Selected Topics in Plasma Astrophysics

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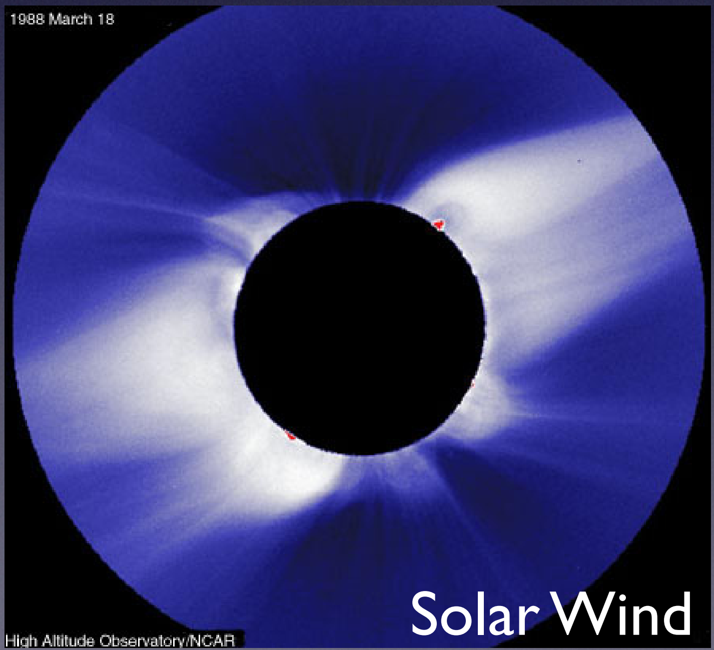


Selected Topics in Plasma Astrophysics

- Range of Astrophysical Plasmas and Relevant Techniques
- Stellar Winds (Lecture I)
  - Thermal, Radiation, and Magneto-Rotational Driven Winds
  - Connections to Other Areas of Astrophysical Fluids/Plasmas
- Instabilities In Ideal Fluids and Dilute Plasmas (Lecture II)
  - Ideal Fluid theory of Convection and MRI
  - How do Anisotropic Conduction & Viscosity Modify Convection and MRI
  - Astrophysical Context: Galaxy Clusters and Accretion Disks

Range of Astrophysical Plasmas & Techniques

Relativistic

Force-Free Electrodynamics
(e.g., pulsars)
(GR)(M)HD
(e.g., BH accretion/jets)
PIC
(e.g., rel. shocks)
Dynamical Space-Time + MHD
(e.g., Compact Object Mergers)

Non-Relativistic

Force-Free
(e.g., solar corona)
(M)HD
(e.g, star formation, disks, cosmology)
Kinetic Theory
(e.g., shocks, reconnection, disks, turbulence)

Fluid Models

ideal (M)HD (ok first approx?)

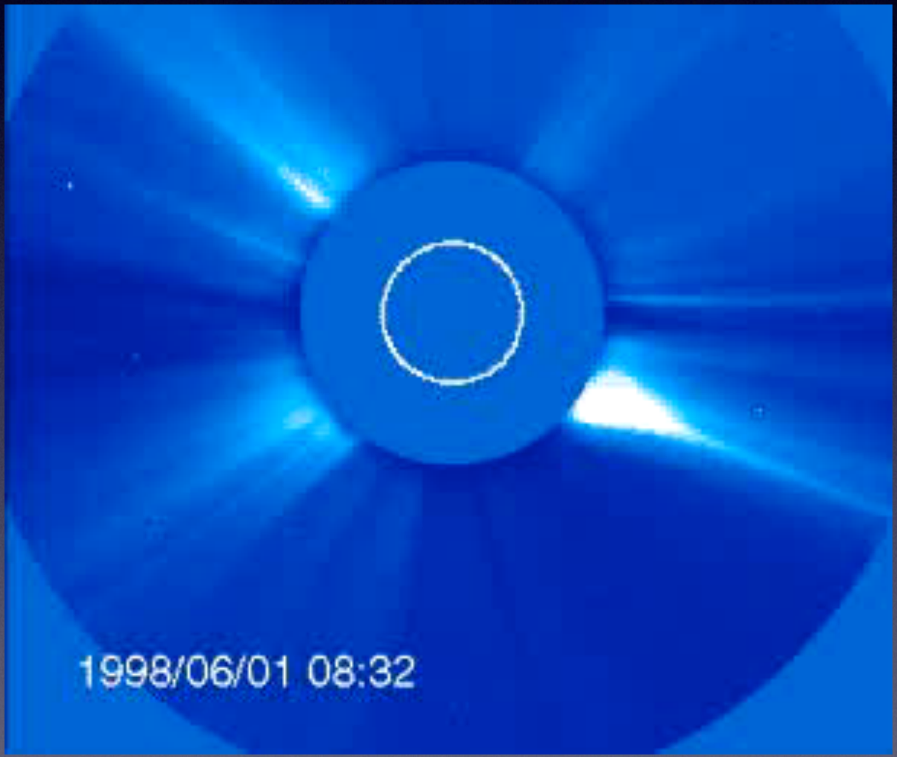
dense plasmas:
- non-ideal: resistivity, Hall, ambipolar (e.g., star formation)
- multi-fluid: dust + gas/plasma (e.g., planet formation)
- radiation (M)HD (e.g., star formation, disks, BH growth)

dilute plasmas:
- non-ideal: anisotropic conduction & viscosity (e.g., galaxy clusters)
- multi-fluid: pressure tensor & anisotropic conduction (e.g., solar wind, disks)
- multi-fluid: plasma + cosmic rays (e.g., galaxy formation)

Stellar Winds

- Thermally driven winds (sun-like stars)
  - hydrodynamic theory, kinetic theory
- Magnetocentrifugically driven winds
  - rotation as energy source, tapped via B-fields
- Radiation pressure driven winds: $L > L_{Edd}$
  - continuum driven: (e.g., dust, $\kappa > \kappa_{electron}$)
  - line-driven (e.g., Fe & other metal lines in massive stars)
- Ideas developed in the stellar context later key in other astrophysical arenas
  - thermally driven galactic winds; line and continuum driven winds from accreting black holes; magnetically driven winds from disks (ang. momentum transport); microinstabilities regulate pressure anisotropy in collisionless plasmas …

