NSF Physics Frontier Center Workshop
Chicago, Illinois, September 8–10, 2003

UVCS Observations of Ion Heating in the Solar Corona

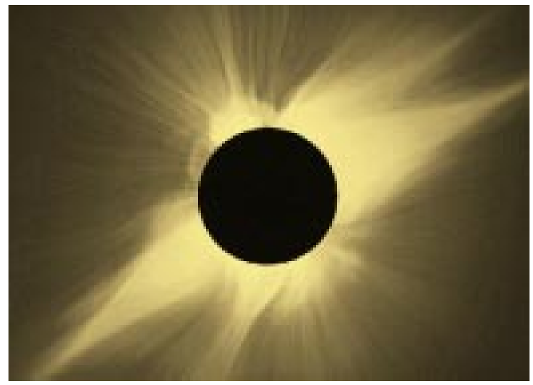
Adriaan van Ballegooijen & Steven R. Cranmer
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA

- **Background**
  - ⟶ Coronal heating and solar wind acceleration
  - ⟶ Observational constraints (remote → *in situ*)
- **Complexity: current challenges**
  - ⟶ Proposed heating & acceleration processes
  - ⟶ MHD turbulence, kinetic wave-particle interactions
  - ⟶ Additional nonlinear effects?
- **Future prospects and conclusions**

The Sun’s Outer Atmosphere

The solar photosphere exhibits a ∼blackbody temperature of 5800 K.

The solar corona:

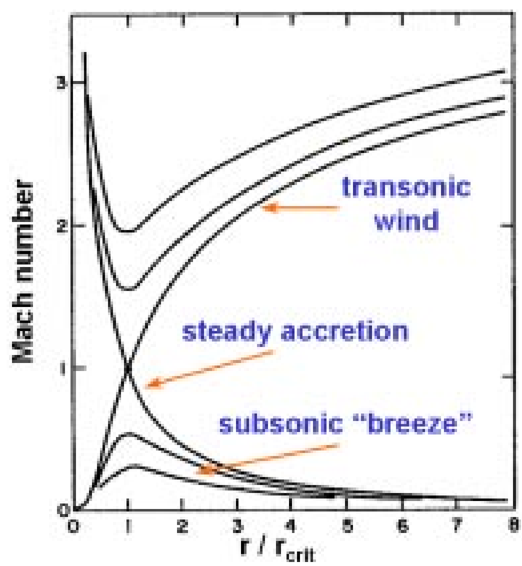


- 1870s: unknown emission lines; a new element called *“coronium?”*
- 1930s: Lines were identified as highly ionized ions: Ca^{12+}, Fe^{9+} to Fe^{13+}

$T > 1$ million K

The solar wind:

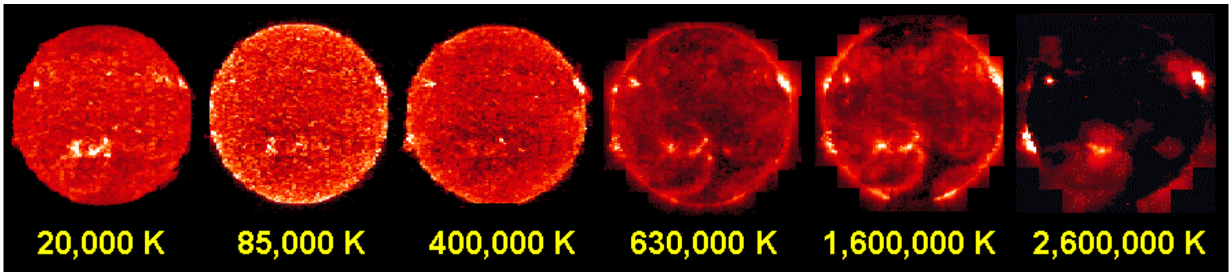
- 1860s to 1950s: evidence builds for outflowing plasma in the solar system (geomagnetic storms, comet tails)
- 1958: E. N. Parker proposed that the hot corona provides enough gas pressure to counteract gravity!
- 1962: *Mariner 2* provided first direct confirmation of the supersonic solar wind.



We still have not uniquely identified the physical processes that heat the corona and accelerate the solar wind . . . .

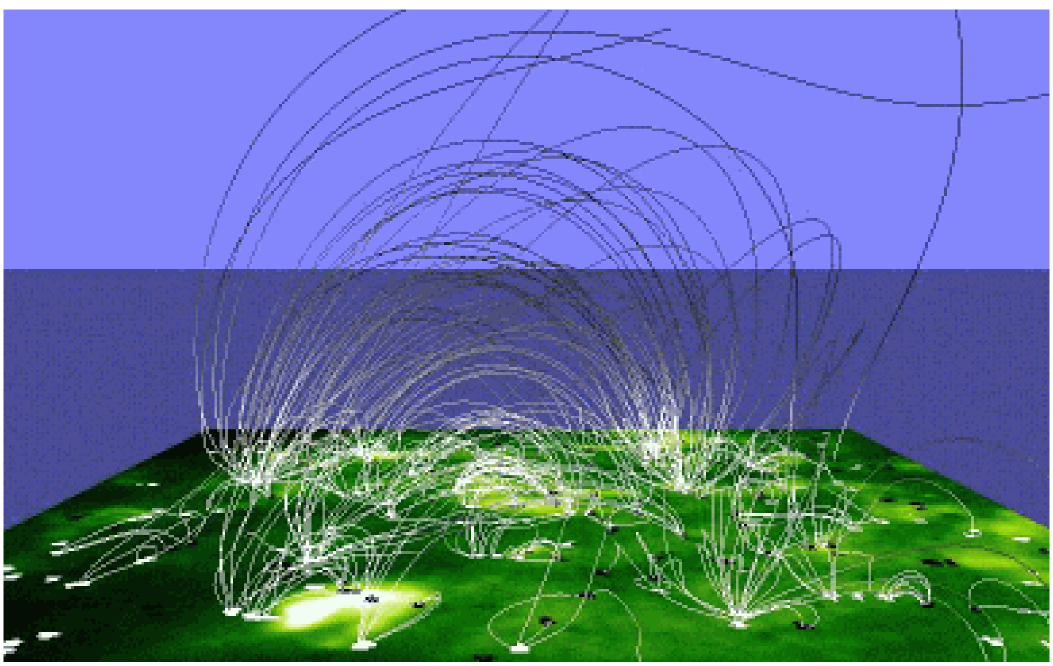
Heating the Coronal Base

⋆ The sharp "transition region" ($10^4 \rightarrow 10^6$ K) is still not well understood.



⋆ Most suggested mechanisms involve the storage and release of magnetic energy in **small-scale** twisted or braided flux tubes.

(Magnetic flux continually emerges from the convective interior, replenishing itself every $\sim$40 hours.)



⋆ **Dissipation** of the magnetic energy as heat probably occurs via Coulomb collisions (e.g., viscosity, resistivity, conductivity).

