X-ray Emission from Massive Stars

Using Emission Line Profiles to Constrain Wind Kinematics, Geometry, and Opacity

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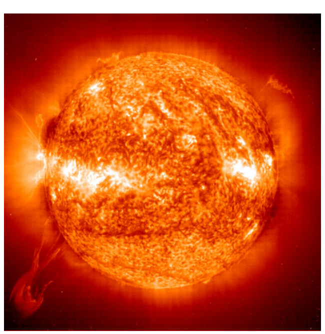

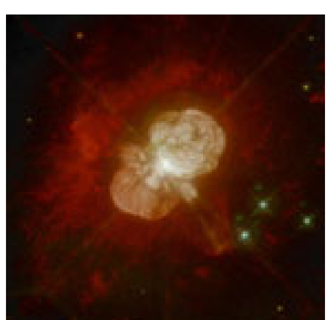

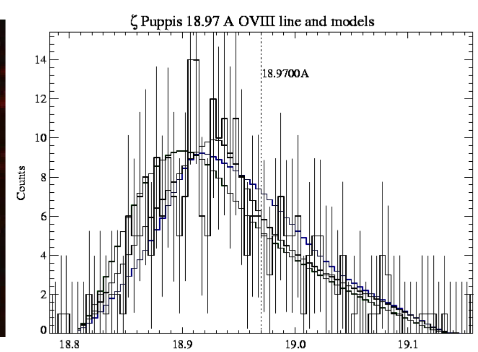

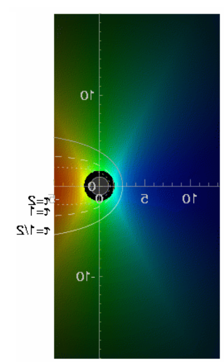

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Outline

1. What you need to know:
    a. X-rays from the Sun - magnetic activity, x-ray spectra
    b. Hot stars
    c. Radiation-driven winds and the Doppler shift
    d. The holy grail of science: a measurement that can discriminate between two contradictory theories
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X-rays are just photons - **light**

...but very, very blue light: 10 octaves higher than visible light (which itself spans only one octave from red to blue)

X-rays from the Sun

Remember - for thermal radiation - the frequency of light (the energy of each photon) is proportional to the temperature of the emitter:

Human body = 300 K $\Rightarrow$ 10 microns, or 100,000 Å (infrared)

Sun, light bulb filament = 6000 K $\Rightarrow$ 5000 Å (visible, yellow)

Hot star's surface = 40,000 K $\Rightarrow$ 750 Å (far ultraviolet)

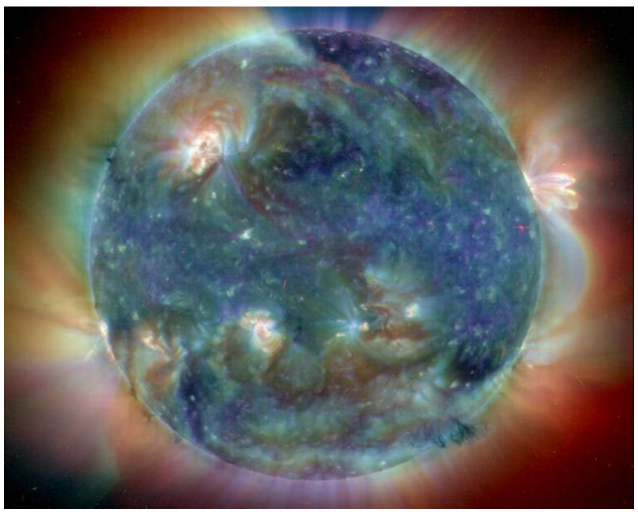
Really hot plasma = 5,000,000 K $\Rightarrow$ 6 Å (X-ray)

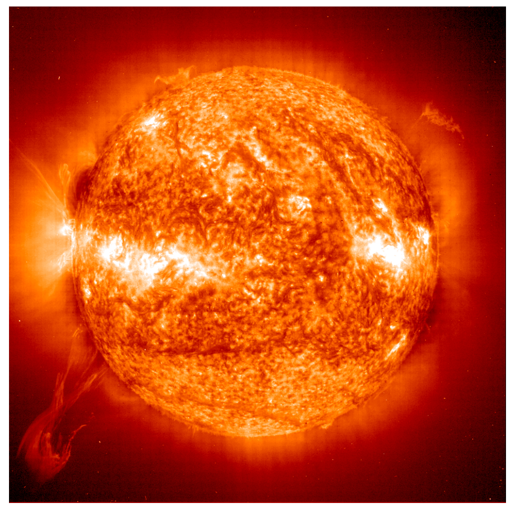
*don't forget that thermal emitters give off photons with a *range* of wavelengths; those listed above represent the peak of the distribution

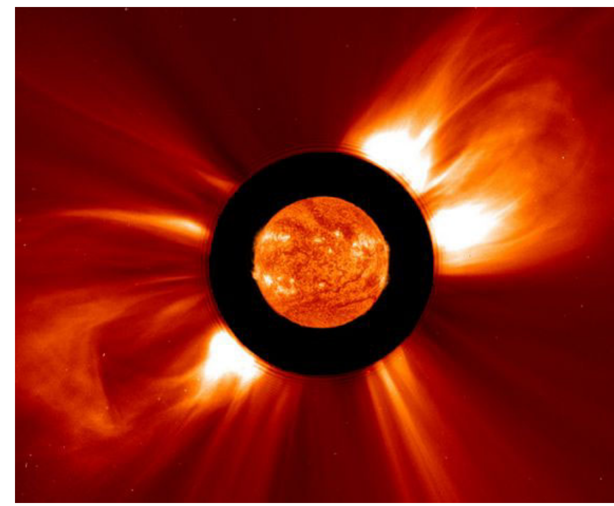
The Sun is a strong source of X-rays

(10^{-5} of the total energy it emits)

It must have ~million degree gas on it







This really hot gas is *not* on the Sun's surface - it is above the surface, in localized structures

We can break light apart into its constituent colors:

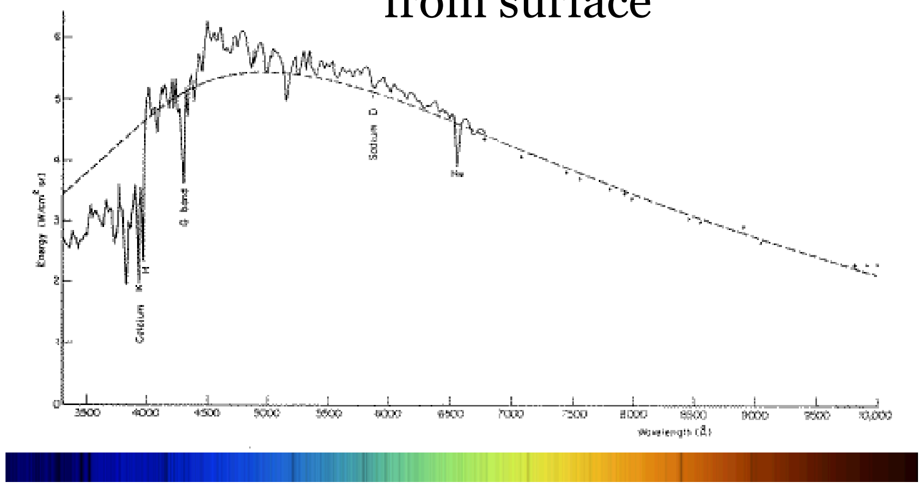
Spectroscopy

And learn about the physical conditions in the light-emitting object/substance:

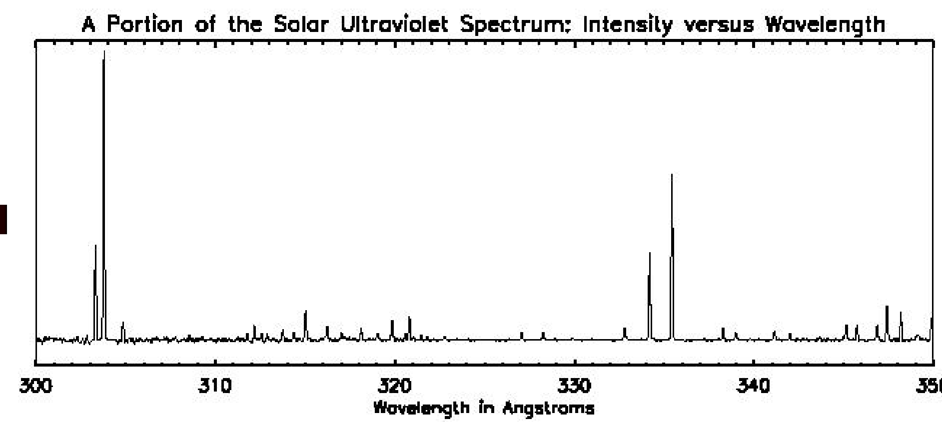
- Composition
- Temperature
- Optical depth (transparent or opaque?)
- Density
- Velocity relative to us

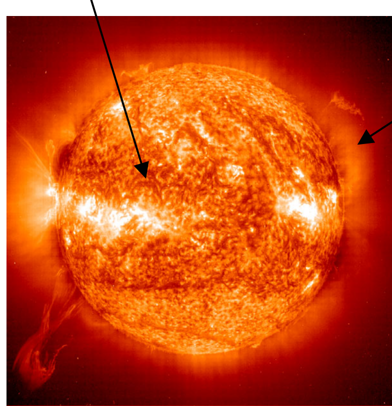
Spectra: continuum vs. line (*demo*)

Visible solar spectrum: continuum, from surface

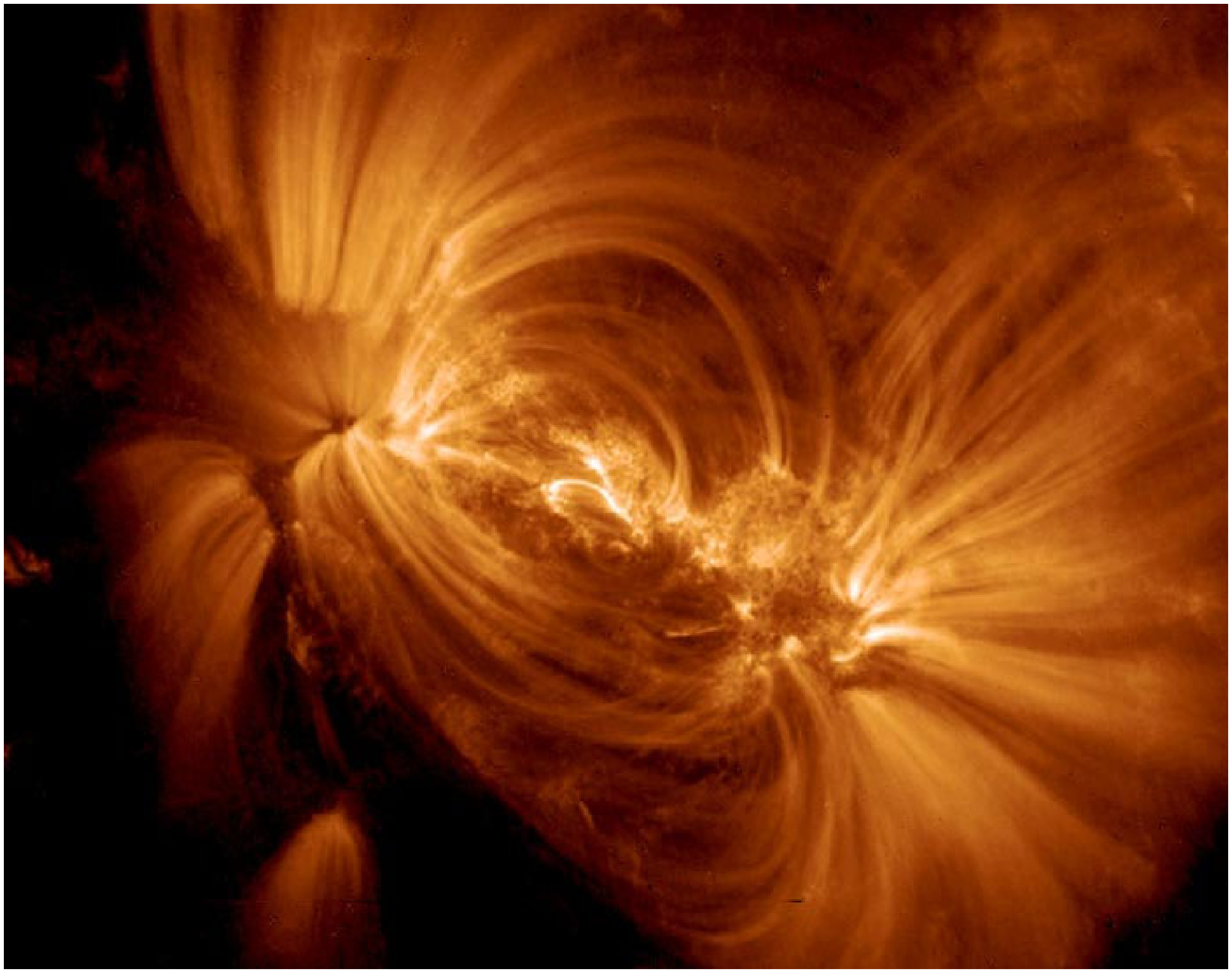


X-ray/EUV solar spectrum: emission lines from hot, thin gas above the surface



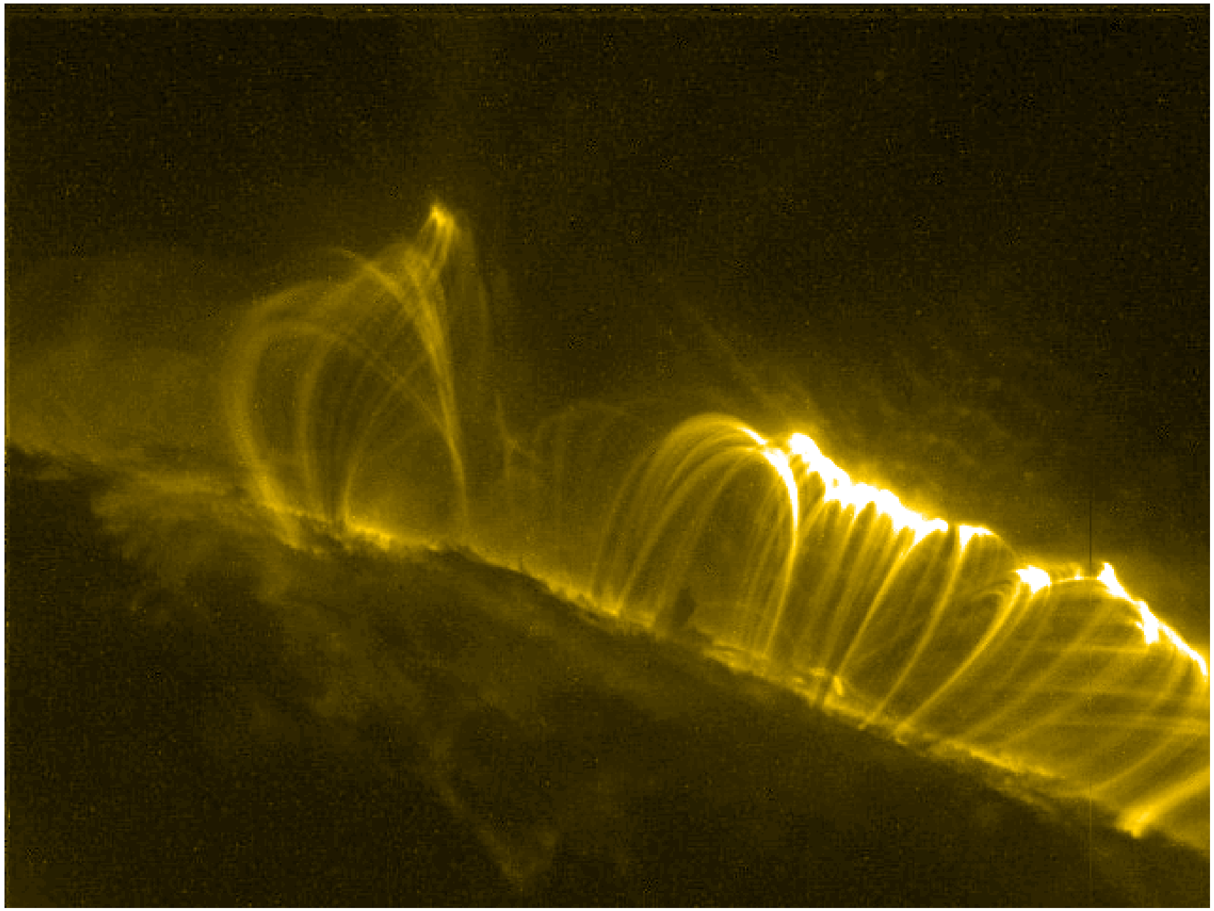


This hot *plasma* is related to magnetic fields on the Sun: confinement, spatial structure, conduits of energy flow, heating

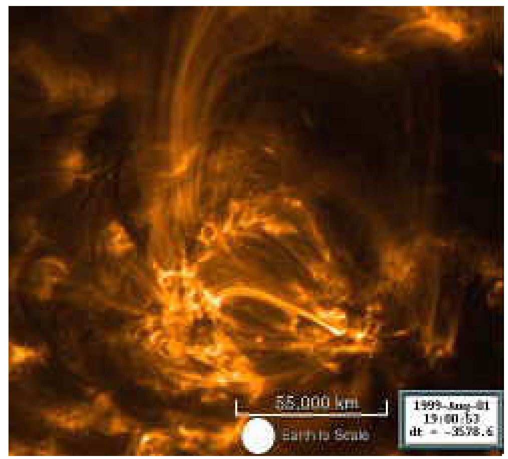


More magnetic structures on the Sun:

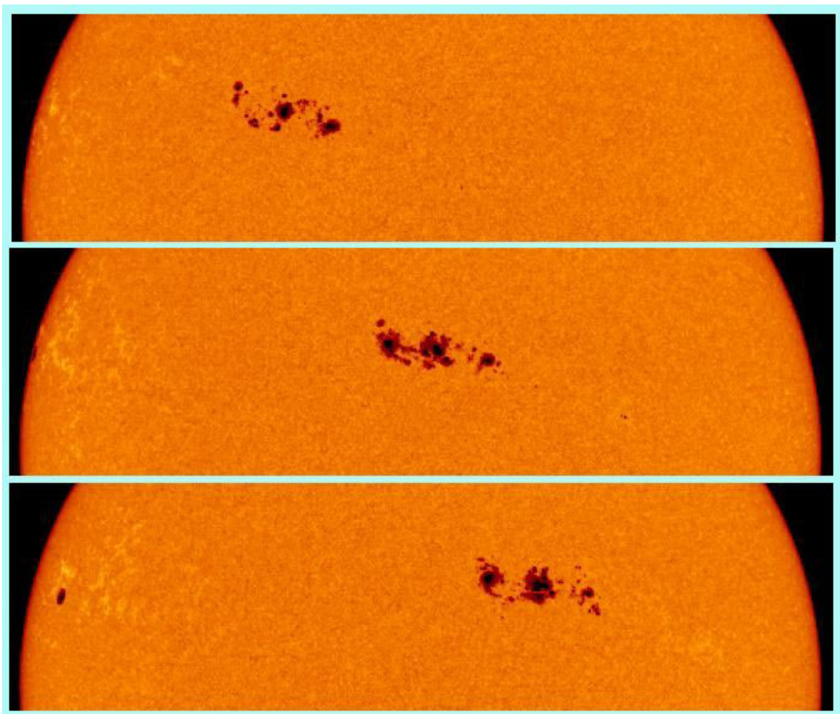
x-ray image from *TRACE*



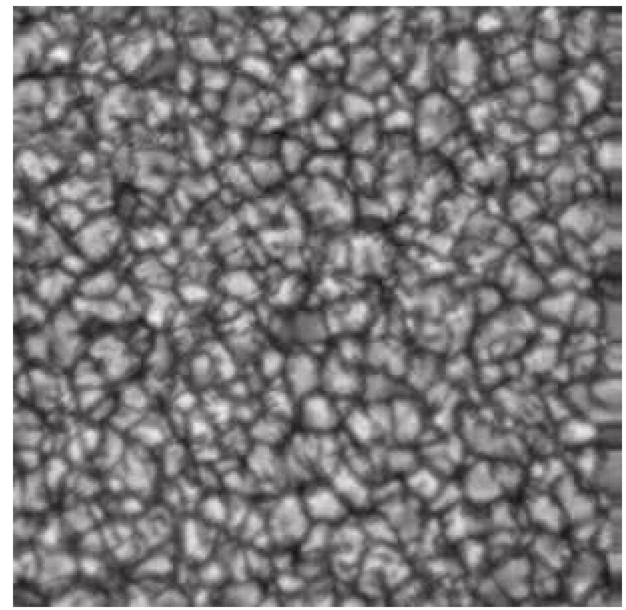
Solar magnetic activity is quite time-variable



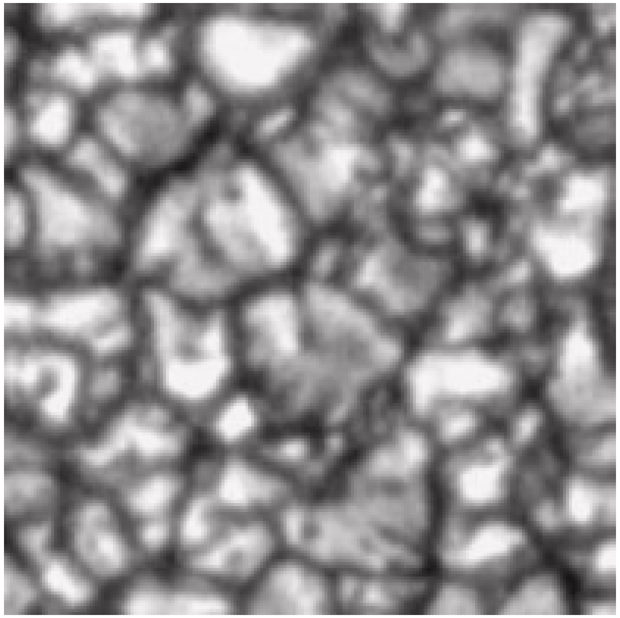
The magnetic dynamo requires convection + rotation to regenerate the magnetic field

