# THE SOLAR WIND THEN AND NOW

PARKER (1958 etc.)

The wind is *electron – driven,*
accelerated mainly by $-\nabla p_e$

because

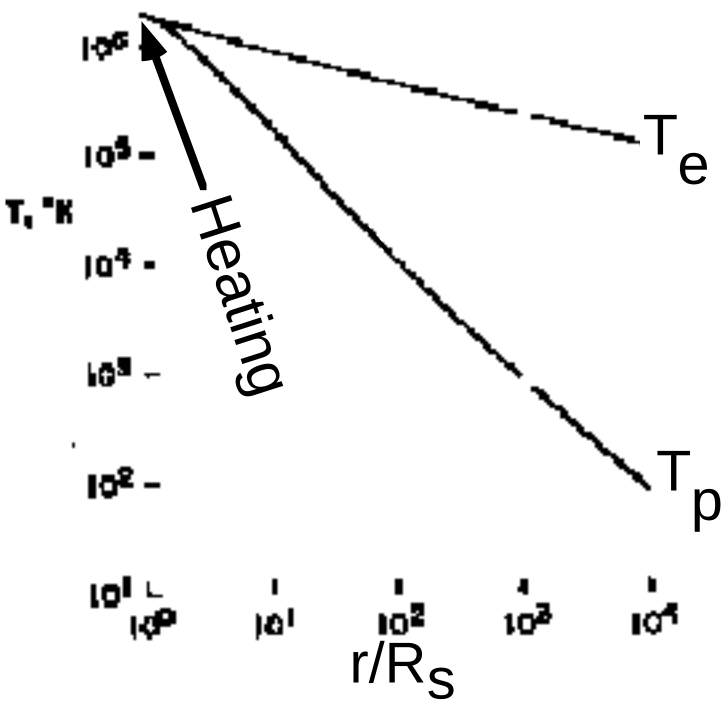
electron heat conduction ($\sim T_e^{7/2}$)
from the hot corona
$\Rightarrow T_e$ declines slowly with r.

> "The model for the hypothetical conduction corona leads to a temperature falling too rapidly with radial distance from the Sun, indicating that the actual solar corona is probably actively heated for some considerable distance by the dissipation of waves."
>
> Parker [**1965**]

# HARTLE AND STURROCK (1968)

Two - fluids: electrons and protons.

An *electron – driven* wind.



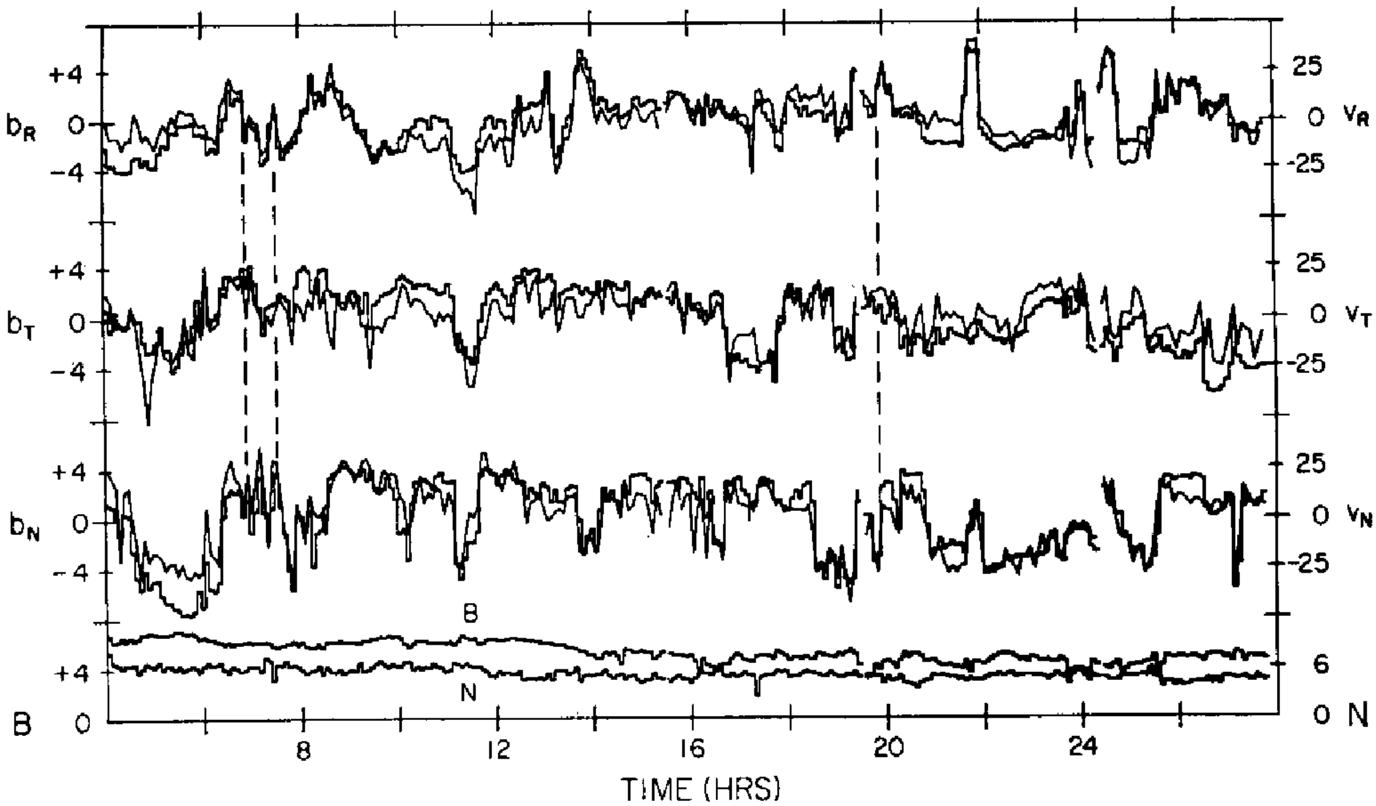

| Prediction (1 AU) | Observed Fast Streams |
| --- | --- |
| $V \approx 250$ km s$^{-1}$ | $V \approx 750$ km s$^{-1}$ |
| $T_p \approx 4400$ K | $T_p \approx 2 \times 10^5$ K |

"Departures [are] attributed to heating by a flux of non – thermal energy"

As Parker, did not address coronal heating.

# BELCHER AND DAVIS (1971)

## Alfvén Waves in the Solar Wind:




- Ubiquitous in high – speed streams.
- Outward - propagating from Sun
  ⇒ solar source?
- Large – amplitude, Long – period.

(•Less 'pure' in slow wind.)

Parker's "waves"?
Hartle and Sturrock's "non – thermal energy"?

# ALAZRAKI AND COUTURIER (1971)
# BELCHER (1971) HOLLWEG (1973 - ∞)

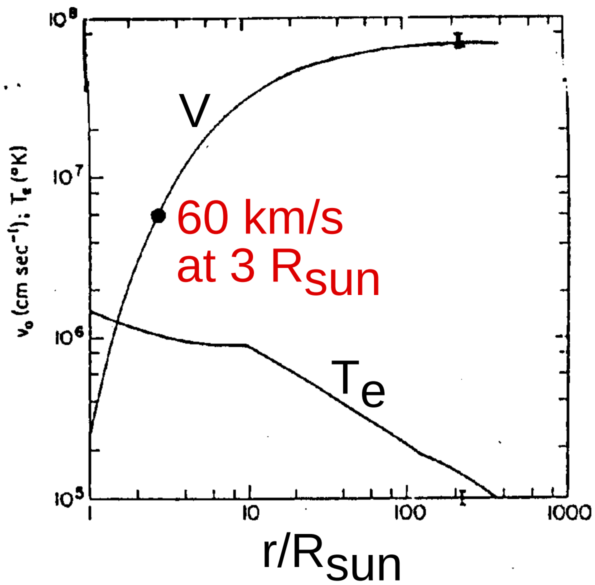
The solar wind is *wave – driven*.

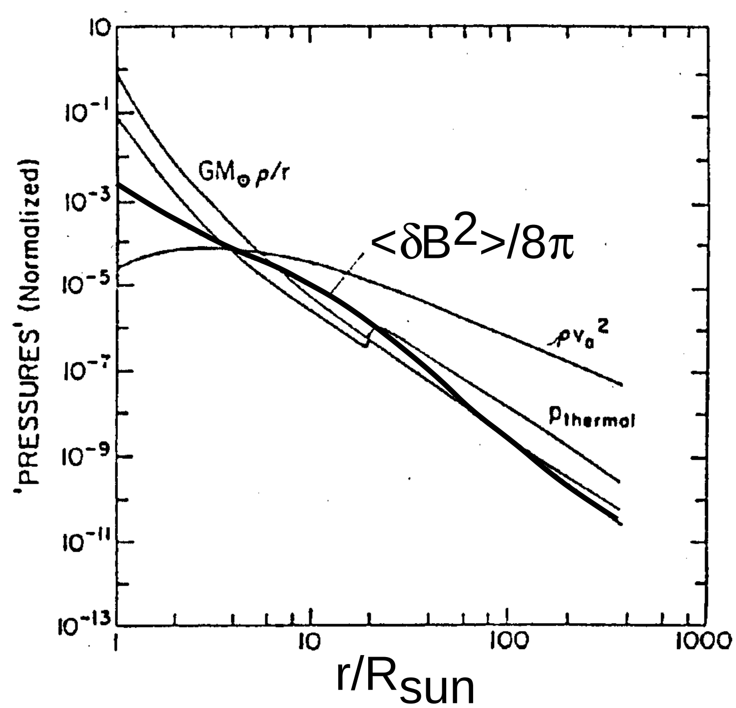
Acceleration from radiation pressure:

$$\rho V \frac{dV}{dr} = -\nabla p - \rho g - \nabla \frac{\langle \delta \mathbf{B}^2 \rangle}{8\pi}$$

Heating via
nonlinear saturation
or
turbulent cascade.

**Slow acceleration close to Sun:**




Hollweg [**1978**].

# WAVE-DRIVEN WIND SUCCEEDED FAR FROM SUN. BUT FAILED CLOSE TO SUN

EARLY 90's

⇓

GOOD CORONAL HOLE DENSITY DATA

⇓

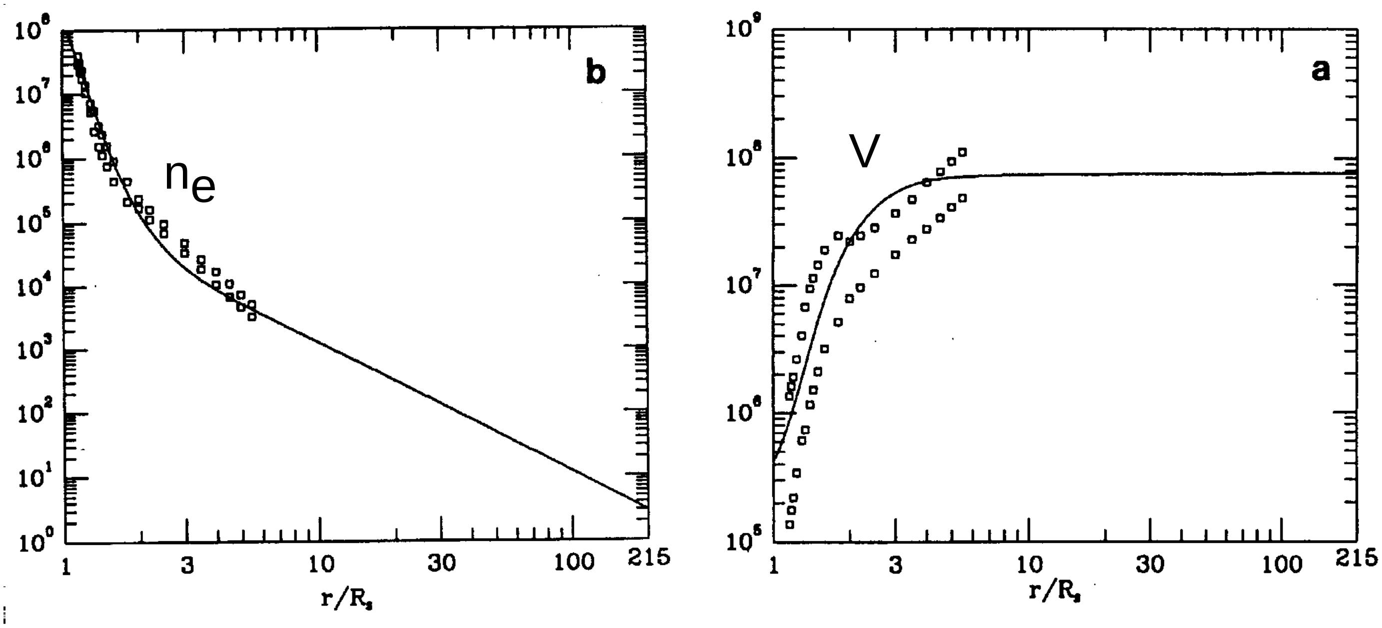
RAPID DENSITY FALL - OFF

⇓

| RAPID ACCELERATION CLOSE TO SUN |
| --- |

Papers by Guhathakurta, Fisher, Habbal, Esser, [**1995** – ...]