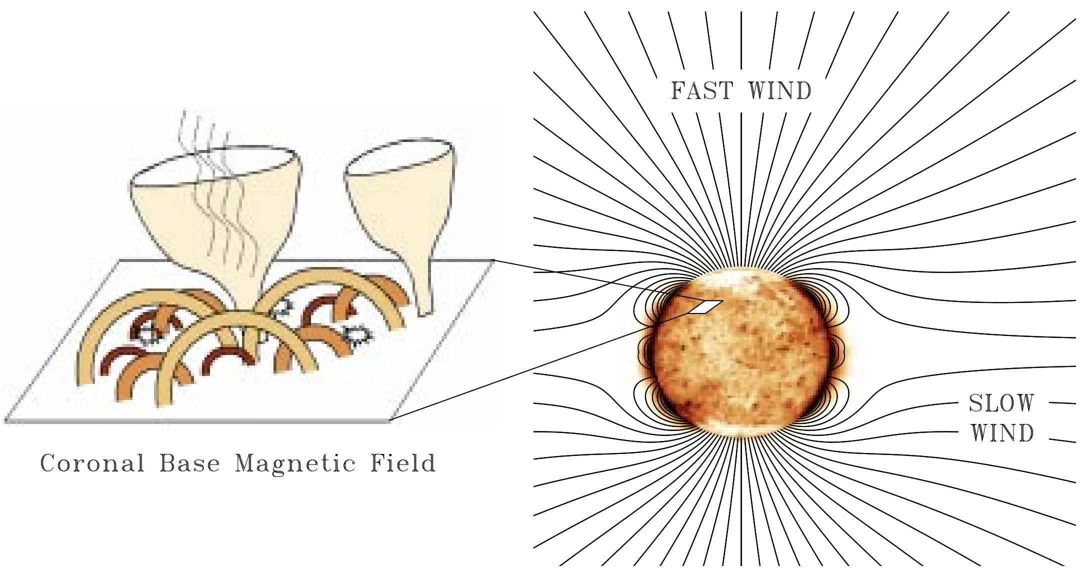
Heating the Extended Corona

Above 2 $R_\odot$, additional energy deposition is required in order to . . .

- ⋆ accelerate the high-speed ($v > V_{\rm esc}$) component of the solar wind;
- ⋆ produce the proton and electron temperatures measured in interplanetary space;
- ⋆ produce the strong preferential heating ($T_\perp \gg T_\parallel$) of heavy ions (in the wind's acceleration region) seen with UV spectroscopy.

It's a very different environment from the base . . .

- ⋆ Collisional $\longrightarrow$ collisionless

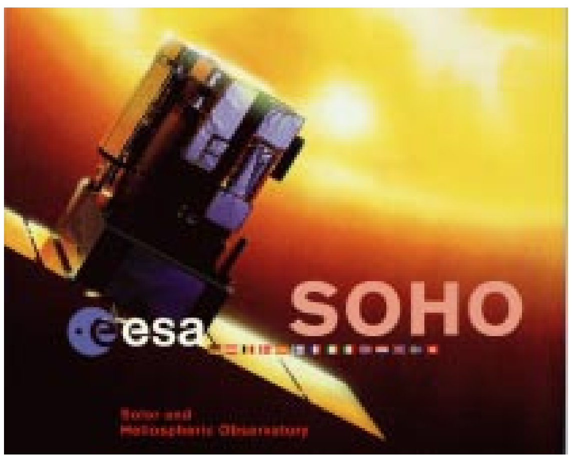


- ⋆ Energy for heating the plasma most likely *propagates* up from the Sun—i.e., **waves, shocks, turbulent fluctuations**—which probably dissipates via wave-particle resonances.

The SOHO Mission

SOHO (the Solar and Heliospheric Observatory) was launched in December 1995 with the goal of solving long-standing mysteries about the Sun:

- ***Solar Interior: What are its structure and dynamics?***
- ***Corona: Why does it exist and how is it heated?***
- ***Solar Wind: Where is it accelerated and how?***



The Ultraviolet Coronagraph Spectrometer (UVCS), one of the 12 instruments on SOHO, studies the extended solar corona where the solar wind is formed.

UVCS blocks out the bright disk of the Sun, in effect creating an "artificial eclipse," to be able to observe the much fainter ultraviolet light from the extended corona.

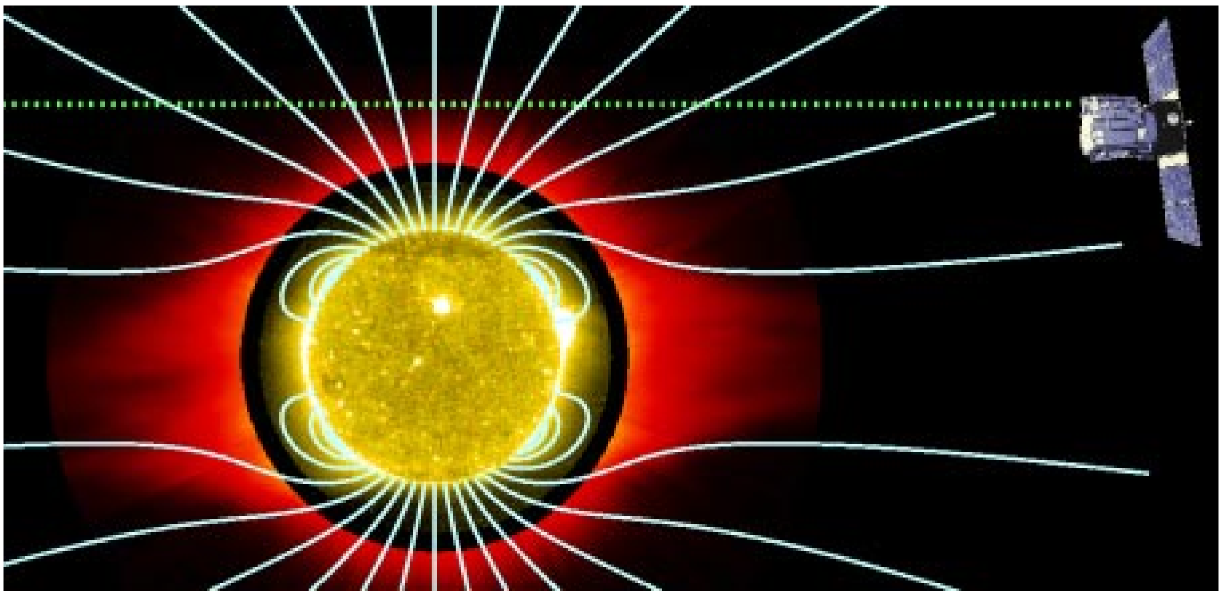
Plasma Diagnostics in the Extended Corona

collisionally excited line intensities (ratios)	• abundances, ionization state • electron density & temperature
resonantly scattered line intensities (ratios)	• velocity distributions in sunward direction ($T_{\|\|}$, $u_{\|\|}$)
spectral line shapes	• proton, ion, electron velocity distributions along line of sight ($T_{\perp}$) • departures from Maxwellians
Doppler shifts	• bulk motions along line of sight • chirality of helical flux tubes
visible polarimetry	• electron density, morphology
EUV spectropolarimetry	• velocity distribution anisotropies & flux tube orientation • magnetic field strength