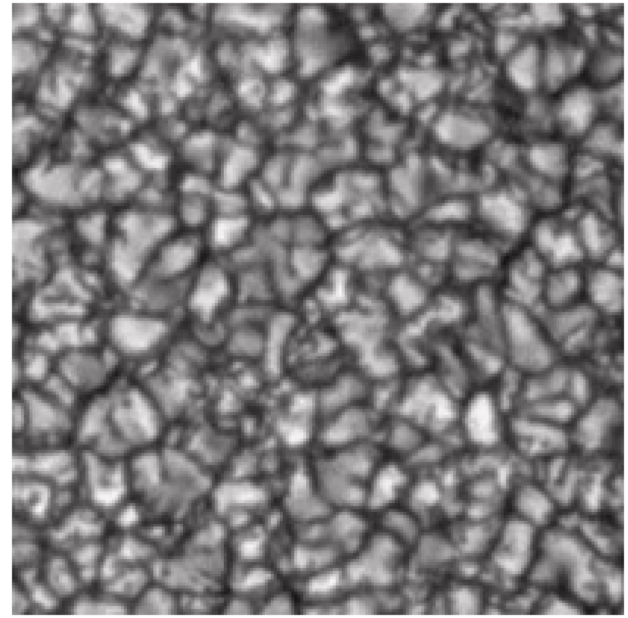


Sunspots over several days



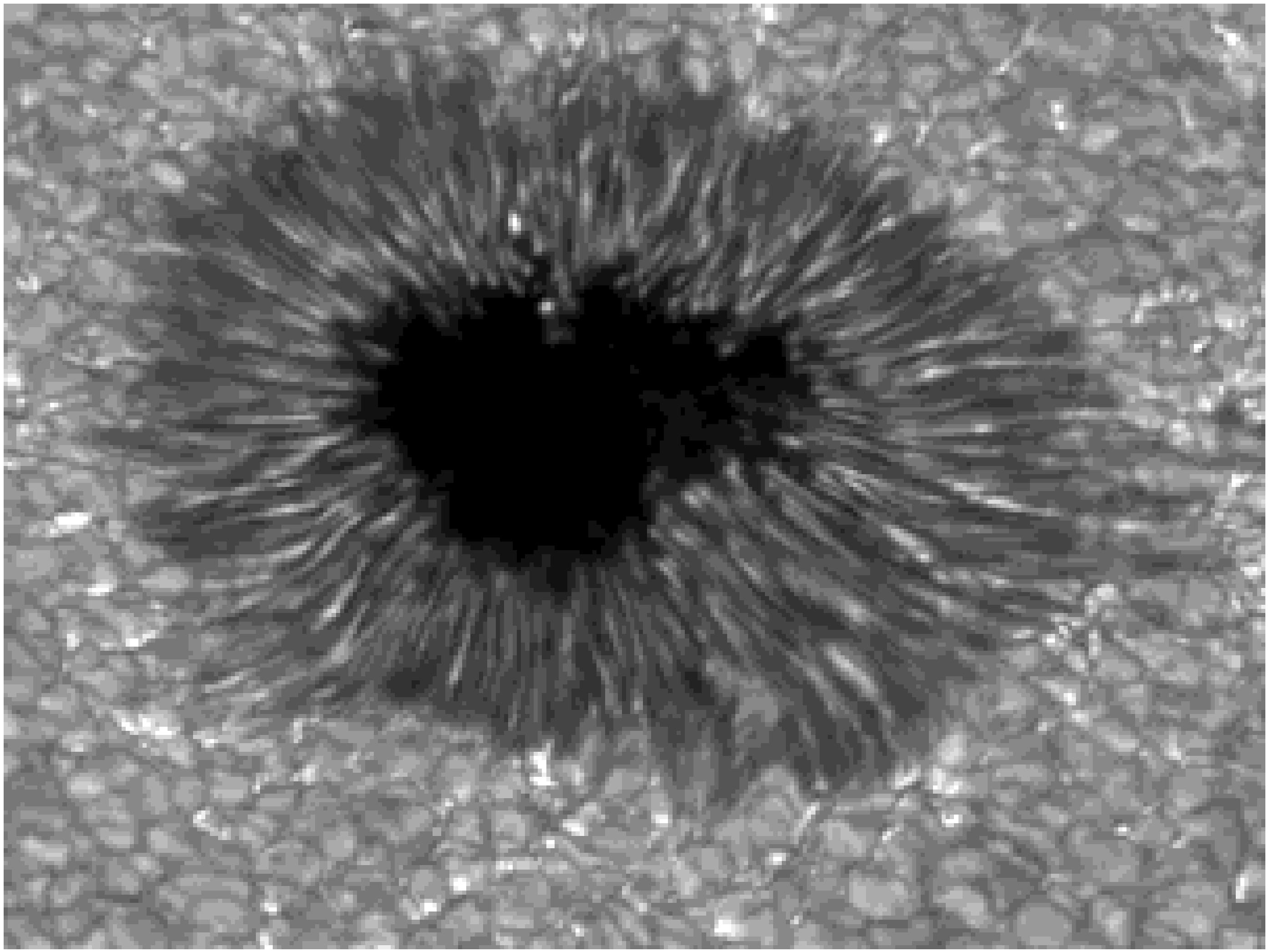
Note granulation, from convection, like a boiling pot of water



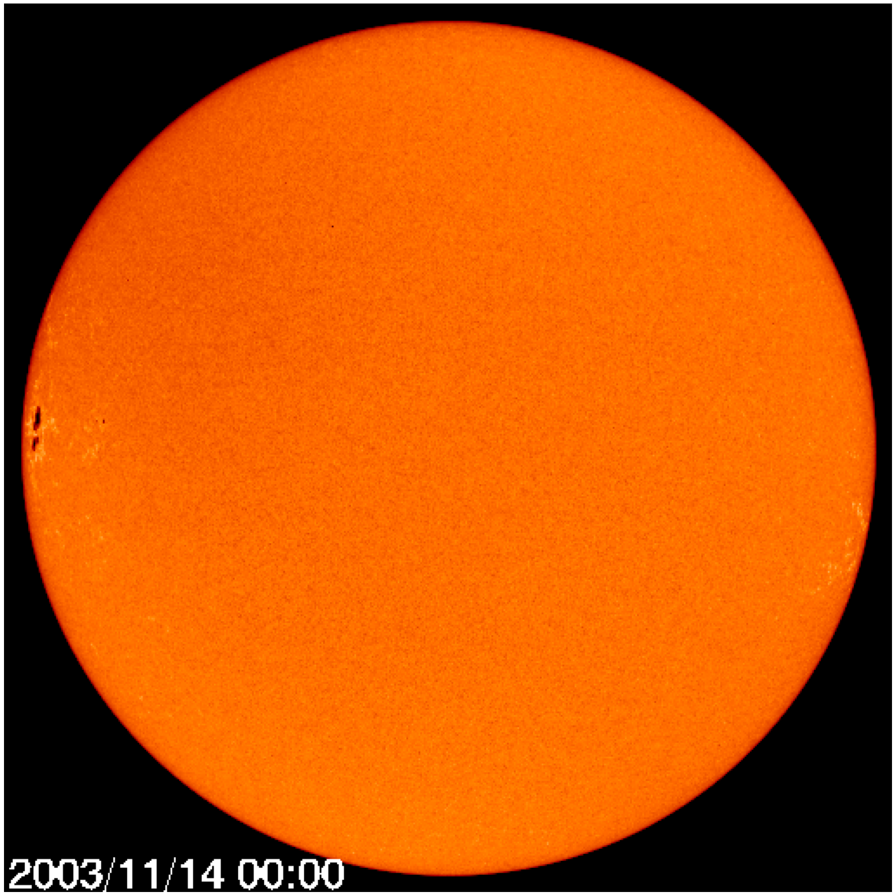


More granulation movies

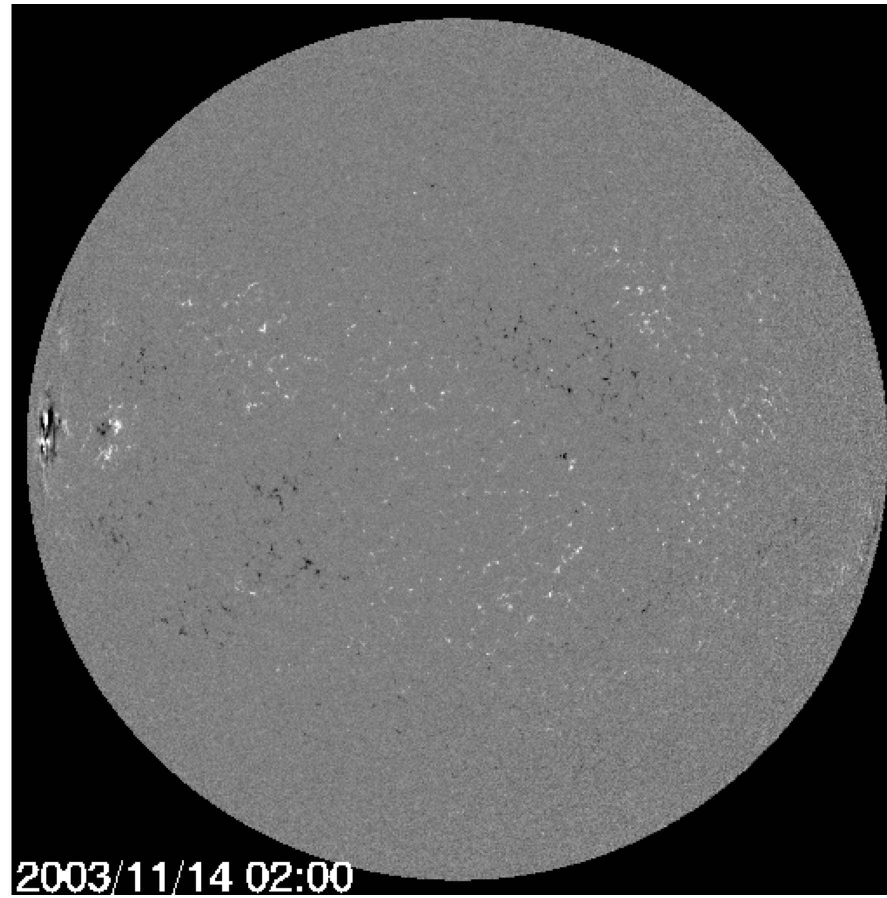
Sinister-looking sunspot, with granulation visible around it



Sunspots are areas of strong magnetic fields (kG)

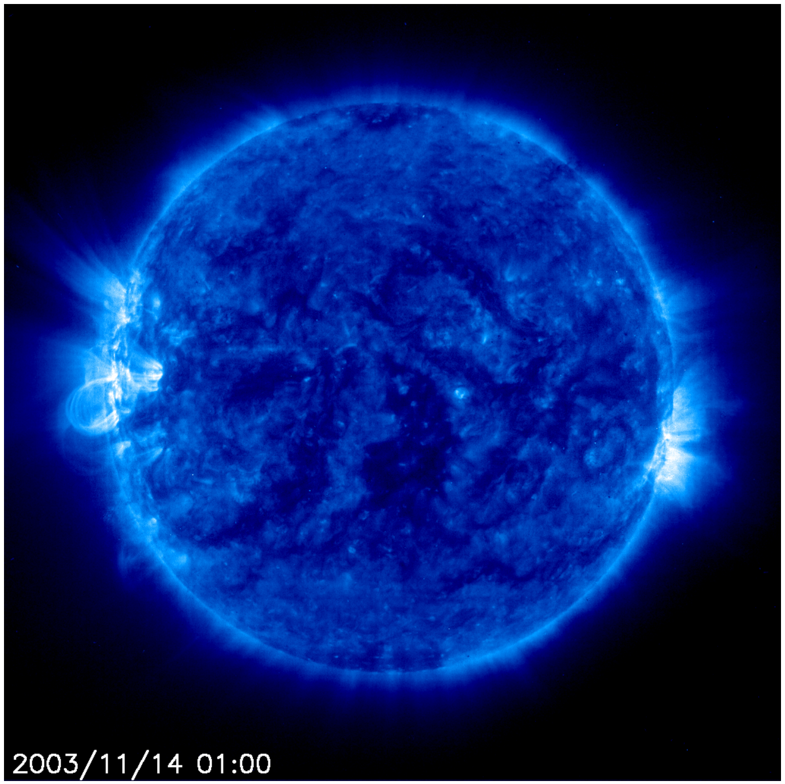


white light image of the Sun

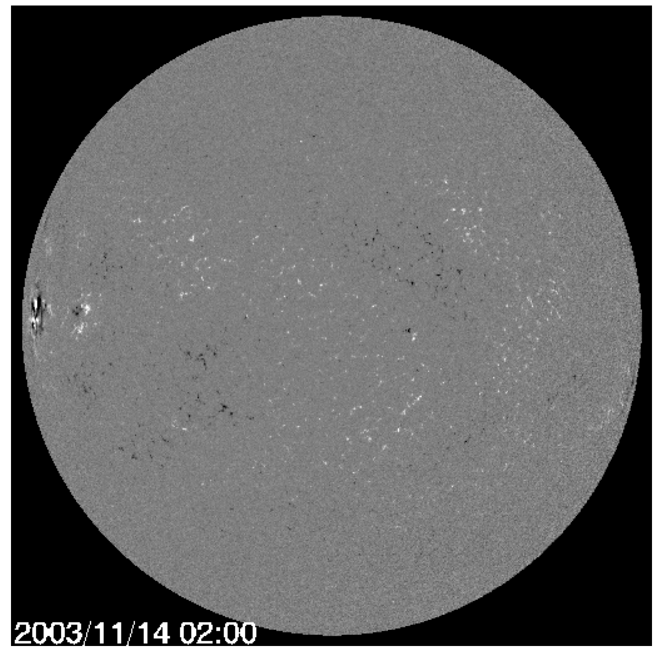


magnetogram (Zeeman splitting)

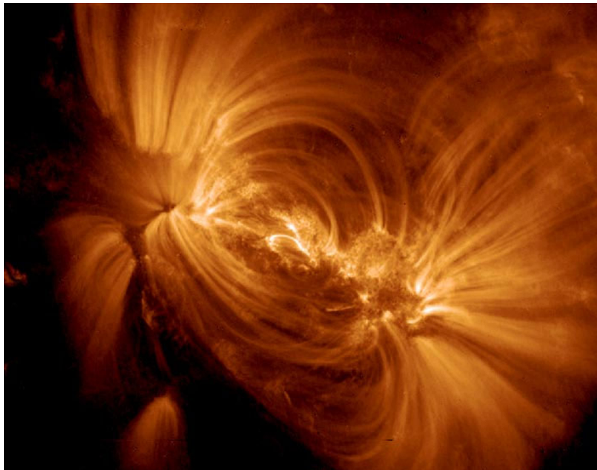
The x-rays are correlated with sunspots and magnetic field strength



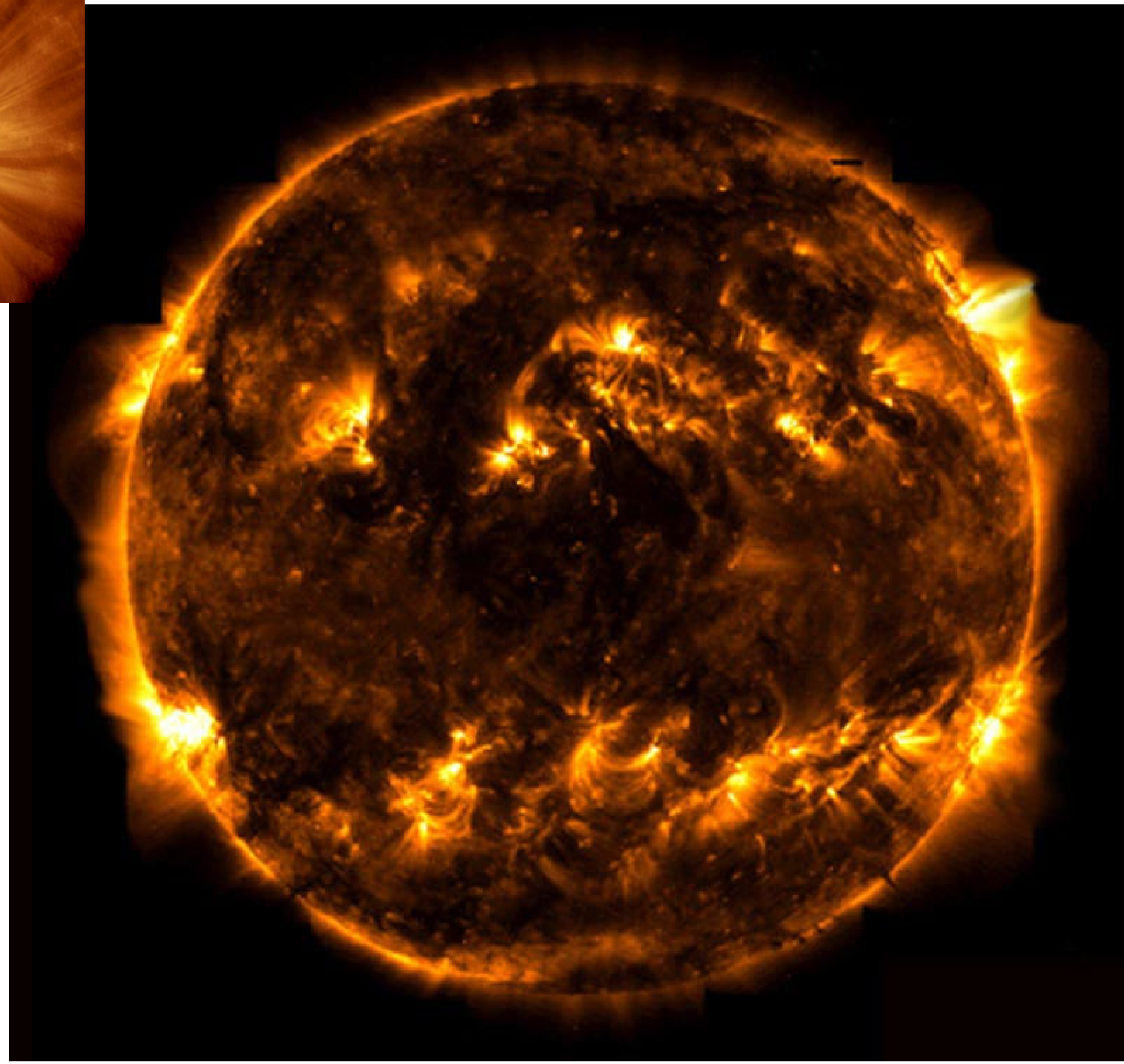
Fe XV at 284 Å



magnetogram



TRACE composite



OK, so the Sun emits x-rays - quite beautifully - and they're associated with its magnetic activity, related to convection and rotation…

But what of *hot, mssive stars*?

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Hot Stars

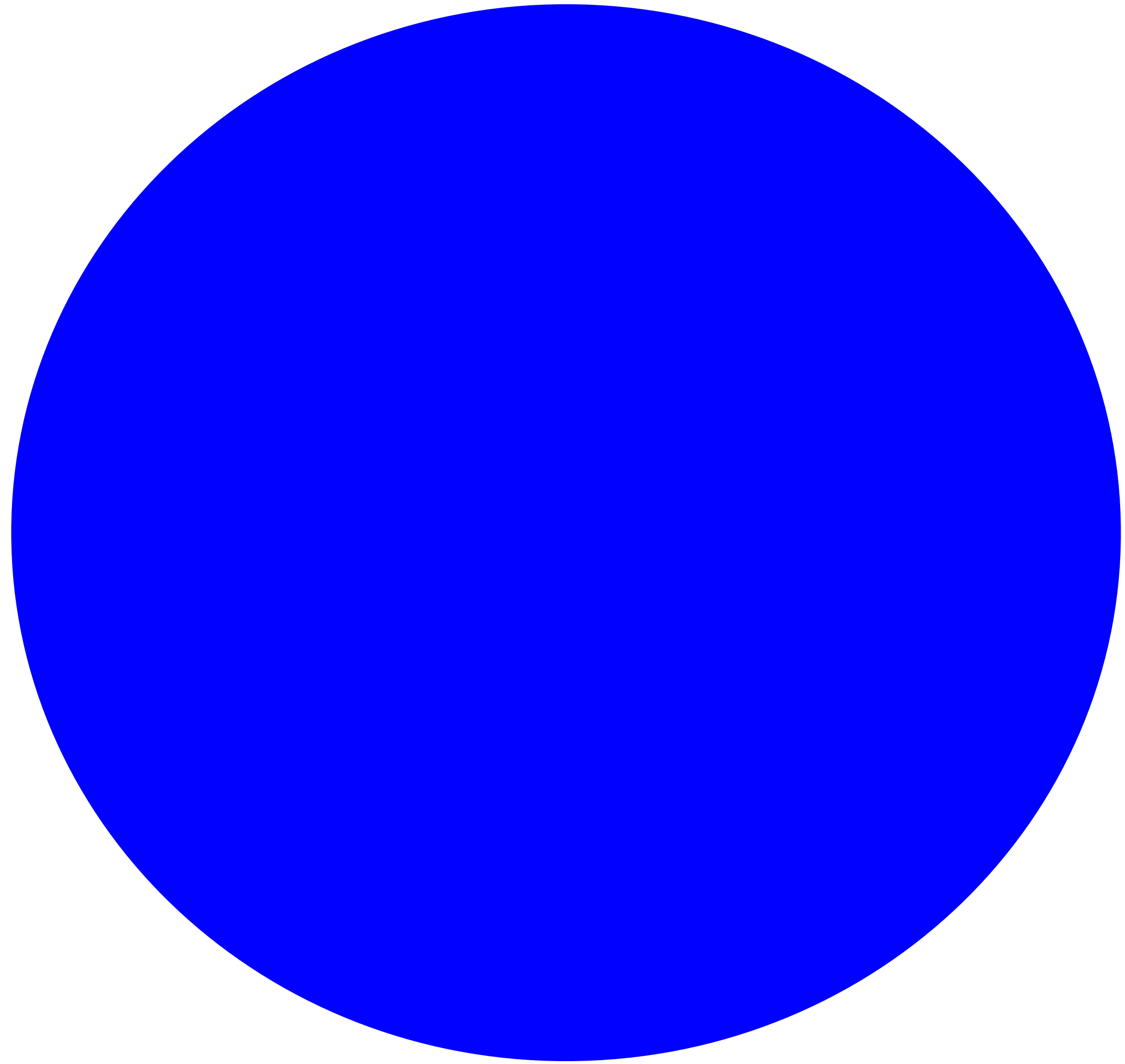
Stars range in (surface) temperature from about 3500 K to 50,000 K

Their temperatures correlate with mass and luminosity (massive stars are hot and very bright): a 50,000 K star gives of a million times the luminosity of the Sun (T_{sun} = 6000 K)

Stars hotter than about 8000 do ***not*** have convective outer layers - no convection - no dynamo - no hot corona...

