X-ray Emission from Massive Stars

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

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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
2. What we have observed/measured with the new generation of high-resolution x-ray telescopes
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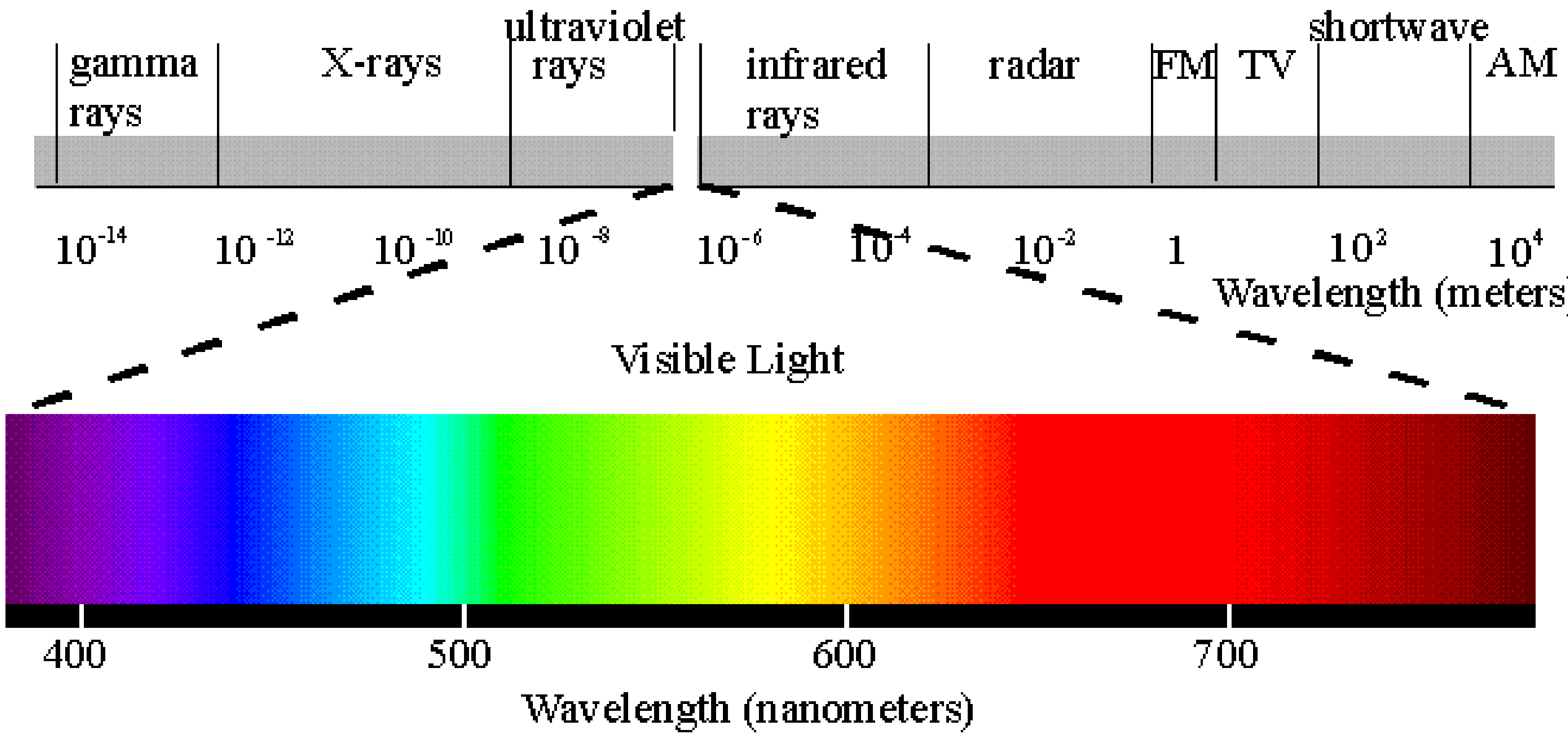
4. Are magnetic fields important in *young* massive stars?