Ultraviolet Spectroscopy of the Corona

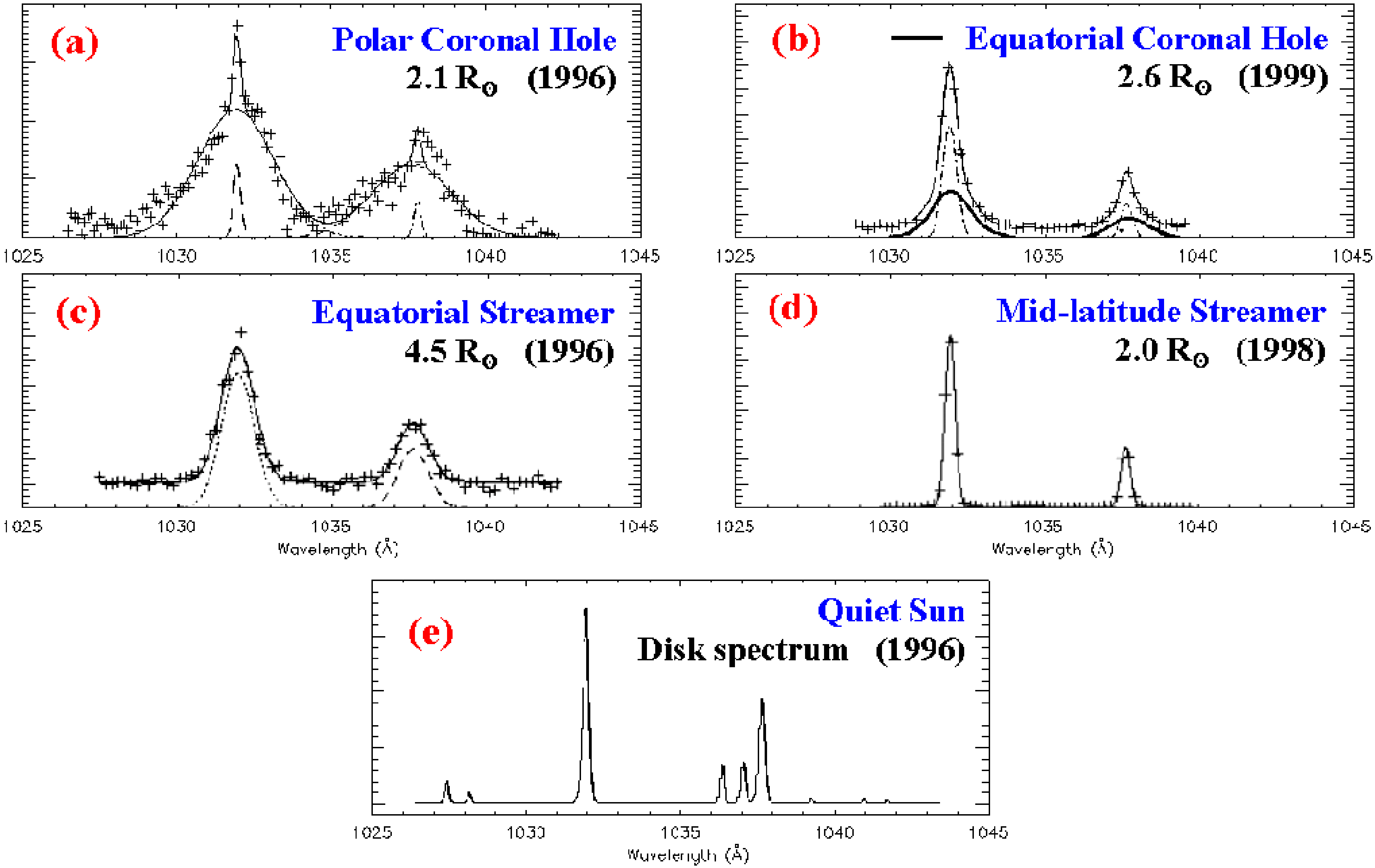
- ⋆ **Motivation:** measure plasma properties of hot ($> 10^6$ K) protons, electrons, and ions as they **accelerate.** (Too near Sun for *in situ*.)

  1979–1995: H I Lyα measured with rockets, Spartan 201
  1996–present: dozens of lines measured with UVCS/SOHO



- ⋆ Occultation of the solar disk is required because the extended corona is **6** to **10** orders of magnitude less bright than the disk.
- ⋆ The scattered photon emission is usually **optically thin:** some degree of deconvolution required.
- ⋆ **Simplest diagnostic:** WIDTHS of emission lines provide a near-direct measurement of the velocity distribution projected along the line of sight (Doppler broadening): i.e., $\sim T_\perp$ **in coronal holes.**

O VI 1032, 1037 Å Line Profiles



Emission Line Formation (1)

There are two major sources of spectral line photons in the extended corona:

★ **Electron impact excitation → de-excitation**

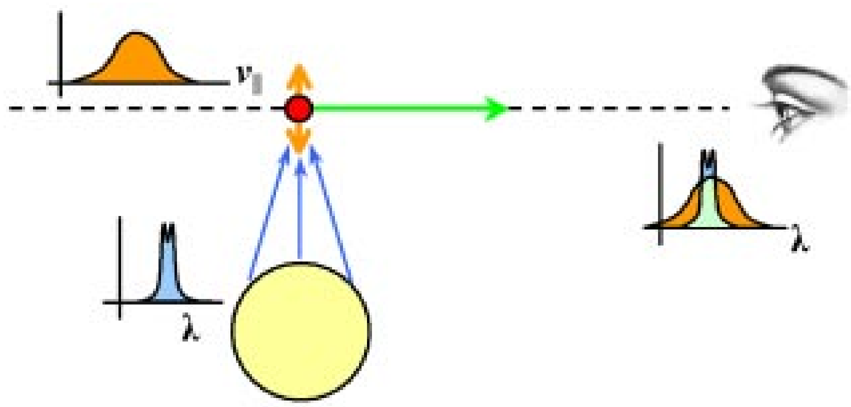
⇒ Profile width depends on line-of-sight velocity distribution

⇒ Total intensity $\propto n_{\rm e}\, n_{\rm atom}\, q(T_{\rm e})$

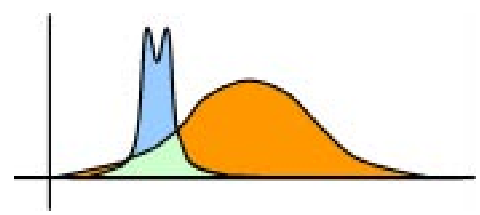
★ **Resonant scattering of disk photons**

⇒ Profile width depends on line-of-sight velocity distribution

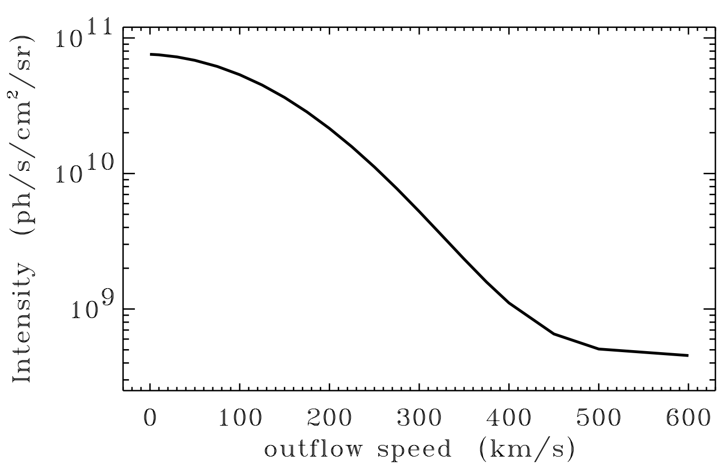
⇒ Total intensity depends on the **radial** component of the velocity distribution:



⇒ If atoms are **flowing** in the same direction as the incoming disk photons . . .
"Doppler dimming"

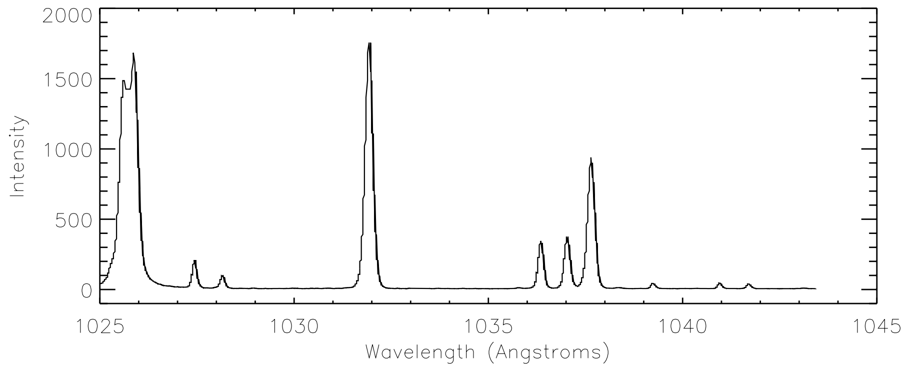


⇒ For the H I Lyman α (1216 Å) line, at 2 $R_\odot$:

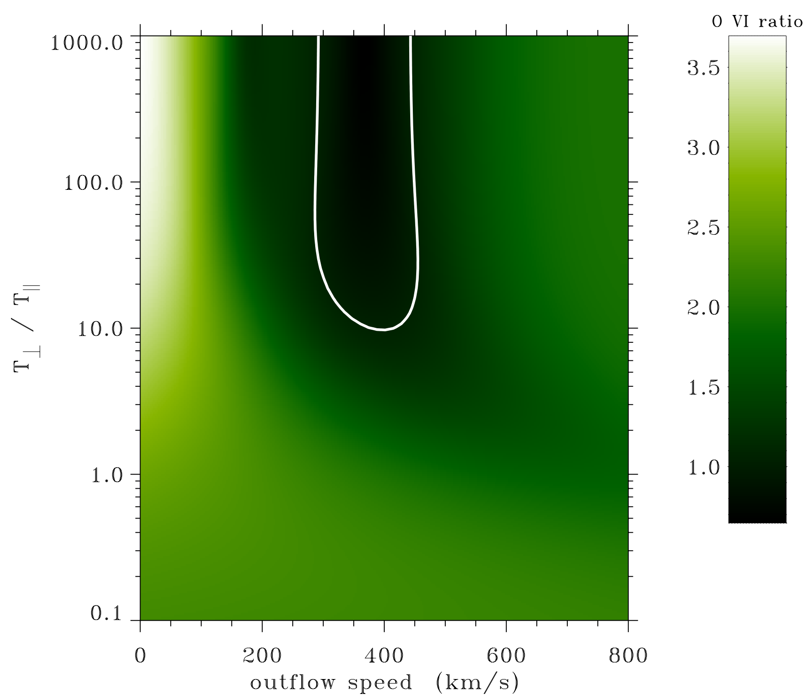


Emission Line Formation (2)

- ⋆ After H I Lyα, the O VI 1032, 1037 Å doublet are the next brightest lines in the extended corona. **On the disk:**



- ⋆ The "isolated" 1032 line Doppler dims like H I Lyα.
- ⋆ The 1037 line is **"Doppler pumped"** by neighboring C II line photons when $v_{\parallel} \sim$ 175 and 370 km/s.
- ⋆ The ratio ($\mathcal{R} = I_{1032}/I_{1037}$) depends on both the **bulk outflow speed** of O^{5+} ions and their $\boldsymbol{T_{\parallel}}$. For polar coronal holes at 3 $R_{\odot}$:



Low ratios ($\mathcal{R} < 1$) imply **fast outflow** and $T_{\perp} \gg T_{\parallel}$

Proton-Neutral Coupling

- In the low corona ($r \lesssim 1.5\,R_\odot$), protons and H^0 strongly coupled by:

$H^+ + H \rightleftarrows H + H^+$		(charge exchange)
$e^- + H \rightleftarrows e^- + e^- + H^+$		(electron collisions)
$h\nu + H \rightleftarrows e^- + H^+$		(photoioniz./ rad. recomb.)

- In the solar wind ($r \gtrsim 10\,R_\odot$), the coupling times become **longer** than wind flow time; protons and H^0 become more fully decoupled; e.g., $\boldsymbol{u_{\parallel H} < u_{\parallel p}}$. ($H^0$ is no longer a proxy for protons ...)

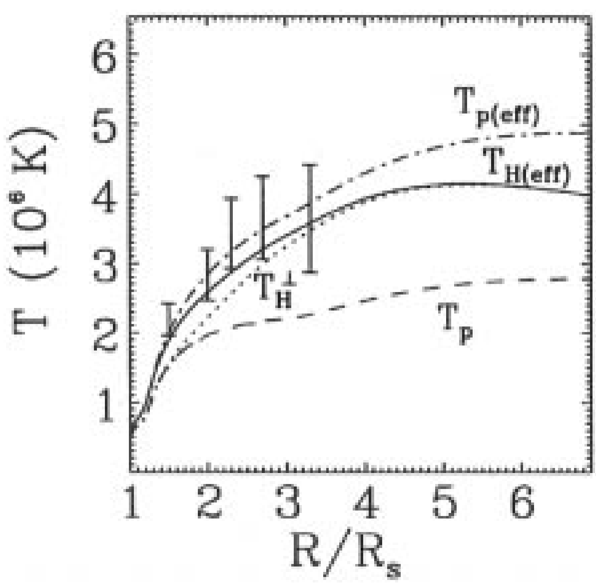
- IN BETWEEN ($r \sim$ 2–5 $R_\odot$), coupling times are still short compared to the wind flow time, but protons and H^0 can decouple if **transverse MHD waves** are present:

$$\boldsymbol{\delta B_\perp \propto -\delta u_{\perp p}} \quad ;$$

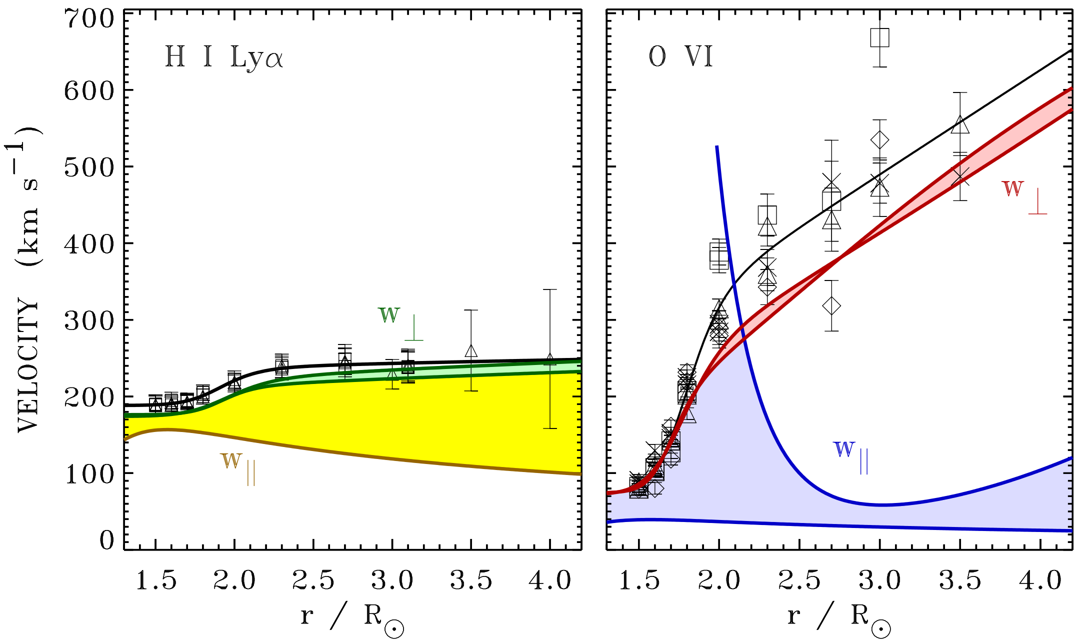
$\boldsymbol{\delta u_{\perp H}}$ cannot "keep up" with proton wave response

Perpendicular decoupling leads to frictional heating; i.e., $\boldsymbol{T_{\perp H} > T_{\perp p}}$.