...no X-rays **?**

Our Sun is a somewhat wimpy star…



ζ Puppis:

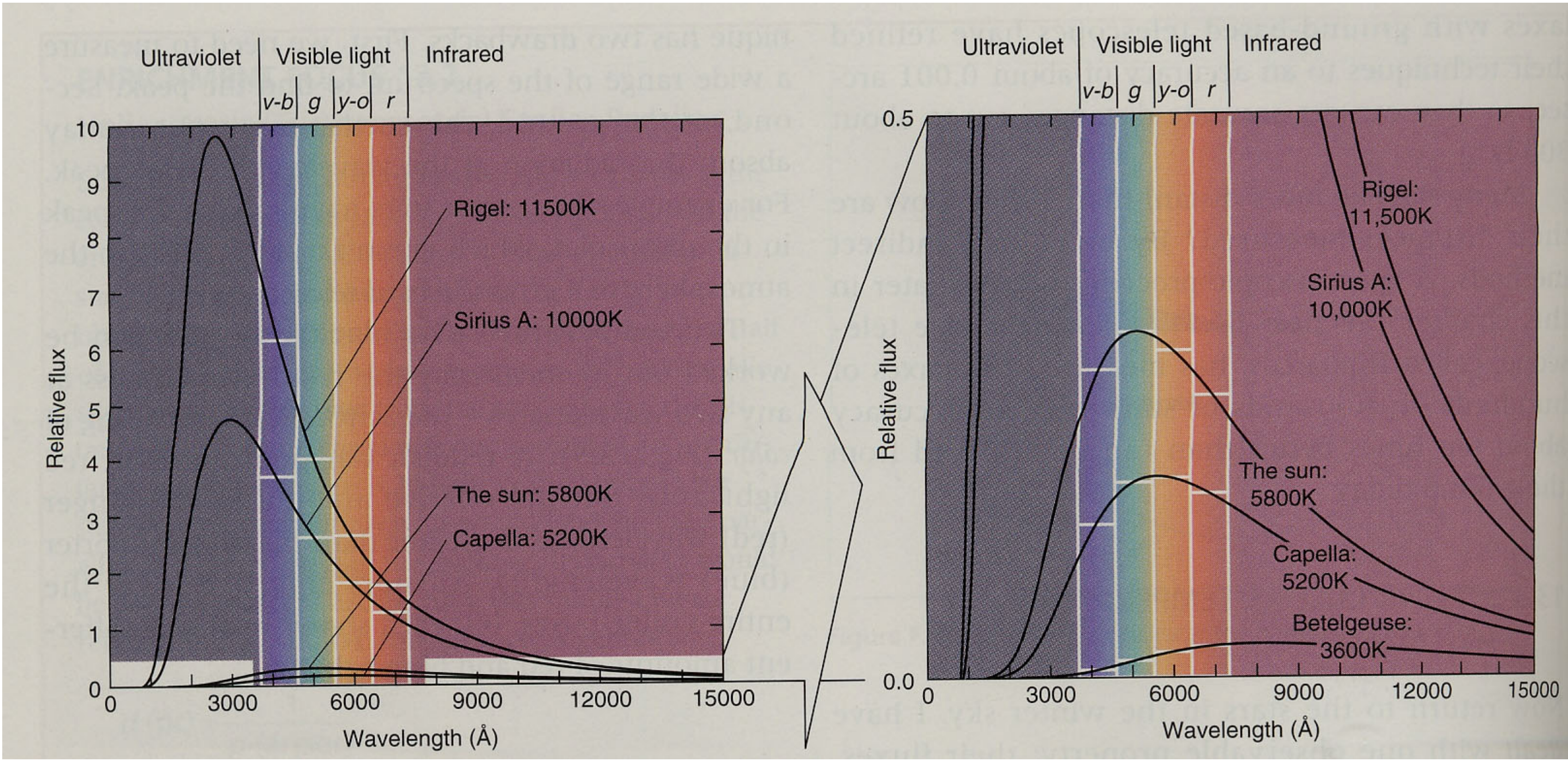
42,000 K vs. 6000 K

10^6 L_{sun}

50 M_{sun}

Optical image of the constellation Orion

Note: many of the brightest stars are blue (i.e. hot, also massive)

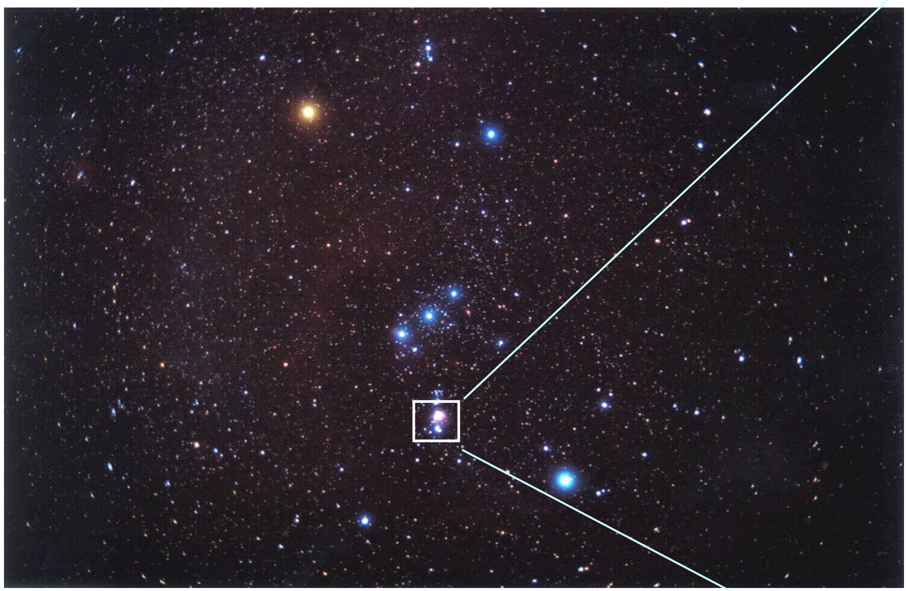


Hot stars are much brighter than cool stars, and they give off most of their energy in the ultraviolet

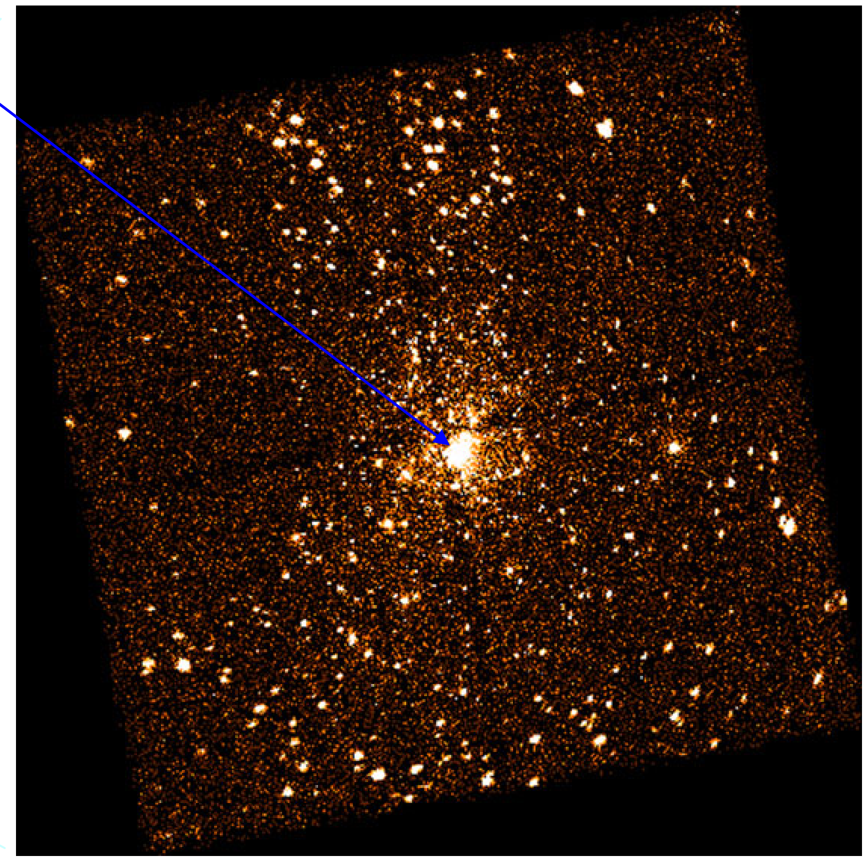
But they're not nearly hot enough to emit any significant amount of X-rays from their surfaces

In 1979 the *Einstein Observatory*, made the surprising discovery that many O stars (the hottest, most massive stars) are strong X-ray sources

θ^1 Ori C: a 45,000 K "O" star



Chandra X-ray image of the Orion star forming region



Note: X-rays don't penetrate the Earth's atmosphere, so X-ray telescopes must be in space

So, we've got a **good scientific mystery**: how do massive stars make X-rays?

Could we have been wrong about the lack of a magnetic dynamo - might massive star X-rays be similar to solar X-rays?

Before we address this directly, we need to know about one very important property of massive stars (that might provide an alternate explanation)...

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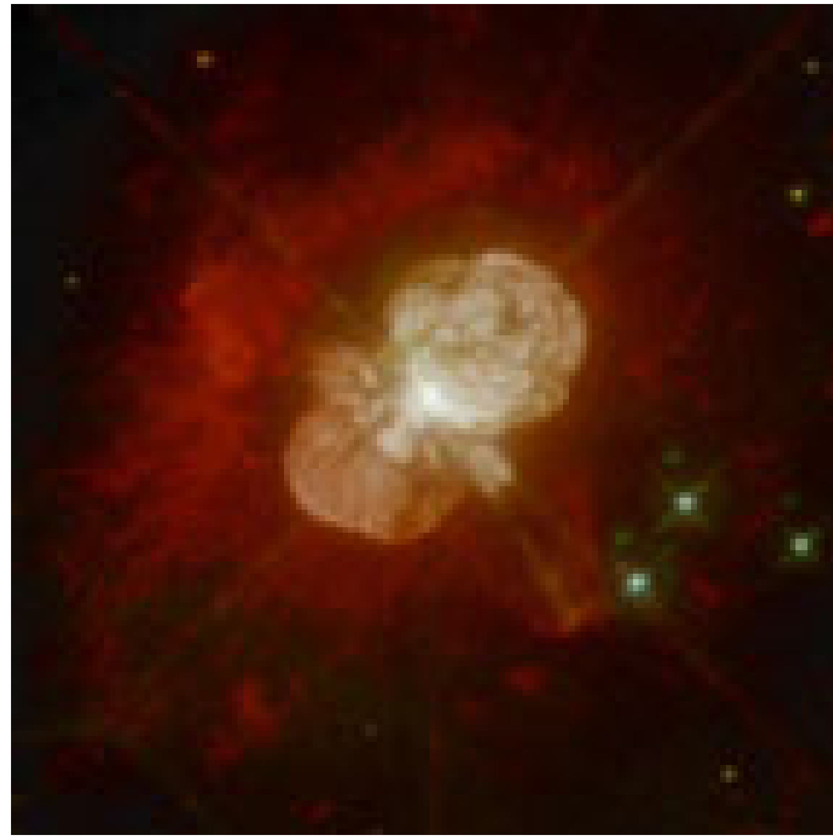
Massive stars have very strong radiation-driven **stellar winds**

What is a stellar wind?

It is the steady loss of mass from the surface of a star into interstellar space

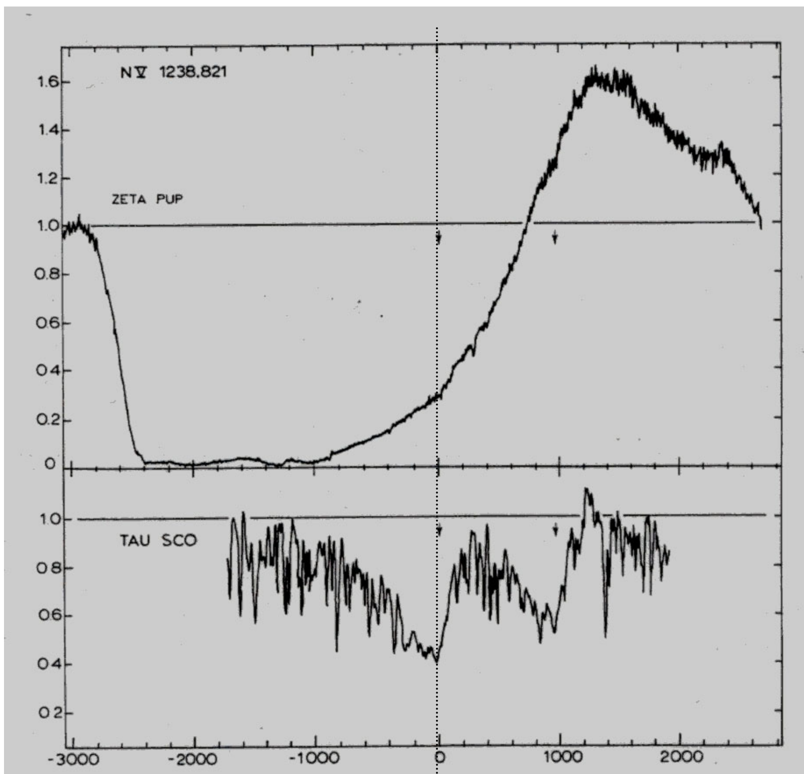
The Sun has a wind (the "solar wind") but the winds of hot stars can be a *billion* times as strong as the Sun's

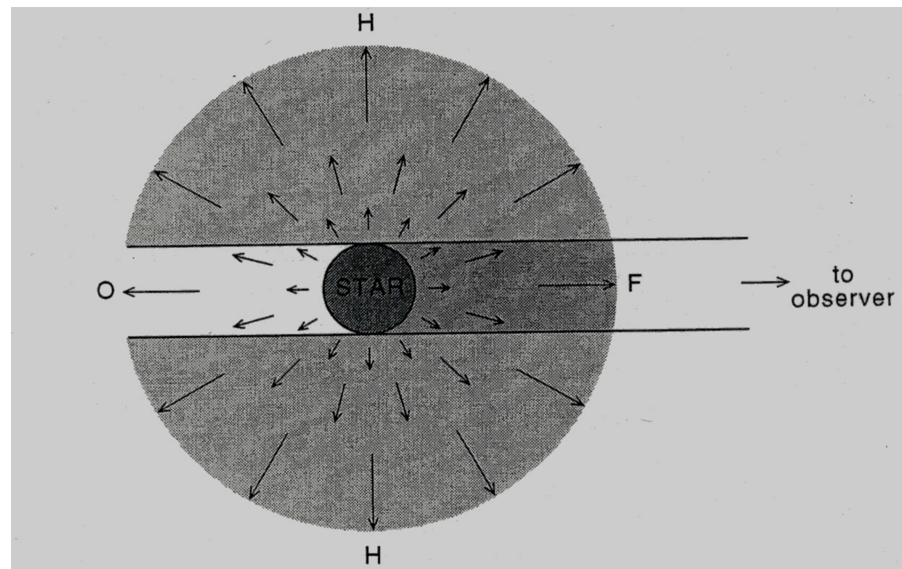


Hubble Space Telescope image of η Car; an extreme example of a hot star wind

How do we know these hot-star winds exist?

Spectroscopy! Doppler shifts change wavelengths of lines in noticeable ways. (*demo*)





blue wavelength red

Why do hot star winds exist?

The winds of hot, massive stars are very different in nature from the solar wind

The solar wind is actually driven by the gas pressure of the hot corona

But hot star winds are driven by **radiation pressure**

Remember, photons have momentum as well as energy:

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$$

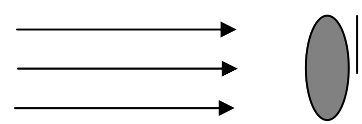
And Newton tells us that a change in momentum is a **force**:

$$F = ma = m\frac{dv}{dt} = \frac{dp}{dt}$$

So, if matter (an atom) absorbs light (a photon) momentum is transferred to the matter

Light can force atoms to move!

The *flux* of light, F (ergs s^{-1} cm^{-2})



r_e, the radius of an electron, giving a cross section, σ_T (cm^2)

$$\frac{dp}{dt} = \frac{F\sigma}{c} = \frac{L\sigma_T}{4\pi c R^2}$$

The rate at which momentum is absorbed by the electron

$$a_{rad} = \frac{L\kappa_T}{4\pi c R^2}$$

By replacing the cross section of a single electron with the opacity (cm^2 g^{-1}), the combined cross section of a gram of plasma, we get the acceleration due to radiation

For a (very luminous) hot star, this can compete with gravity…but note the $1/R^2$ dependence, if $a_{\mathrm{rad}} > a_{\mathrm{grav}}$, a star would blow itself completely apart.

But note, free electron opacity, and the associated Thompson scattering, can be significantly augmented by absorption of photons in *spectral lines* - atoms act like a resonance chamber for electrons: a bound electron can be ‘driven’ much more efficiently by light than a free one (i.e. it has a much larger cross section), but it can only be driven by light with a very specific frequency.

Radiation driving in spectral lines not only boosts the radiation force, it also solves the problem of the star potentially blowing itself apart:

As the line-driven material starts to move off the surface of the star, it is Doppler-shifted, making a previously narrow line broader, and increasing its ability to absorb light.

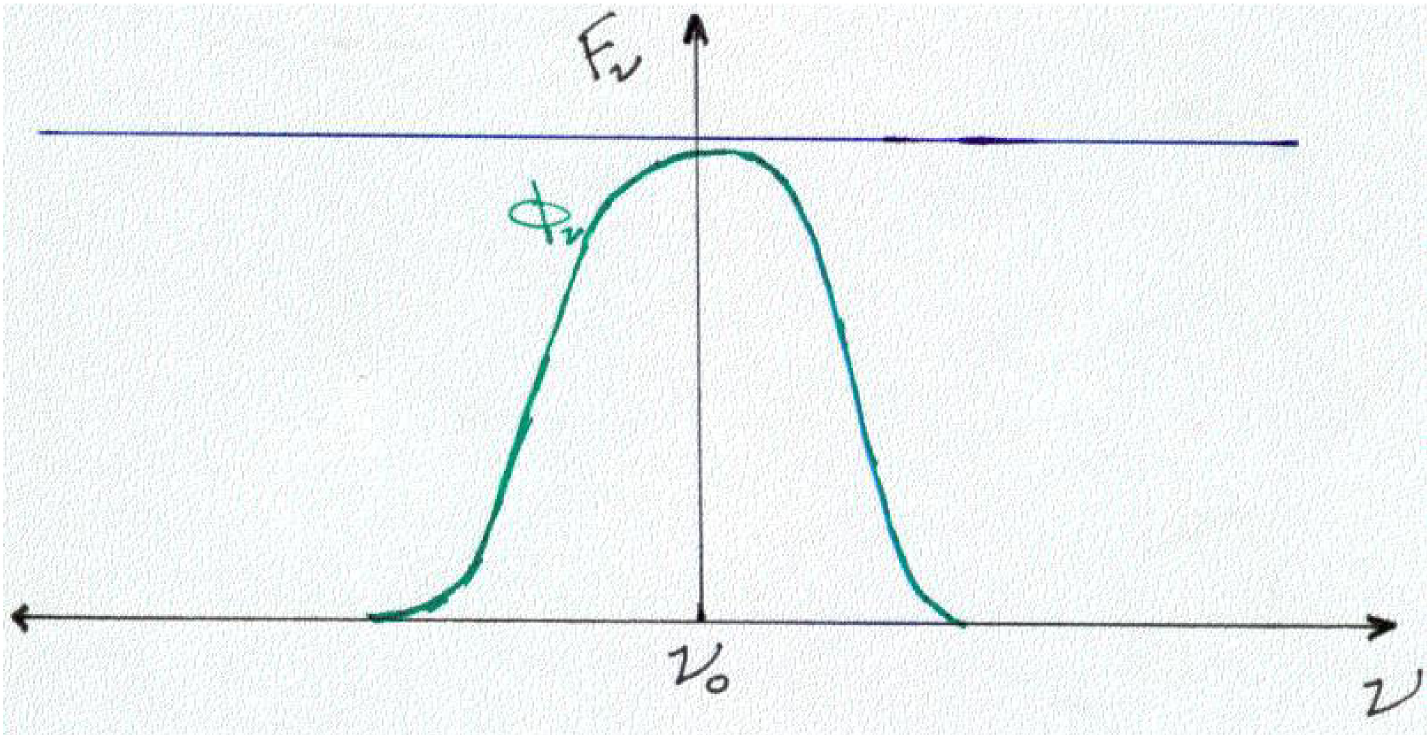
The *Doppler desaturation* of optically thick (opaque) lines allows a hot star wind to bootstrap itself into existence!

And causes the radiation force to deviate from strictly $1/R^2$ behavior: the radiation force on lines can be less than gravity inside the star but more than gravity above the star's surface.