Solar Corona & Wind



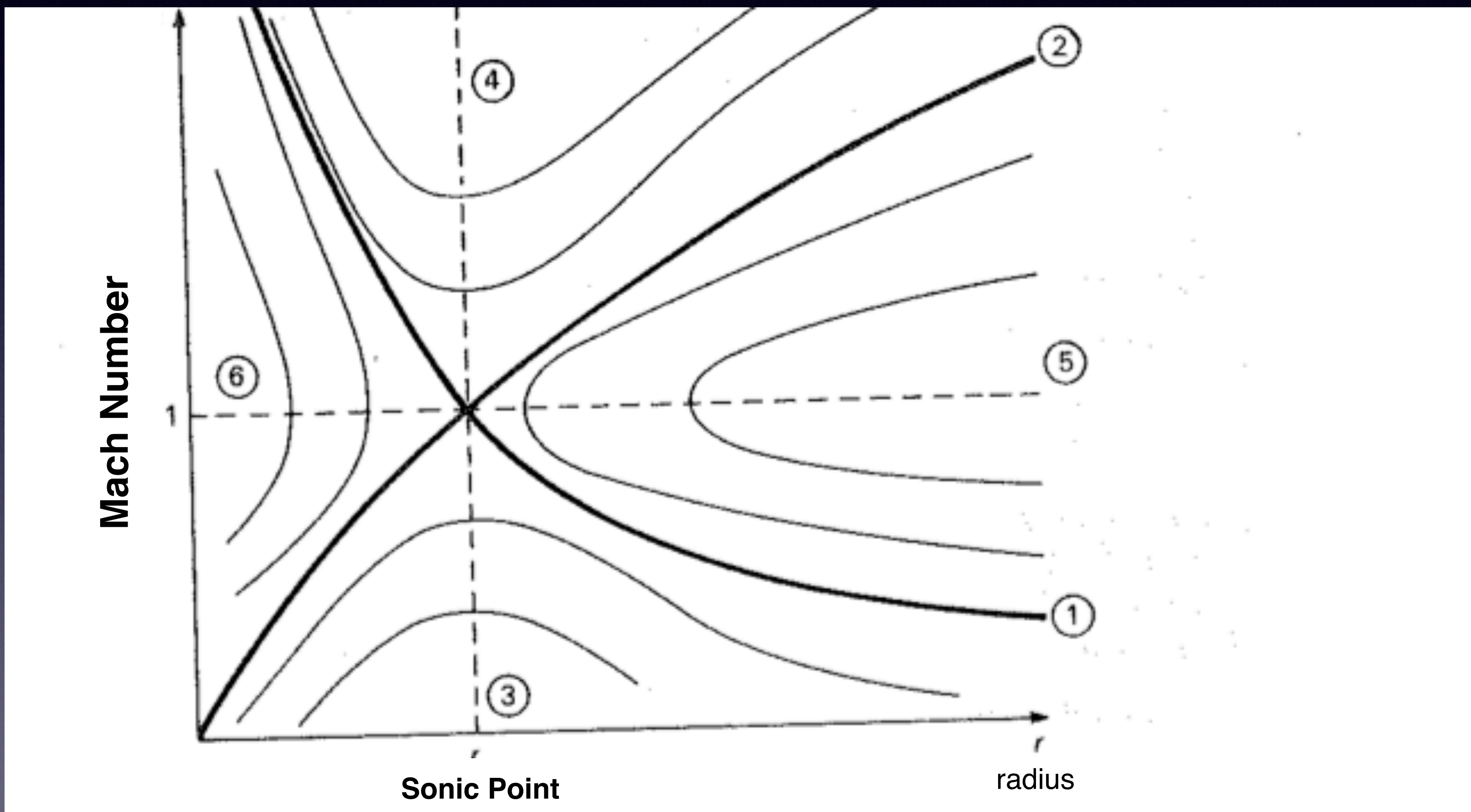
$\dot{M} \sim 10^{-14} M_\odot \, yr^{-1}$

$\dot{E} \sim 10^{-7} L_\odot$

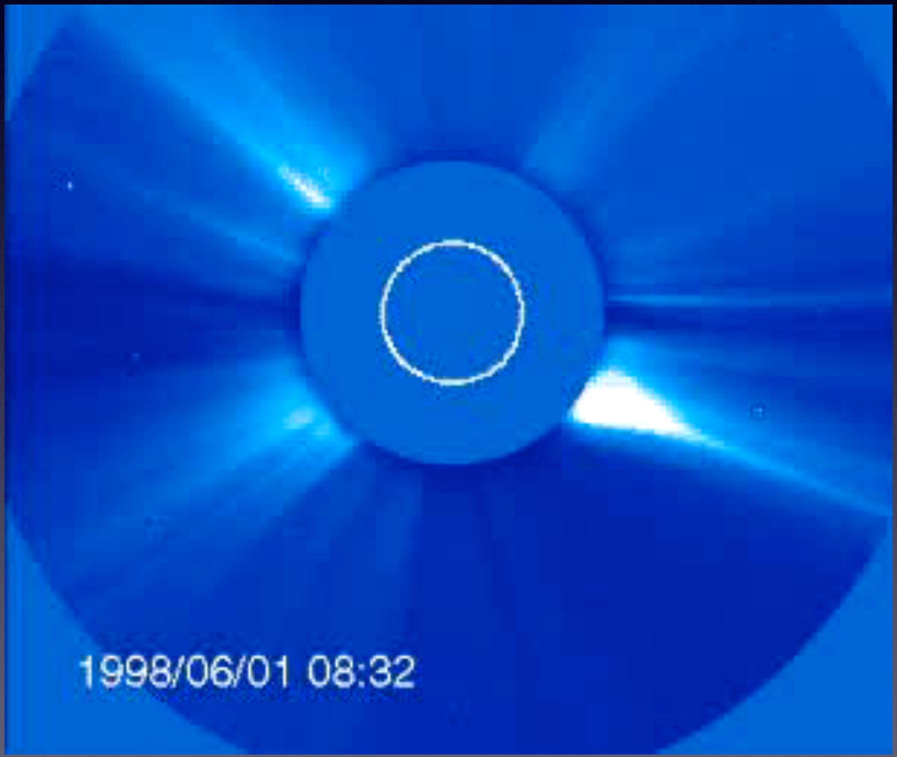
dJ/dt ~ J/10^{10} yrs

- Corona at $R \sim 2 R_{sun}$
  - $n \sim 10^6 \, cm^{-3}$; $B \sim 1$ G
    - $\beta \lesssim 10^{-2}$ (magnetically dominated!)
  - Not in thermal equilibrium:
    - $T_{ion} >> T_p \sim 2 \; 10^6$ K $\gtrsim T_e \sim 10^6$ K
    - $T_\perp \gtrsim T_{||}$
  - $\ell_{mfp} \sim$ few $R_{sun} \sim 10^8 \rho_{Larmor}$ (collisionless!)