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)



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, 500 nm (visible, yellow)
- Hot star's surface = 40,000 K $\Rightarrow$ 750 Å (far ultraviolet)

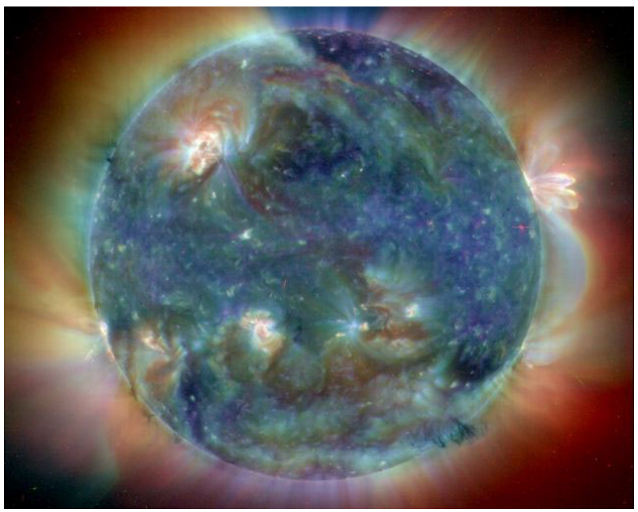
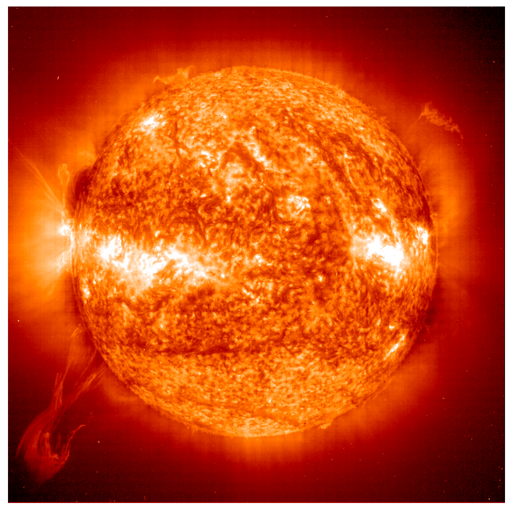
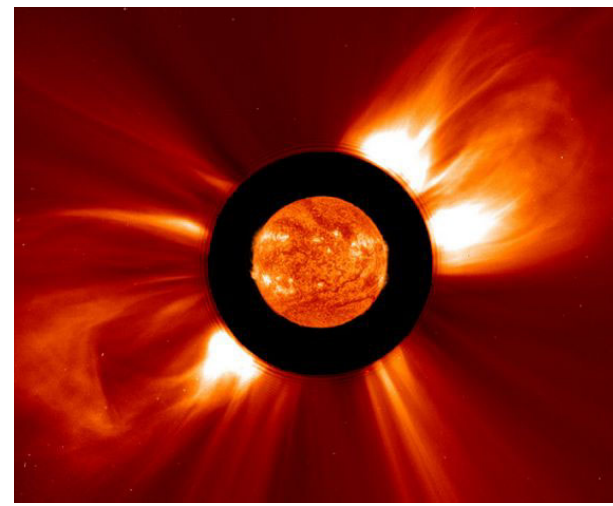
- Really hot plasma = 5,000,000 K $\Rightarrow$ 6 Å (X-ray)

*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 plasma on it

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

We can break light apart into its constituent colors:

Spectroscopy

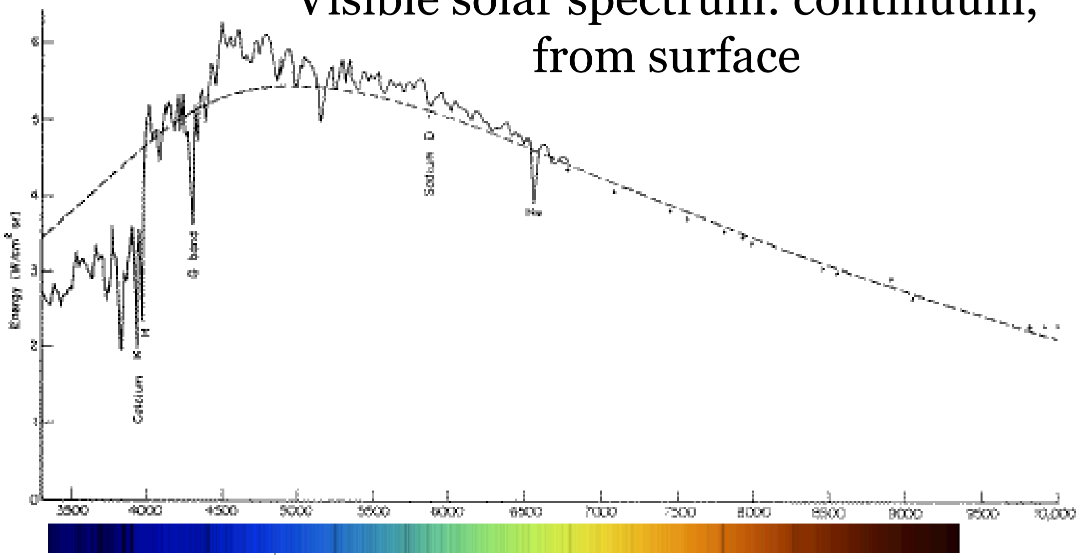
And learn about the physical conditions in the light-emitting object/substance:

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

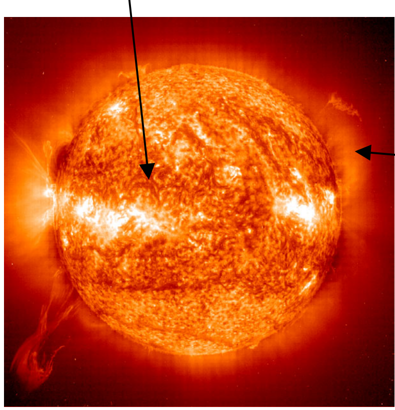
If we're clever, we can use spectroscopy as a proxy for imaging and infer information about spatial structure

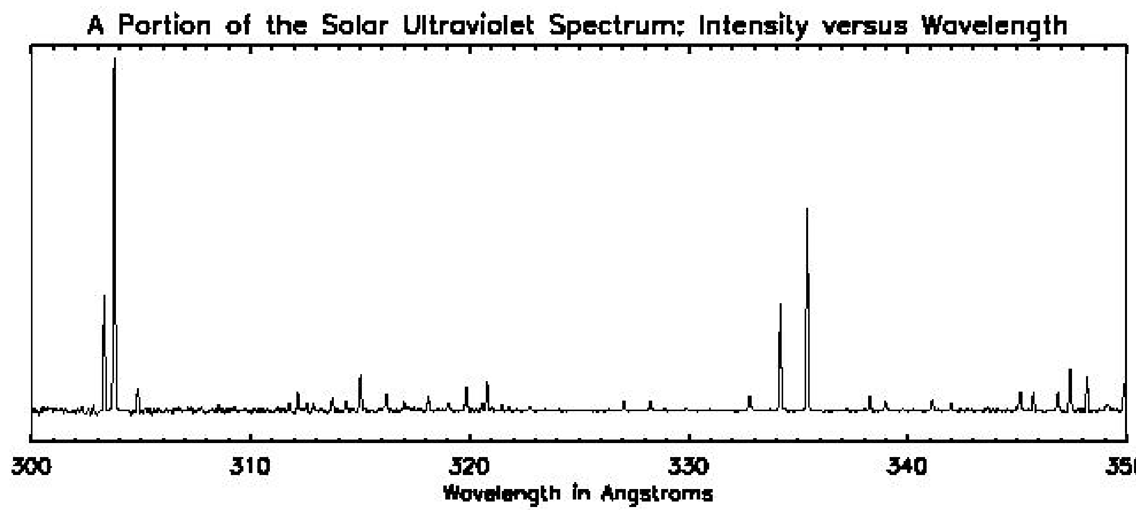