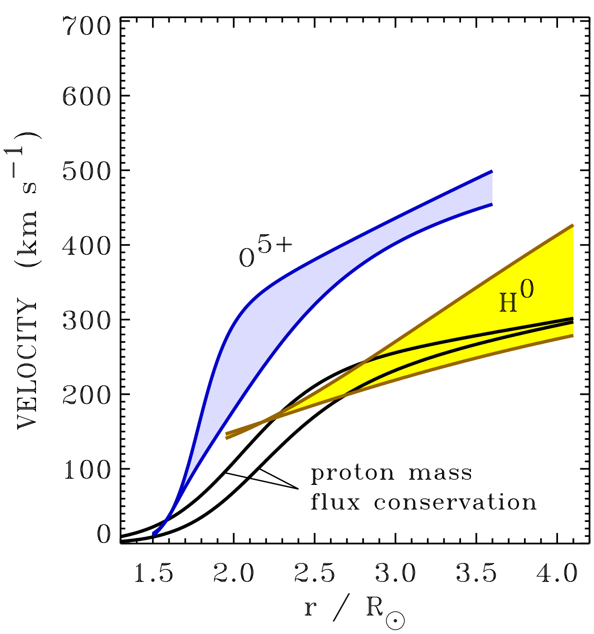
However, H^0 line **broadening** by frictional heating is $\sim$*balanced* by **narrowing** due to $\boldsymbol{\delta u_{\perp H} \ll \delta u_{\perp p}}$. It is difficult to measure these effects (Allen et al. 2000, JGR, *105*, 23,123).



UVCS Empirical Results for Most-probable speeds:



Outflow velocities:



$$u_{\rm ion} > u_p$$

$$\left(\frac{T_{\rm ion}}{T_p}\right) > \left(\frac{m_{\rm ion}}{m_p}\right)$$

$$T_\perp > T_\parallel$$

(... similar to *in situ*)

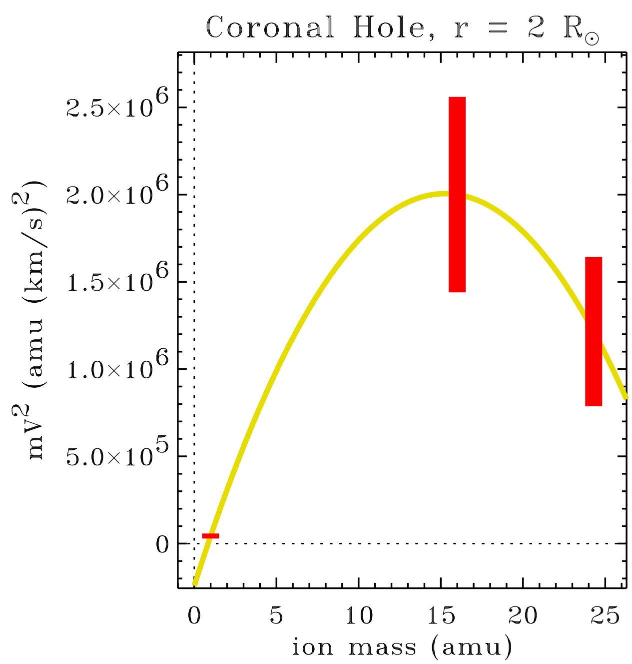
SEE: Kohl et al. (1998), ***Ap. J. Letters***, 501, L127
Cranmer et al. (1999), ***Ap. J.***, 511, 481

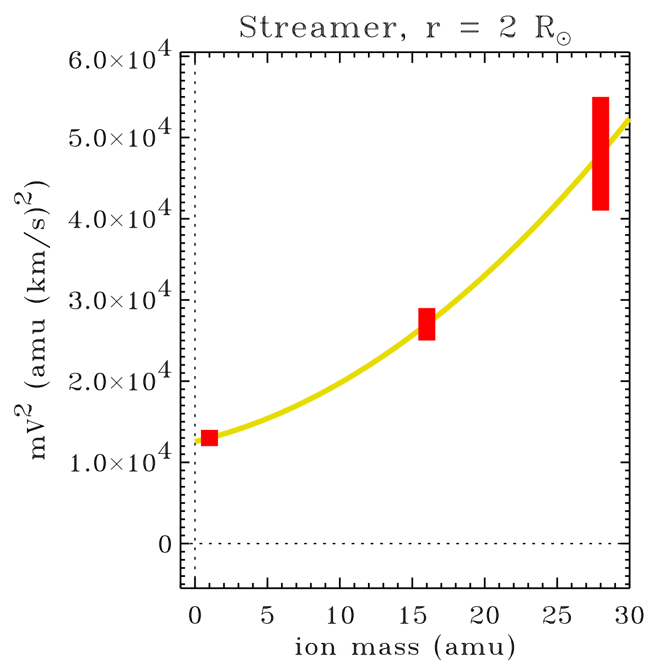
Evidence for Unequal Ion Temperatures

- ⋆ In the extended corona, departures from thermal equilibrium exist for both the low-density **coronal holes** and the high-density **streamers.**
- ⋆ Line profiles give the r.m.s. unresolved velocity V along the line-of-sight. If all ions had **equal** temperatures T, and the lines were broadened by a common "nonthermal" velocity δv, one would expect a linear relationship between the ion mass m and mV^2 . . .

$$mV^2 = kT + m(\delta v)^2$$

However,



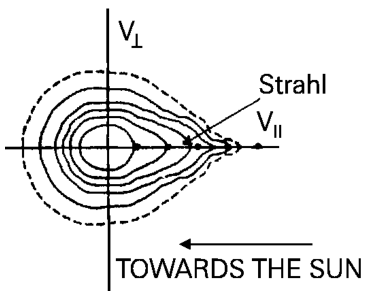


In situ Particle Properties

- *Mariner 2* confirmed the continuous nature of the solar wind in 1962, and found two relatively distinct components:

$$\left\{ \begin{array}{lll} \text{high-speed (500–800 km/s)} & \text{low density} & \sim\text{laminar flow} \\ \text{low-speed (300–500 km/s)} & \text{high density} & \text{variable, filamentary} \end{array} \right\}$$

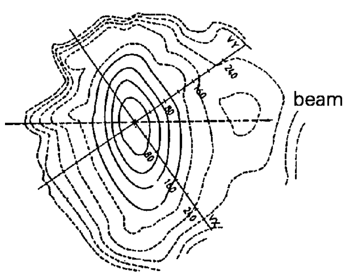
- In the high-speed wind (that emerges from coronal holes),



Electrons: thermal "core" + beamed "halo"

- suprathermals conserve $\mu = (T_\perp / B)$

(see, e.g., Marsch 1999, Space Sci Rev., 87, 1)

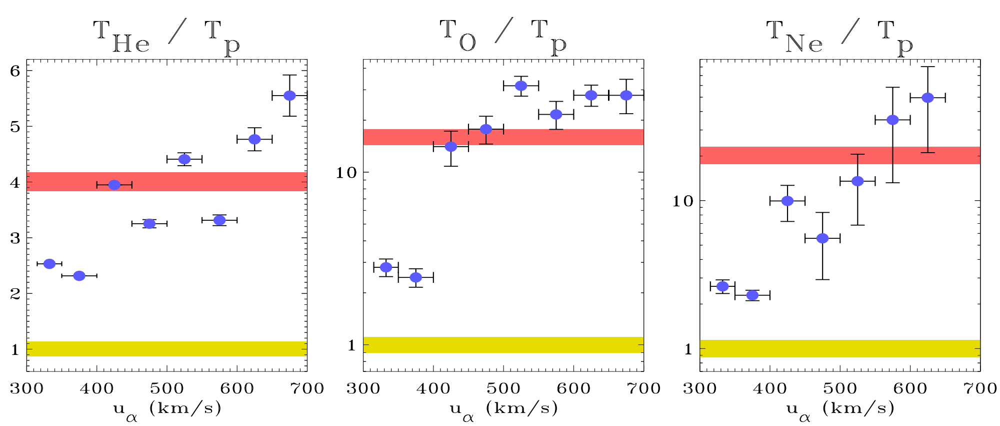


Protons: thermal core exhibits $T_\perp > T_\parallel$

- μ grows ∼linearly with distance (0.3–1 AU)
- beam flows ahead of core at $\Delta V \approx V_A$