Spherical Wind/Accretion Solutions



Solar Corona & Wind



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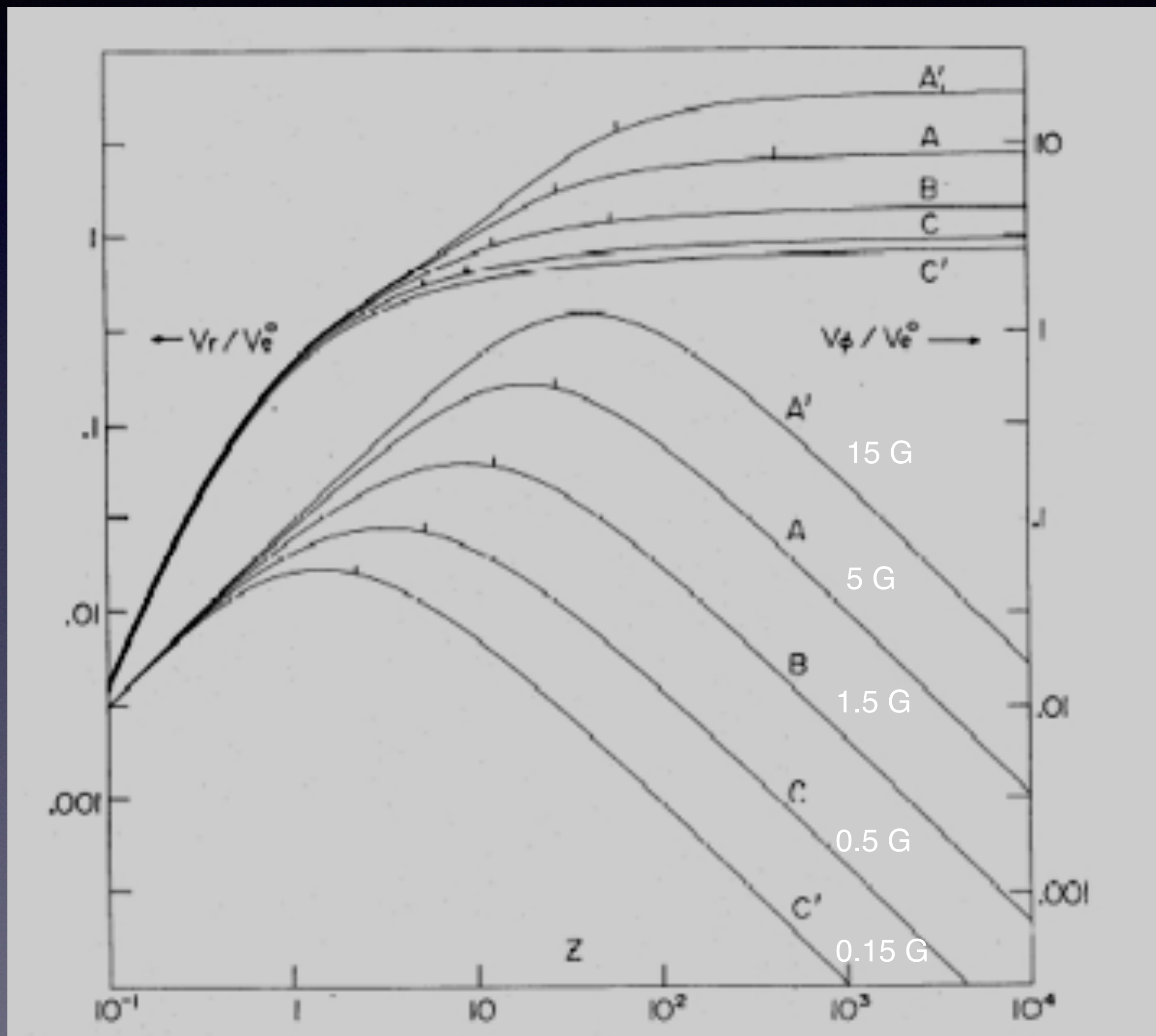
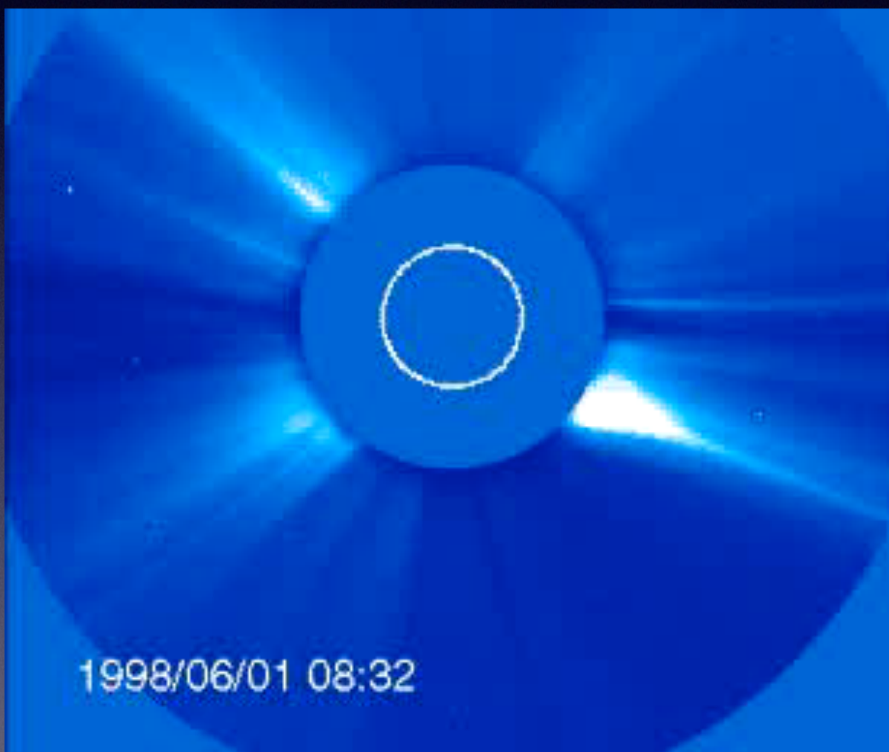
MHD Wind Solutions



Belcher & MacGregor — Sun-like Star

Solar Corona & Wind



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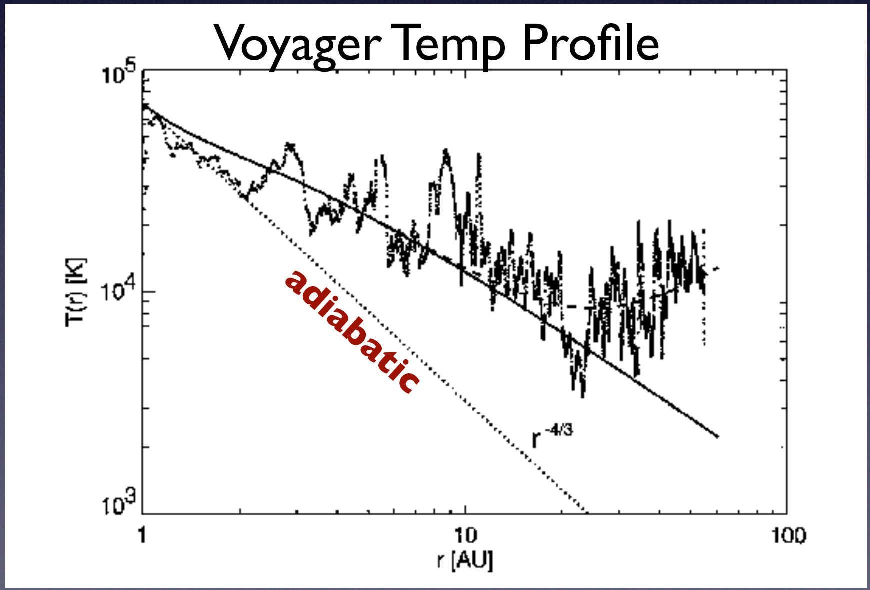
Why is Fluid Model 'Reasonable' for Collisionless Solar Wind?