Esser et al. [**1997**].



n V Area = constant

$(n_p\ V)_{1AU} = 2 \times 10^8\ cm^{-2}\ s^{-1}$ (Ulysses)

$n_{e,hole} = 5 \times 10^4\ cm^{-3}$ at $r = 3\ r_s$

$V = 205\ km\ s^{-1}$ at $r = 3\ r_s$ ($r^2$ geom.)

c.f. 60 $km\ s^{-1}$ earlier.

THE ACTUAL SOLAR WIND
ACCELERATES MORE RAPIDLY
THAN WAVE PRESSURE
CAN ACCOUNT FOR.

# OTHER DIFFICULTIES:
# HEAVY IONS (especially $He^{++}$)

$$V_{ions} - V_p \approx v_A \text{ (the Alfvén speed)}$$

$$T_i / T_p \approx m_i / m_p$$

(Less obvious in slow wind.)

## Most likely explanation:
## Heating & acceleration by CYCLOTRON RESONANCE.

Abraham-Shrauner, B., and W.C. Feldman, Nonlinear Alfvén waves in high-speed solar wind streams, *J. Geophys. Res.*, *82*, 618, **1977**.

Hollweg, J.V., and J.M. Turner, Acceleration of solar wind He++. 3. Effects of resonant and nonresonant interactions with transverse waves, *J. Geophys. Res.*, *83*, 97, **1978**.

McKenzie, J.F., W.-H. Ip, and W.I. Axford, The acceleration of minor ion species in the solar wind, *Astrophys. Space Sci.*, *64*, 183, **1979**.

Marsch, E., C.K. Goertz, and K. Richter, Wave heating and acceleration of solar wind ions by cyclotron resonance, *J. Geophys. Res.*, *87*, 5030, **1982**.

McKenzie, J.F., and E. Marsch, Resonant wave acceleration of minor ions in the solar wind, *Astrophys. Space Sci.*, *81*, 295, **1982**.

Isenberg, P.A., and J.V. Hollweg, Finite amplitude Alfvén waves in a multi-ion plasma: propagation, acceleration, and heating, *J. Geophys. Res.*, *87*, 5023, **1982**.

Isenberg, P.A., and J.V. Hollweg, On the preferential acceleration and heating of solar wind heavy ions, *J. Geophys. Res.*, *88*, 3923, **1983**.

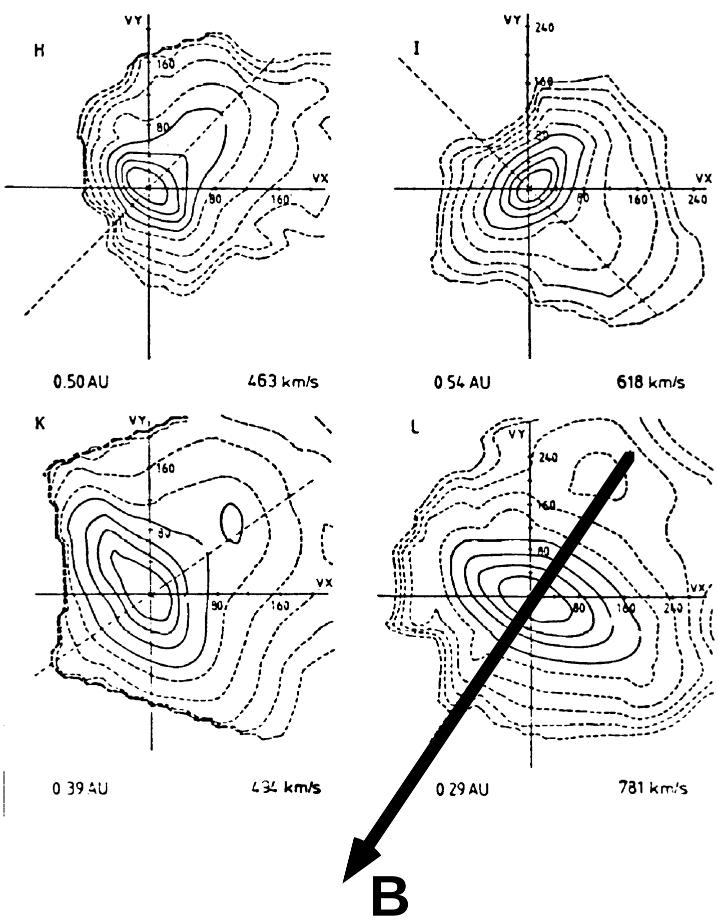
Isenberg, P.A., Resonant acceleration and heating of solar wind ions: anisotropy and dispersion, *J. Geophys. Res.*, *89*, 6613, **1984**.

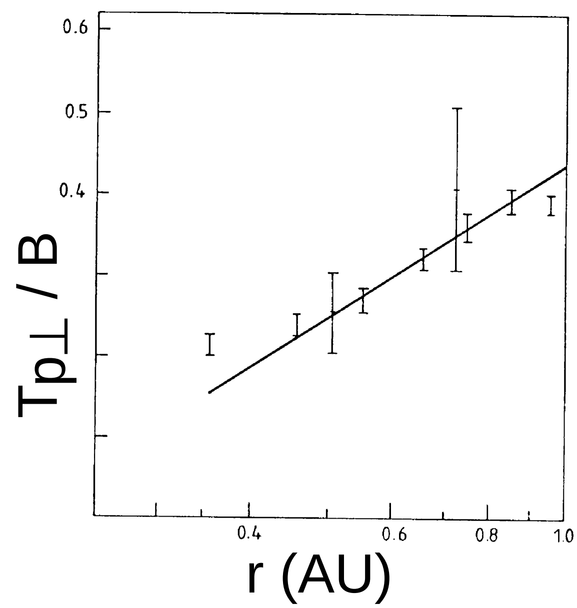
Hollweg, J.V., and Isenberg, P.A., Review Paper, J. Geophys. Res., July **2002**.

# OTHER INDICATIONS OF CYCLOTRON RESONANCE

## DISTRIBUTIONS and MAGNETIC MOMENTS

## ⇒ PERPENDICULAR HEATING




Both from Marsch (1991)

(Recall that the magnetic moment would be conserved adiabatically.)

# HOLLWEG (1986); H & JOHNSON (1988)

## CYCLOTRON RESONANCES APPLIED TO THE ACCELERATION REGION

- Alfvén waves are launched from the coronal base.
- Dissipate at Kolmogorov turbulence rate:

$$Q = \frac{\rho <\delta \mathbf{V}^2>^{3/2}}{L_{corr}} \quad \mathrm{erg\ cm^{-3}\ s^{-1}}$$

- Energy cascades to $\Omega_{cyclotron}$. Only protons are heated.

- Waves evolve via WKB with dissipation.

Note: Pure outgoing WKB inconsistent with turbulence since $\frac{1}{2}\rho <\delta \mathbf{V}^2> = \frac{<\delta \mathbf{B}^2>}{8\pi}$ $\Rightarrow$ the nonlinear terms cancel.

Oughton et al. [**2001**]; Dmitruk et al. [**2001, 2002**].