X-rays from shock-heating in line-driven winds

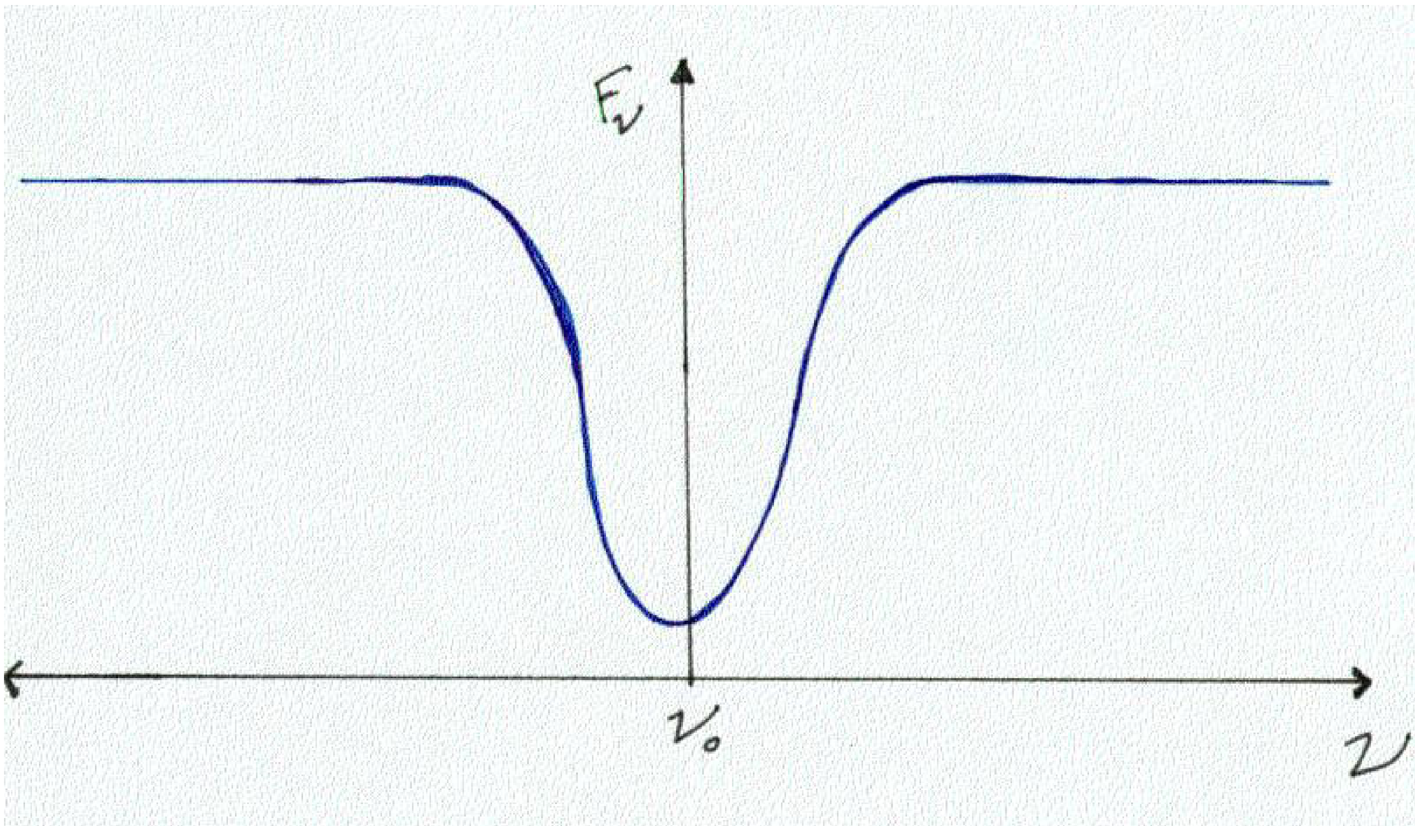
The Doppler desaturation that's so helpful in driving a flow via momentum transfer in spectral lines is inherently unstable

Consider a scattering spectral line from a parcel of atoms in the wind

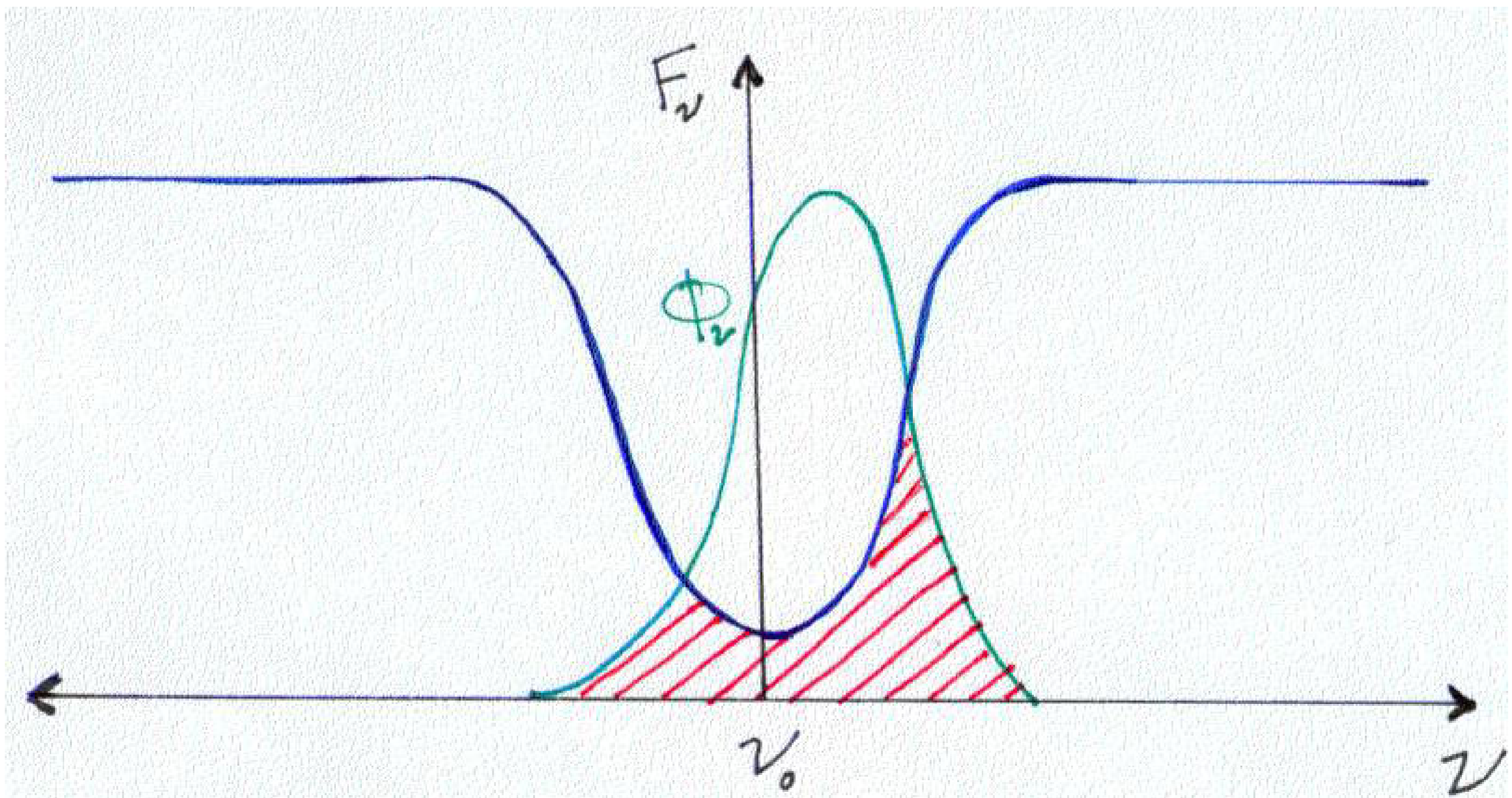


This line's *profile*, or frequency-dependent opacity, is shown in green. This is essentially the probability that a photon of a given frequency will be scattered, or absorbed, by the atom

After atoms of this type have absorbed the photospheric light, the remaining light looks like this:



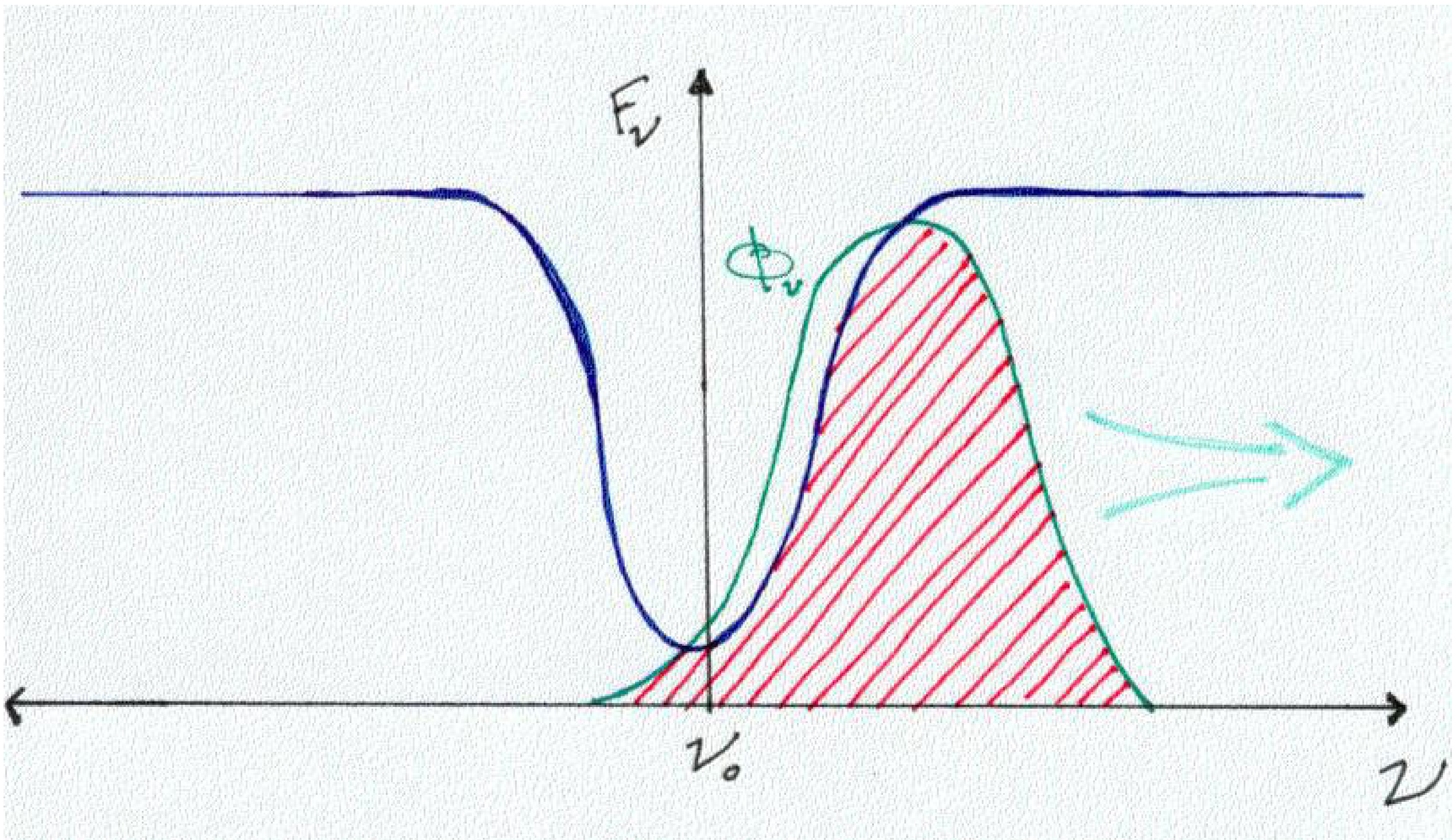
Absorbing the light has *accelerated* the parcel, however, so the line profile is now *blueshifted* a bit



The red cross-hatched area shows the light that can be absorbed by this parcel of atoms -- note that the shifting of the profile out of the “Doppler shadow” allows for more momentum to be absorbed, and thus more acceleration, than if the line weren’t blueshifted

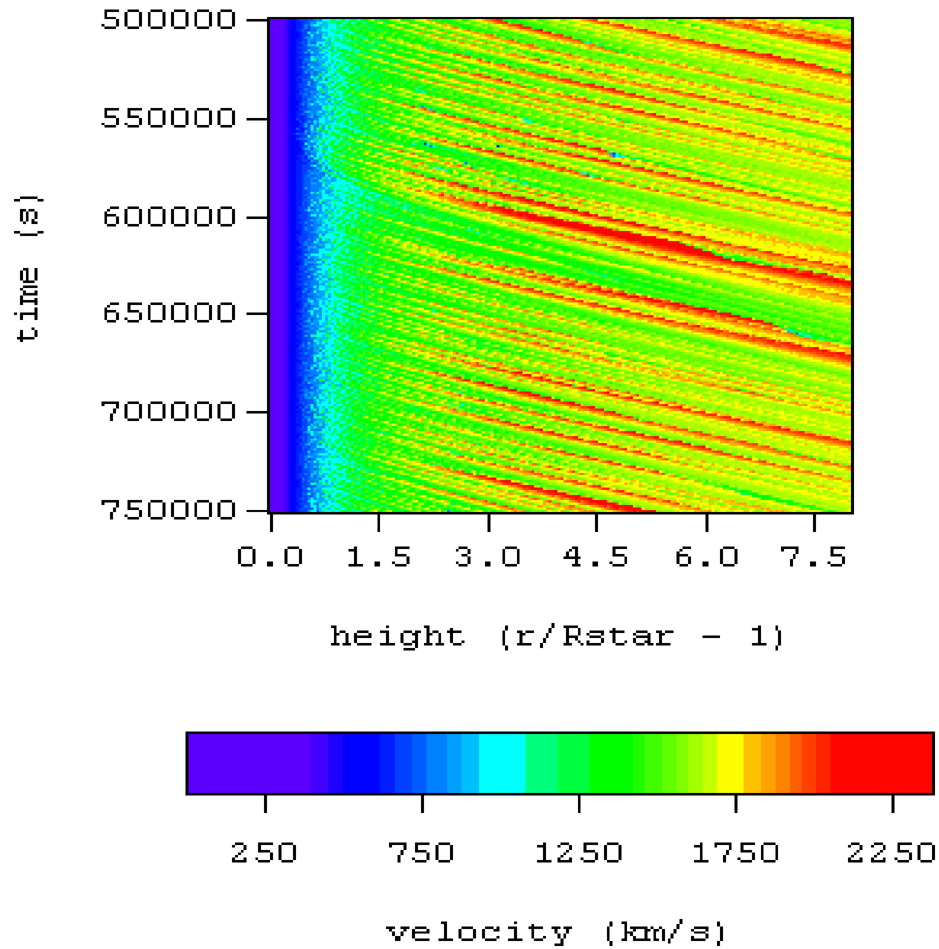
If the parcel of atoms gets an extra little push, it will “see” more photospheric flux, get a bigger acceleration and thus more blueshift, and therefore receive even more flux, etc.

Line-driving has an inherent instability

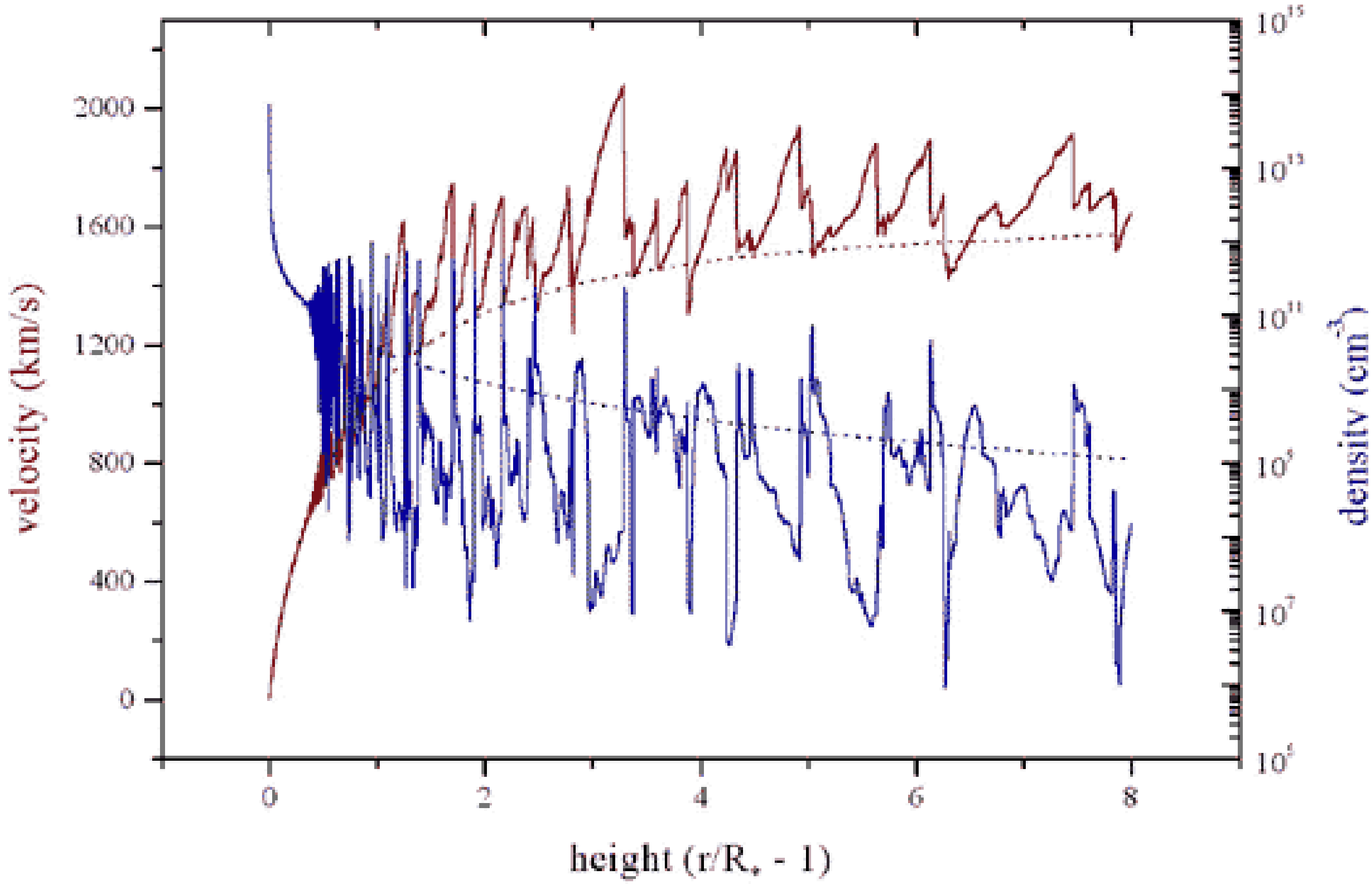


Numerical modeling of the hydrodynamics show lots of structure: turbulence, shock waves, collisions between "clouds"

This chaotic behavior is predicted to **produce X-rays** through **shock-heating** of some small fraction of the wind.



A snapshot at a single time from the same simulation. Note the discontinuities in velocity. These are shock fronts, compressing and **heating** the wind, producing **x-rays**.



Even in these instability shock models, most of the wind is cold and is a source of x-ray continuum opacity - x-rays emitted by the shock-heated gas can be absorbed by the cold gas in the rest of the wind

Keep this in mind, because it will allow us to learn things about the physical properties of a shocked wind via spectroscopy

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X-ray line profiles can provide the most direct observational constraints on the x-ray production mechanism in hot stars

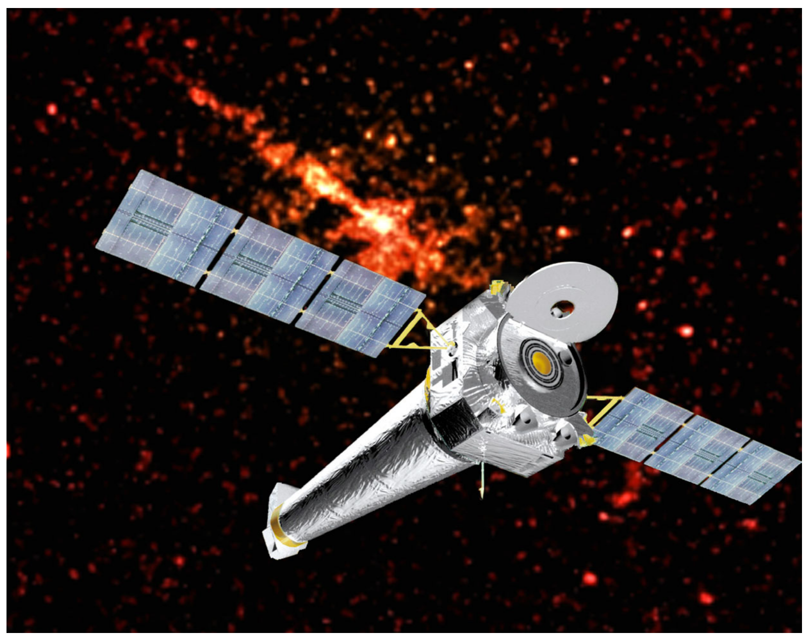
Wind-shocks : broad lines

Magnetic dynamo : narrow lines

The Doppler effect will make the x-ray emission lines in the wind-shock scenario broad, compared to the x-ray emission lines expected in the coronal/dyanamo (solar-like) scenario

So, this wind-shock model - based on the line-force instability - is a plausible alternative to the idea that hot star x-rays are produced by a magnetic dynamo

This basic conflict is easily resolved if we can measure the x-ray spectrum of a hot star at high enough resolution…