Spectra: continuum vs. line

Visible solar spectrum: continuum, from surface

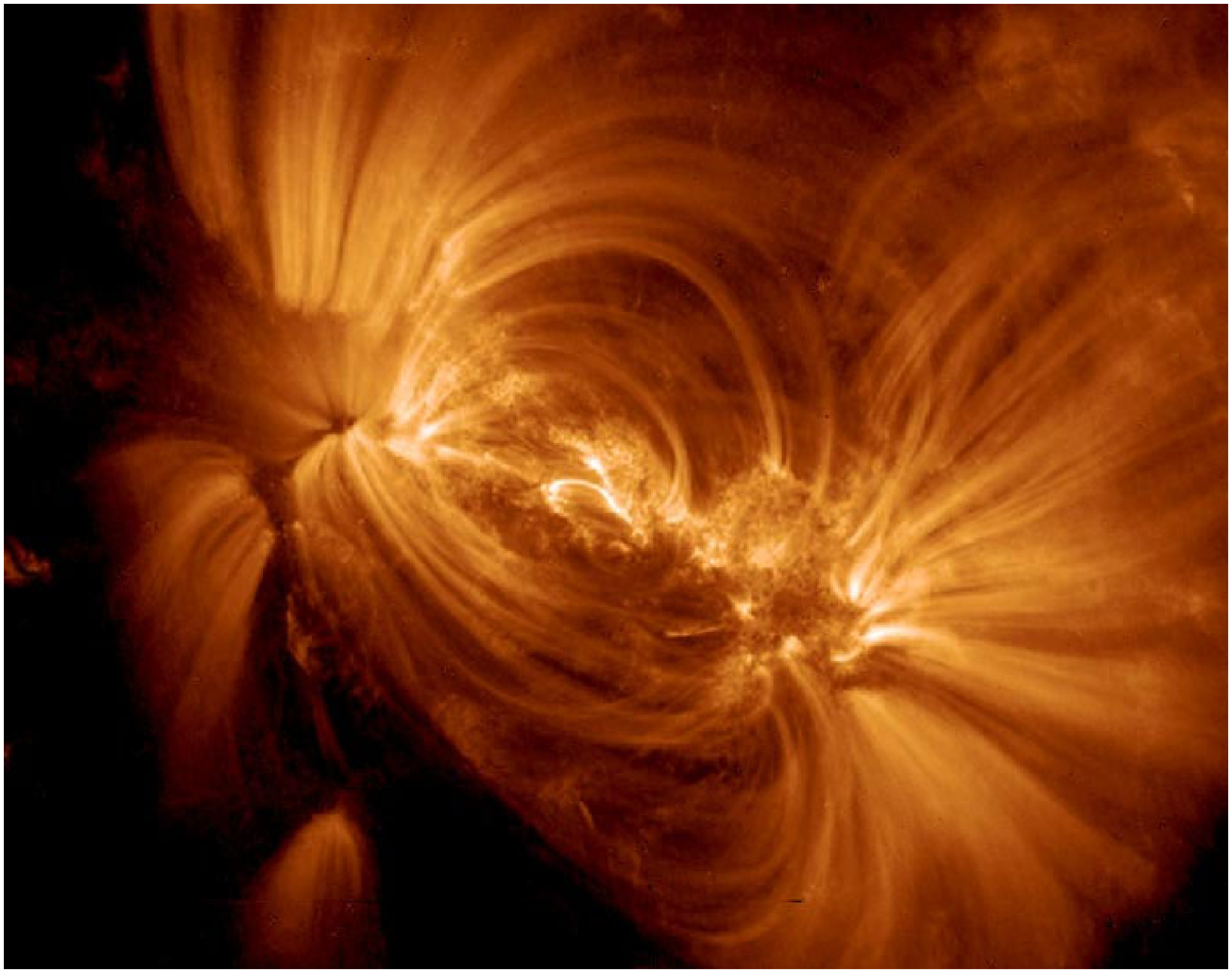


X-ray/EUV solar spectrum: emission lines from hot, thin gas above the surface