$F_{wave} = 5.4 \times 10^{5}$ erg cm$^{-2}$ s$^{-1}$ $f_{max} = 4$

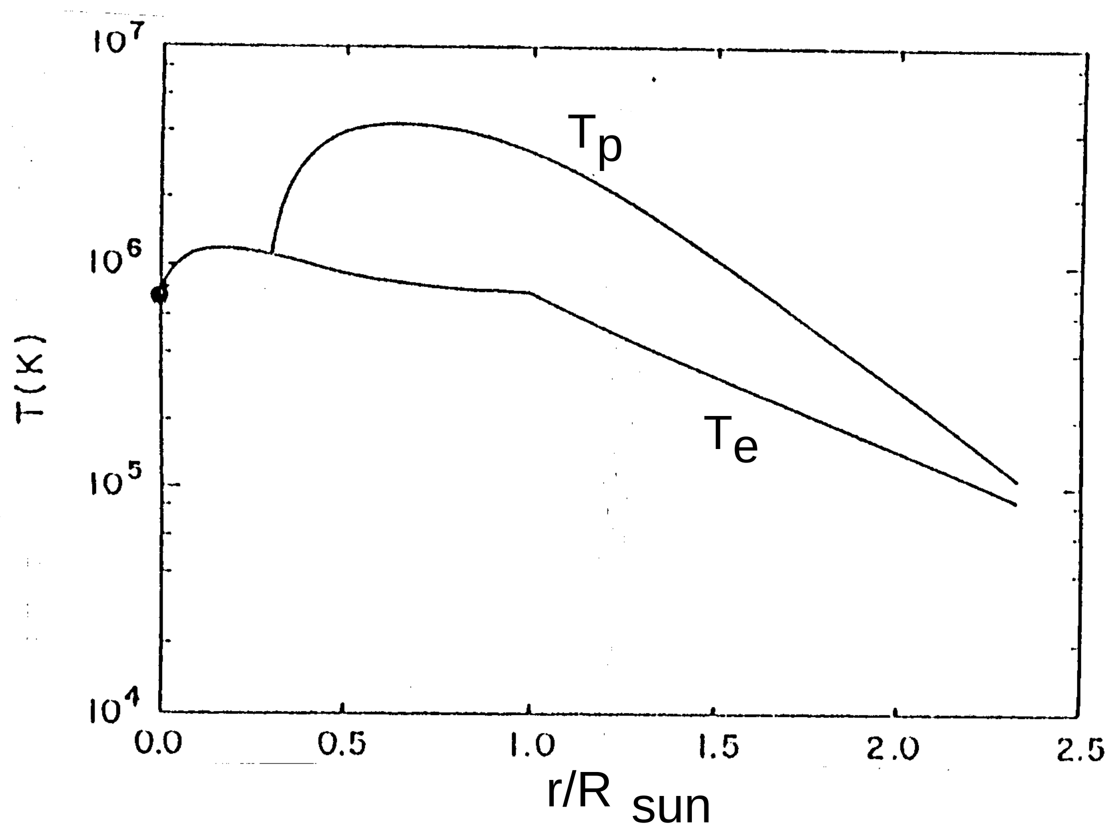
$n_e T = 8.3 \times 10^{13}$ at base

$r_{critical} = 2.4\ r_s \Rightarrow$ **RAPID ACCELERATION.**

$n_p V(1\ AU) = 3.9 \times 10^{8}$ cm$^{-2}$ s$^{-1}$

$V(1\ AU) = 762$ km/s $\Rightarrow$ **HIGH - SPEED FLOW.**

$T_e(1\ AU) = 8.8 \times 10^{4}$ K $T_p(1\ AU) = 1.1 \times 10^{5}$ K



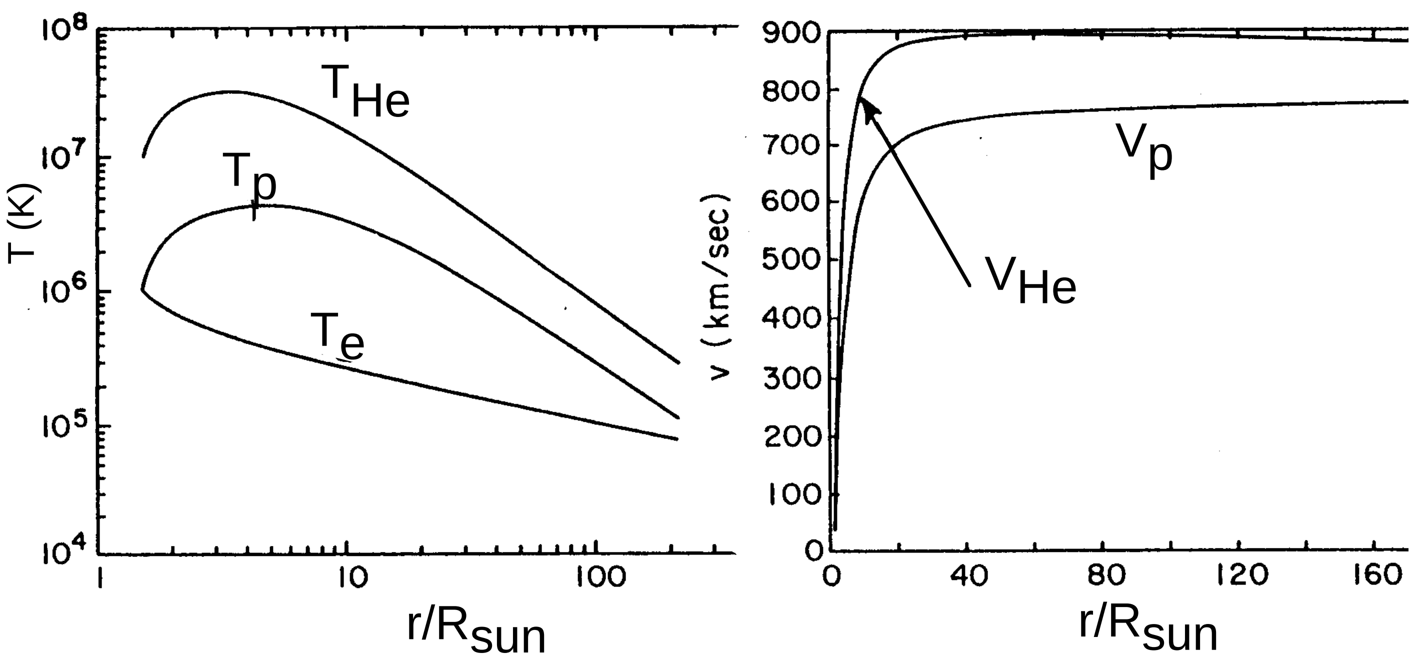

This model was rejected because
the available data argued
against high coronal $T_p$.

# ISENBERG (1990)

Same idea as Hollweg and Johnson (1988), but INCLUDED $He^{++}$.

Use quasilinear theory to apportion the cascaded energy between protons and helium.

ANTICIPATED the UVCS / SOHO results:
Hot and fast CORONAL ions.

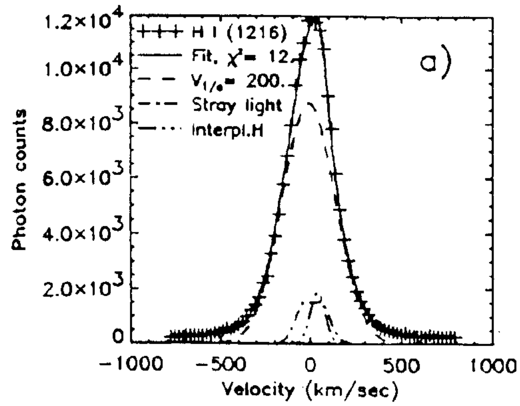


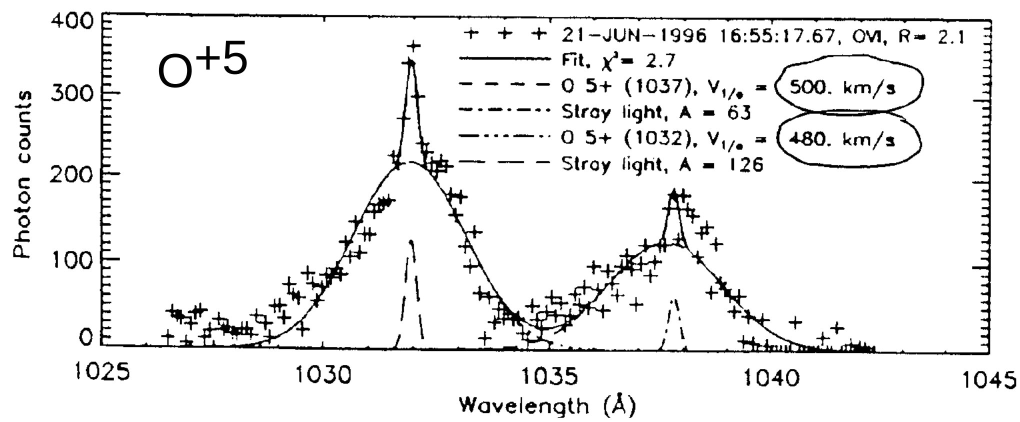

Nonetheless,
this model was rejected because
the available data argued
against high coronal $T_p$.

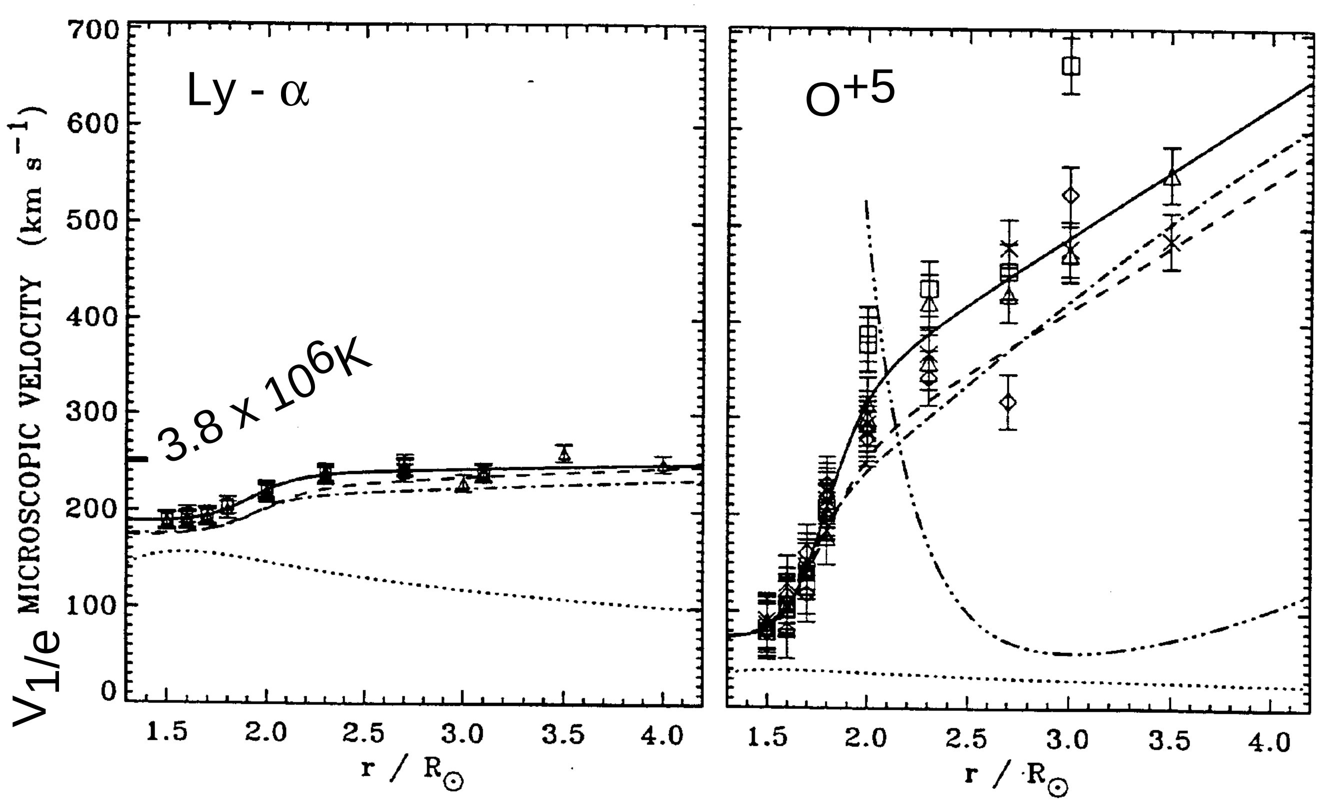
# THE UVCS / SOHO RESULTS

Coronal Holes

Kohl et al. 1997




Caution: width of distribution function a mix of temperature and non - thermal motions (waves or turbulence).

# THE UVCS / SOHO RESULTS

$T_p > T_e$ $\qquad$ $T_p \approx (3 - 4) \times 10^6 K$

$$\frac{T_{oxygen}}{T_p} > \frac{m_{oxygen}}{m_p}$$

$T_\perp >> T_{||}$ (definite for $O^{+5}$)

Suggesting:

Cyclotron resonant heating.

Solar wind may be *proton – driven* via $-\nabla \bullet \bar{\bar{p}}_p$.

Coronal heating is *proton and ion* – dominated. Not $j^2/\sigma$.

$T_{ion} > T_p$ and $V_{ion} > V_p$ may originate in the corona.

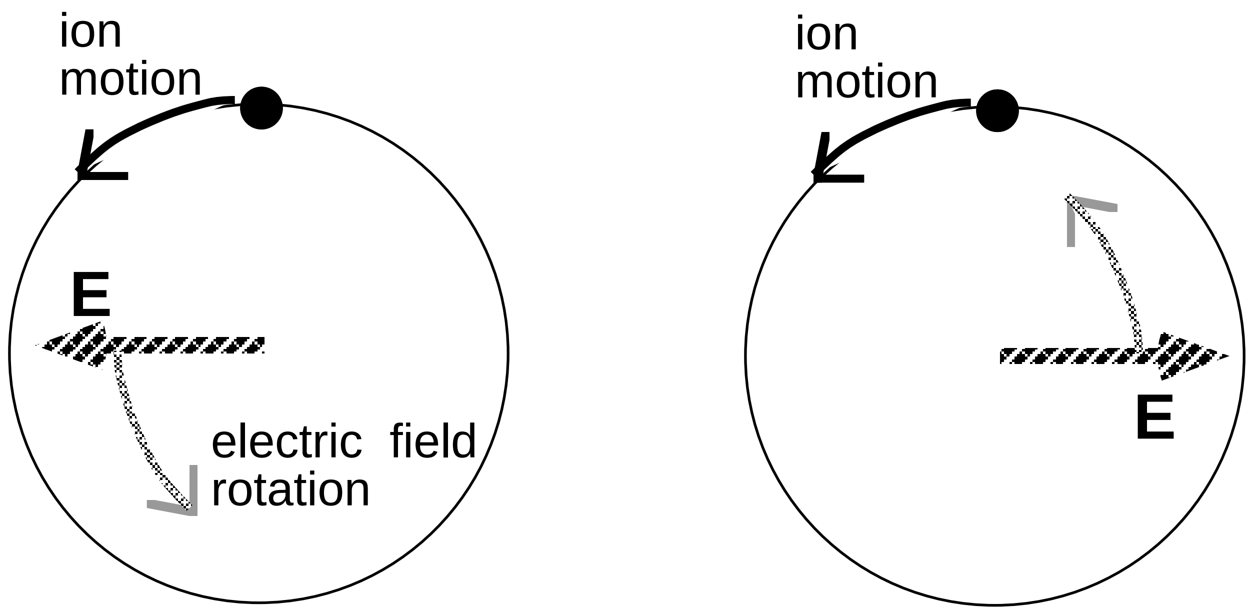
Coronal heating extends into the acceleration region.