In 1999 this became possible with the launch of the *Chandra* X-ray Observatory

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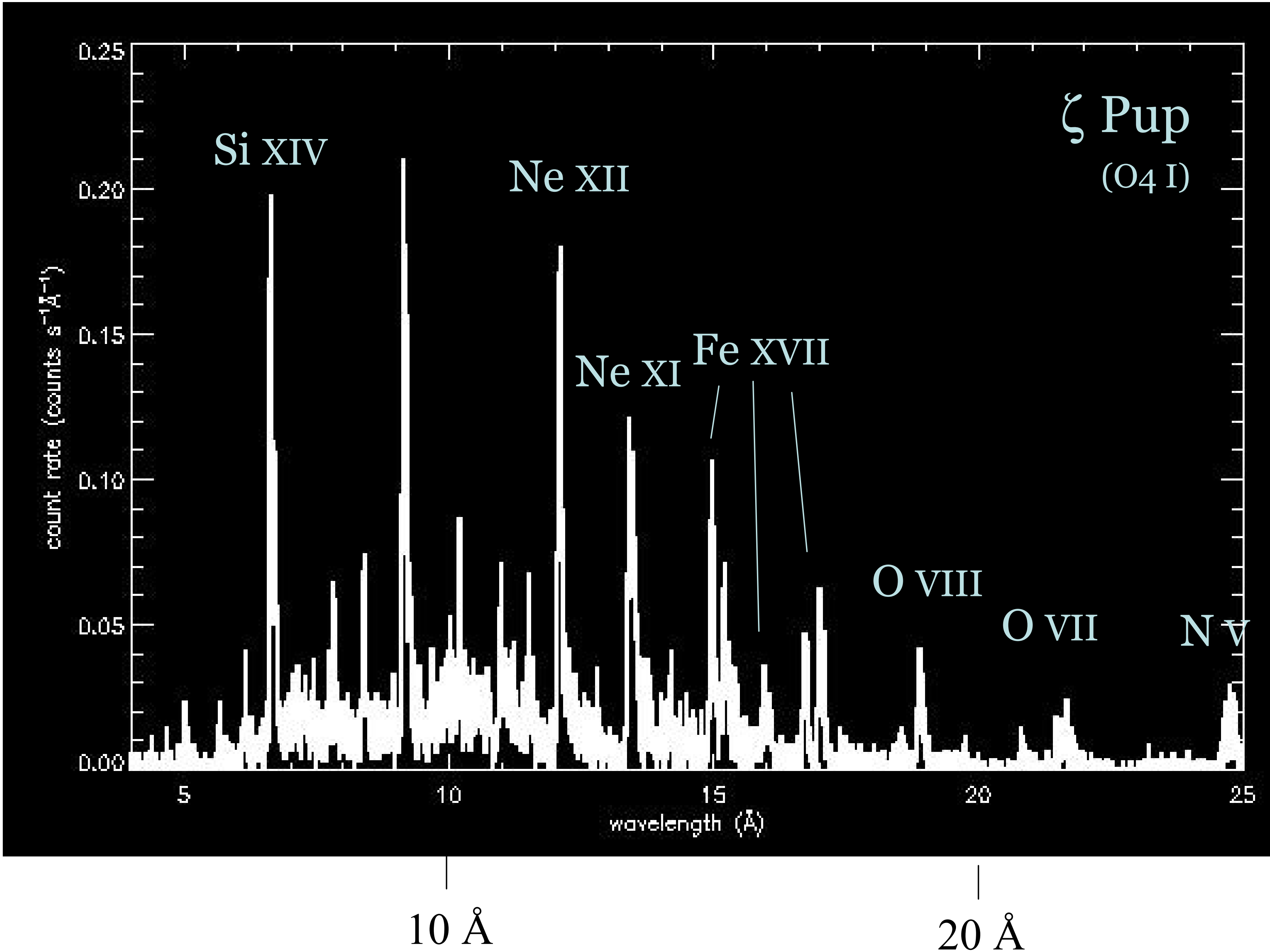
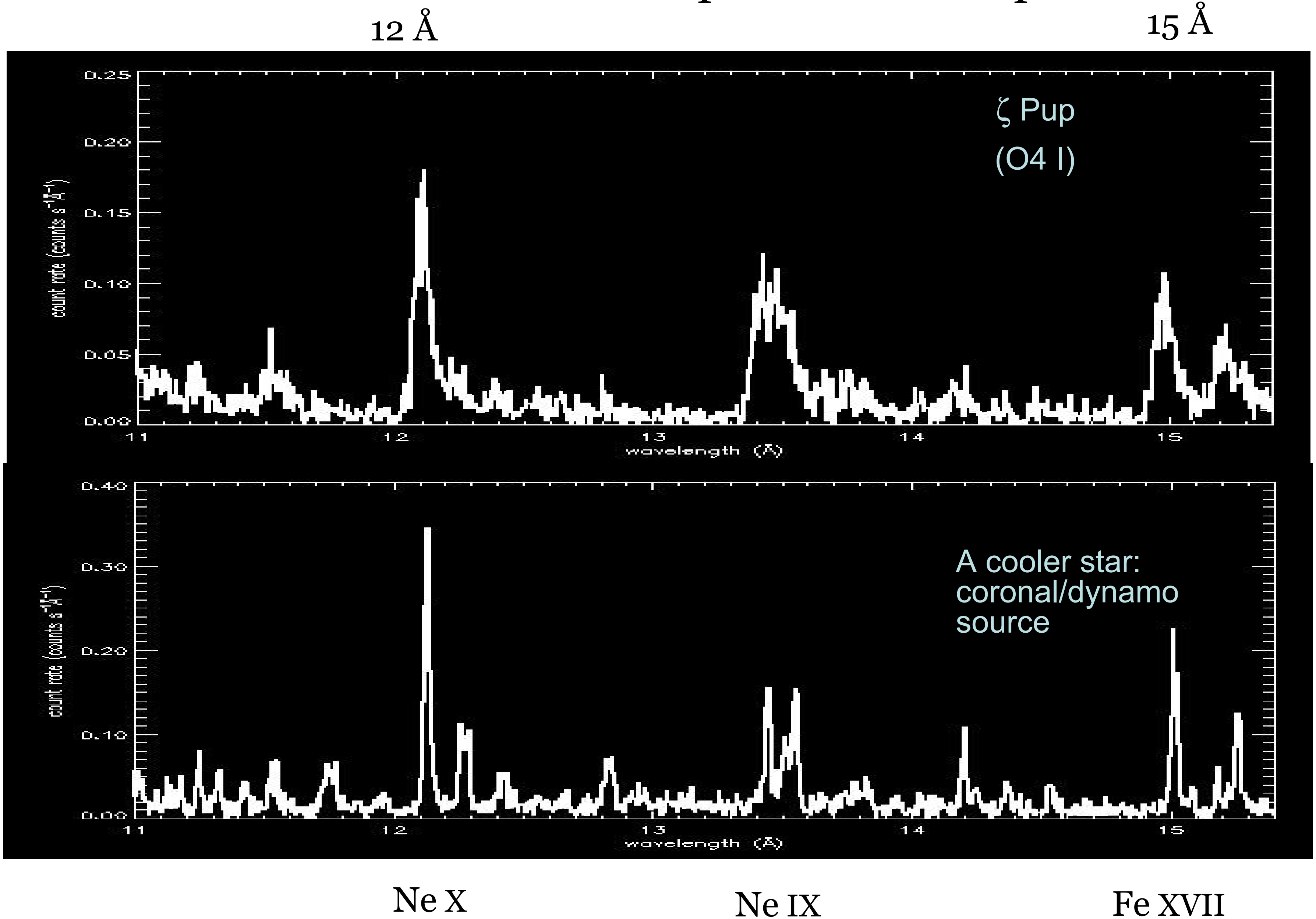
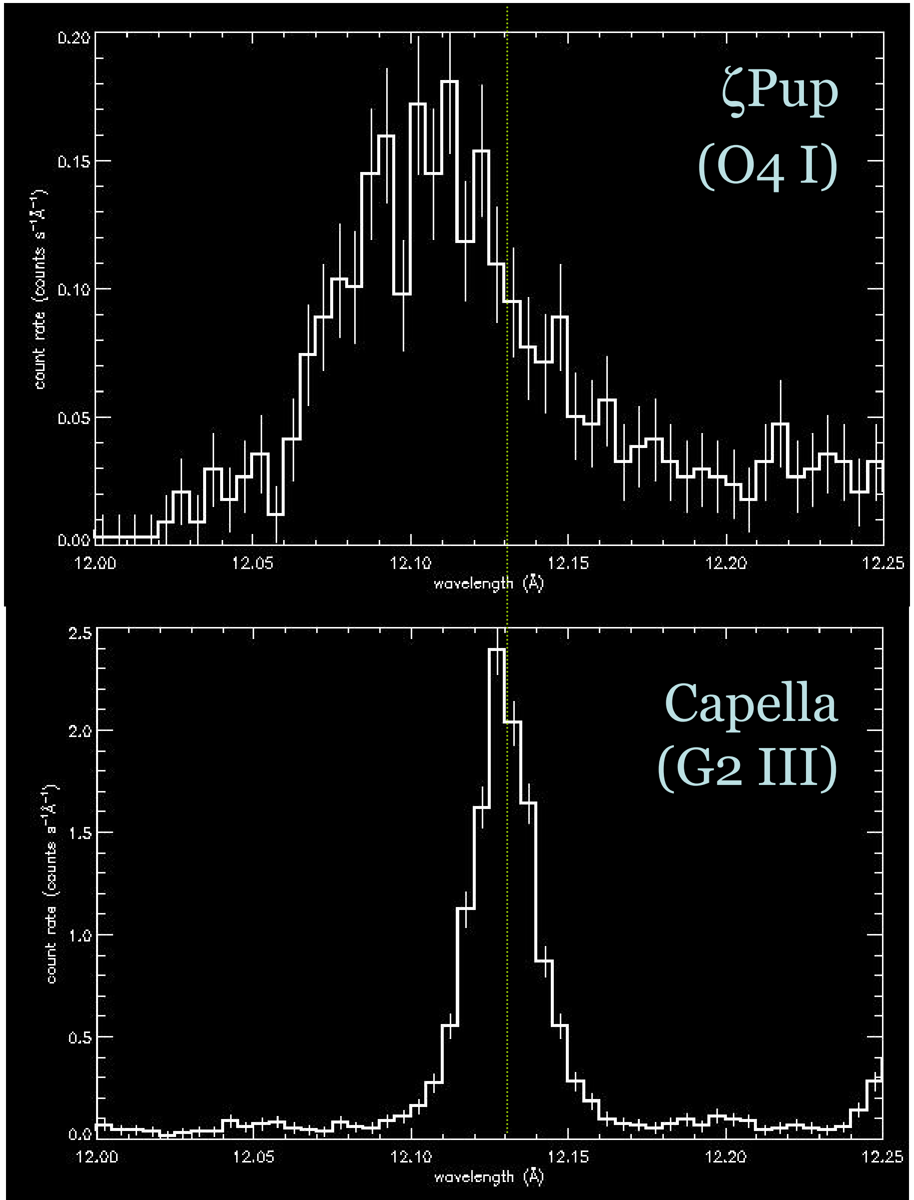


ζ Pup
(O4 I)
Si XIV
Ne XII
Ne XI
Fe XVII
O VIII
O VII
N V
count rate (counts s⁻¹Å⁻¹)
0.00
0.05
0.10
0.15
0.20
0.25
5
10
15
20
25
wavelength (Å)
10 Å
20 Å

Focus in on a characteristic portion of the spectrum



Differences in the line shapes become apparent when we look at a single line (here Ne X, Lyα)



The x-ray emission lines in the hot star ζ Pup *are* broad -- the wind shock scenario is looking good!

But note, the line isn't just broad, it's also blueshifted and asymmetric…

We can go beyond simply wind-shock vs. coronal:

We can use the *line profile shapes* to learn about the velocity distribution of the shock-heated gas and even its spatial distribution within the wind, as well as learning something about the amount of cold wind absorption (and thus the amount of cold wind).

What Line Profiles Can Tell Us

The wavelength of an emitted photon is proportional to the line-of-sight velocity:

- Line *shape* maps emission at each velocity/wavelength interval

Continuum absorption by the cold stellar wind affects the line shape

- Correlation between line-of-sight velocity and absorption optical depth will cause *asymmetries* in emission lines

The shapes of lines, if they're broad, tells us about the distribution and velocity of the hot plasma in the wind -- maybe discriminate among specific wind shock models/mechanisms

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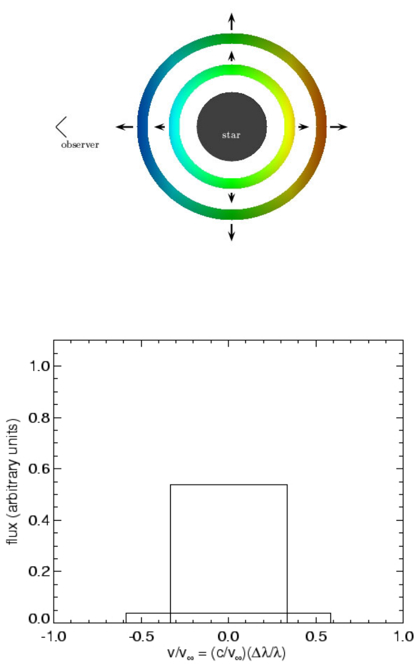
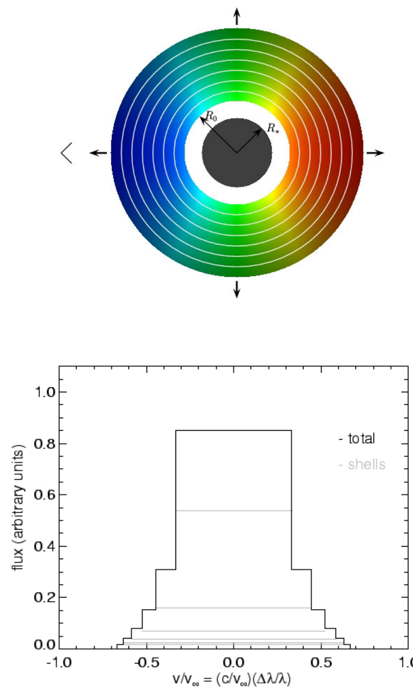
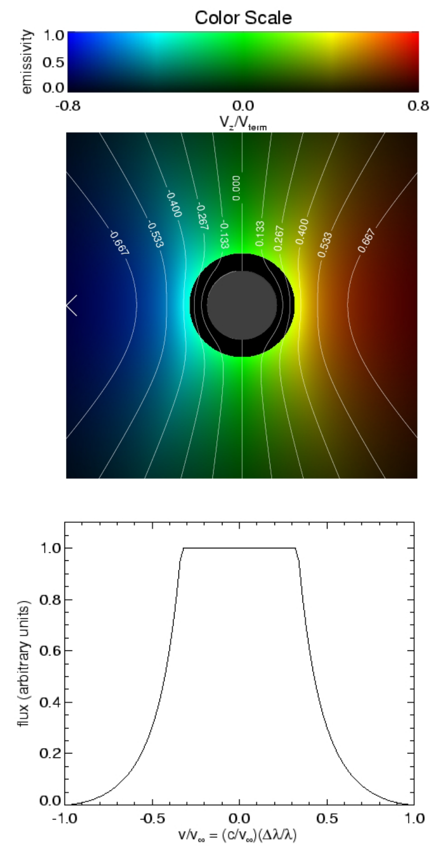
Emission Profiles from a Spherically Symmetric, Expanding Medium

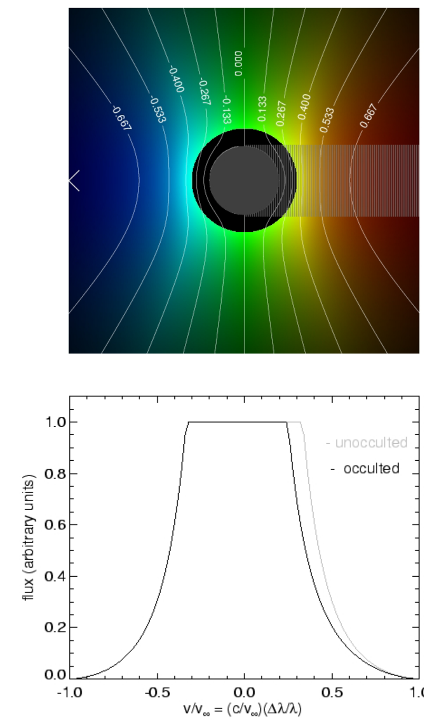


A uniform shell gives a rectangular profile.



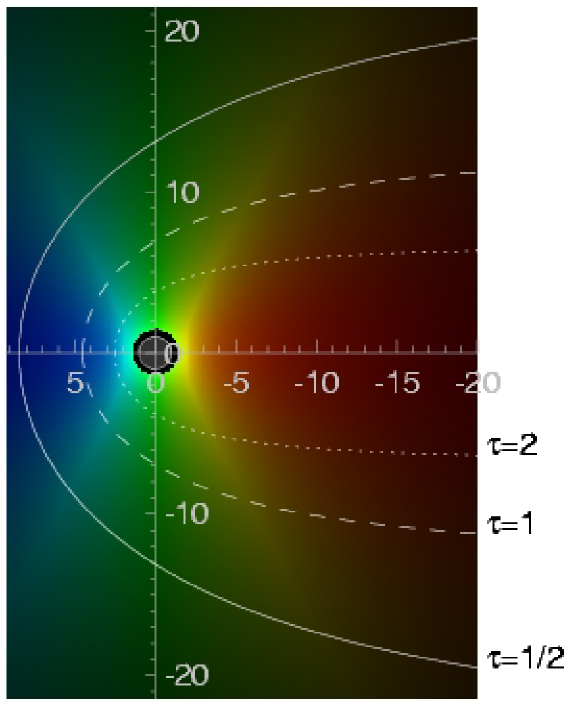


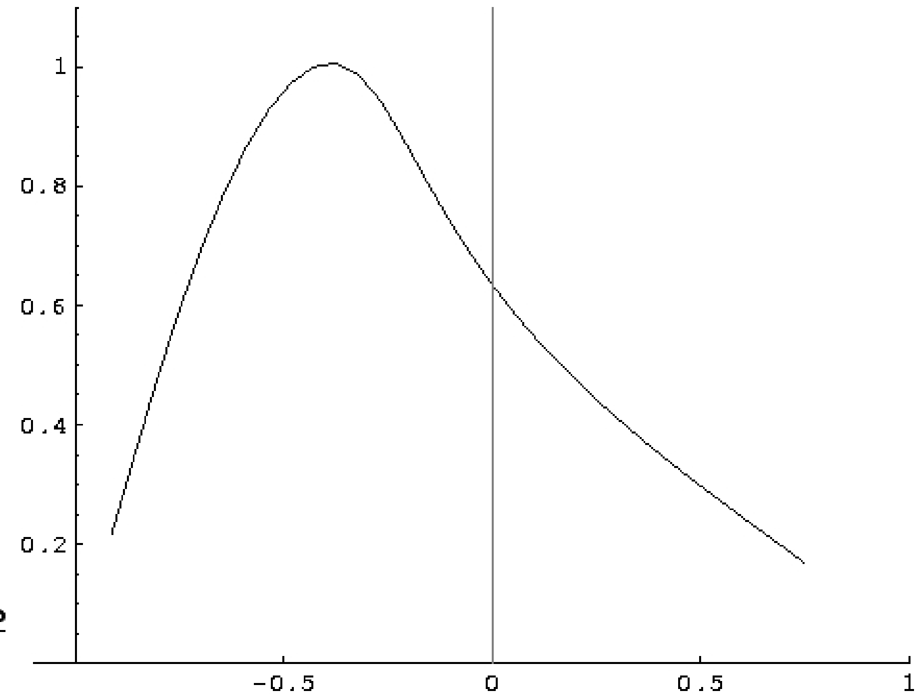
A spherically-symmetric, x-ray emitting wind can be built up from a series of concentric shells.



Occultation by the star removes *red* photons, making the profile asymmetric

Continuum Absorption Acts Like Occultation

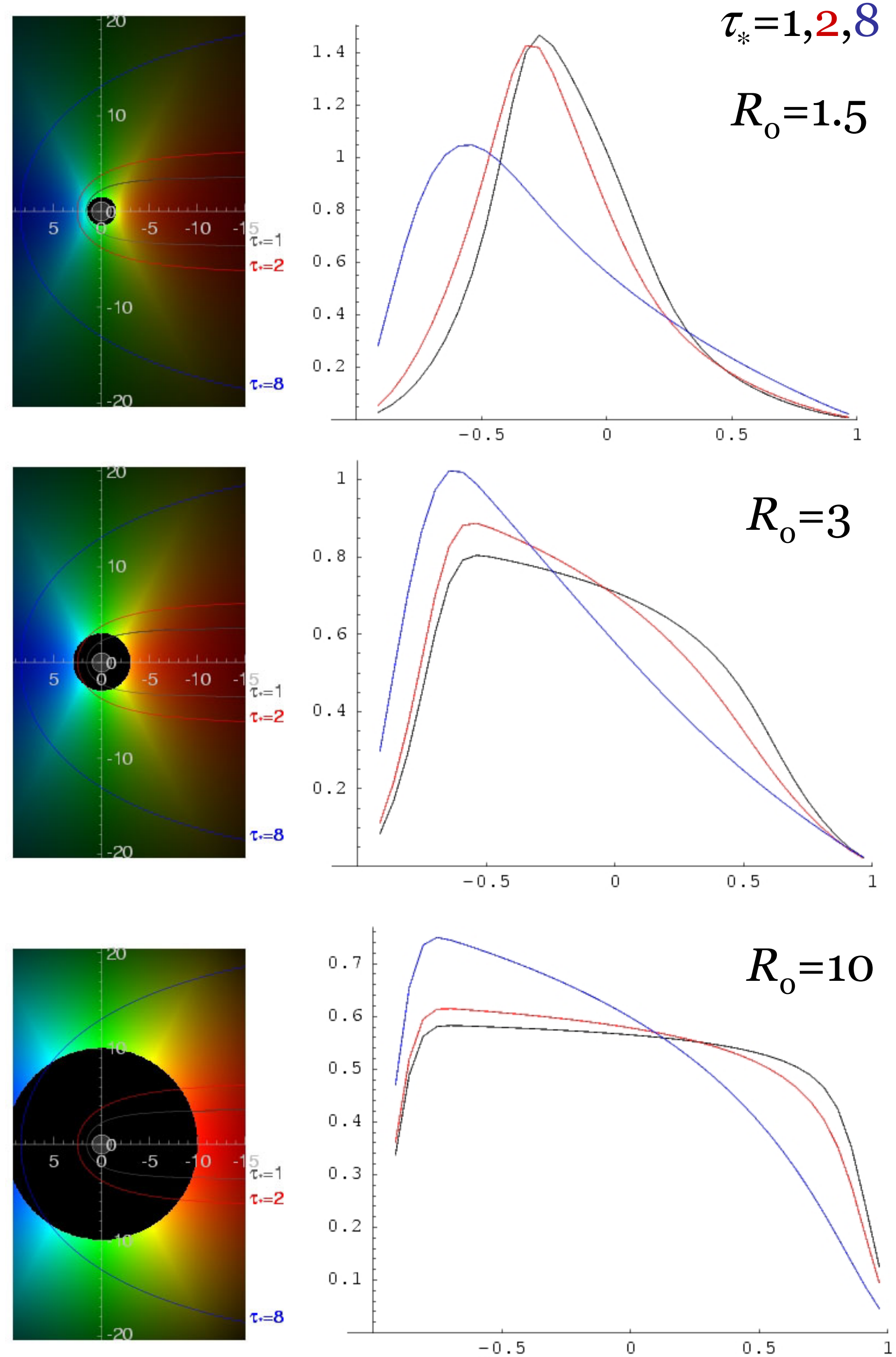




Red photons are preferentially absorbed, making the line asymmetric: The peak is shifted to the blue, and the red wing becomes much less steep.

A wide variety of wind-shock properties can be modeled

Line profiles change in characteristic ways with τ_* and R_o, becoming broader and more skewed with increasing τ_* and broader and more flat-topped with increasing R_o.