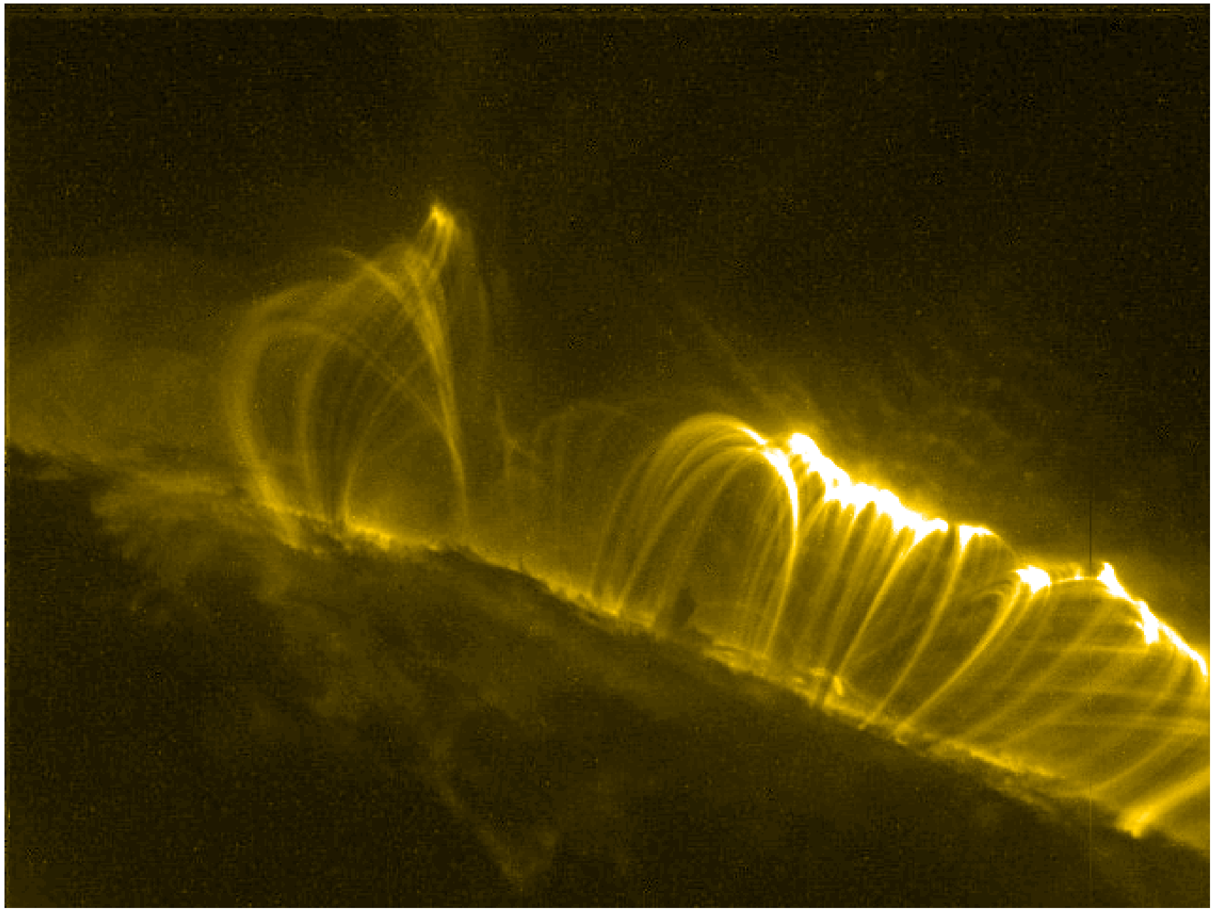


This hot *plasma* is related to magnetic fields on the Sun: confinement, spatial structure, conduits of energy flow, heating

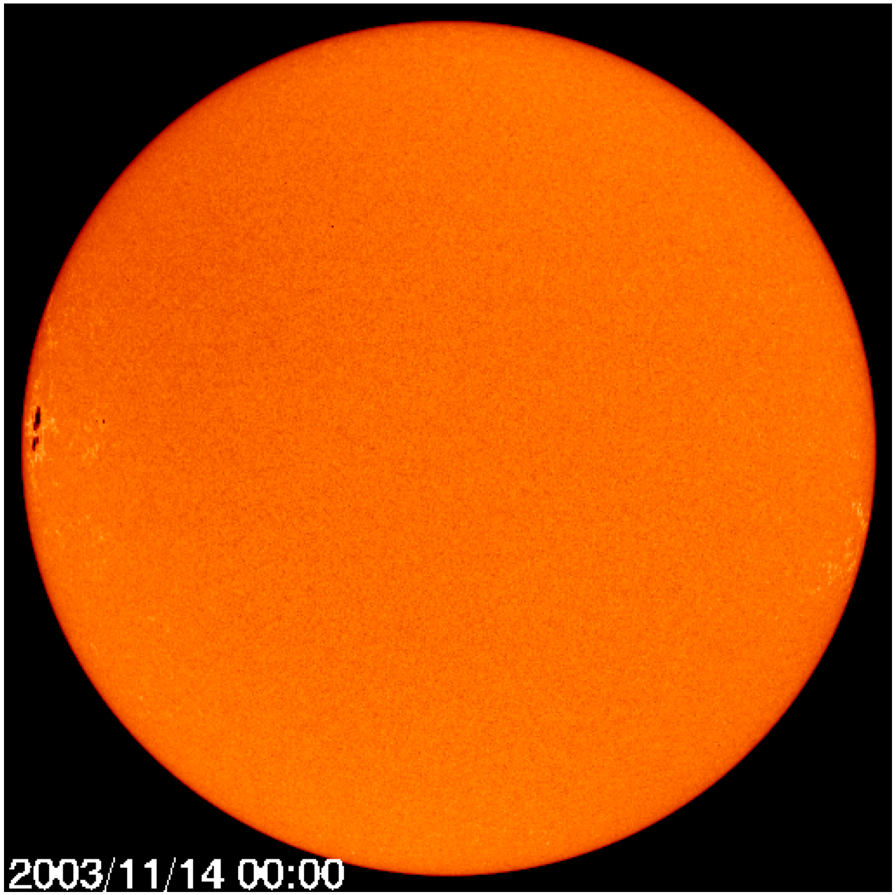


More magnetic structures on the Sun:

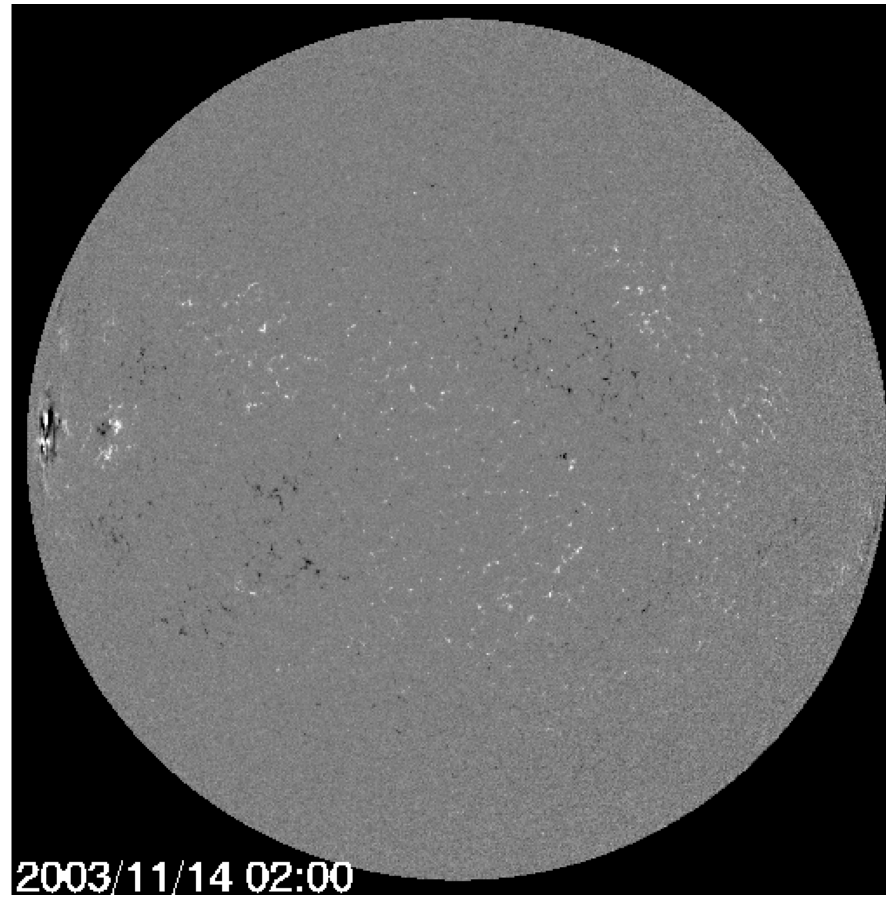
x-ray image from *TRACE*



Sunspots are areas of strong magnetic fields (kG)