Coronal heating and wind acceleration must be treated together.

# ION – CYCLOTRON RESONANT HEATING

$$\omega - k_{||} v_{||} = \Omega$$

frequency seen by particle — gyro-frequency




The ion gains energy secularly — The ion loses energy secularly

Gain or loss of energy depends on phase of particle motion relative to the wave.

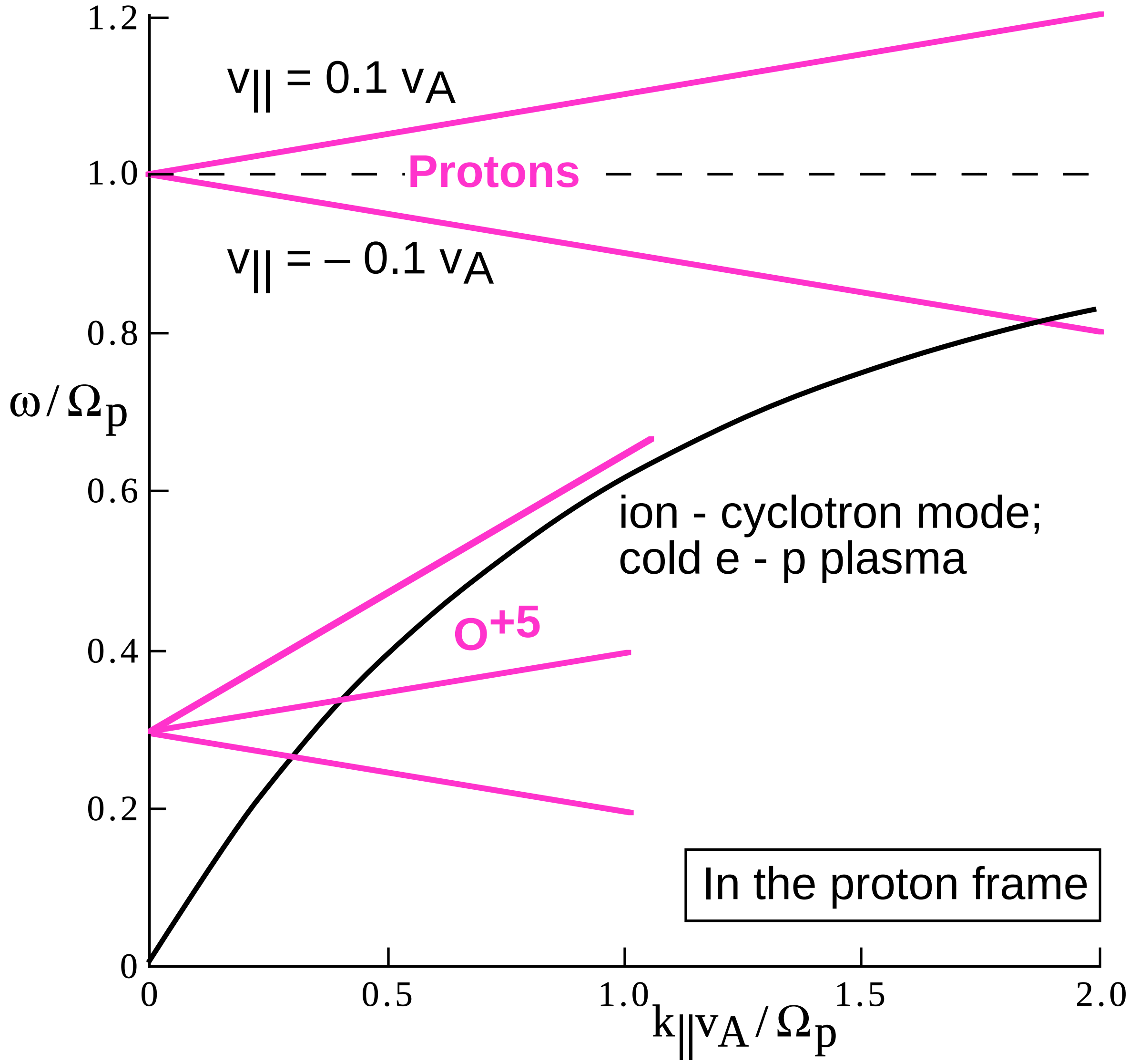
In a random field, phase will be random, and the particle will random walk.

Diffusion in velocity space

⇓

heating, acceleration

# RESONANCE CONDITION: $\omega - k_{||} v_{||} = \Omega$

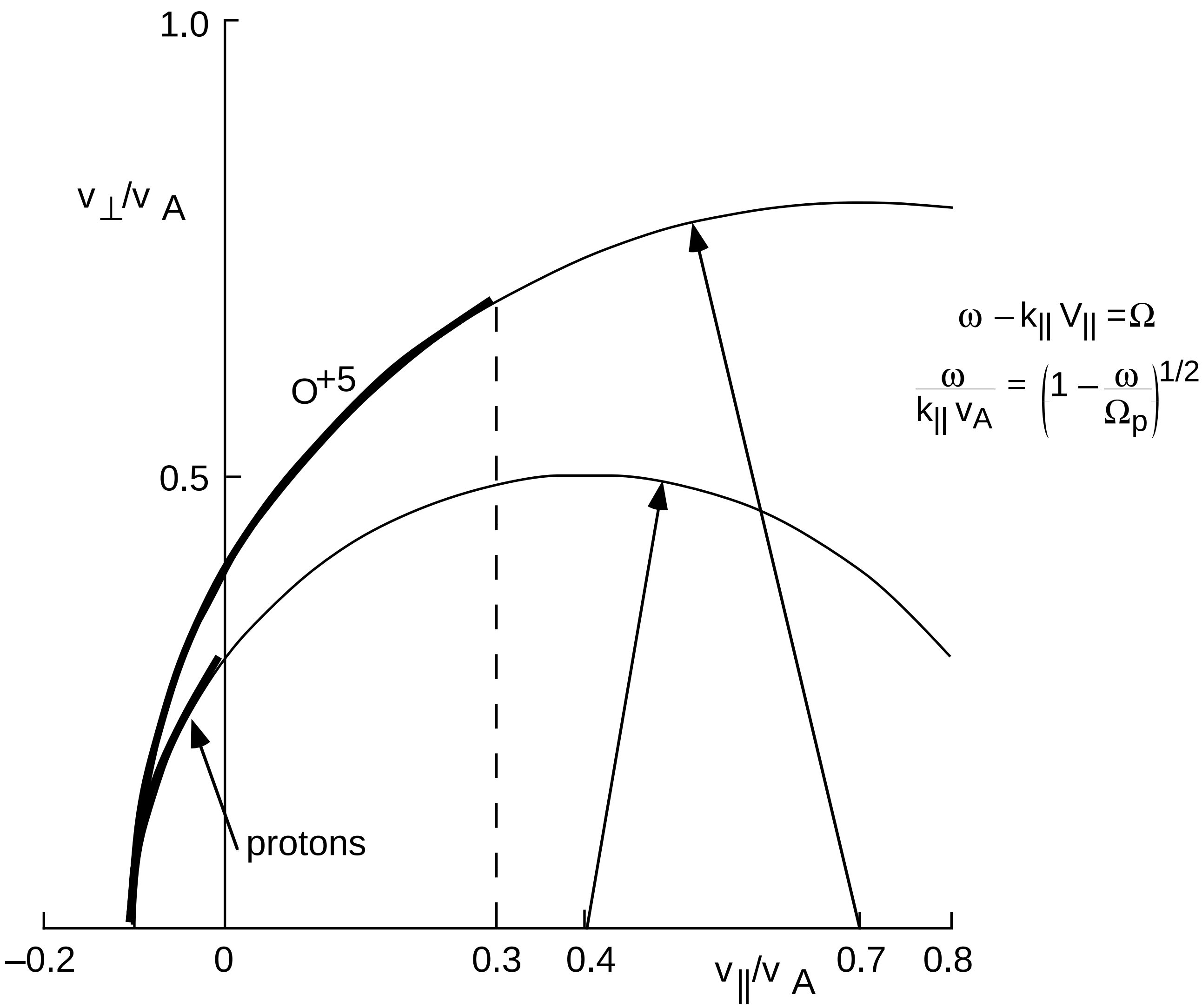



HEAVY IONS HAVE THE ADVANTAGE

- Only sunward - going protons (& $He^{++}$) are resonant with outward - going waves.
- Sunward- <u>and</u> outward - going heavy ions can resonate.

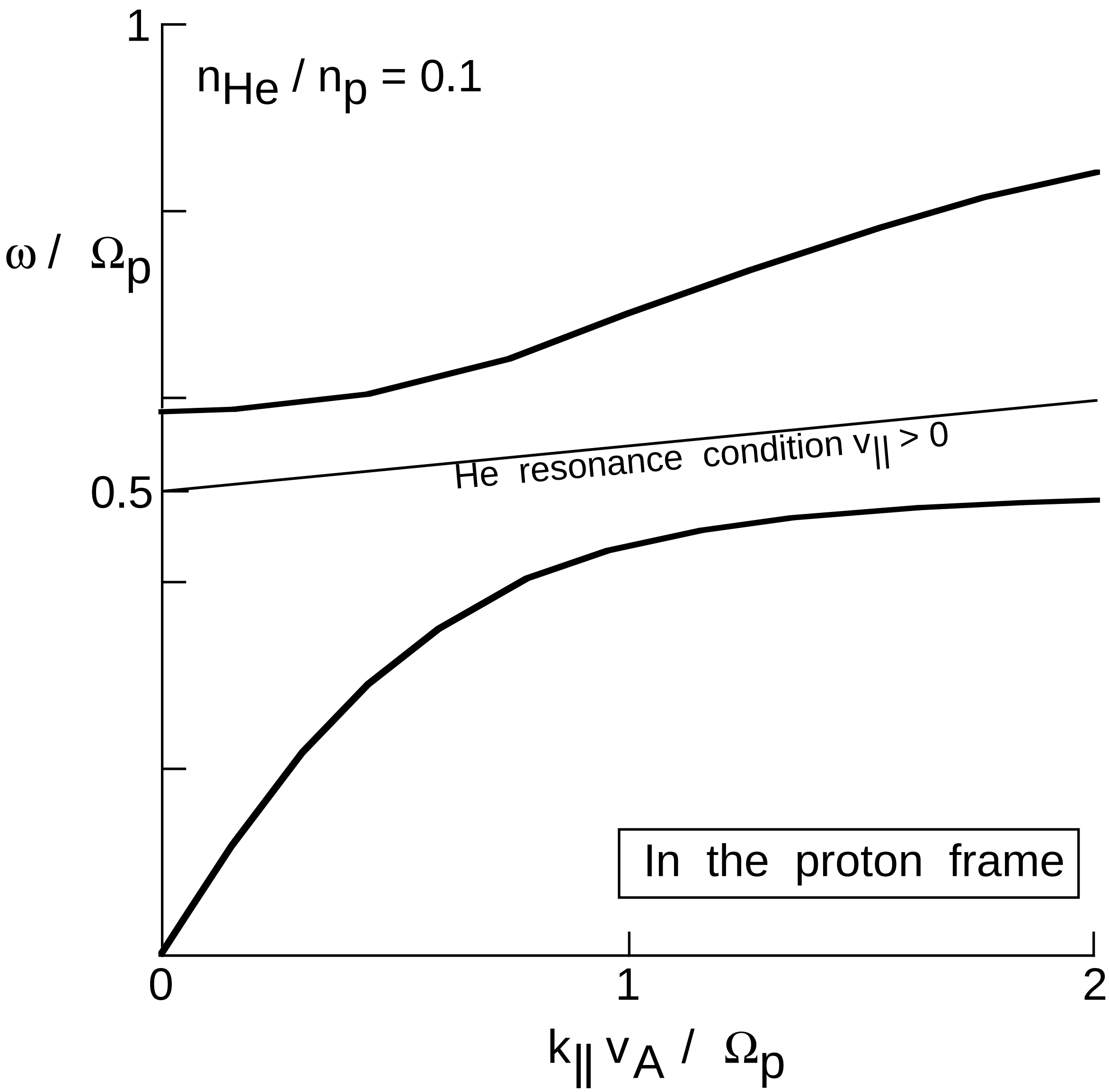
# FIVE EFFECTS

- In the wave frame, particle energy is constant
  ⇒ diffusion along circ. arcs centered on $v_{phase}$.
- Heating implies acceleration.
- $p^+$ diffusion is "cut off" at lower $V_{||}$ than heavy ion diffusion.
- Heavy ions resonate with faster waves.
- Heavy ions resonate with lower frequency waves, which have more power.