The model has four parameters:

$$\beta : v(r) = (1 - R_* / r)^\beta$$

$$R_o, q : j \propto \rho^2 r^{-q} \quad \text{for } r > R_o$$

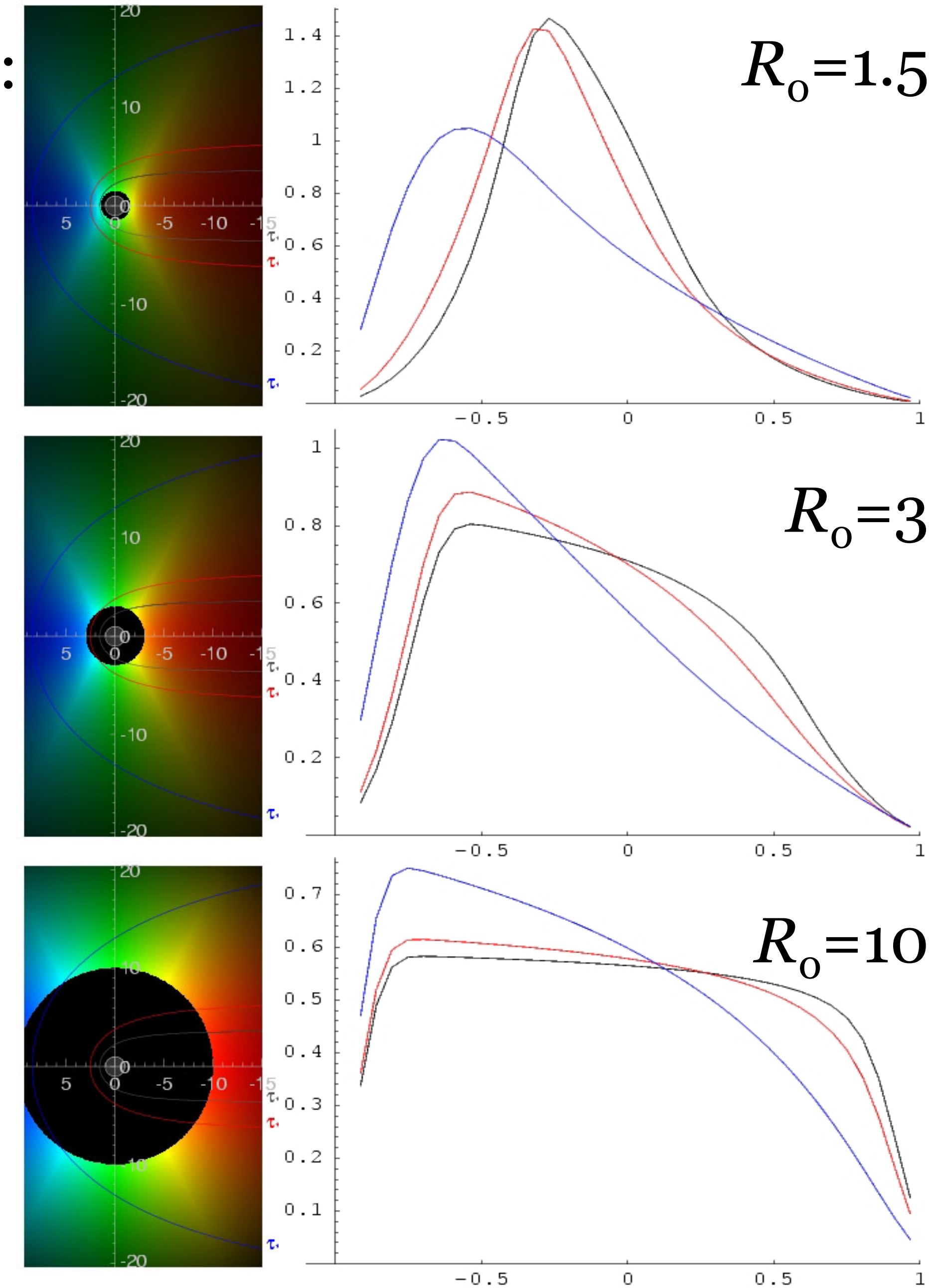
$$\tau_* : \tau(p = 0; z) = \tau_* \int_z^\infty \frac{dz'}{r'^2 (1 - \frac{1}{r'})^\beta}$$

where $\tau_* \equiv \dfrac{\kappa \dot{M}}{4 \pi R_* v_\infty}$

The line profile is calculated from:

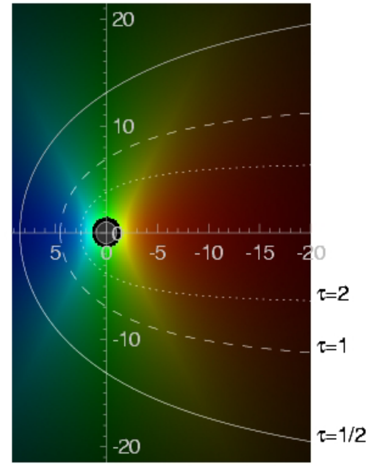
$$L_\lambda = 8 \pi^2 \int_{-1}^{1} \int_{R_*}^{\infty} j e^{-\tau} r^2 dr d\mu$$

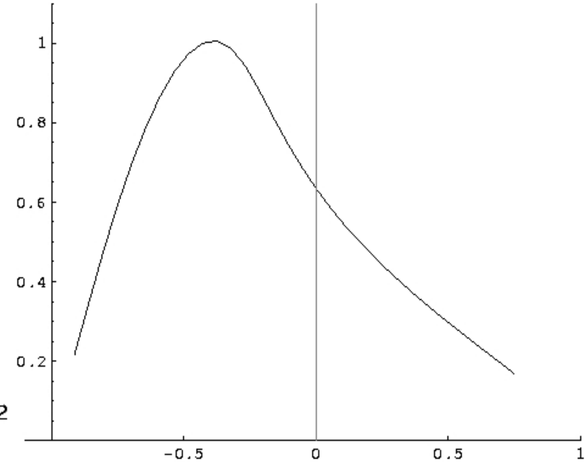
Increasing R_o makes lines broader; increasing τ_* makes them more blueshifted and skewed.



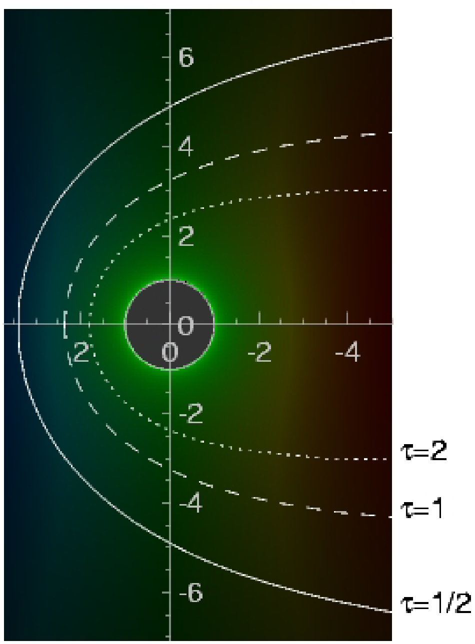
τ_*=1,2,4

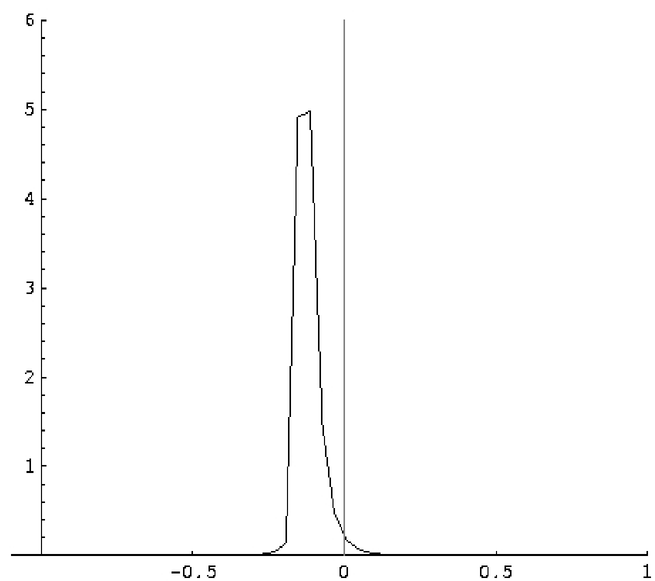
In addition to the
wind-shock model,





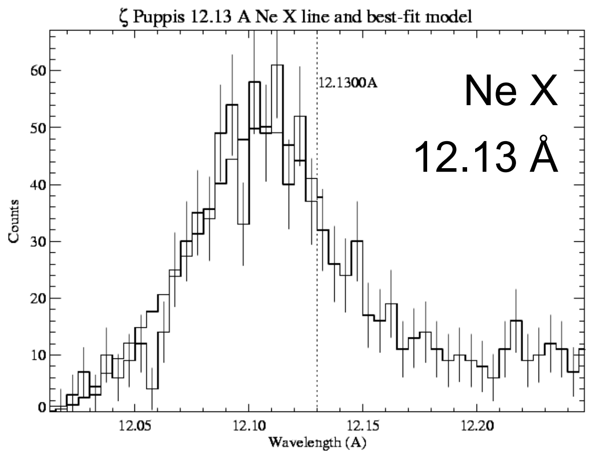
our empirical line profile model can also describe a corona

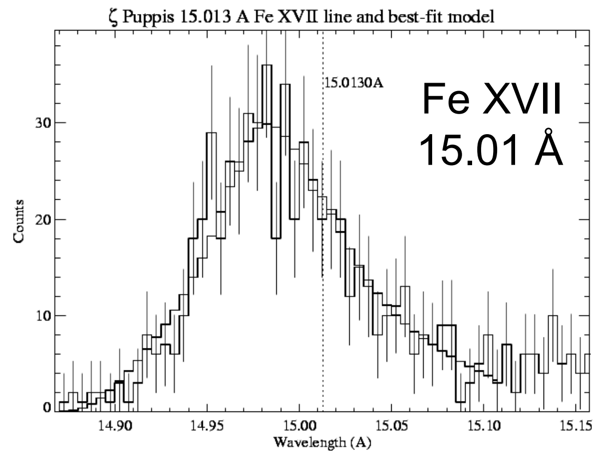


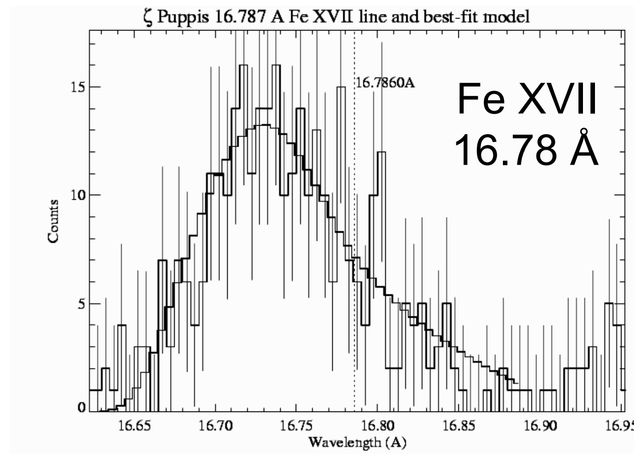


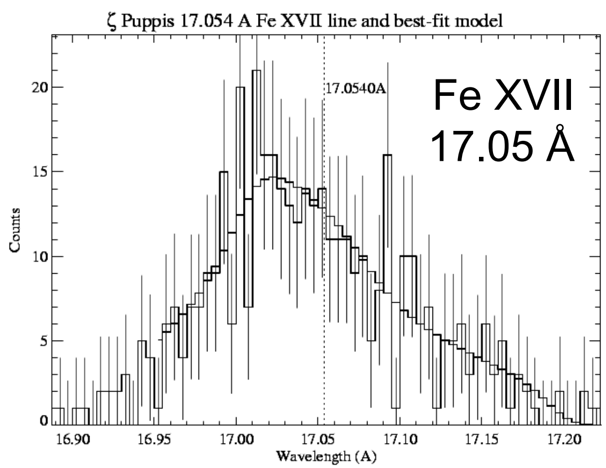
With most of the emission concentrated near the photosphere and with very little acceleration, the resulting line profiles are very narrow.

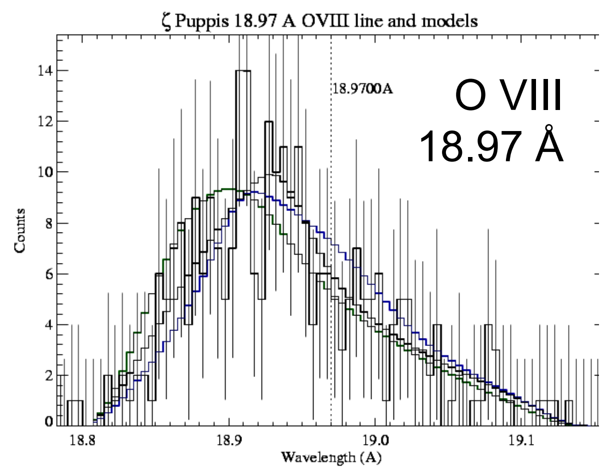
We fit all the (8) unblended strong lines in the *Chandra* spectrum of ζ Pup: all the fits are statistically good

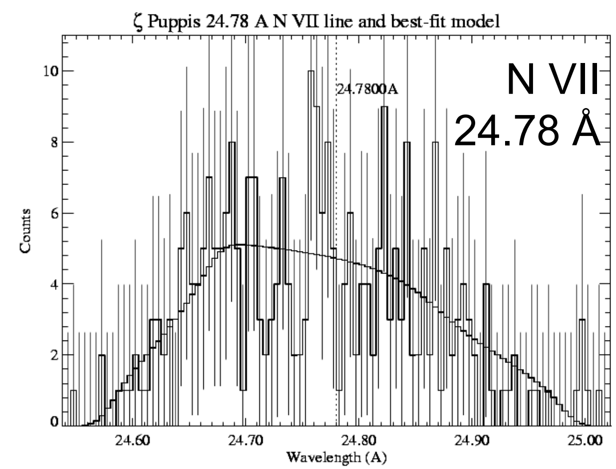




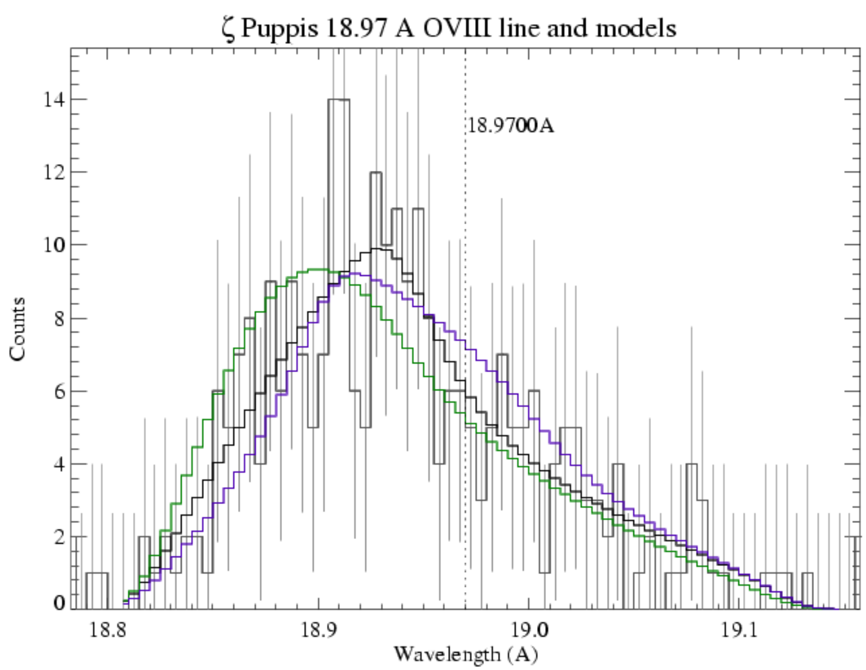




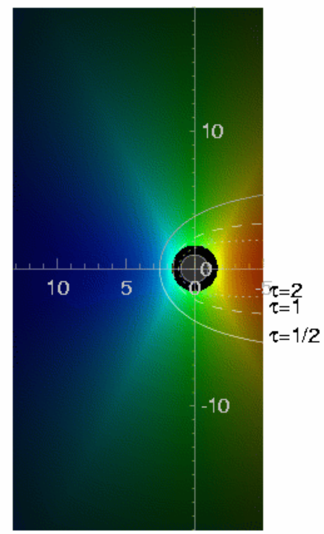




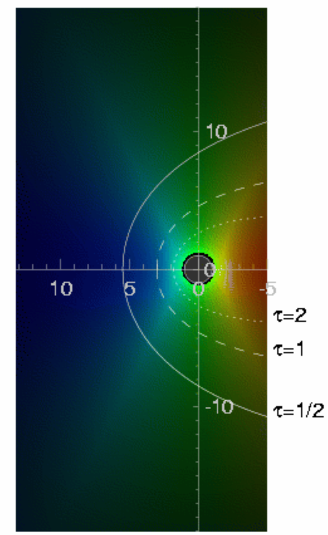
We place *uncertainties* on the derived model parameters



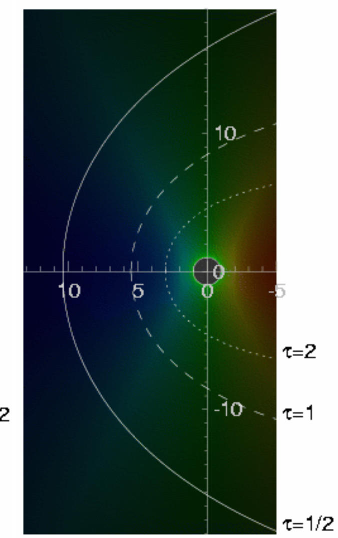
lowest τ_*



best τ_*



highest τ_*

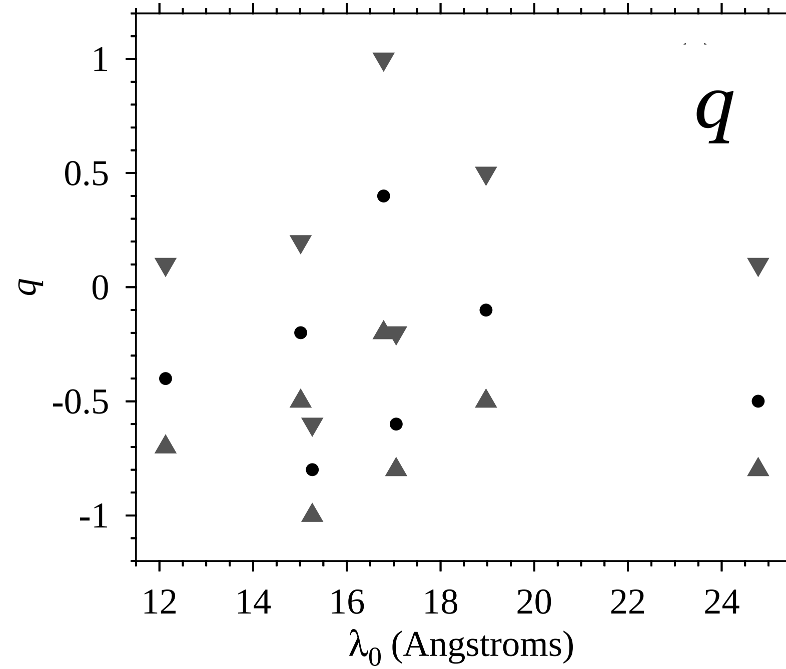


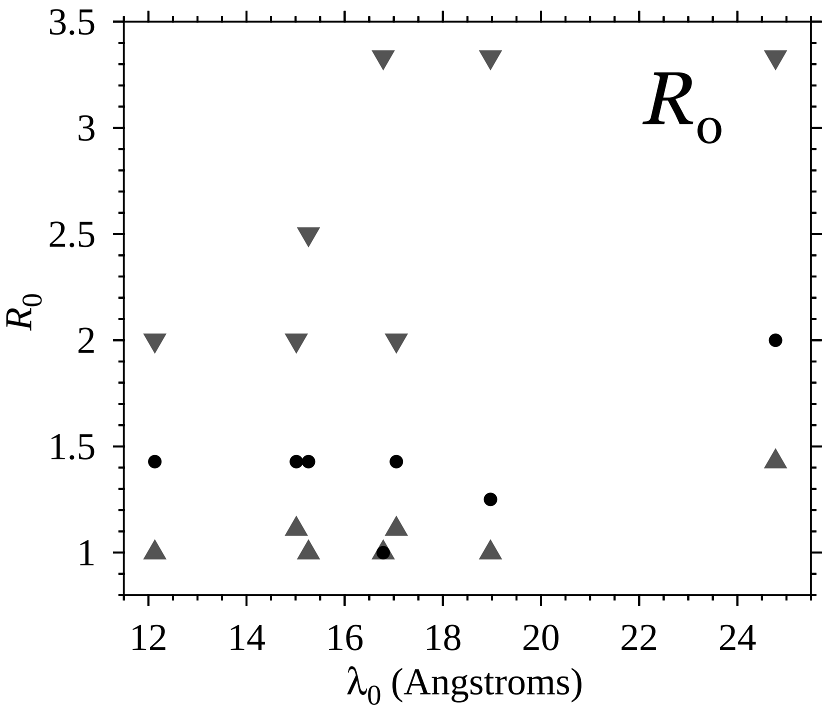
Here we show the best-fit model to the O VIII line and two models that are marginally (at the 95% limit) consistent with the data; they are the models with the highest and lowest τ_* values possible.

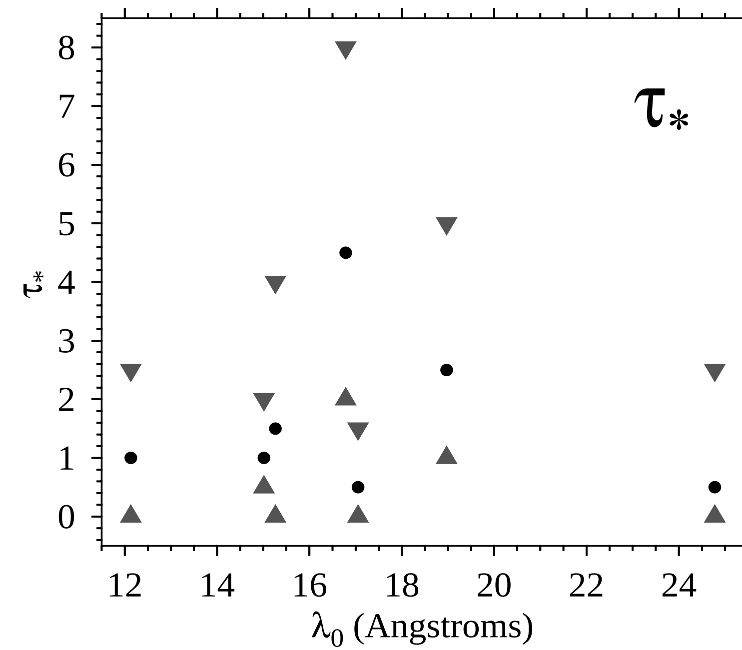
Outline

1. What you need to know:
    a. X-rays from the Sun - magnetic activity, x-ray spectra
    b. Hot stars
    c. Radiation-driven winds and the Doppler shift
    d. The holy grail of science: a measurement that can discriminate between two contradictory theories
2. What we have observed/measured with the new generation of high-resolution x-ray telescopes
3. Our empirical model and fits to the data
4. **An answer…and more questions**

Graphical depiction of the best fit (black circles) and 95% confidence limits (gray triangles) on the three fitted parameters for seven of the lines in the ζ Pup spectrum.