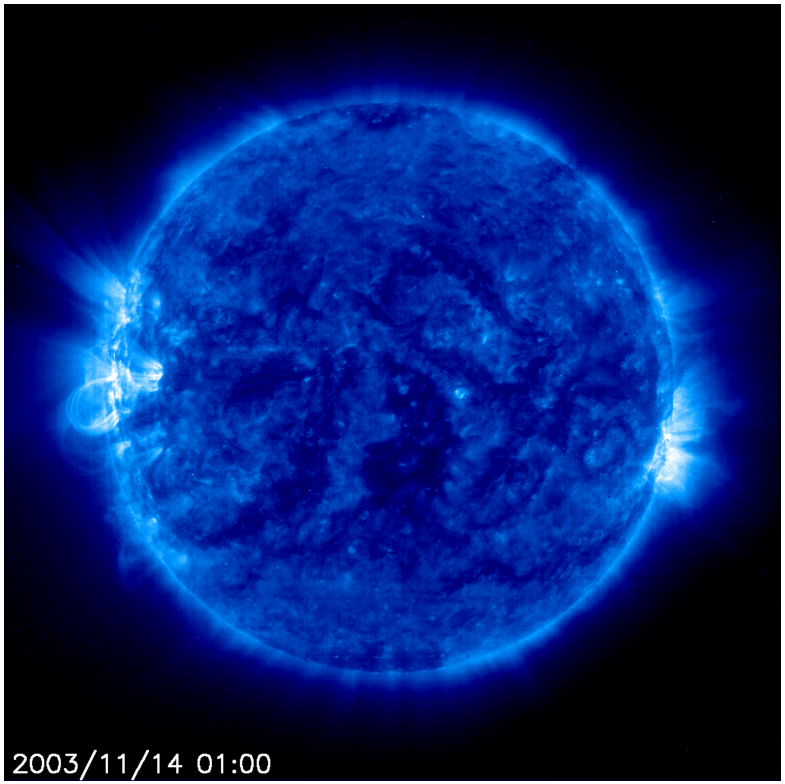


white light image of the Sun

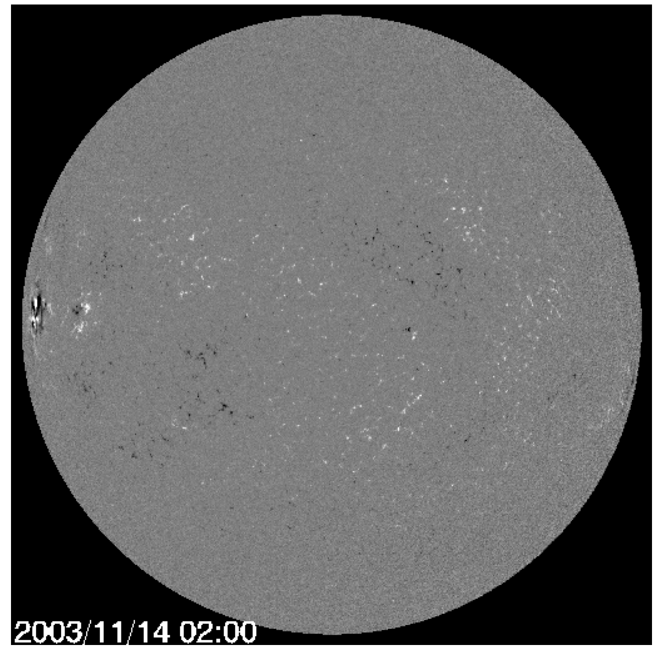


magnetogram (Zeeman splitting)

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

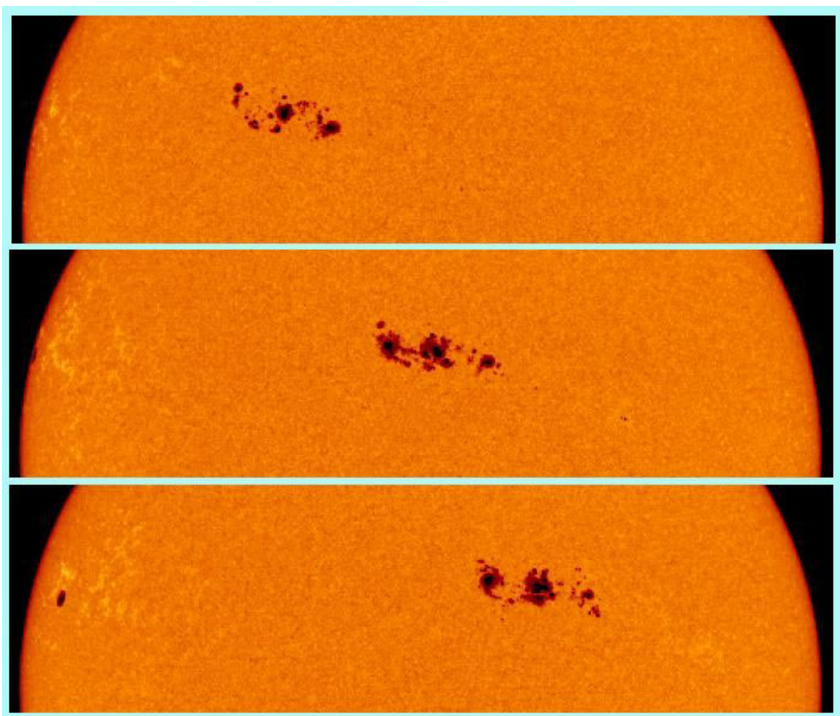


Fe XV at 284 Å

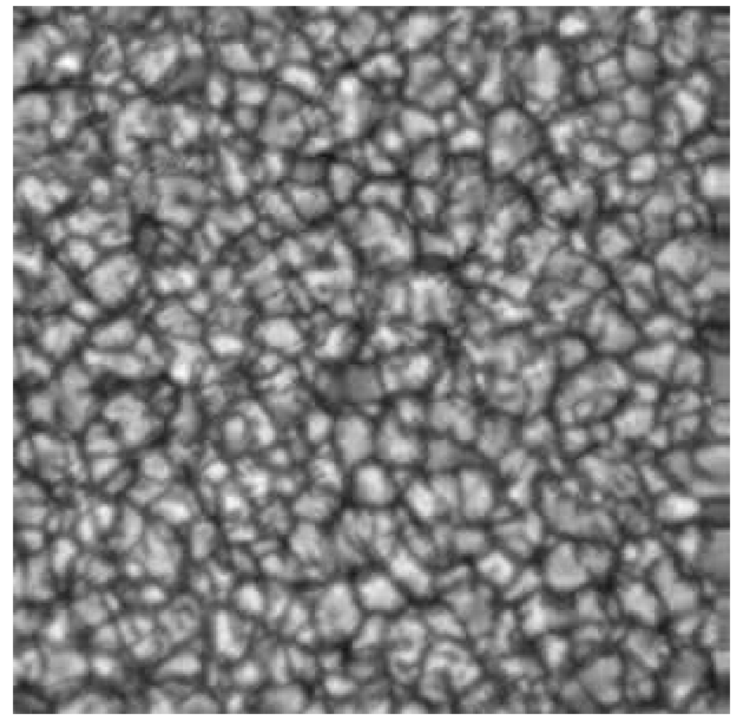


magnetogram

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

How are *hot, massive stars* different?