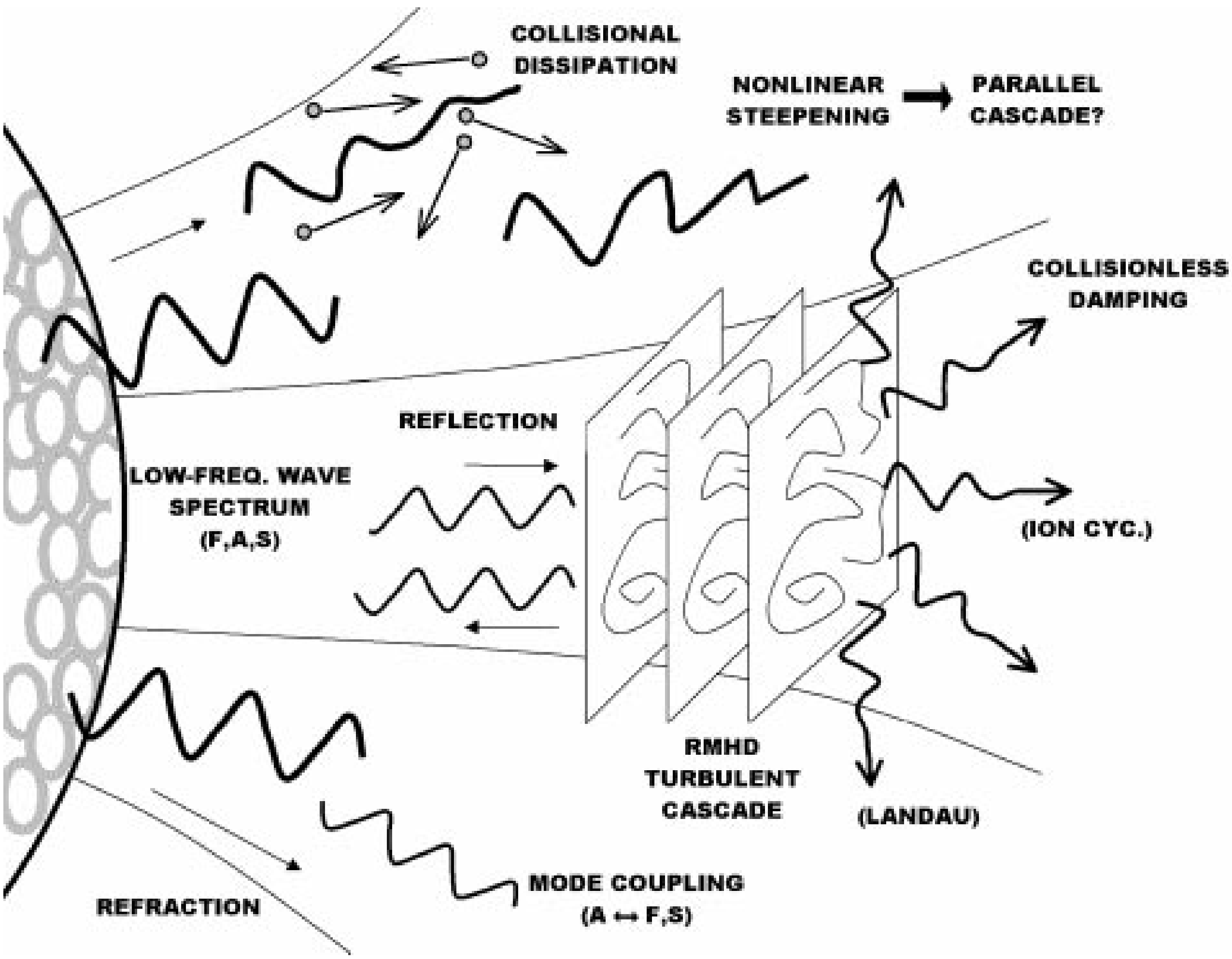
Heavy ions: flow faster than protons $(\Delta V \approx V_A)$

- $(T_{\rm ion}/T_{\rm p}) \gtrsim (m_{\rm ion}/m_{\rm p})$



(Collier et al. 1996, Geophys. Res. Letters, 23, 1191)

Complexity: Current Challenges



How is the the Extended Corona Heated?

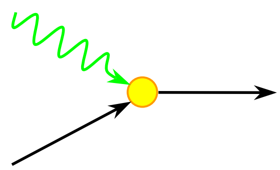
- ⋆ Energy for heating plasma must ultimately *propagate* up from the Sun; i.e., **waves, shocks, turbulent fluctuations.**

- ⋆ Collisional damping (i.e., viscous, Ohmic, conductive) of waves seems to be . . .

too weak (fast-mode/Alfvén)	**too strong (slow-mode/acoustic)**

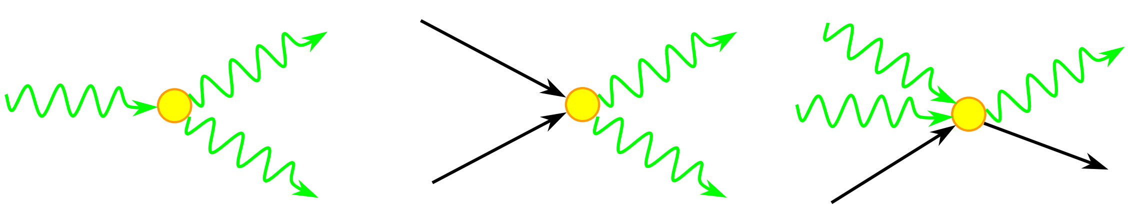
- ⋆ Collisionless damping mechanisms seem to be the most likely . . .

Quasi-linear wave-particle resonances:



Landau damping	**Ion cyclotron damping**
$\omega - u_{\parallel} k_{\parallel} = 0$	$\omega - u_{\parallel} k_{\parallel} = \pm n \Omega_{\mathrm{ion}}$
$T_e > T_p$ (low-β)	$T_{\mathrm{ion}} \gg T_p > T_e$
$T_{\parallel} > T_{\perp}$	$T_{\perp} > T_{\parallel}$

Nonlinear resonances:

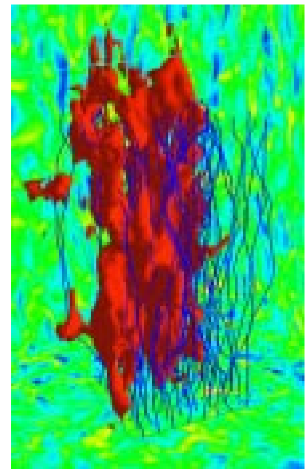


Multiple scales: MHD turbulence

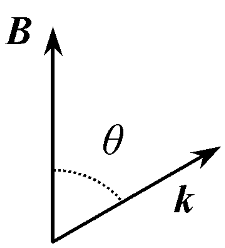
★ *In situ* δB, δv, $\delta \rho$ data (on time-scales from seconds to years) show evidence for turbulent cascade.