- B-field $\Rightarrow \rho_{Larmor} << R$
  - No Free Streaming in 2 Directions
- Along B: pressure is origin of acceleration; need kinetic theory in detail but perhaps not to factors ~ few
- Kinetic instabilities limit how much distribution function can deviate from Maxwellian
  - mirror, firehose, ion cyclotron, electron whistler, …

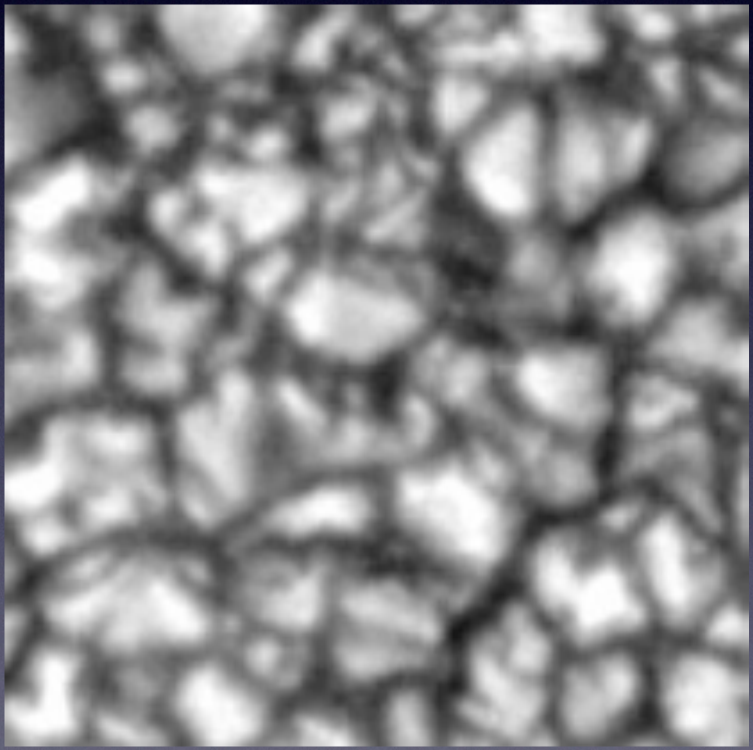
Solar Corona & Wind

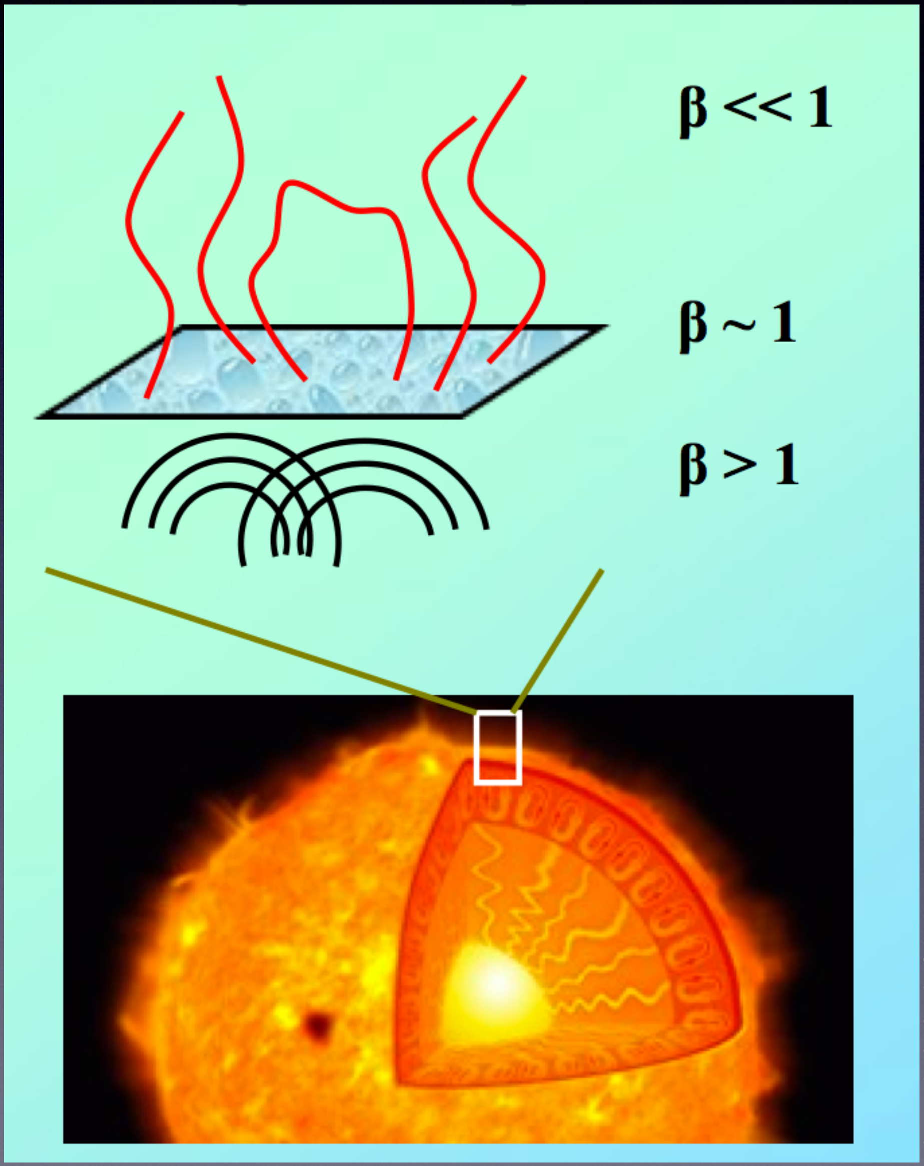
- Heating ↔ Pressure ↔ Accel. of Solar Wind
  - Early models invoked e^- conduction but $T_{ion} \gtrsim T_e$ in fast wind
  - Ion Heating Key: Kinetic Physics
  - Htg at all radii: ~1-10^4 $R_\odot$
- Heating: Alfven wave turbulence
  - observed in situ & least damped MHD mode in collisionless plasmas
    e.g., Belcher & Davis 1971; Barnes 1956



Matthaeus et al. 1999

Whence Alfven Waves?