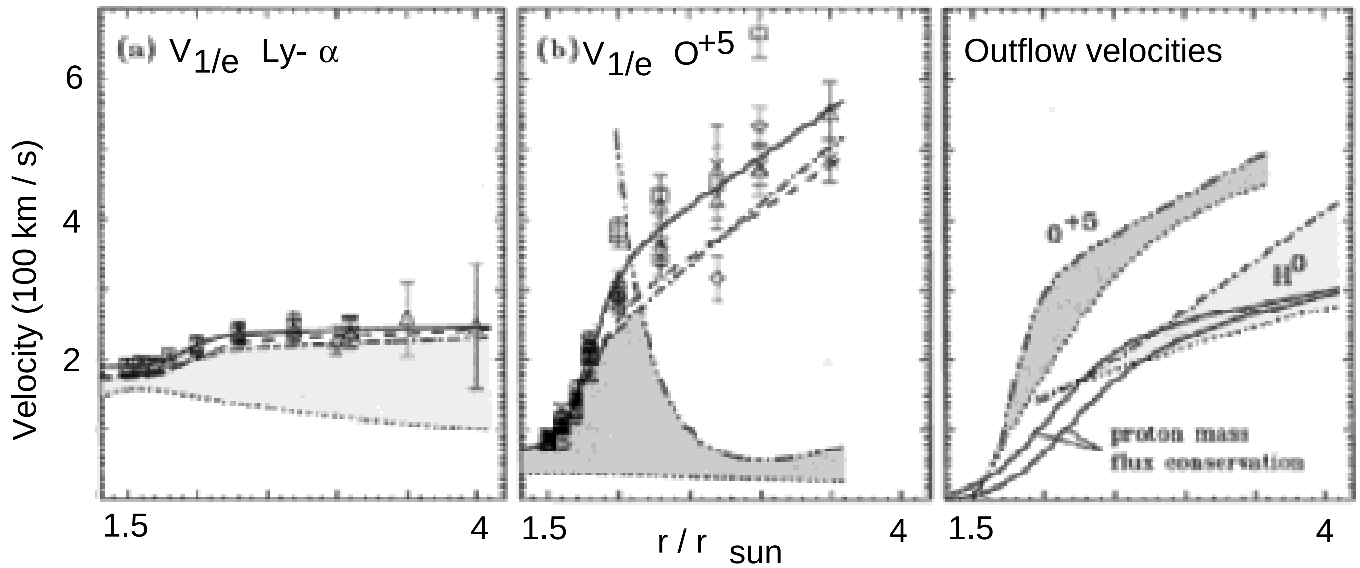

Ions can attain larger $V_\perp$ than $p^+$ ⇒ $T_{\perp i} > (m_i / m_p)\, T_{\perp p}$
as observed

# $He^{++}$
# THE FAMOUS HELIUM GAP



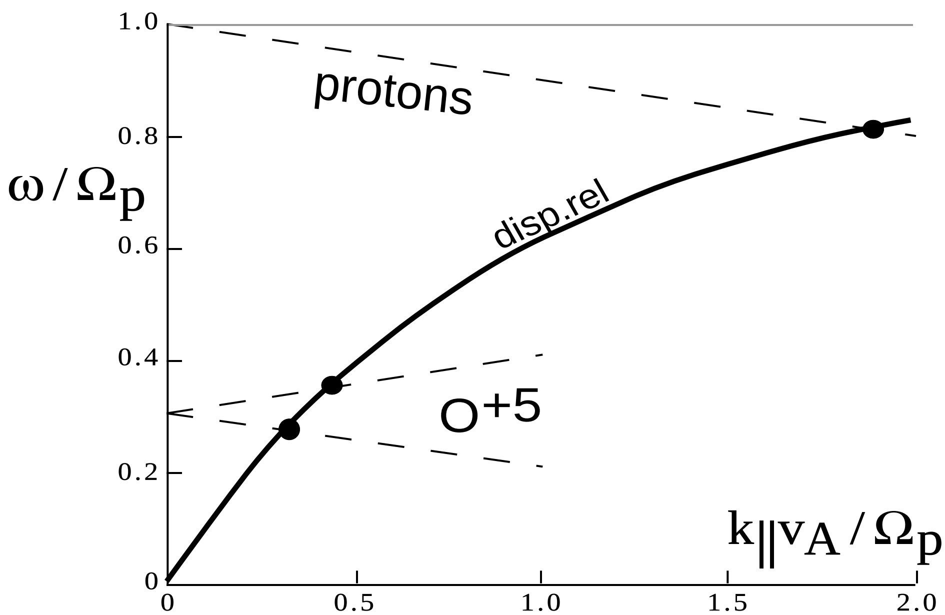

- ONLY THE SUNWARD $p^+$ AND SUNWARD $He^{++}$ RESONATE WITH THE OUTGOING LEFT - HAND MODE.
- FULL KINETIC SOLUTIONS ARE REQUIRED.
- BI - MAXWELLIANS ARTIFICIALLY TAKE HEAT FROM THE RESONANT PARTICLES AND REDISTRIBUTE IT AMONGST ALL PARTICLES..

# UVCS ⇒ A DIFFICULT REQUIREMENT:



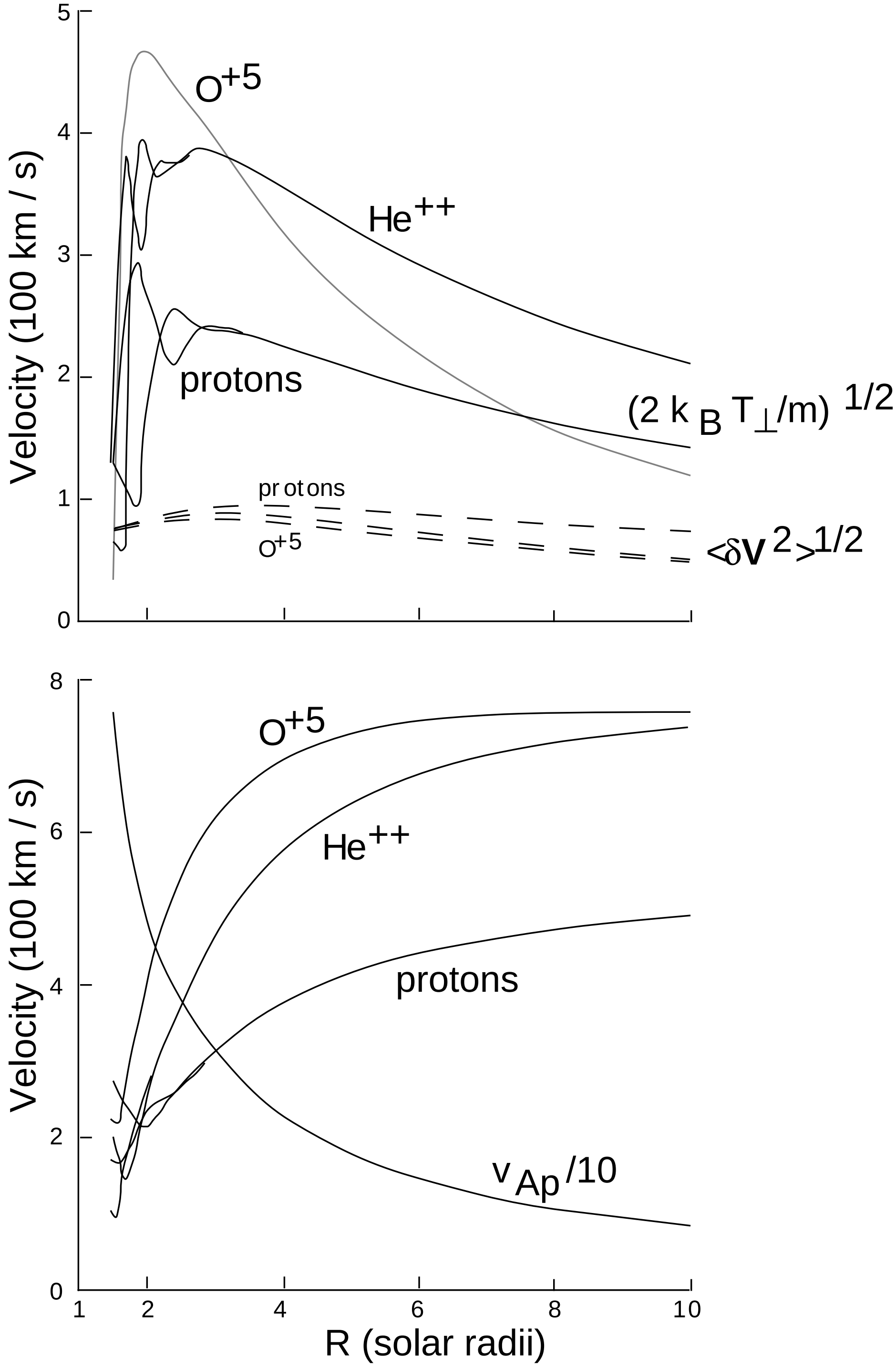

RESONANCES WORK IN THE OPPOSITE DIRECTION:

- Protons become more resonant as $v_A$ decreases.
- $O^{+5}$ becomes less resonant as their flow speed increases.




Models give
$O^{+5}$ temperature does not continue rising
out to 3.5 $r_{sun}$

# 2 $p^+$ BEAMS 2 $He^{++}$ BEAMS $O^{+5}$



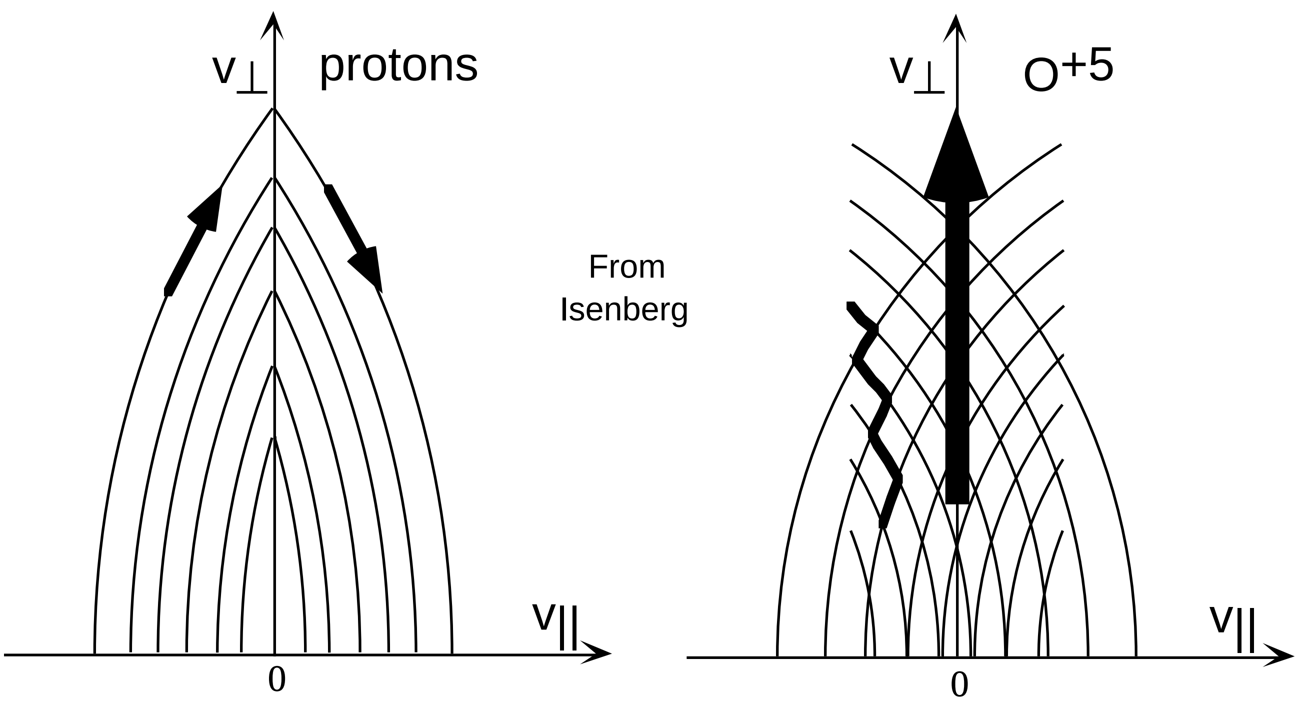

- $O^{+5}$ accelerates rapidly ⇒ strong adiabatic cooling.
- $O^{+5}$ accelerates rapidly ⇒ $O^{+5}$ resonance becomes weaker.
- $O^{+5}$ temperature does not continue rising out to 3.5 $r_{sun}$.