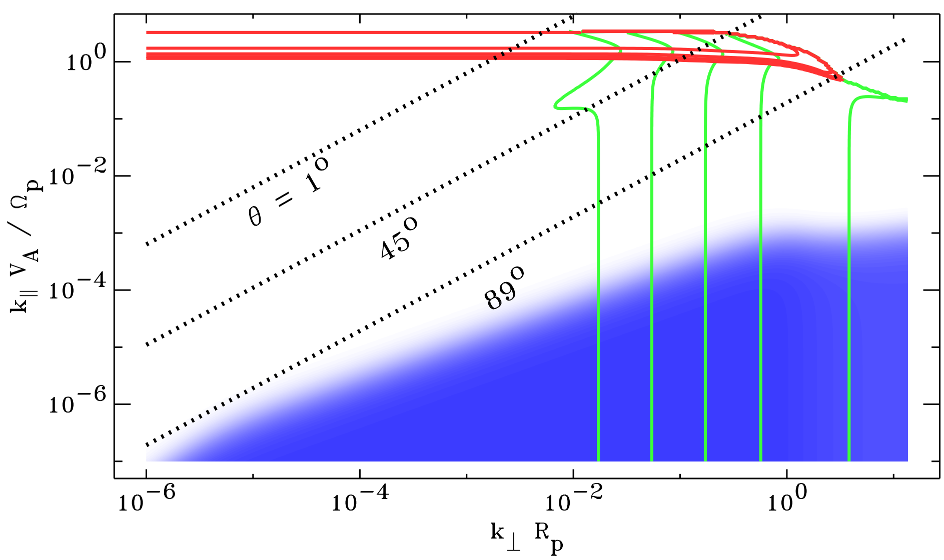
★ In the low-beta corona, MHD turbulence should proceed **anisotropically,** i.e., mainly from low to high $\boldsymbol{k}_\perp$ while leaving $\boldsymbol{k}_\parallel$ relatively unchanged.

(In a strong background magnetic field, it is easier to mix field lines in directions perpendicular to **B** than it is to bend them.) (e.g., Stone et al. 1998) ⟹



★ When this anisotropic spectrum damps, how much heat goes into **electrons, protons,** and heavy ions?





★ *In situ* solar wind observations support this picture, but large-$k_\parallel$ fluctuations are **also** seen (e.g., Leamon et al. 1998, 2000).

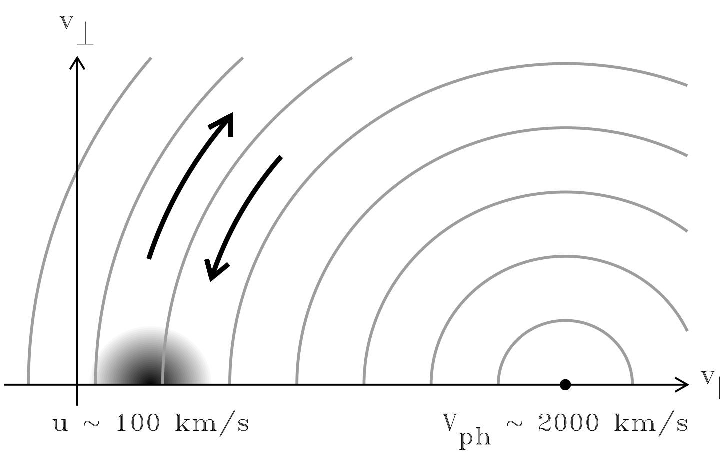
(see also Cranmer & van Ballegooijen 2003)

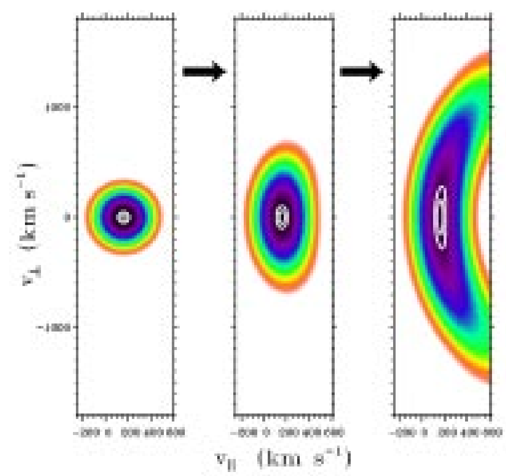
Ion Cyclotron Resonance

- ⋆ **1970s–present:** Preferential ion heating/acceleration and anisotropies (detected both *in situ* and remotely) led theorists to investigate the damping of parallel-propagating **ion cyclotron waves.**

- ⋆ Circularly polarized Alfvén waves with $\boldsymbol{\omega - v_{\parallel} k_{\parallel} \approx \Omega_{\mathrm{ion}}}$ are **resonant** with ion Larmor orbits. The wave's **E**-fields are **AC** in Sun's frame, but **DC** in ion's frame!

- ⋆ Dissipation of ion cyclotron waves produces **diffusion** in velocity space, along contours of ∼constant energy in the frame moving with the wave phase speed. $(V_{\mathrm{A}} \gg v_{\mathrm{th}})$





- ⋆ Anisotropy grows naturally as long as there is an energy supply of resonant waves in the corona. **(Saturated by dispersion...)**

- ⋆ Ions are accelerated *along* field both by: **(a)** forward curvature of velocity distribution, and **(b)** by magnetic mirroring of high–$v_{\perp}$ ions.

Problems with Gradual Generation . . .

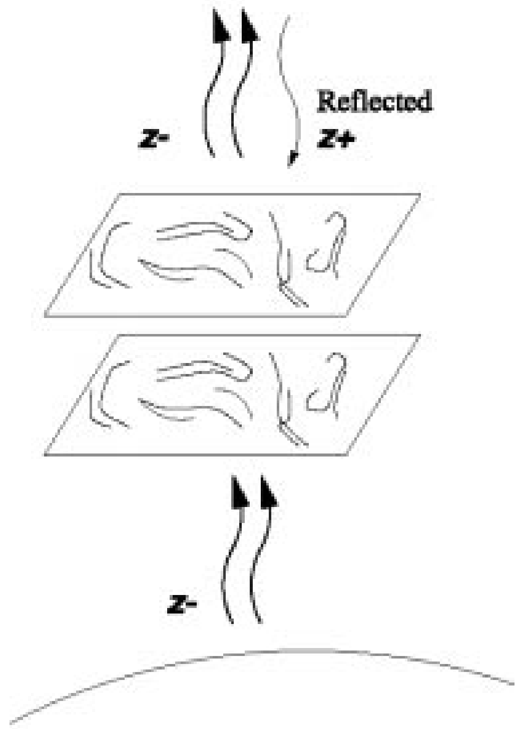
- ⋆ Most of the work on gyroresonance in the solar wind has been for waves propagating *along* the field $(k_{\|})$.

- ⋆ However, both simulations and analytic descriptions of MHD turbulence predict cascade from small to large *perpendicular* wavenumbers $(k_{\perp})$.

  (Alfvénic fluctuations with large $k_{\perp}$ do not necessarily have large $\omega \rightarrow \Omega_{\mathrm{ion}}$)

- ⋆ Perpendicular ("2D") turbulence does dissipate on the smallest scales, but this may not heat and accelerate ions preferentially.

  (Landau damping in a low–β plasma tends to heat **electrons** *preferentially...)*



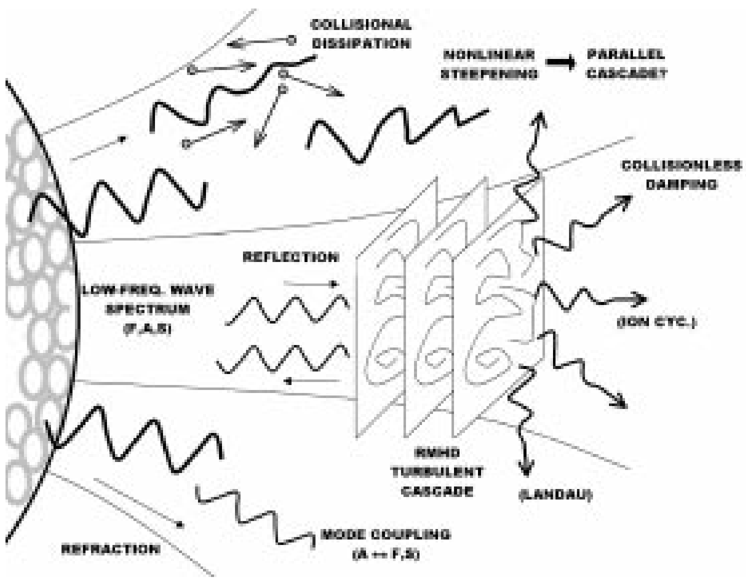
- ⋆ *In situ* solar wind observations support this picture, but large-$k_{\|}$ fluctuations are **also** seen (e.g., Leamon et al. 1998, 2000).