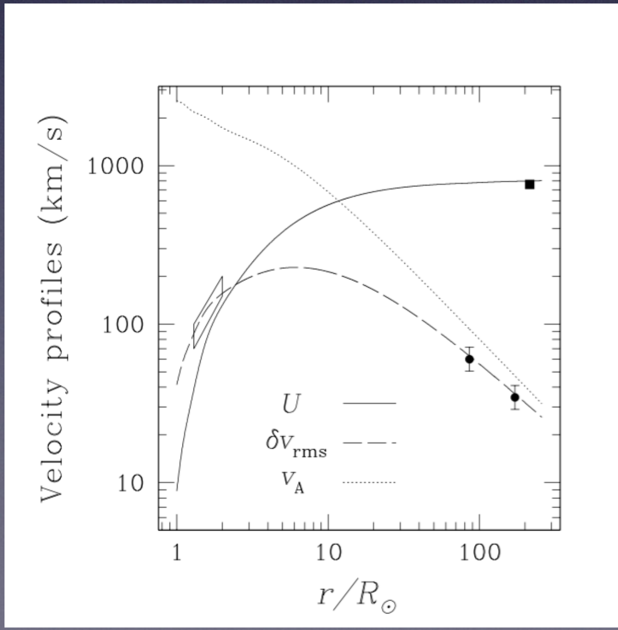


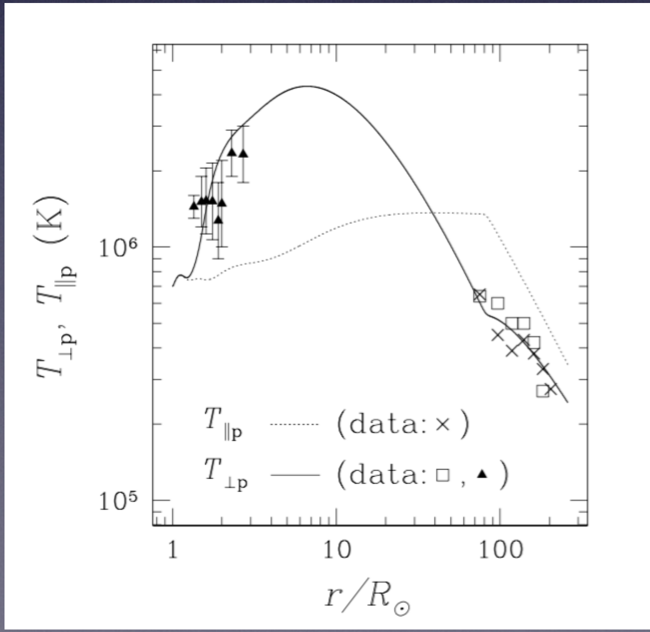


Steve Cranmer

Solar Corona & Wind

- *State of the Art Global Models:*
  - 1D w/ detailed microphysics (or multi-D w/ less microphysics)
  - Multi-Fluid Closure Models: p, e, alpha, minor ions
    - separate $T_\perp, T_{||}$ evolution w/ heat fluxes & $\perp$, || htg
  - Waves/Turbulence Evolved w/ Model Eqns





kinetic models of htg and heat flux used in global fluid models

Chandran+ 2012

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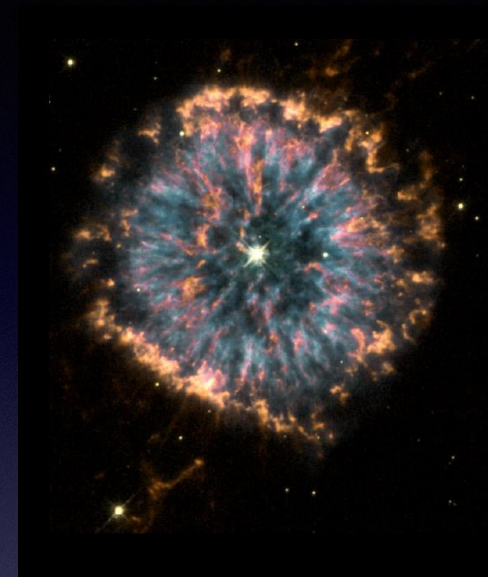
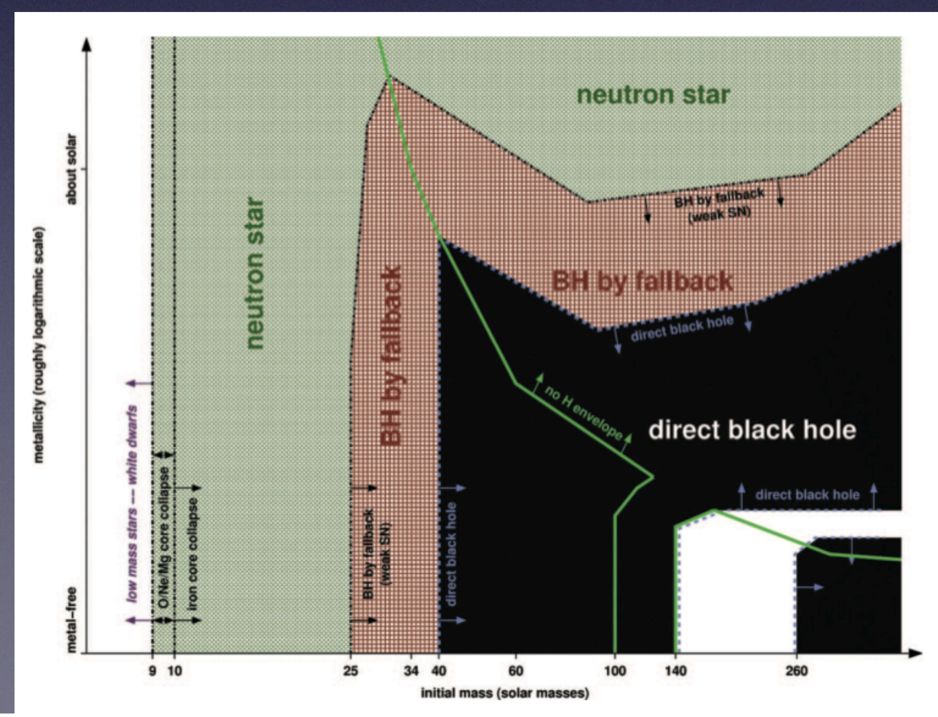
Radiation Pressure Driven Winds



- RGB and AGB Stars
  - Dust Driven. At low T_{eff} dust forms in stellar atmosphere (above photosphere) $\lesssim 10^3$ K.
  - $\kappa_{dust} >> \kappa_{electron} \Rightarrow L > L_{Edd}$ on dust $\Rightarrow$ Wind

- Massive Stars
  - $L > L_{Edd}$ on metal lines $\Rightarrow$ Wind

    (acceleration can be inside or outside photosphere)



Radiation Pressure Driven Winds

- Thermally Driven Winds: $\dot{E} \sim \frac{1}{2}\dot{M}v_\infty^2 \sim \frac{5}{2}\dot{M}c_s^2$

- Radiation Pressure Driven Winds:

$$\dot{P} \simeq \dot{M}v_\infty \sim L/c \qquad v_\infty \sim v_{\rm esc}$$

- AGB: $L \sim 10^4\, L_\odot$ $v_\infty \sim 10$ km/s $\dot{M} \sim 3\ 10^{-5}\, M_\odot\, yr^{-1}$
- $30\, M_\odot$ star: $L \sim 10^{5.5}\, L_\odot$ $v_\infty \sim 10^3$ km/s $\dot{M} \sim 10^{-5}\, M_\odot\, yr^{-1}$