# AN ANSWER FOR OXYGEN?
# (AND OTHER IONS)

- INWARD - GOING WAVES:
  generated by instabilities;
  reflections.

HEAVY IONS LIKE $O^{+5}$ WILL UNDERGO SECOND - ORDER FERMI ACCELERATION
Isenberg [**2001**]

PROTONS AND $He^{++}$ WILL NOT UNDERGO THIS PROCESS.

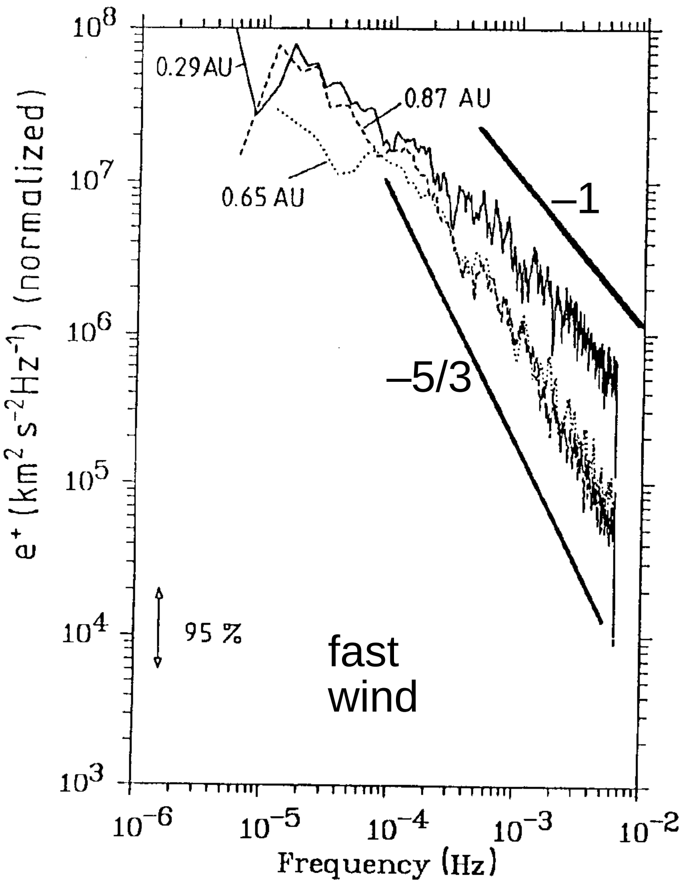


# WHENCE THE CYCLOTRON WAVES. 1?

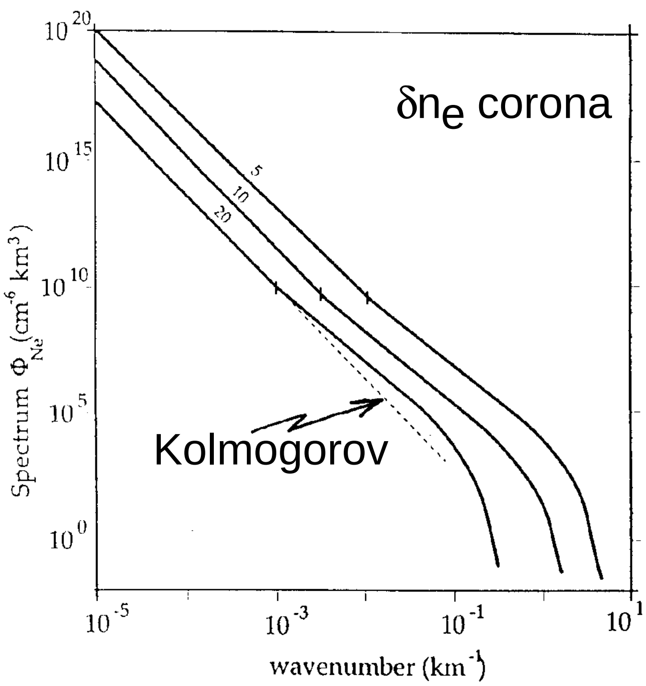
## TURBULENT CASCADE TO HIGH ω, k.

Hollweg [**1986**], Hollweg & Johnson[**1988**], Isenberg[**1990**]

In situ and radio science ⇒ 'turbulent' spectra.




Marsch & Tu (1990)




Coles & Harmon (1989)

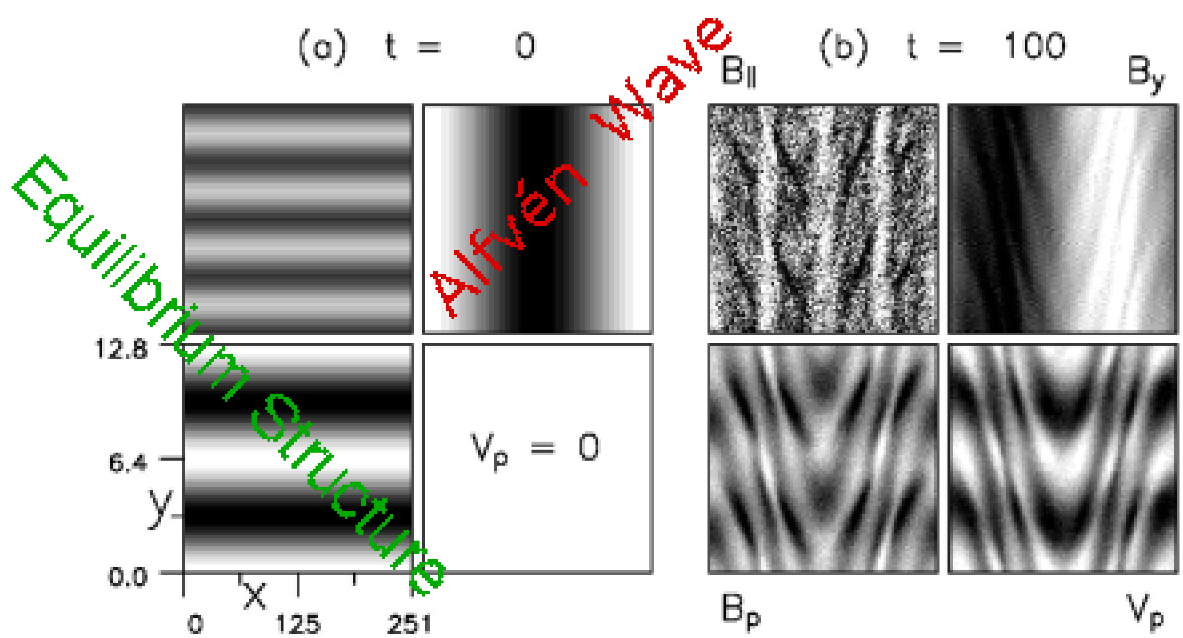
# PROBLEMS WITH TURBULENCE AS SOURCE OF ION - CYCLOTRON WAVES

• MHD turbulence ⇒ high $k_{\perp}$
(not high $k_{||}$ needed for cyclotron resonance).
(Matthaeus and many others.)

On the other hand:
in situ data show power at high - $k_{||}$
(though there is a preference for high $k_{\perp}$).

Recent results from Vasquez et al:
Advection of
cross - field pressure balanced structures
by medium - frequency Alfvén waves
can give the required high $k_{||}$.

Vasquez, Markovskii, and Hollweg [**2004**].



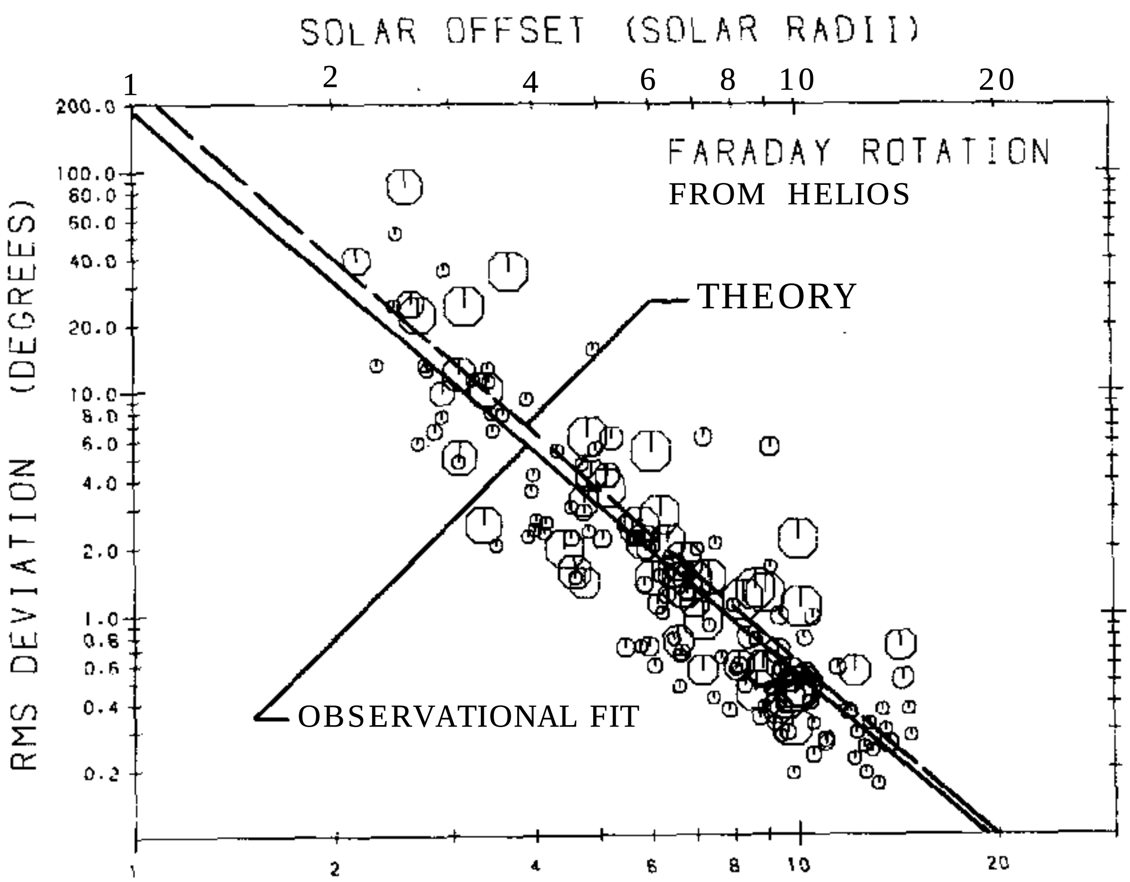
# PROBLEMS WITH TURBULENCE contd.