Studies of (multiple harmonic) ion cyclotron resonance with highly *oblique* $(\mathbf{k} \cdot \mathbf{B} \approx 0)$ waves are underway . . . .

A “wish list” for solar wind models?

Generation and nonlinear evolution of the solar wind **fluctuation spectrum** must be understood.

Self-consistent **kinetic models** (corona $\rightarrow$ wind) of protons, electrons, and ions are needed.



- ★ Because the multitude of proposed physical processes **interact with one another** on a wide range of scales, their impact can only be evaluated when they are all included together.

- ★ There is a need for scalable “phenomenological” terms that encapsulate the physics of nonlinear steepening, multi-mode coupling, refraction, etc., and allow them to be included in “linear” wave transport equations.

Selected References

Ambrosiano, J., Matthaeus, W. H., Goldstein, M. L., & Plante, D. 1988, J. Geophys. Res., 93, 14383

Axford, W. I., & McKenzie, J. F. 1997, in Cosmic Winds and the Heliosphere, (U. Arizona Press, Tucson), 31

Bale, S. D., Hull, A., Larson, D. E., et al. 2002, Ap.J. Letters, 575, L25

Banaszkiewicz, M., Axford, W. I., & McKenzie, J. F. 1998, Astron. Astrophys., 337, 940

Berk, H. L., & Roberts, K. V. 1967, Phys. Fluids, 10, 1595

Biglari, H., & Diamond, P. H. 1989, Physica D, 37, 206

Brambilla, M. 1998, Kinetic Theory of Plasma Waves: Homogeneous Plasmas (Oxford: Clarendon)

Carlson, C. W., McFadden, J. P., Ergun, R. E., et al. 1998, Geophys. Res. Letters, 25, 2017

Chandrasekhar, S. 1943, Rev. Mod. Phys., 15, 1

Collier, M. R., et al. 1996, Geophys. Res. Letters, 23, 1191

Cranmer, S. R. 1998, Ap.J., 508, 925

Cranmer, S. R. 2000, Ap.J., 532, 1197

Cranmer, S. R. 2001, J. Geophys. Res., 106, 24937

Cranmer, S. R. 2002, Space Sci. Rev., 101, 229

Cranmer, S. R., Field, G. B., & Kohl, J. L. 1999a, Ap.J., 518, 937

Cranmer, S. R., et al. 1999b, Ap.J., 511, 481

Cranmer, S. R., and van Ballegooijen, A. A. 2003, Ap.J., 594, 573

Dmitruk, Matthaeus, W. H., Milano, L. J., Oughton, S., Zank, G. P., & Mullan, D. J. 2002, Ap.J., 575, 571

Ergun, R. E., Carlson, C. W., McFadden, J. P., et al. 1998, Phys. Rev. Lett., 81, 826

Esser, R., & Habbal, S. R. 1995, Geophys. Res. Lett., 22, 2661

Esser, R., Fineschi, S., Dobrzycka, D., et al. 1999, Ap.J. Letters, 510, L63

Feldman, W. C., & Marsch, E. 1997, in Cosmic Winds and the Heliosphere, (U. Arizona Press, Tucson), 617

Giordano, S., Antonucci, E., Noci, G., Romoli, M., & Kohl, J. L. 2000, Ap.J., 531, L79

Goldreich, P., & Sridhar, S. 1995, Ap.J., 438, 763

Goldreich, P., & Sridhar, S. 1997, Ap.J., 485, 680

Hollweg, J. V. 1986, J. Geophys. Res., 91, 4111

Hollweg, J. V. 1999, J. Geophys. Res., 104, 24781

Hollweg, J. V., & Isenberg, P. A. 2002, J. Geophys. Res., 107 (A7), 1147, 10.1029/2001JA000270

Isenberg, P. A., Lee, M. A., & Hollweg, J. V. 2000, Solar Phys., 193, 247

Ko, Y.-K., et al. 1997, Solar Phys., 171, 345

Kohl, J. L., et al. 1997, Solar Phys., 175, 613

Kohl, J. L., et al. 1998, Ap.J. Letters, 501, L127

Kohl, J. L., et al. 1999, Ap.J. Letters, 510, L59

Krauss-Varban, D., Omidi, N., & Quest, K. B. 1994, J. Geophys. Res., 99, 5987

Leamon R. J., Smith, C. W., Ness, N. F., Matthaeus, W. H., & Wong, H. K. 1998, J. Geophys. Res., 103, 4775

Leamon R. J., Matthaeus, W. H., Smith, C. W., Zank, G. P., Mullan, D. J., & Oughton, S. 2000, Ap.J., 537, 1054

Leith, C. E. 1967, Phys. Fluids, 10, 1409

Li, X. 1999, J. Geophys. Res., 104, 19773

Li, X., Habbal, S. R., Hollweg, J. V., & Esser, R. 1999, J. Geophys. Res., 104, 2521

Li, X., Habbal, S. R., Kohl, J. L., & Noci, G. 1998, Ap.J. Letters, 501, L133

Marsch, E., 1999, Space Sci. Rev., 87, 1

Marsch, E., Goertz, C. K., & Richter, K. 1982, J. Geophys. Res., 87, 5030

Marsch, E., & Tu, C.-Y. 2001, J. Geophys. Res., 106, 227

Matthaeus, W. H., Oughton, S., Pontius, D. H., & Zhou, Y. 1994, J. Geophys. Res., 99, 19267

Matthaeus, W. H., Zank, G. P., Oughton, S., Mullan, D. J., & Dmitruk, P. 1999, Ap.J. Letters, 523, L93

Parker, E. N. 1991, Ap.J., 372, 719

Spitzer, L., Jr. 1962, Physics of Fully Ionized Gases, 2nd ed. (New York: Wiley)

Stawicki, O., Gary, S. P., & Li, H. 2001, J. Geophys. Res., 106, 8273

Stix, T. H. 1992, Waves in Plasmas (New York: AIP)

Stone, J. M., Ostriker, E. C., & Gammie, C. F. 1998, Ap.J. Letters, 508, L99

Tanaka, M., Sato, T., & Hasegawa, A. 1989, Phys. Fluids B, 1, 325

Tu, C.-Y., & Marsch, E. 1995, Space Sci. Rev., 73, 1

Tu, C.-Y., & Marsch, E. 1997, Solar Phys., 171, 363

Tu, C.-Y., & Marsch, E. 2001, J. Geophys. Res., 106, 8233

Turikov, V. A. 1984, Physica Scripta, 30, 73

van Ballegooijen, A. A. 1986, Ap.J., 311, 1001

Wilhelm, K., Marsch, E., Dwivedi, B. N., et al. 1998, Ap.J., 500, 1023

Withbroe, G. L., Kohl, J. L., Weiser, H., & Munro, R. H. 1982, Space Sci. Rev., 33, 17

Zhou, Y., & Matthaeus, W. H. 1990, J. Geophys. Res., 95, 14881