Line-Driven Winds

(Lucy & Solomon 1970; Castor, Abott, Klein 1975)

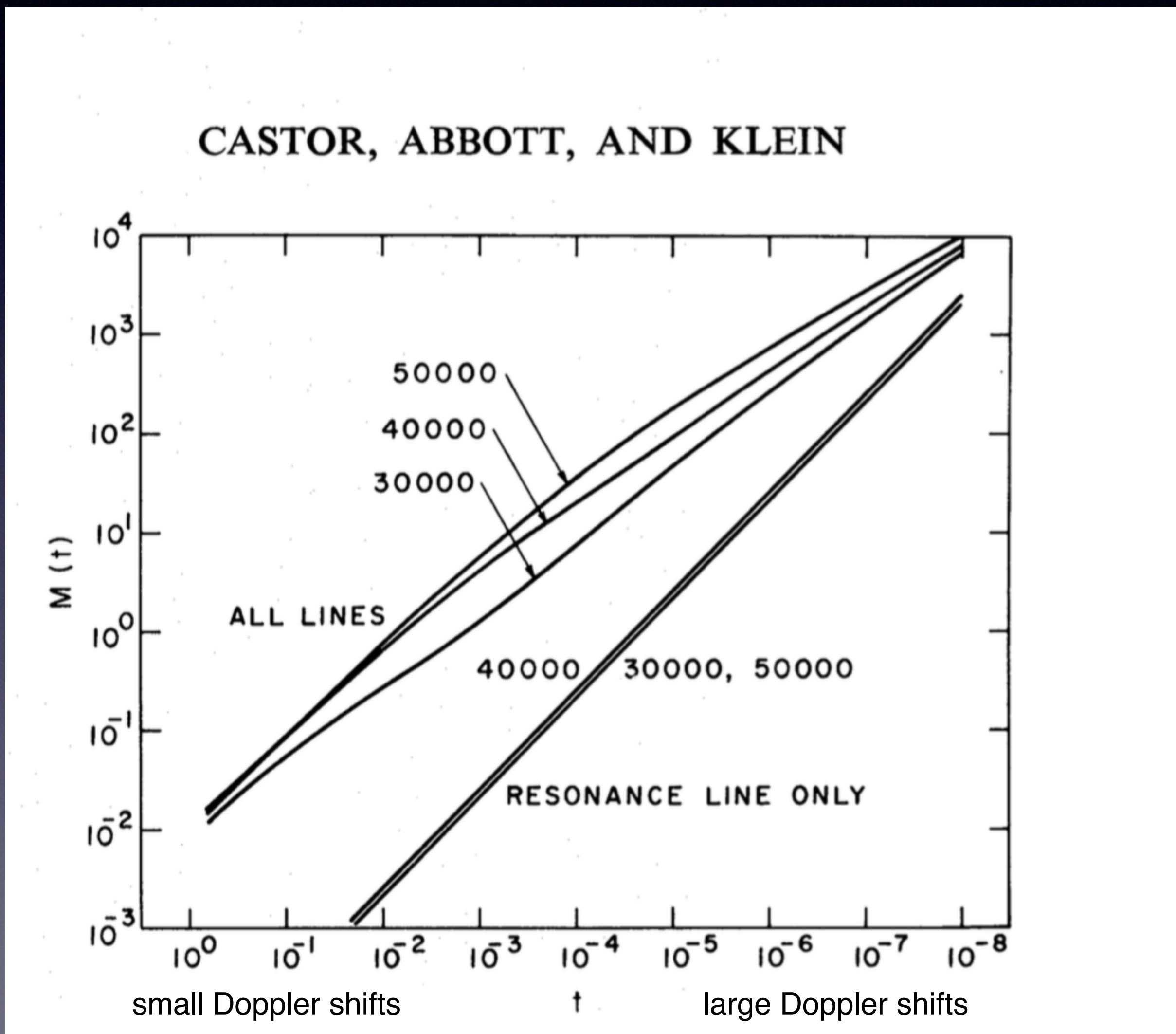
- scattering and absorption by metal lines
  ⇒ opacity ↑ and L_{Edd} ↓

- acceleration ⇒ v ↑ ⇒ lines broader bec. of Doppler shift ⇒ absorb more flux ⇒ acceleration ⇒ v ↑ …

- $v_{wind} \sim v_{esc}(R_*)$ $\dot{M} v_{esc} \sim L/c$

- most well studied model for mass loss in massive stars but probably not the dominant source of mass loss