- Is there sufficient low - frequency power?

CORONAL FARADAY ROTATION FLUCTUATIONS
$\Rightarrow \delta\mathbf{B}$

HELIOS SPACECRAFT
NEAR SUPERIOR CONJUNCTION:

Hollweg, Bird, Volland, Edenhofer, Stelzried, and Seidel, [**1982**].




Similar results were obtained by
Andreev, Efimov, Samoznaev, Chashei, and Bird [**1997**].

# NATURAL RADIO SOURCES:

from data at 8.6 $R_s$ "...the wave flux in MHD waves or turbulence with [large] spatial scales is inadequate"
Mancuso and Spangler [**1999**]

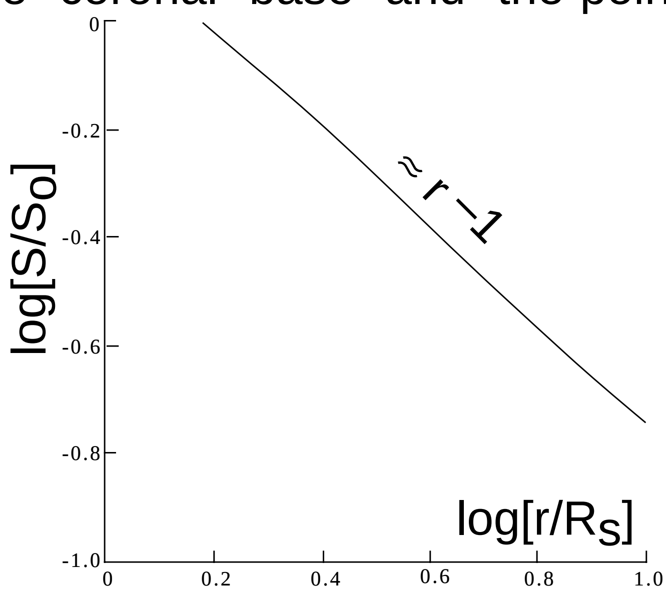
from data in 16 - 26 $R_S$: "If [$\delta n/n \approx \delta B/B$], then the turbulence in the inner solar wind is ... perhaps incapable of playing a significant role"
Spangler [**2003**].

# PROBLEMS WITH ALL RADIO STUDIES:

1.
$$\langle \delta RM^2 \rangle \sim \int n_e^2 \langle \delta B_s^2 \rangle L_{corr,s}\, ds$$

$\Uparrow$ uncertain

2. These studies have not looked carefully at dissipation between the coronal base and the point of observation.




Hollweg, J.V., and P.A. Isenberg, Generation of the fast solar wind: A review with emphasis on the resonant cyclotron interaction, *J. Geophys. Res.*, July, 2002.

# Does the cascade originate from waves with period $\approx$ 5 min. ?

Ap.J. 465, 436, 1996

## OBSERVATIONS OF MAGNETOHYDRODYNAMIC OSCILLATIONS IN THE SOLAR ATMOSPHERE WITH PROPERTIES OF ALFVÉN WAVES

ROGER K. ULRICH
Department of Physics and Astronomy, University of California, Los Angeles, CA 90024
*Received 1995 August 23; accepted 1996 January 12*

### ABSTRACT

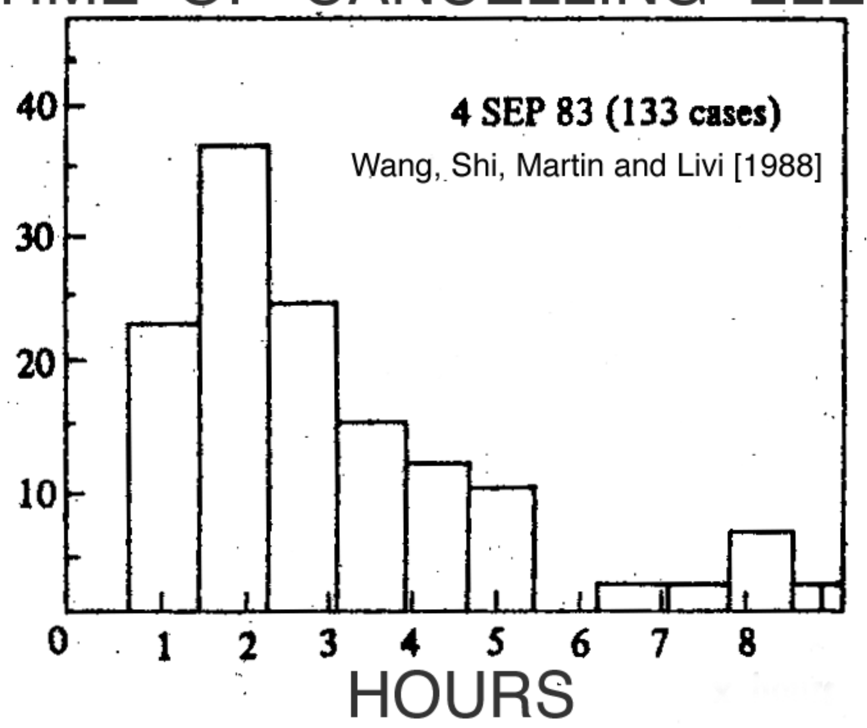
This paper reports observations of magnetohydrodynamic oscillations in the solar atmosphere with properties of Alfvén waves. These oscillations have periods in the 5 minute band. Phase relations between magnetic field variations and velocity variations are consistent with outgoing Alfvén waves. The aperture used for the observations is large, 20″ × 20″, and the velocity amplitude is reduced due to the resultant spatial filtering. If the magnetic and velocity variations are scaled up to be typical of the 5 minute oscillations as observed with 2″ × 2″ resolution, the outward energy flux is of order $3 \times 10^7$ ergs $cm^{-2}$ $s^{-1}$ in regions with a high magnetic field. Observations employing two parts of the Na D1 line separated by roughly 150–225 km in altitude of formation show phase lags in the magnetic field variations appropriate for outgoing waves. Velocity phase lags are very well determined and show that the vertical group velocity is larger in the magnetic regions than in the nonmagnetic regions. The power spectrum of the magnetic variations includes a peak at frequencies greater than the center of the 5 minute velocity oscillations superimposed on a background spectrum that includes substantial power at low frequencies.

# PROBLEMS WITH TURBULENCE contd.

• What on the Sun determines most power at hour timescales?

Flux cancellation events take place on hour timescales ($10^{18}$ Mx / Hr)

LIFETIME OF CANCELLING ELEMENTS



# WHENCE THE CYCLOTRON WAVES .2?

## CHROMOSPHERIC RECONNECTIONS LAUNCH HIGH FREQUENCY WAVES - KILOHERTZ!

Axford, Marsch, McKenzie, Tu

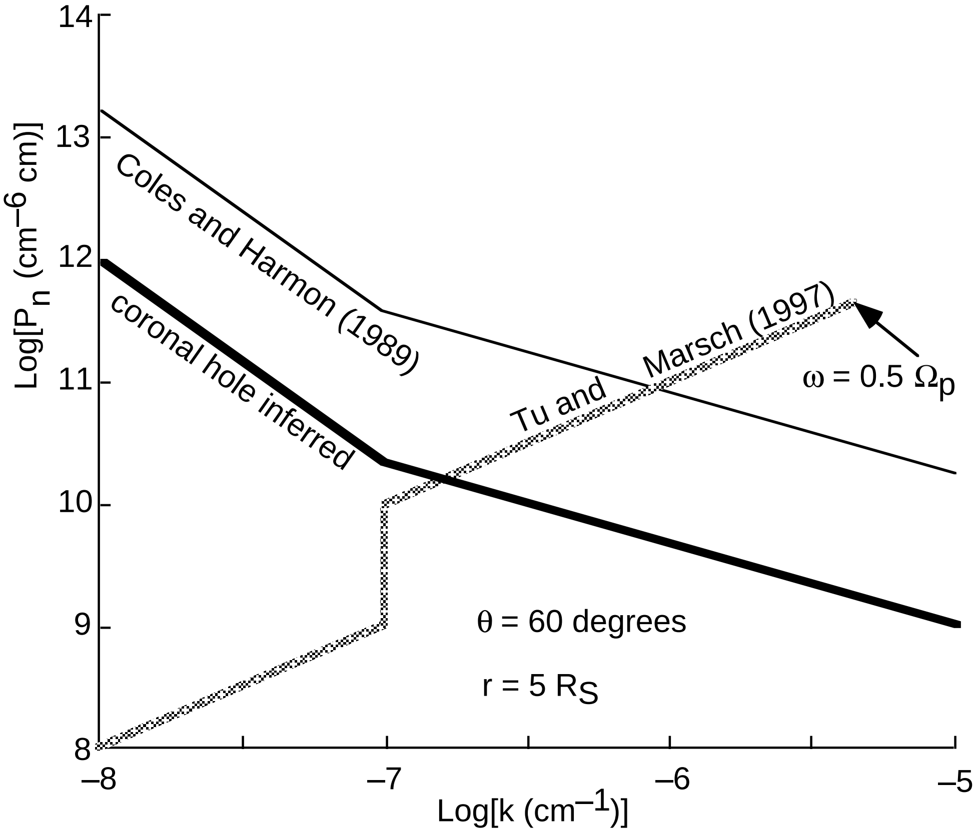
## TEST OF TU AND MARSCH (1997): IPS

Hollweg [**2000**].

They assume a specified magnetic power spectrum $P_B$.

Oblique propagation ⇒ Alfvén waves are weakly compressive.

$P_B \Rightarrow P_n$ which can be measured by IPS.



# WHENCE THE CYCLOTRON WAVES .3?

- INSTABILITIES ⇒ (oblique) high-freq. waves.

  $\delta j_{\perp}$ associated with low - freq. waves
  Markovskii [**2001**], Markovskii & Hollweg [**2002**].

  neutralized proton beams launched by
  reconnection events. Voitenko & Goossens [**2002**]

  low - freq. waves ⇒ instabilities ⇒ electron heating
  Viñas, Wong & Klimas [**2000**]

# RECENT IDEAS: 1:

**Markovskii** and Hollweg [**2004**]:
"MICROFLARES" AT CORONAL BASE

⇓

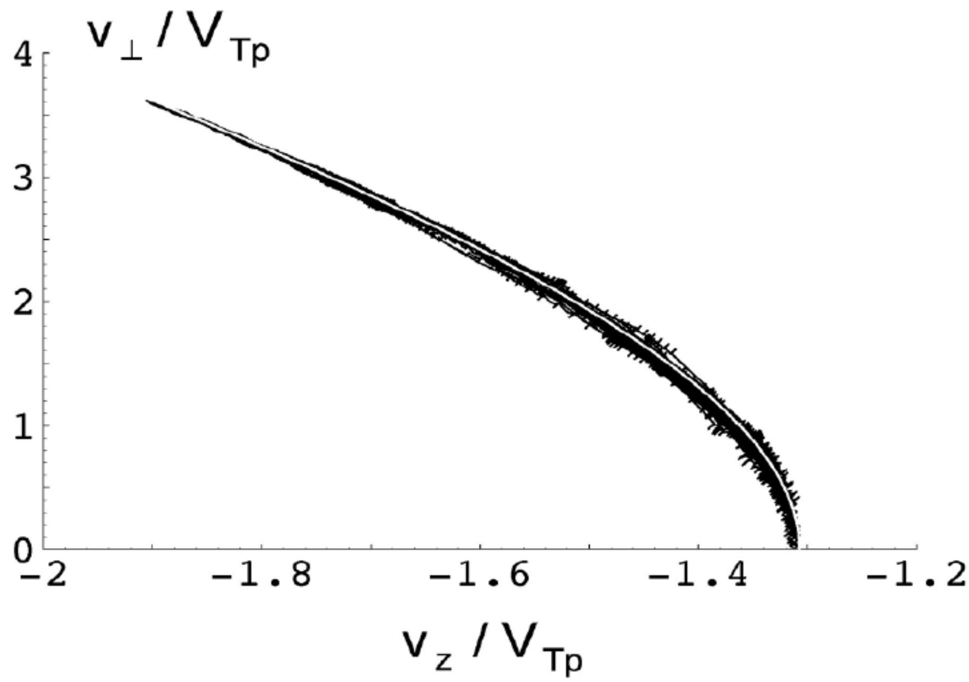
LAUNCH INTERMITTENT BURSTS OF LARGE $q_e$ INTO CORONA

⇓

DRIVE ION CYCLOTRON WAVES UNSTABLE
(electrostatic or electromagnetic; inward - propagating; highly oblique.)