Lines are well fit by our three parameter model: ζ Pup's x-ray lines are consistent with a spatially distributed, spherically symmetric, radially accelerating wind scenario, with reasonable parameters:

$\tau_* \sim 1$:4 to 15 times less than predicted

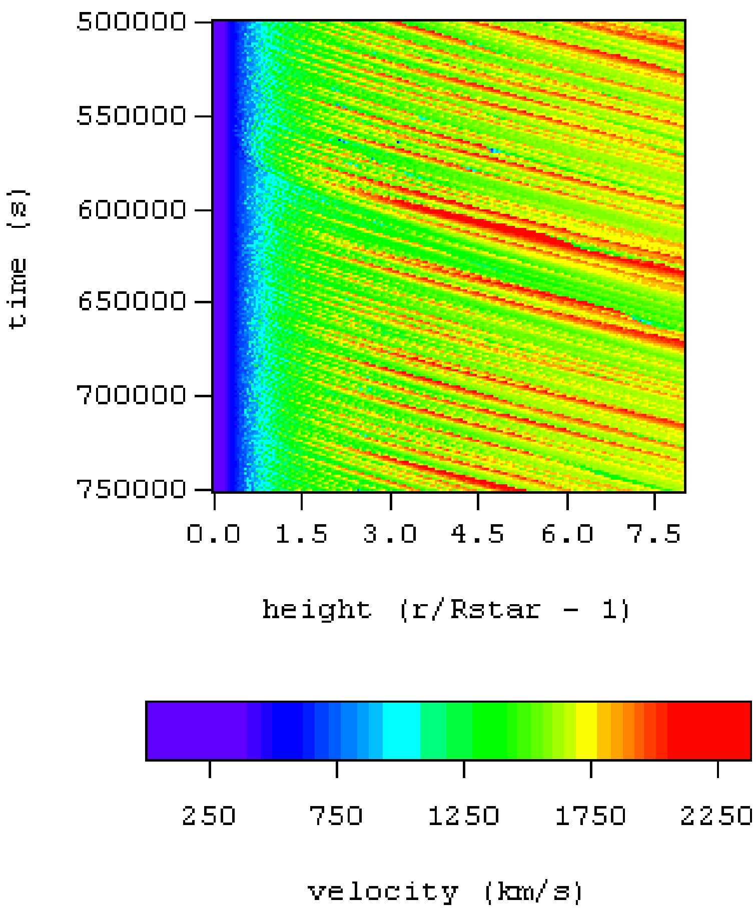
$R_o \sim 1.5$

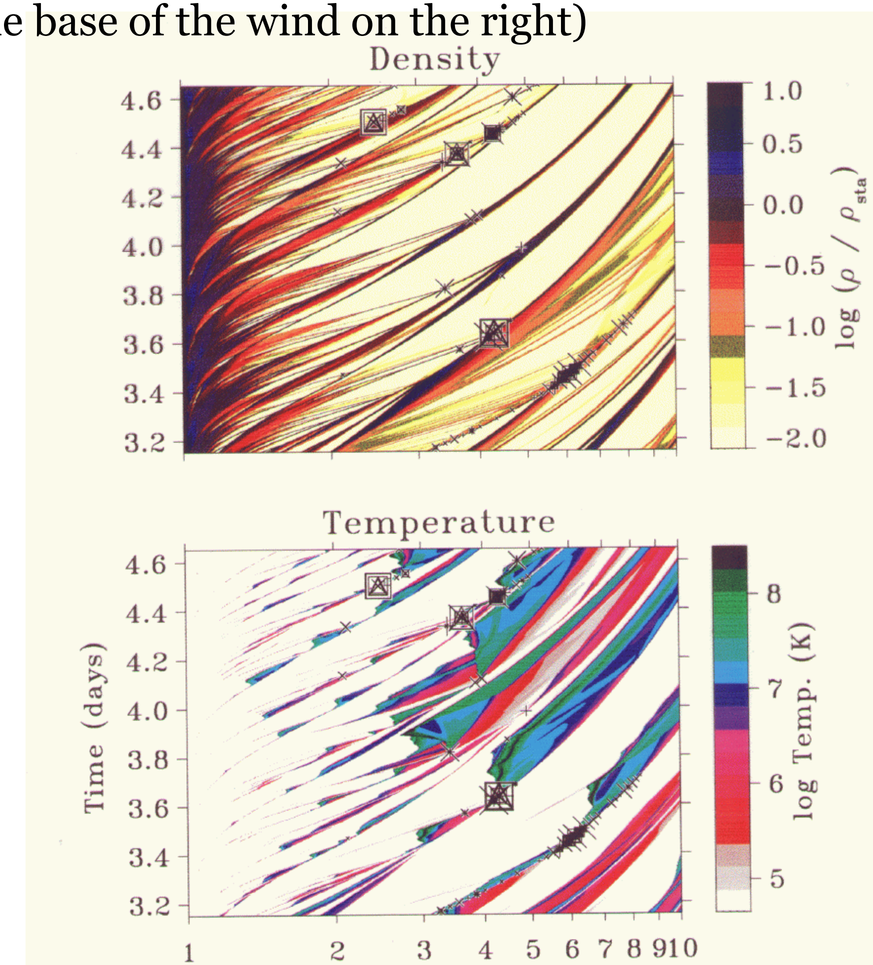
$q \sim 0$

But, the level of *wind absorption is significantly below* what's expected.

And, there's *no significant wavelength dependence* of the optical depth (or any parameters).

R_o of several tenths of a stellar radius is expected based on numerical simulations of the line-force instability (self-excited on the left; sound wave purturbations at the base of the wind on the right)



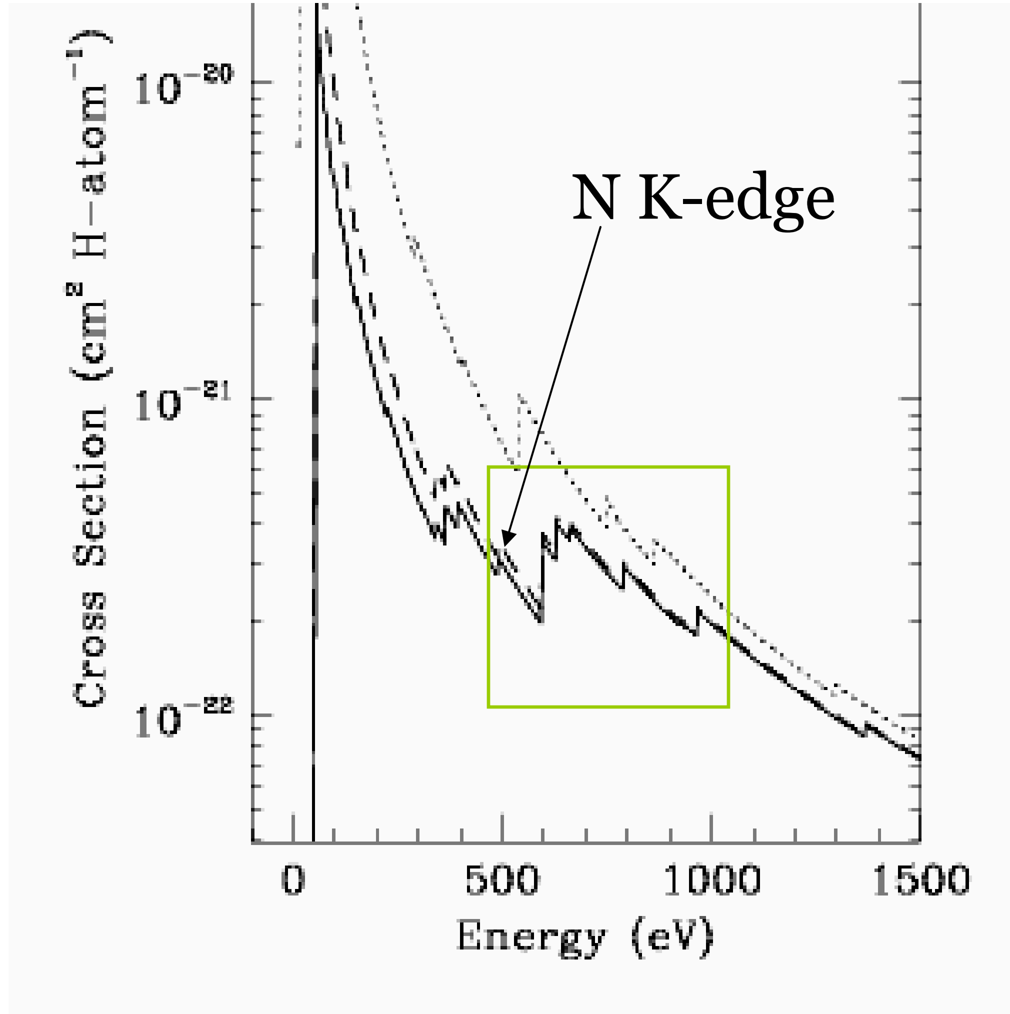


Location of the X-ray-emitting plasma near the photosphere is also indicated by He-like *f*/*i* ratios (Kahn et al. 2001)

We do expect some wavelength dependence of the cross sections (and thus of the wind optical depth), BUT the lines we fit cover only a modest range of wavelengths. And in the case of ζ Pup, nitrogen overabundance (not in calculation shown at right) could flatten out the wavelength dependence even more.

OR perhaps **clumping** plays a role. And clumping (alt. "porosity") certainly could play a role in the overall reduction of wind optical depth.

Wind opacity for canonical B star abundances.



Note: dotted line is interstellar.

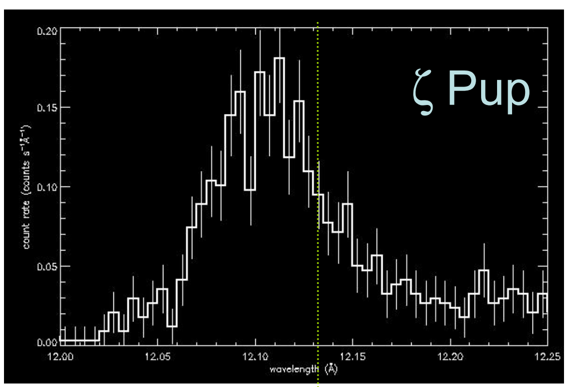
Conclusions for normal, O supergiants

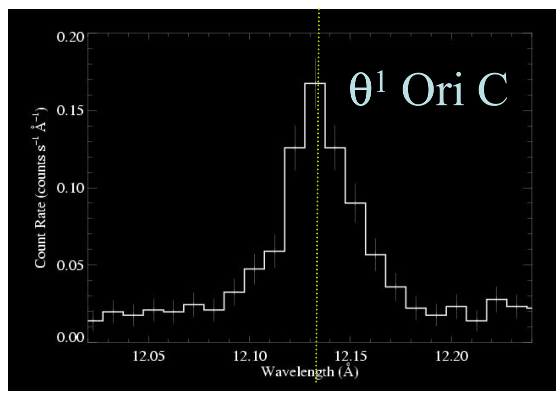
Spherically symmetric, standard wind-shock model fits the *Chandra* data for ζ Pup

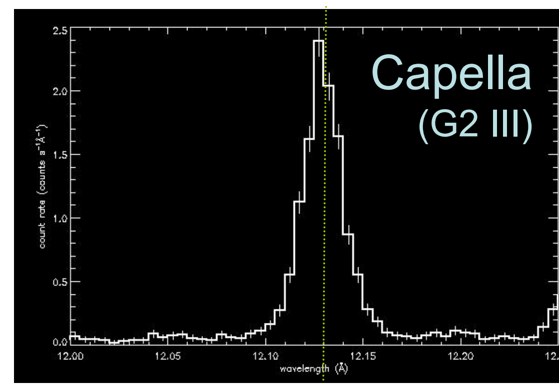
But the level of continuum absorption in the wind must be reduced from expected values by factors of ~5 (clumping?)

Some of the other hot stars observed with *Chandra* show broad, blushifted, and asymmetric line profiles, similar to those seen in ζ Pup

But…some hot stars have x-ray spectra with quite *narrow* lines, that are especially strong and high energy - not consistent with line-force instability wind shocks







θ^1 Ori C is the *young* hot star at the center of the Orion nebula

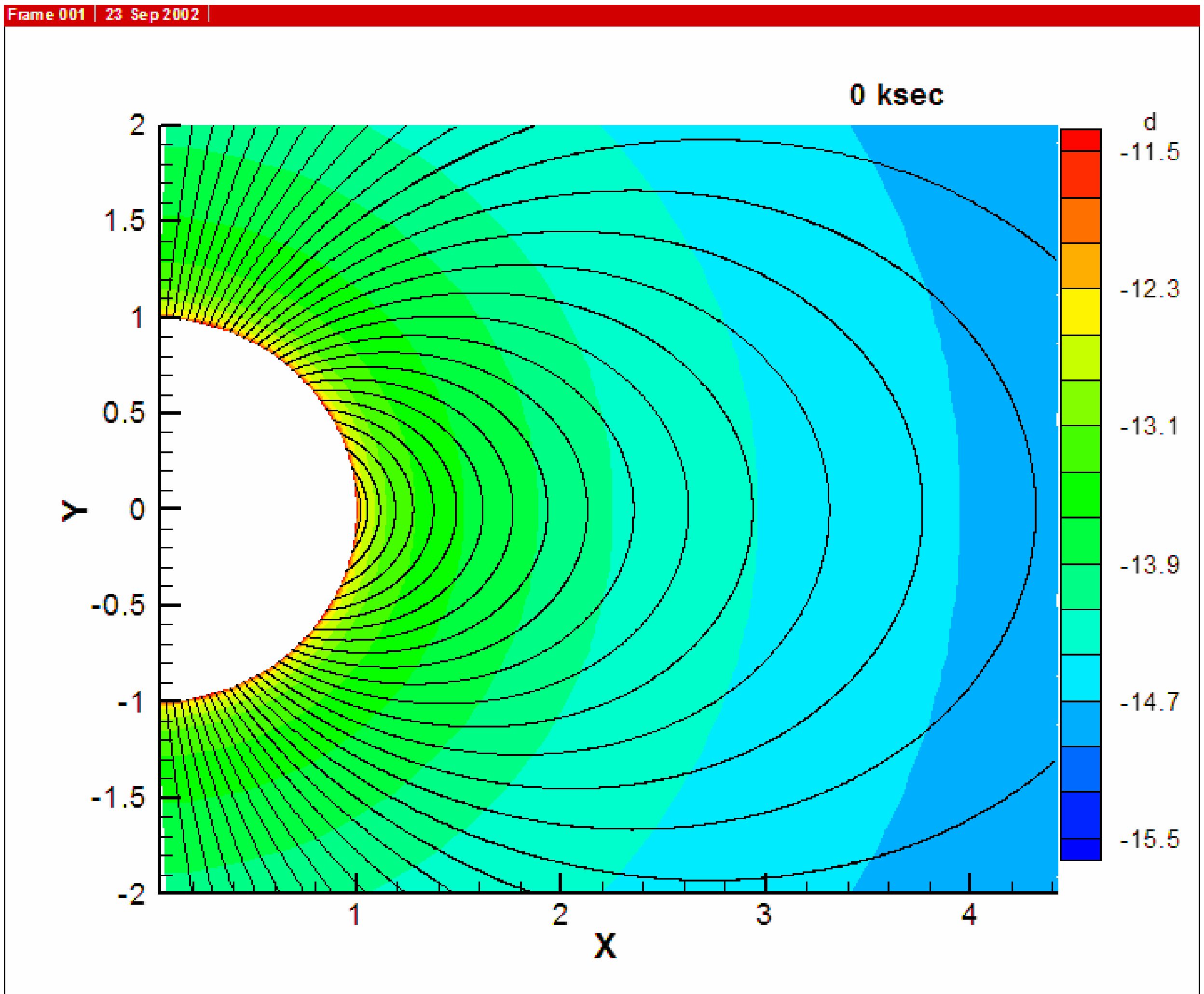
Although there’s not good reason to think that these young O stars have convection or magnetic dynamos, they may have magnetic fields that remain from the the collapsing interstellar clouds out of which they formed

In fact, θ^1 Ori C itself has recently had a magnetic field detected on it: A large scale dipole filed with a strength of 1100 G (compare to 1 G for the Earth’s field)

They also have strong line-driven winds, so one might ask how does a wind behave in the presence of a large-scale magnetic field?

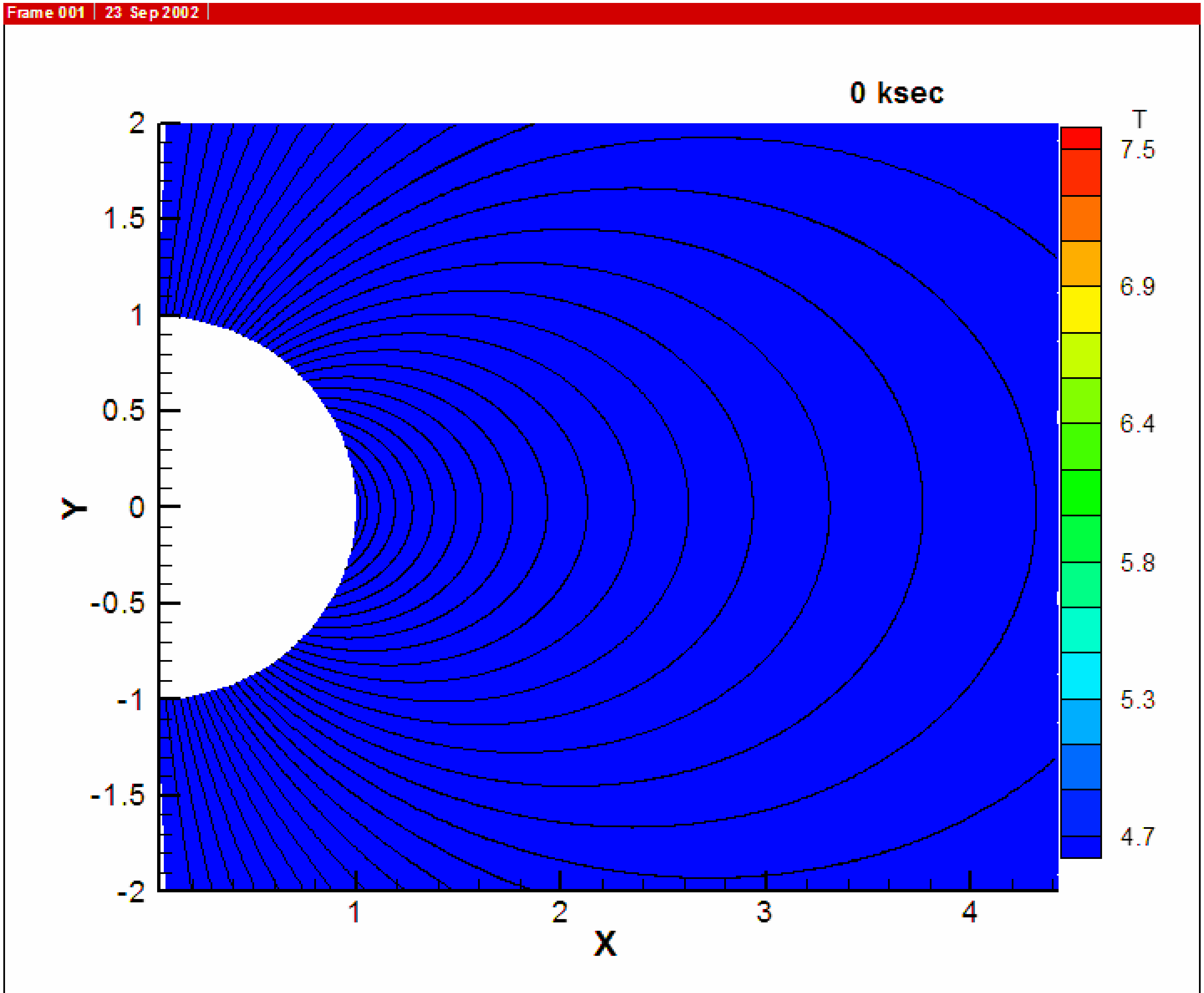
We have done MHD simulations of winds + dipole fields: the ionized winds flow along the field lines, but if the wind energy is large enough, it can change the field morphology

This is a movie of density, evolving from an initial spherically symmetric steady-state wind.



