac{\partial u}{\partial r} - 2uq_{e\perp}\frac{1}{A}\frac{dA}{dr} - \frac{k^2 nT_{e\|}}{m_e}\frac{\partial T_{e\perp}}{\partial r} - \frac{1}{A}\frac{dA}{dr}\frac{k^2 nT_{e\perp}}{m_e}(T_{e\|}-T_{e\perp}) + \left[\frac{\delta q_{e\perp}}{\delta t}\right]' \tag{6}$$

Proton parallel energy equation

$$\frac{\partial T_{p\|}}{\partial t} = -u\frac{\partial T_{p\|}}{\partial r} - 2T_{p\|}\frac{\partial u}{\partial r} - \frac{1}{nk}\frac{\partial q_{p\|}}{\partial r} - \frac{1}{A}\frac{dA}{dr}\frac{q_{p\|}}{nk} + \frac{2}{A}\frac{dA}{dr}\frac{q_{p\perp}}{nk} + \frac{1}{nk}Q_{mp\|} + \frac{1}{nk}\frac{\delta E_{p\|}}{\delta t} \tag{7}$$

Proton perpendicular energy equation

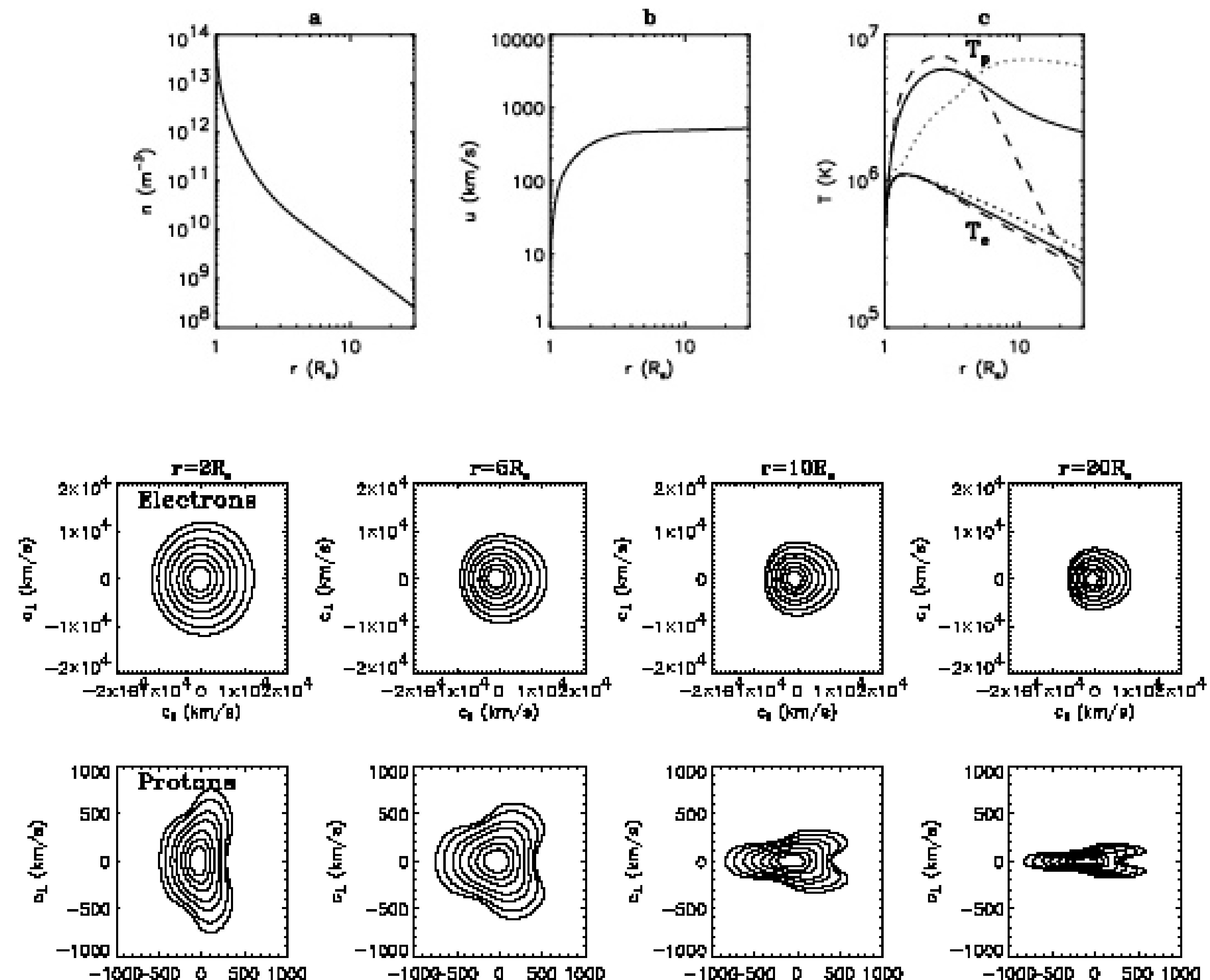
$$\frac{\partial T_{p\perp}}{\partial t} = -u\frac{\partial T_{p\perp}}{\partial r} - \frac{1}{A}\frac{dA}{dr}uT_{p\perp} - \frac{1}{nk}\frac{\partial q_{p\perp}}{\partial r} - \frac{2}{A}\frac{dA}{dr}\frac{q_{p\perp}}{nk} + \frac{1}{nk}Q_{mp\perp} + \frac{1}{nk}\frac{\delta E_{p\perp}}{\delta t} \tag{8}$$