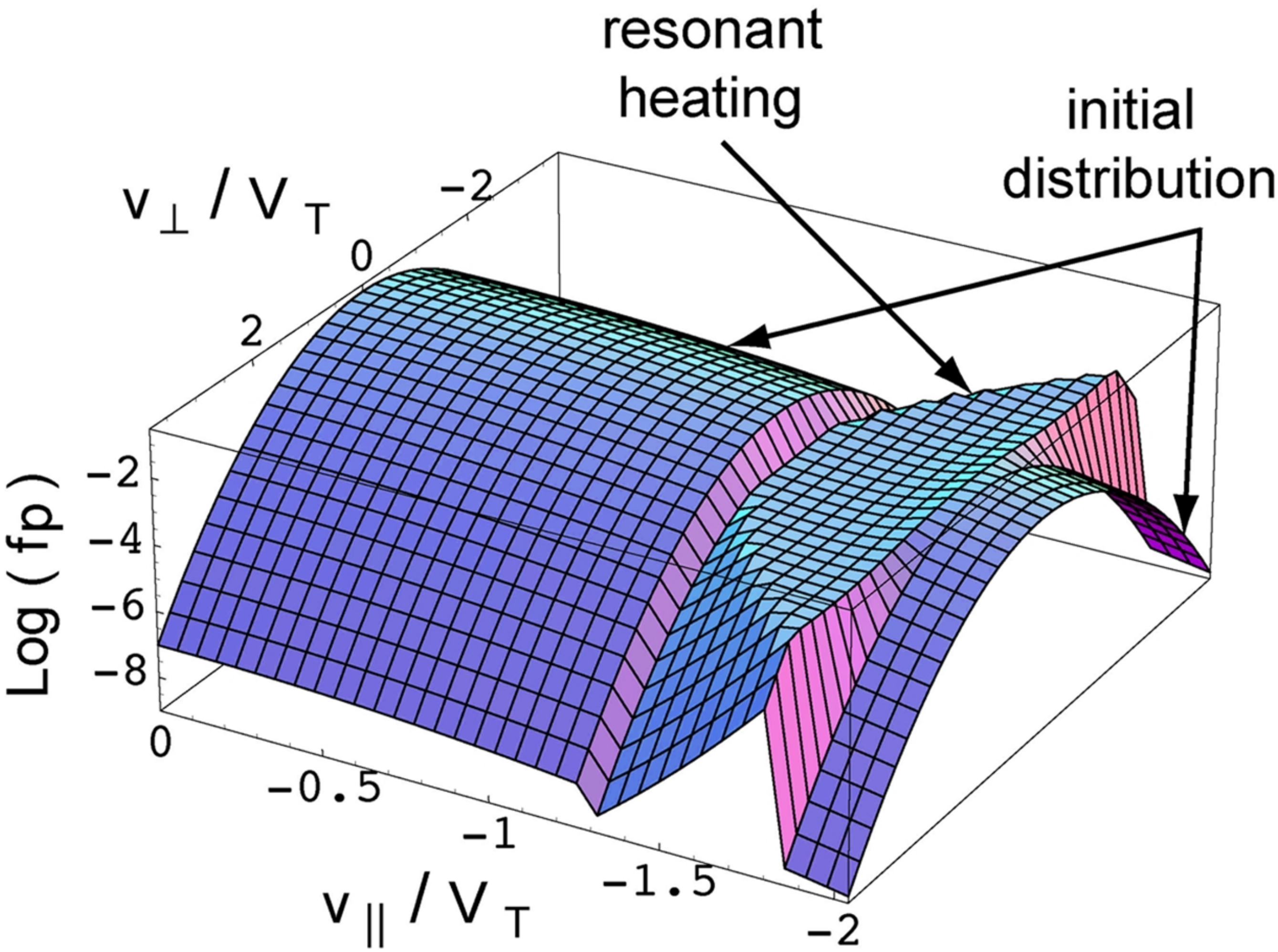
⇓

RESONANT PROTONS DIFFUSE ALONG HYPERBOLAE
(since $\omega \approx$ independent of k.)



$\Downarrow$

RESONANT PROTONS ARE PERPENDICULARLY HEATED.



# RECENT IDEAS: 2

## NON-WKB CORONAL TURBULENCE

Dmitruk et al., **2002**.

$$\frac{\partial z_-}{\partial t} + V_A \frac{\partial z_-}{\partial r} = -R_1 z_+ + R_2 z_- - z_+ \cdot \nabla_\perp z_-$$

$$\frac{\partial z_+}{\partial t} - V_A \frac{\partial z_+}{\partial r} = R_1 z_- - R_2 z_+ - z_- \cdot \nabla_\perp z_+$$

Standard linear non-WKB Alf waves
e.g. Heineman and Olbert 1980

Turbulent damping

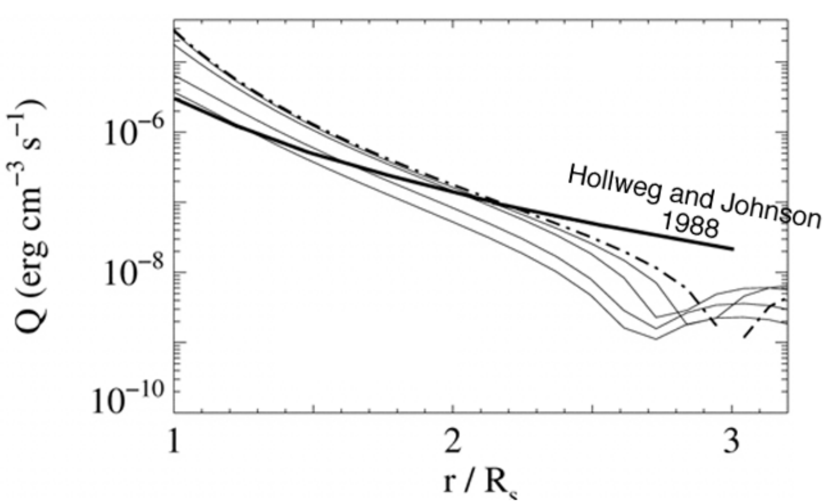
Take damping $\approx z_\pm |z_\mp| / \{2 \lambda_\perp(r)\}$

where $\lambda_\perp$ = correlation length.

If $\lambda_\perp \Rightarrow 0$, the volumetric heating rate is:

$$Q(r) \approx \begin{cases} F_{A_0} (A_0/A)|dV_A/dr|(V_{A_0}/V_A^2), & \text{if } r < r_m \\ F_{A_0} (A_0/A)|dV_A/dr|(V_{A_0}/V_{A_m}^2), & \text{if } r > r_m \end{cases}$$

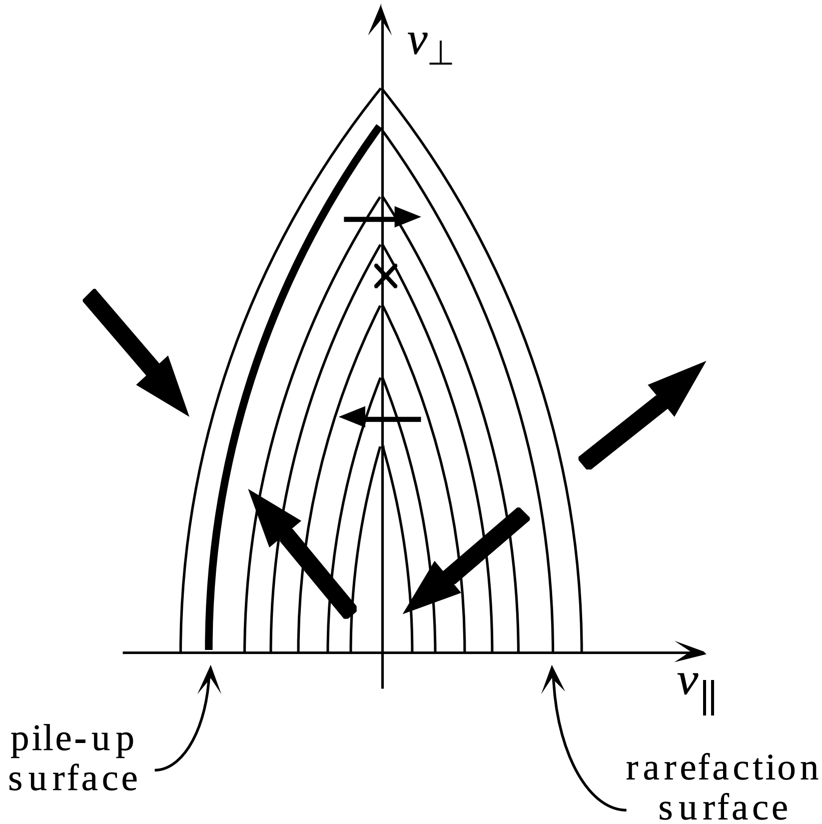
(sub-m = where $V_A$ is max.)

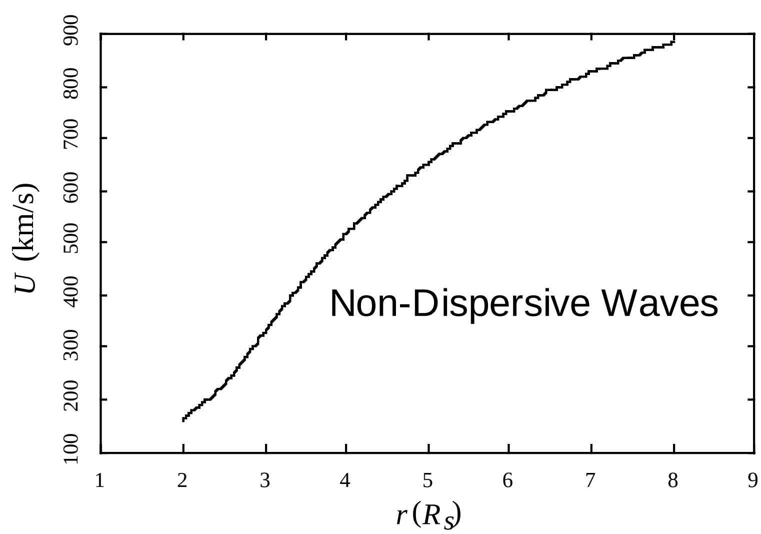


# RECENT IDEAS: 3

## THE "KINETIC SHELL MODEL"

**Isenberg,** Lee, and Hollweg [**2001**]; Isenberg [**2001**, **2004**].




But wave dispersion ⇒ much slower flows!!

# CONCLUSIONS

- We have progressed from an
  *electron - driven* wind through a
  *wave - driven* wind to a
  *proton - driven* wind.

- We realize that
  *coronal heating and solar wind acceleration need to be treated together.*

- In coronal holes, coronal heating works on
  *transverse components of protons & ions*.
  Not $j^2/\sigma$. Not viscosity.

  *Other coronal regions? Slow wind?*

- What is the *source* of the
  high - frequency resonant waves?
  - direct launching of kHz?
  - turbulence + advection?
  - micro - instabilities?

- Need to consider:
  - *Particle kinetics*; MHD *not* the final story;
  - Oblique propagation
    (refraction, instabilities);
  - Outward & inward propagation
    (reflections, instabilities, 2nd order Fermi).