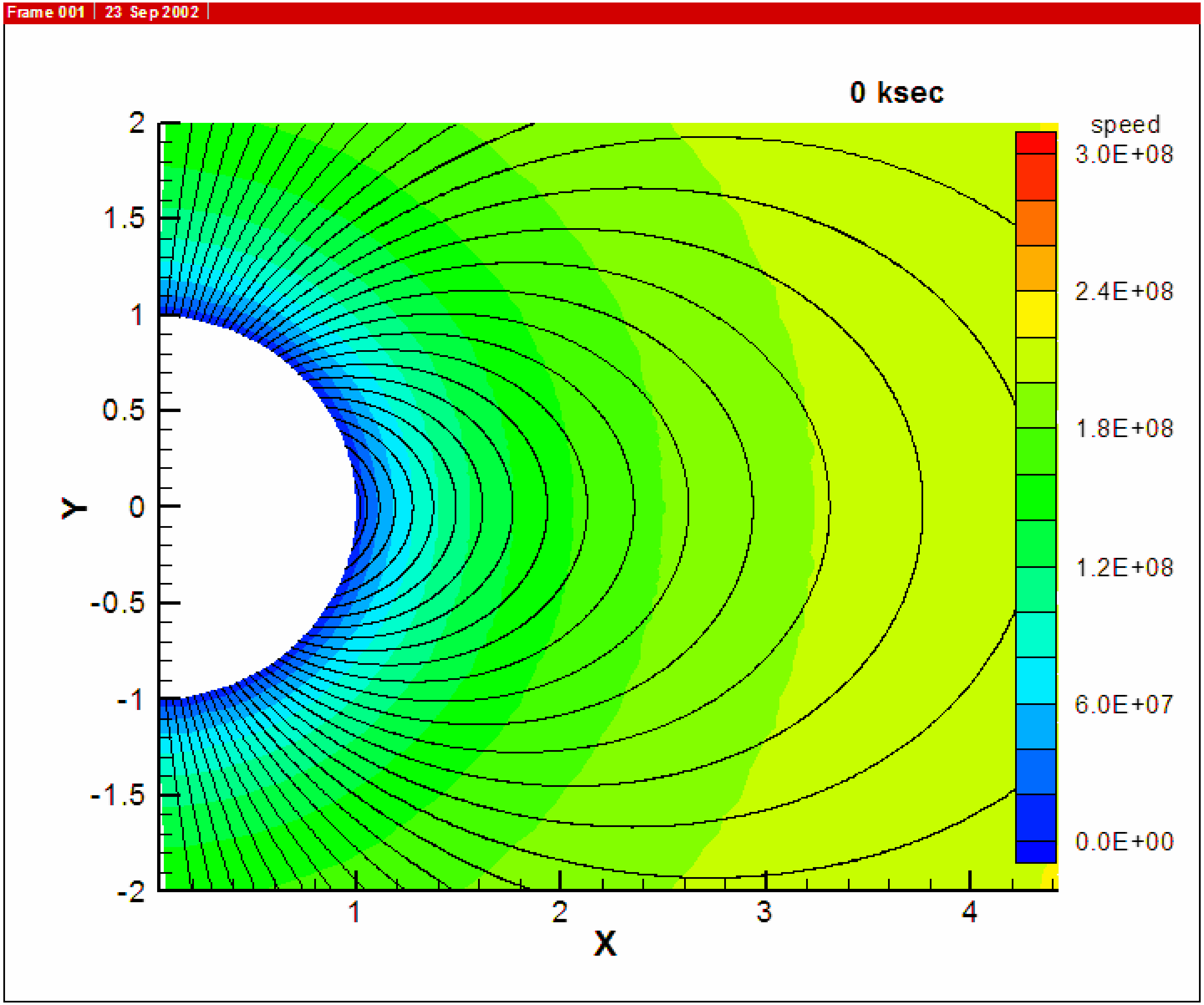
density movie

log Temperature



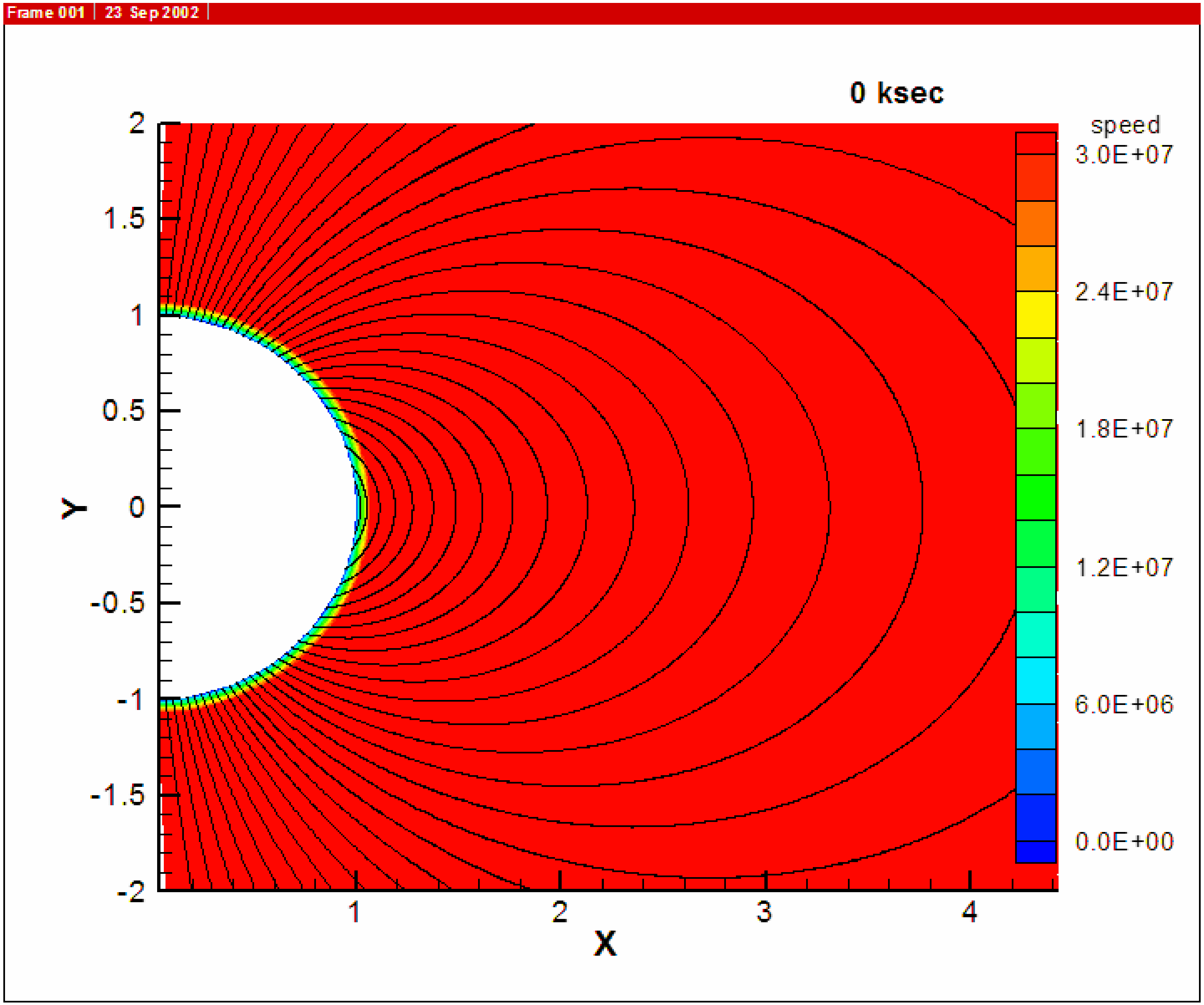
temperature movie

speed



speed movie

Speed (again), but with low speeds emphasized



(low) speed movie

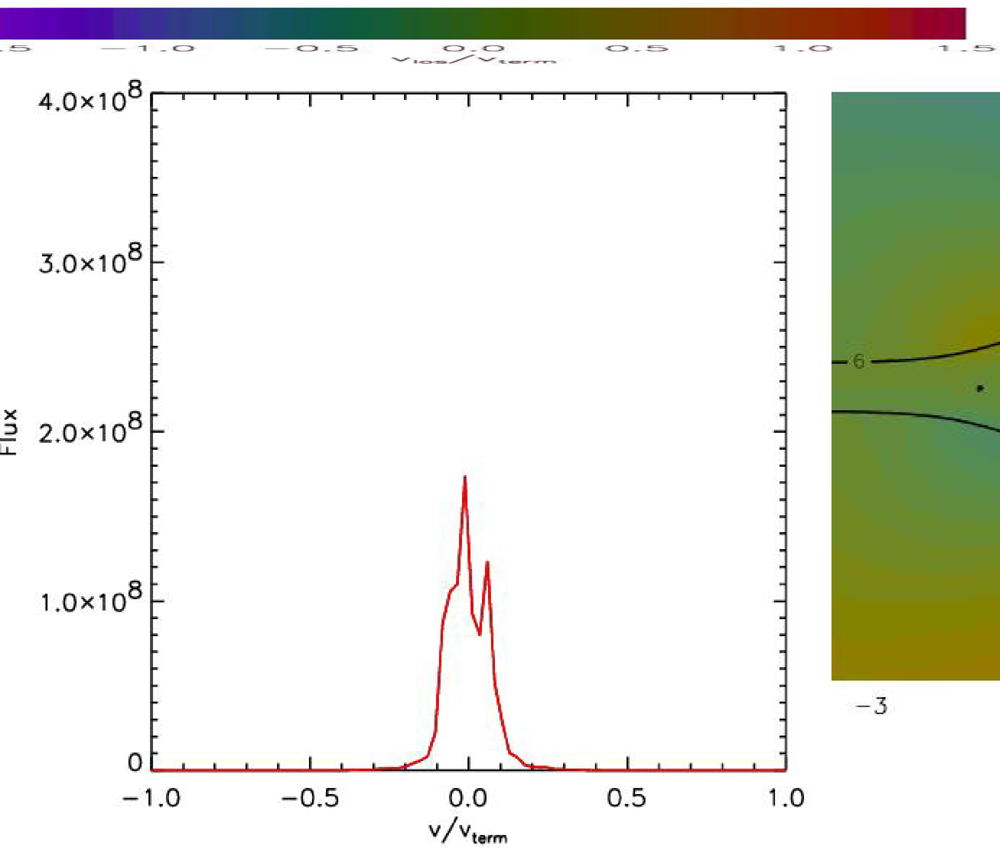
So, a toroidal magnetosphere forms in which flows from the northern and southern hemispheres meet in a strong shock, producing a lot of very hot plasma that is not moving very fast:

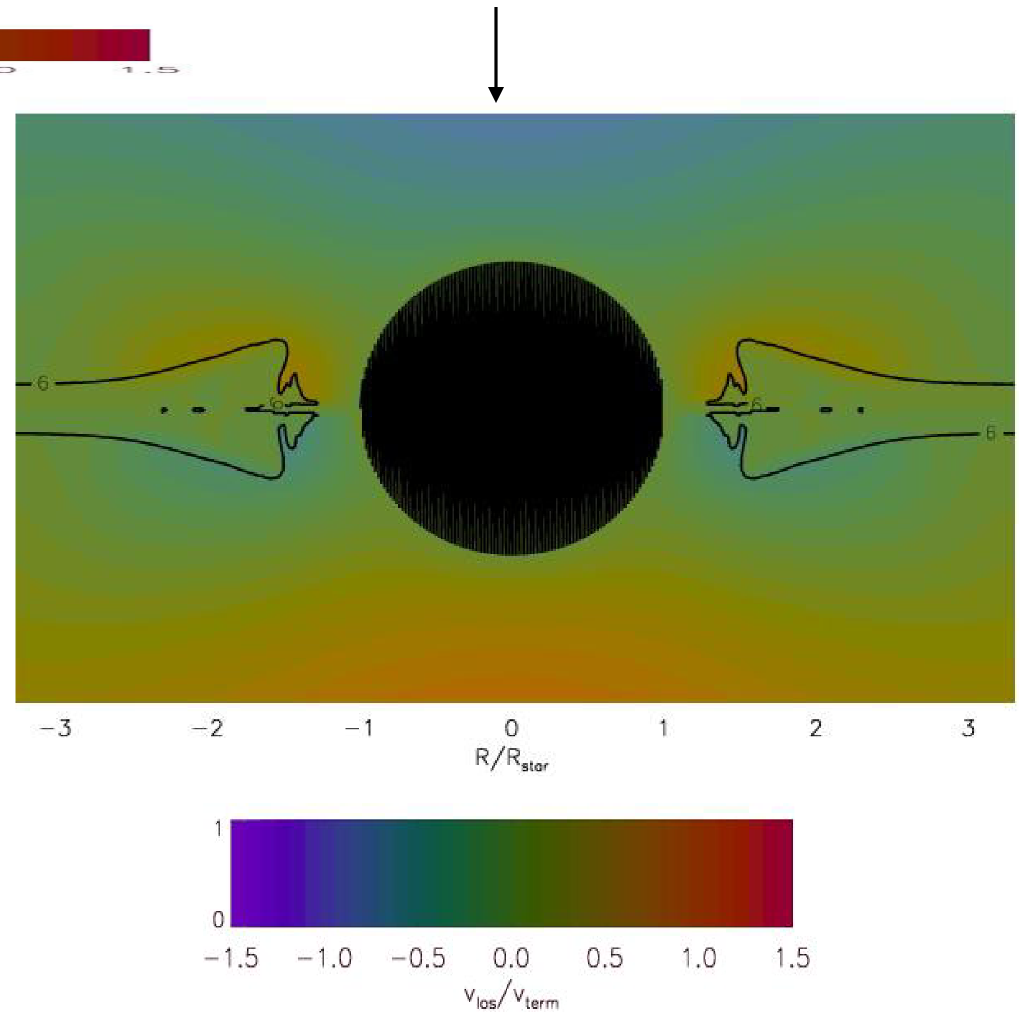
the resultant emission lines should be narrow

We thus synthesize line profiles for a range of viewing angles

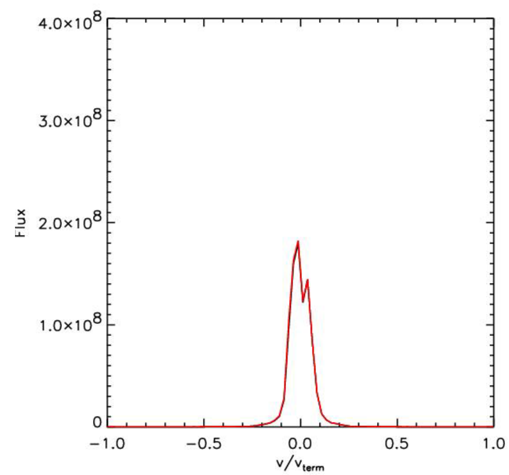
Here we show 0°, looking down the magnetic axis

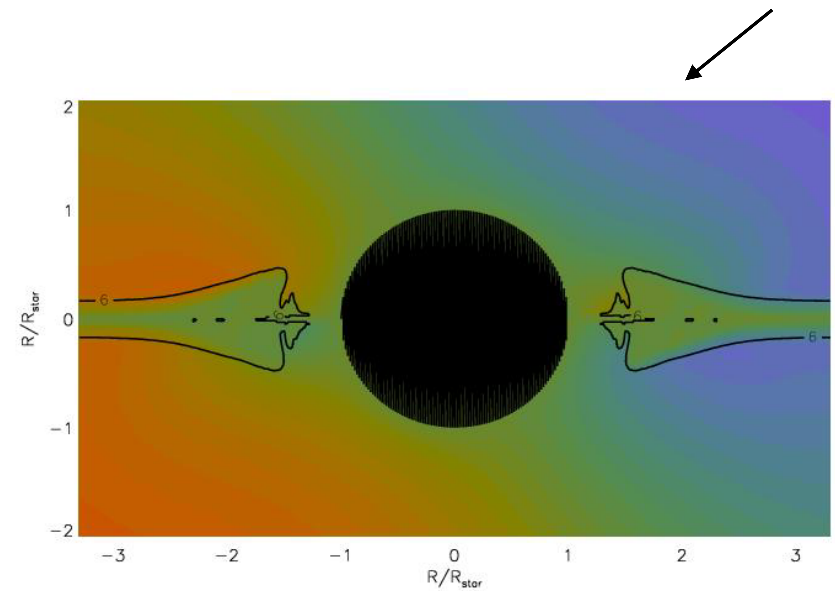
Color contours are now line-of-sight velocity; and the black contours enclose plasma with $T > 10^6$ K

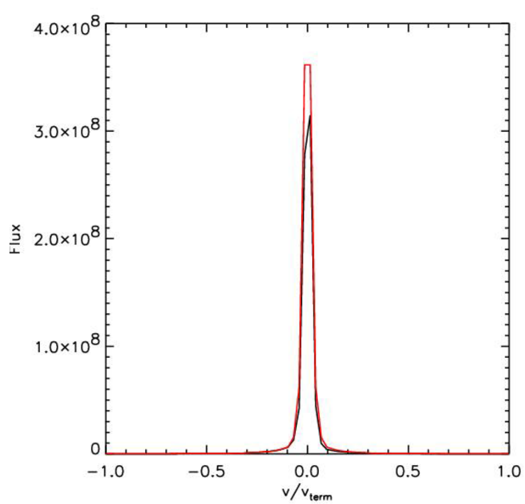


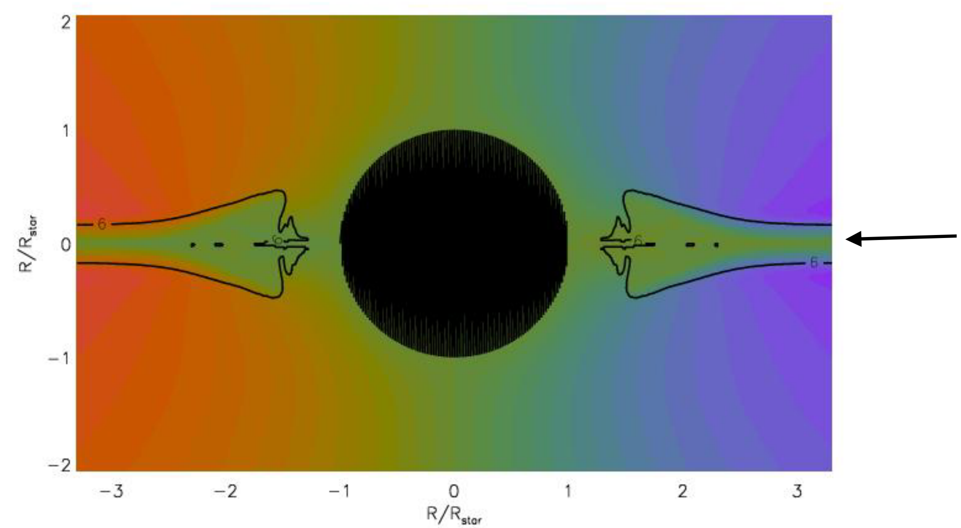


Other viewing angles show similarly narrow lines



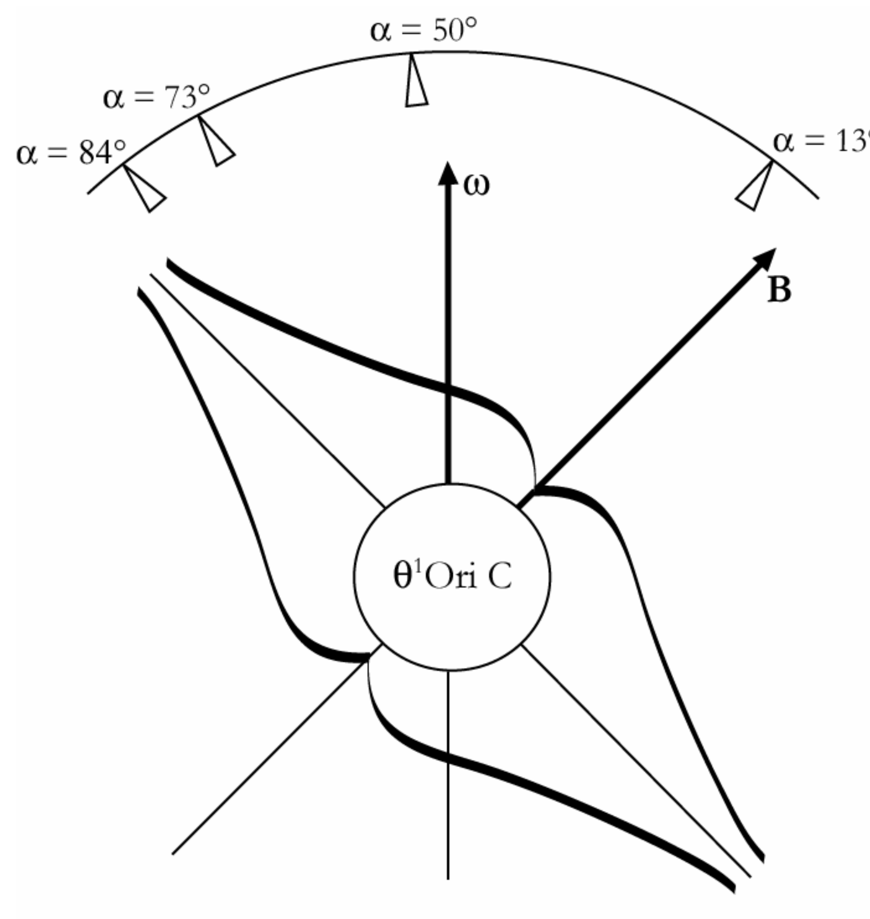






The geometry and viewing angle are relatively well established for this star.

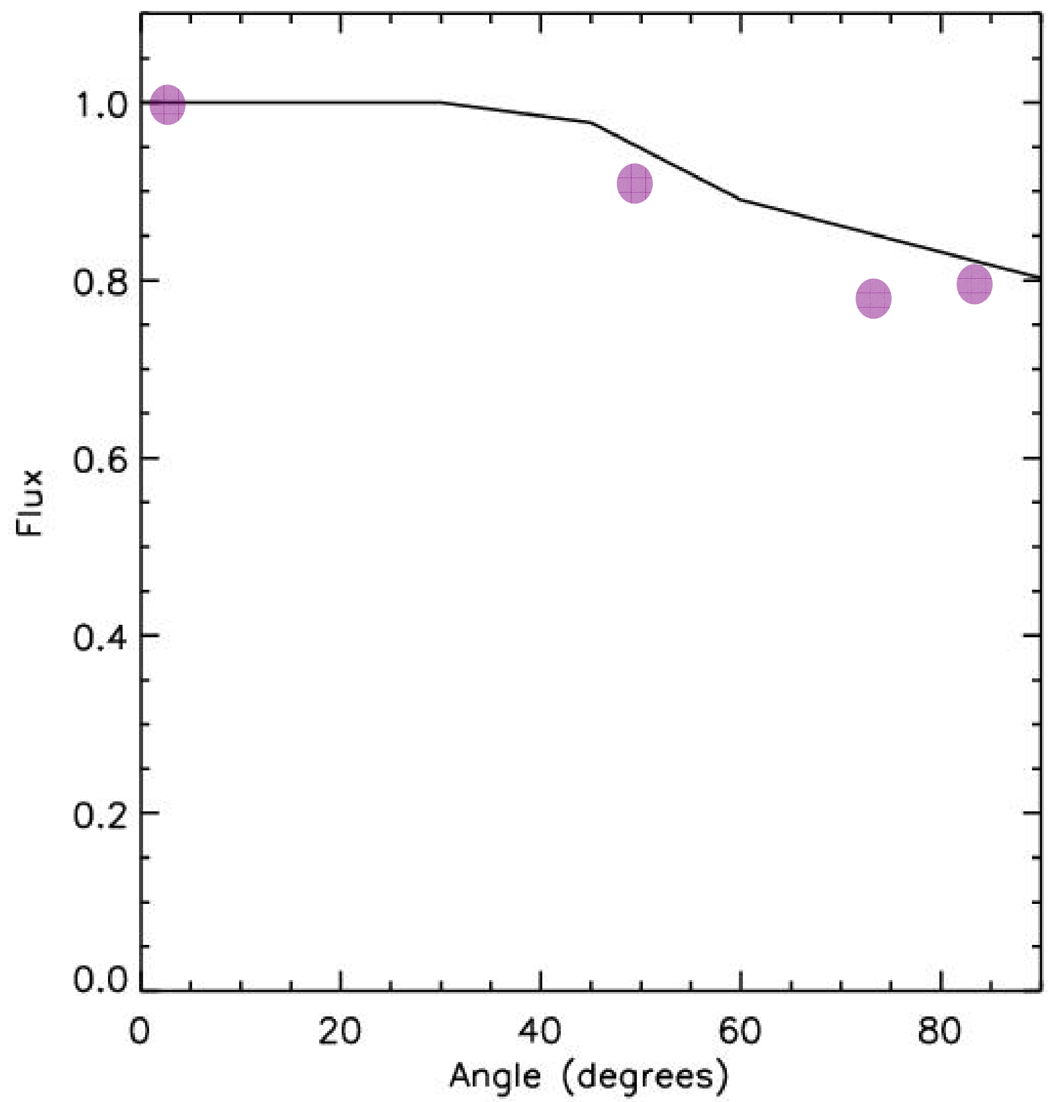
There is a 45°tilt between the rotation axis and both the magnetic axis and the direction of the Earth: we see a full range of viewing angles of the magnetosphere, and have *Chandra* observations for four of them.



Overall X-ray flux synthesized from the same MHD simulation snapshot.

The dip at oblique viewing angles is due to stellar occultation.

Data from four different *Chandra* observations is superimposed.



Summary of magnetically channeled wind shock model applied to θ^1 Ori C

The x-ray emission lines of θ^1 Ori C are quite narrow at all observed viewing angles -- as our MHD simulations predict.

And occultation of the magnetosphere by the star accounts nicely for the modest change in x-ray flux with viewing angle.

Finally, He-like forbidden-to-intercombination line ratios in Mg and S indicate that the bulk of the X-ray emitting plasma is within 1 stellar radius of the photosphere - in accord with the MHD simulations.

Conclusions

- There is a variety of line profile morphologies seen in *Chandra* observations of massive stars, indicating that a surprising variety of high-energy physical processes are occurring in early-type stars

- Supergiants with massive radiation-driven winds have X-ray emitting plasma distributed throughout their winds: Standard wind-shock models explain the data if the mean optical depth of the cool wind component is several times lower than expected (mass-loss rates overestimated? clumping?)

- Young O and early B stars are well explained by the hybrid magnetically channeled wind shock model

- Any time instrumentation improves significantly, surprising discoveries will be made