Line-Driven Winds



$$F_{\rm rad} \equiv \frac{\kappa_e F}{c} M(t)$$

effectively,

L >> L_{Edd} for t << 1

assumes optically thin, i.e., acceleration outside the photosphere

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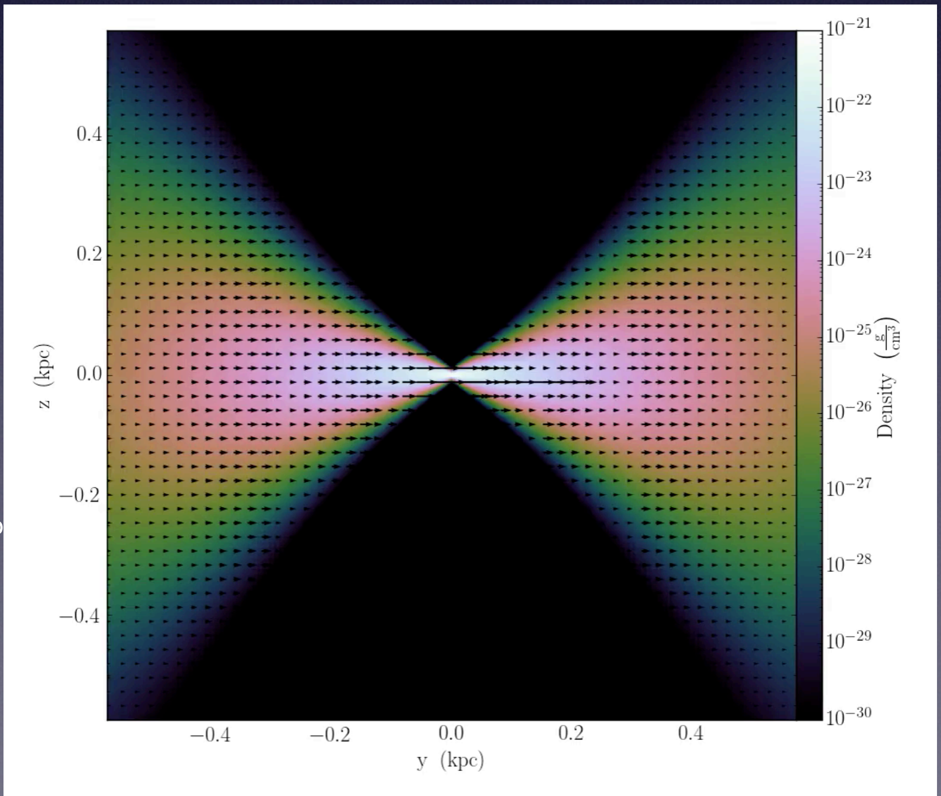
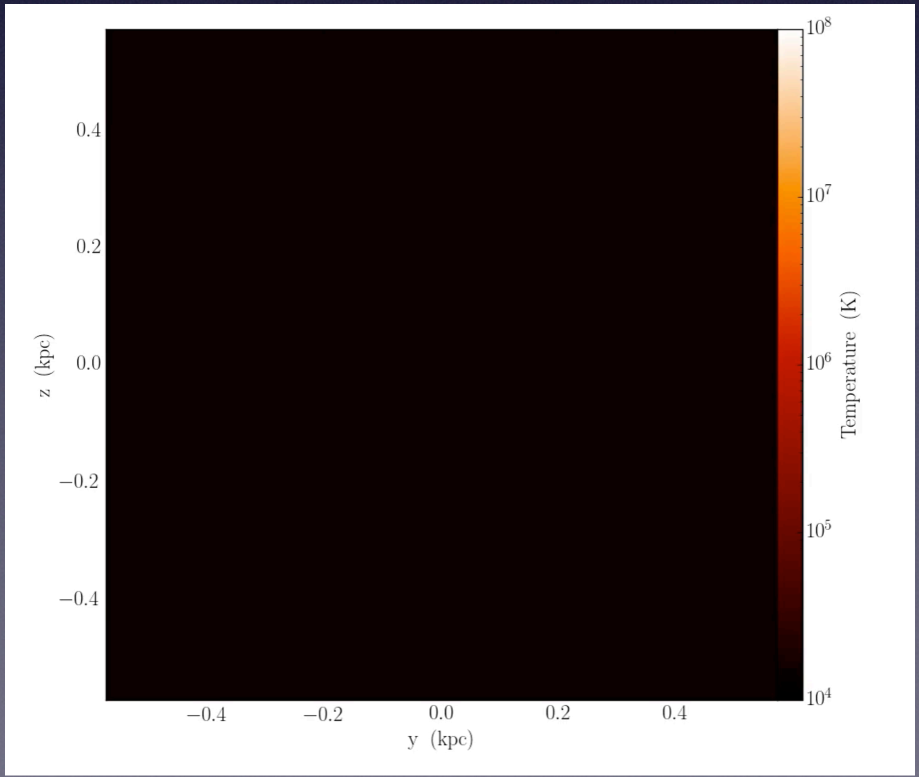
Thermally Driven Galactic Winds

- Energy Injection by Supernovae ⇒ Hot Gas ⇒ Galactic Wind
  - Analytic theory (Chevalier & Clegg 1985) ~ Parker solar wind
  - Key source of 'feedback' in galaxy formation; sets stellar masses of lower mass galaxies