Heat flow equation for parallel energy in the protons

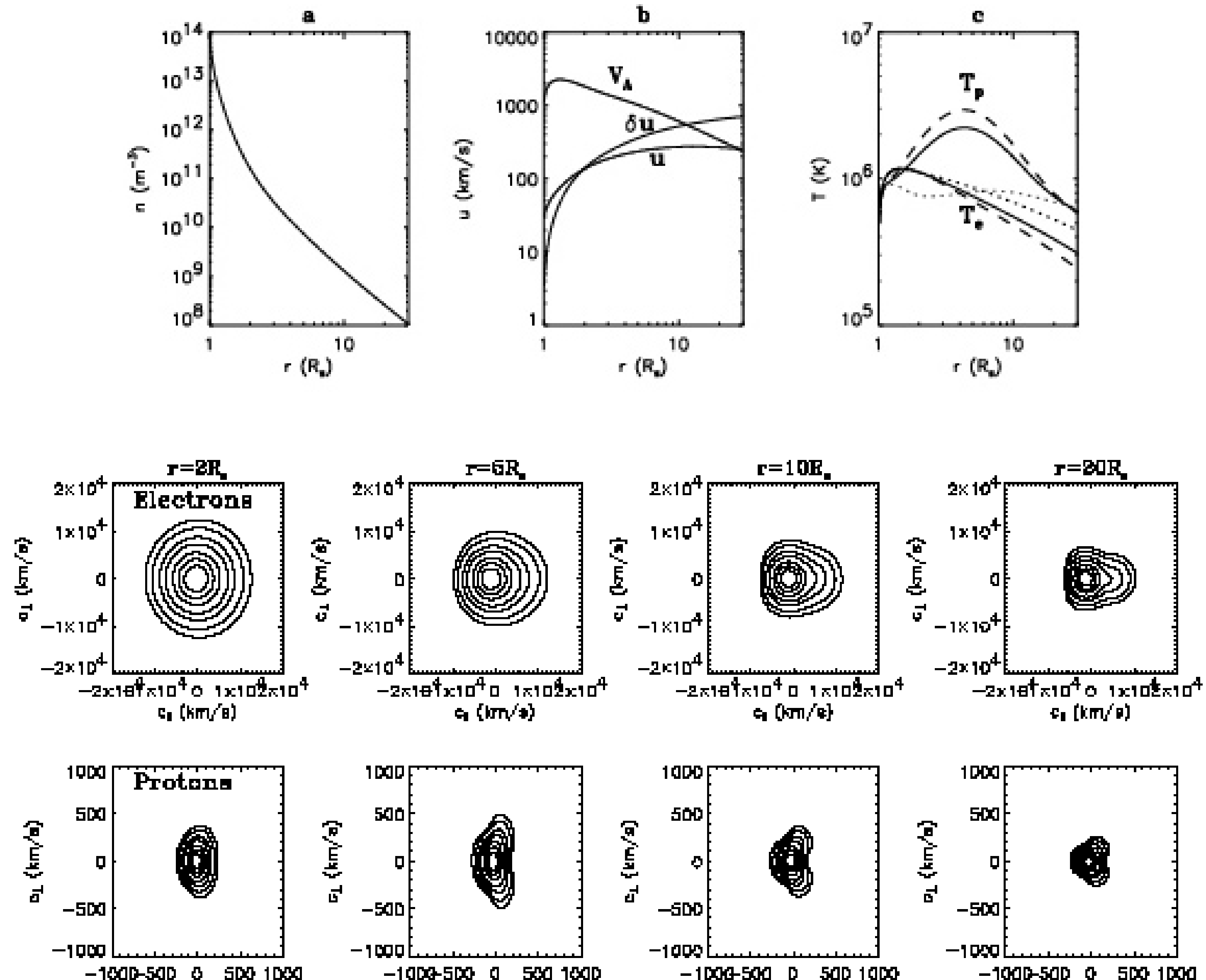
$$\frac{\partial q_{p\|}}{\partial t} = -u\frac{\partial q_{p\|}}{\partial r} - 4q_{p\|}\frac{\partial u}{\partial r} - uq_{p\|}\frac{1}{A}\frac{dA}{dr} - 3\frac{k^2 nT_{p\|}}{m_p}\frac{\partial T_{p\|}}{\partial r} + \left[\frac{\delta q_{p\|}}{\delta t}\right]' \tag{9}$$

Heat flow equation for perpendicular energy in the protons

Cyclotron wave heated model



Alfvén wave accelerated model



Conclusions and Questions

Temperature anisotropies in the corona real? If so, a result of ion-cyclotron waves? and how are these high frequency waves generated?

- Are lower frequency Alfvén waves being generated in the photosphere/chromosphere?
- Why are heavy ion velocities greater than the proton velocities?
- Why is $T_{perp} > T_{par}$ in the in-situ wind?
- What is the FIP effect telling us about the