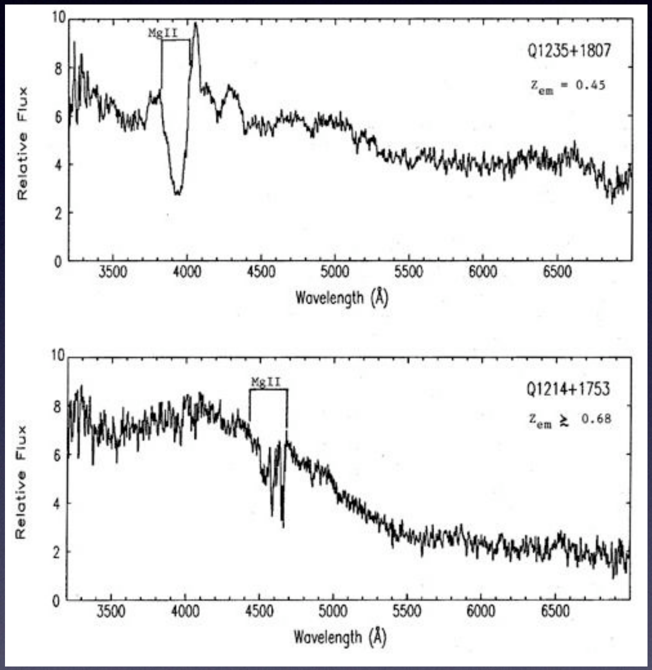


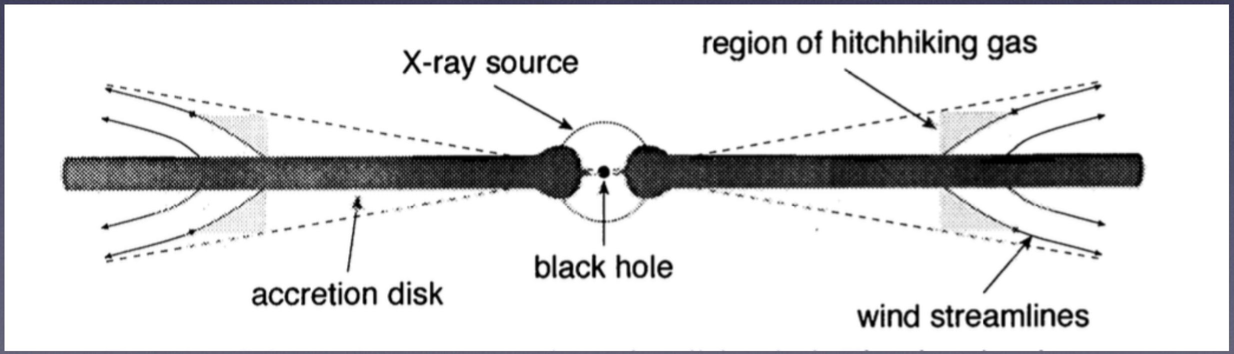


Drummond Fielding

Line Driven Winds from Accreting Black Holes

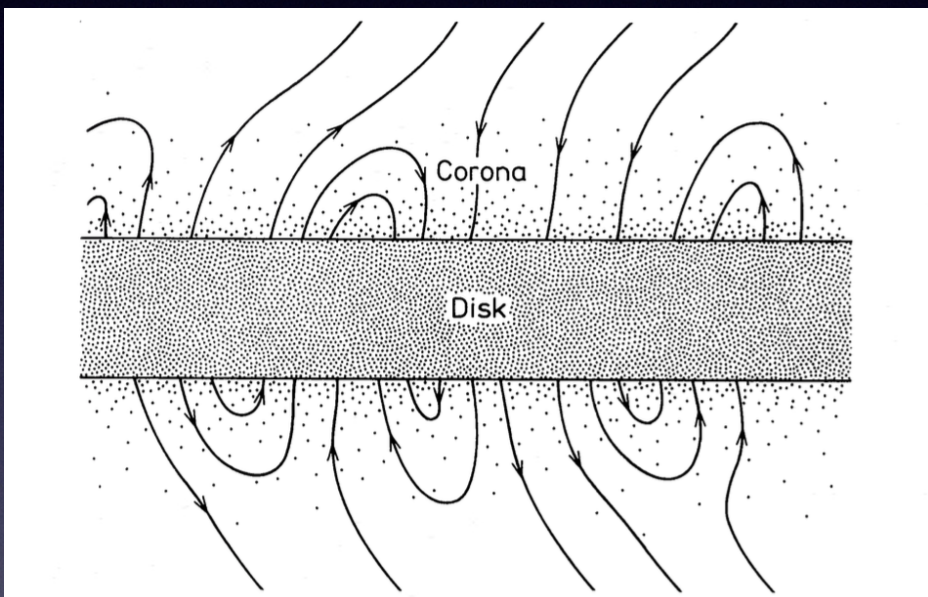
- Broad Absorption Line Quasar winds
  - Seen in ~ 40% of quasars (IR-selected)
  - $\dot{P}$ ~ few L_{AGN}/c; v ~ 10^4 km/s; $\dot{E}$ ~ 0.02 L_{AGN}
  - Can have a large impact on ISM of host galaxy



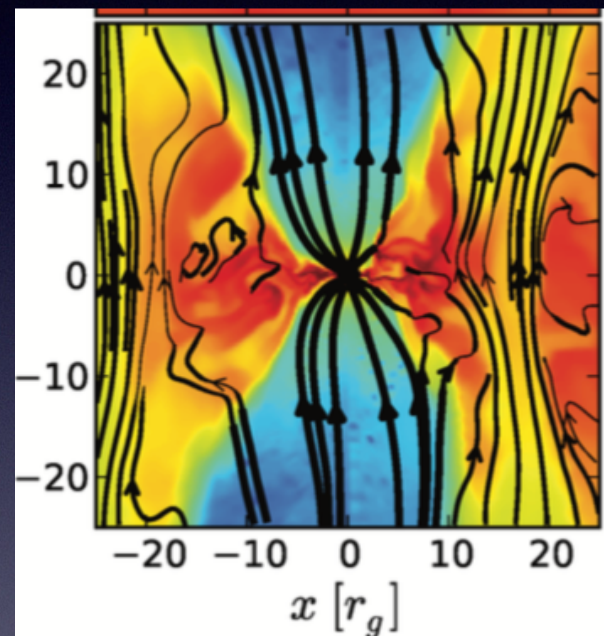


Wind theory (Murray+ 1995) generalization of CAK line driven stellar winds to accretion disks

Magnetized Winds From Accretion Disks



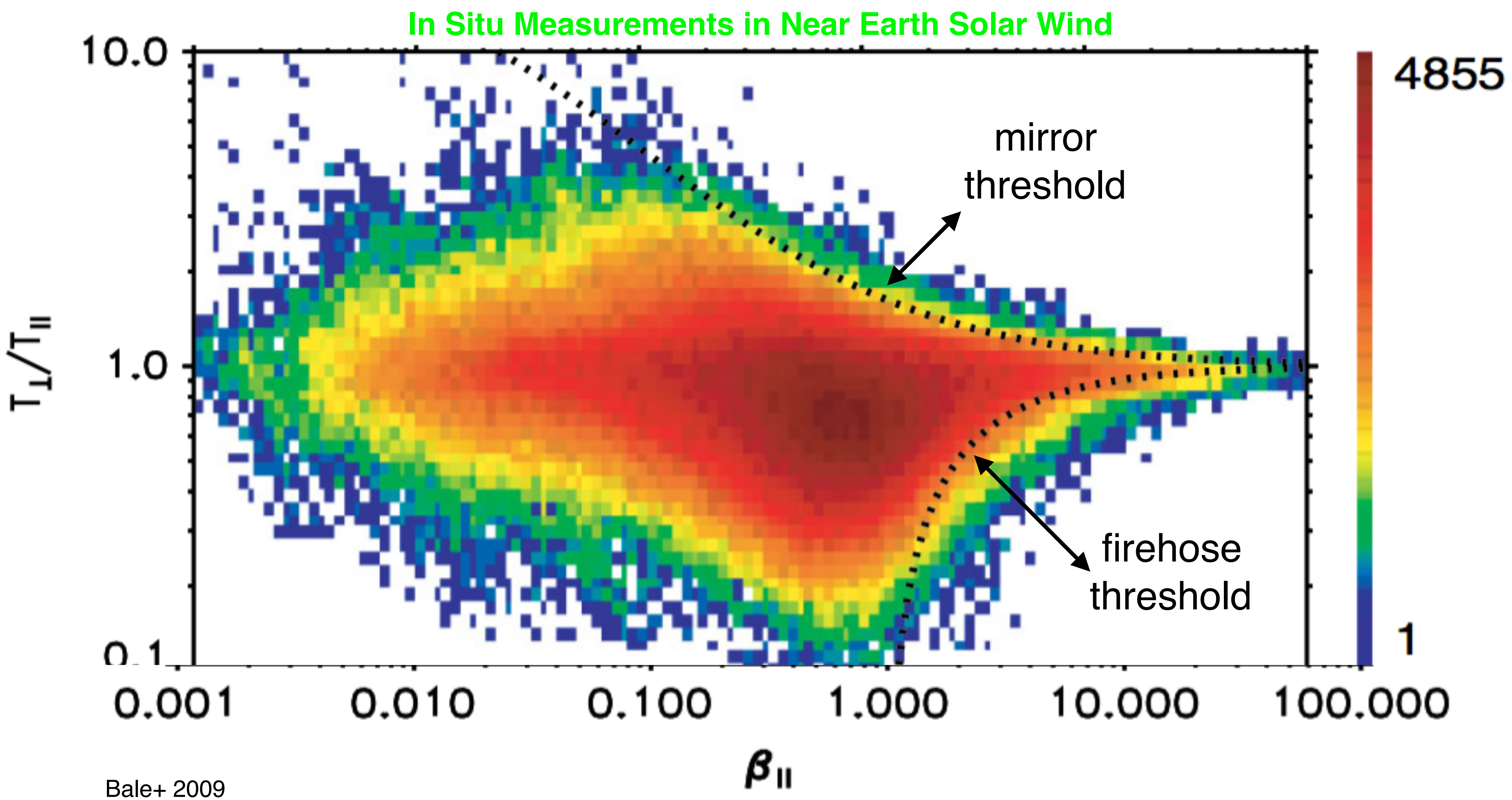
Blandford & Payne 1982 analytic theory explicitly motivated by Weber-Davis theory of the magnetized solar wind



Tchekhovskoy+: BH Accretion with Large-scale B-field

One of the major uncertainties in accretion disk theory is the relative role of angular momentum transport by local instabilities (MRI) and large-scale magnetic torques

- Kinetic instabilities limit how much distribution function can deviate from Maxwellian
  - mirror, firehose, ion cyclotron, electron whistler, …



Bale+ 2009