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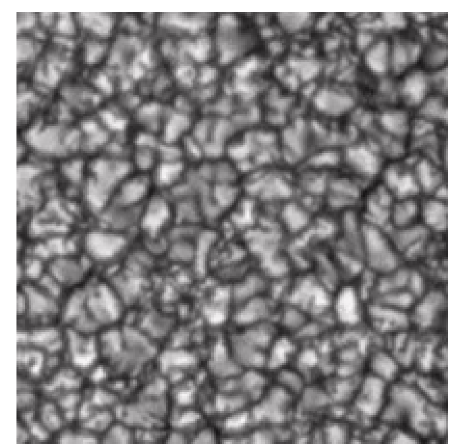
Hot Stars

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

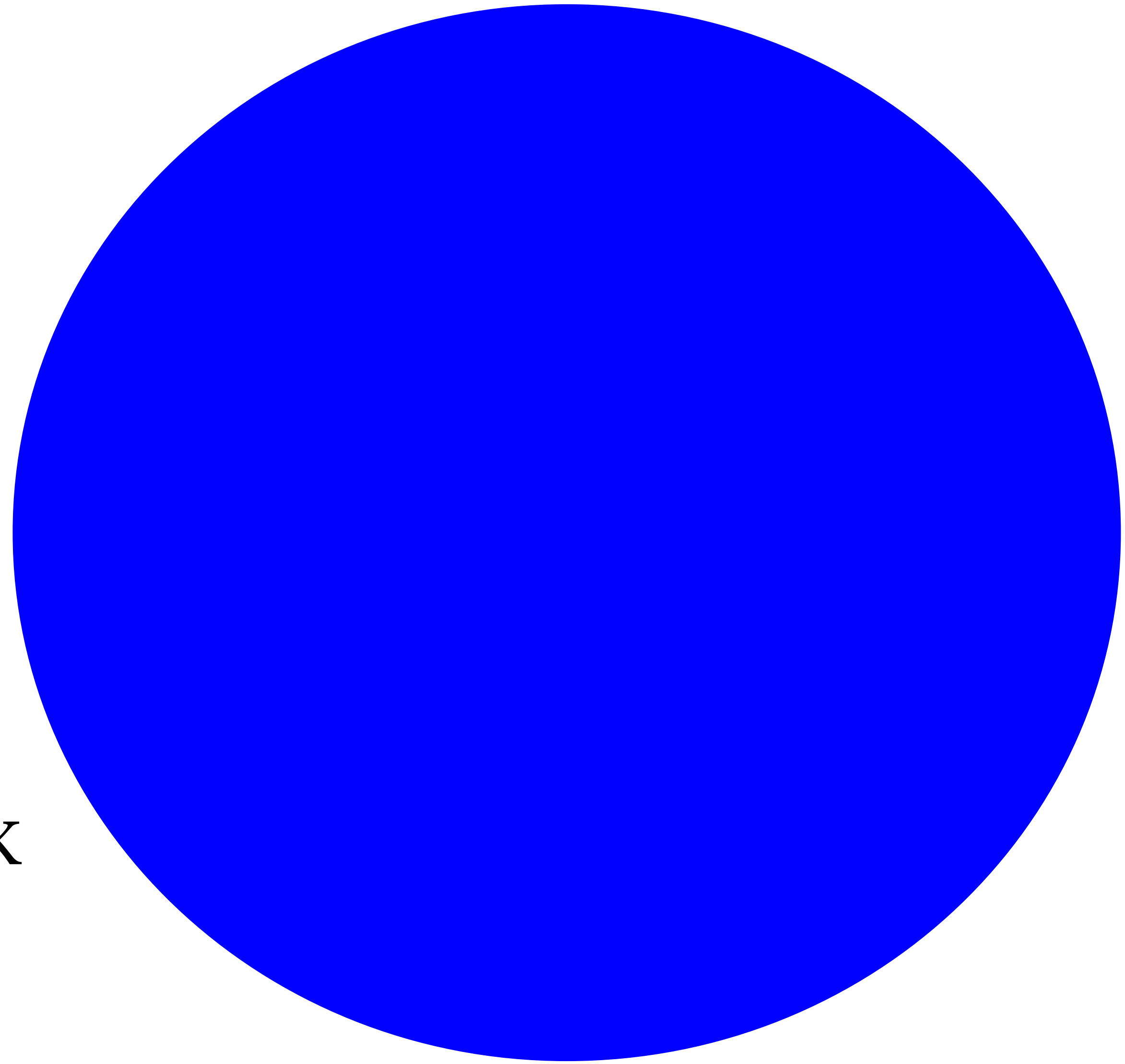
Their temperatures correlate with mass and luminosity (massive stars are hot and very bright): a 50,000 K star gives of a million times the luminosity of the Sun (T_{sun} = 6000 K)

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…

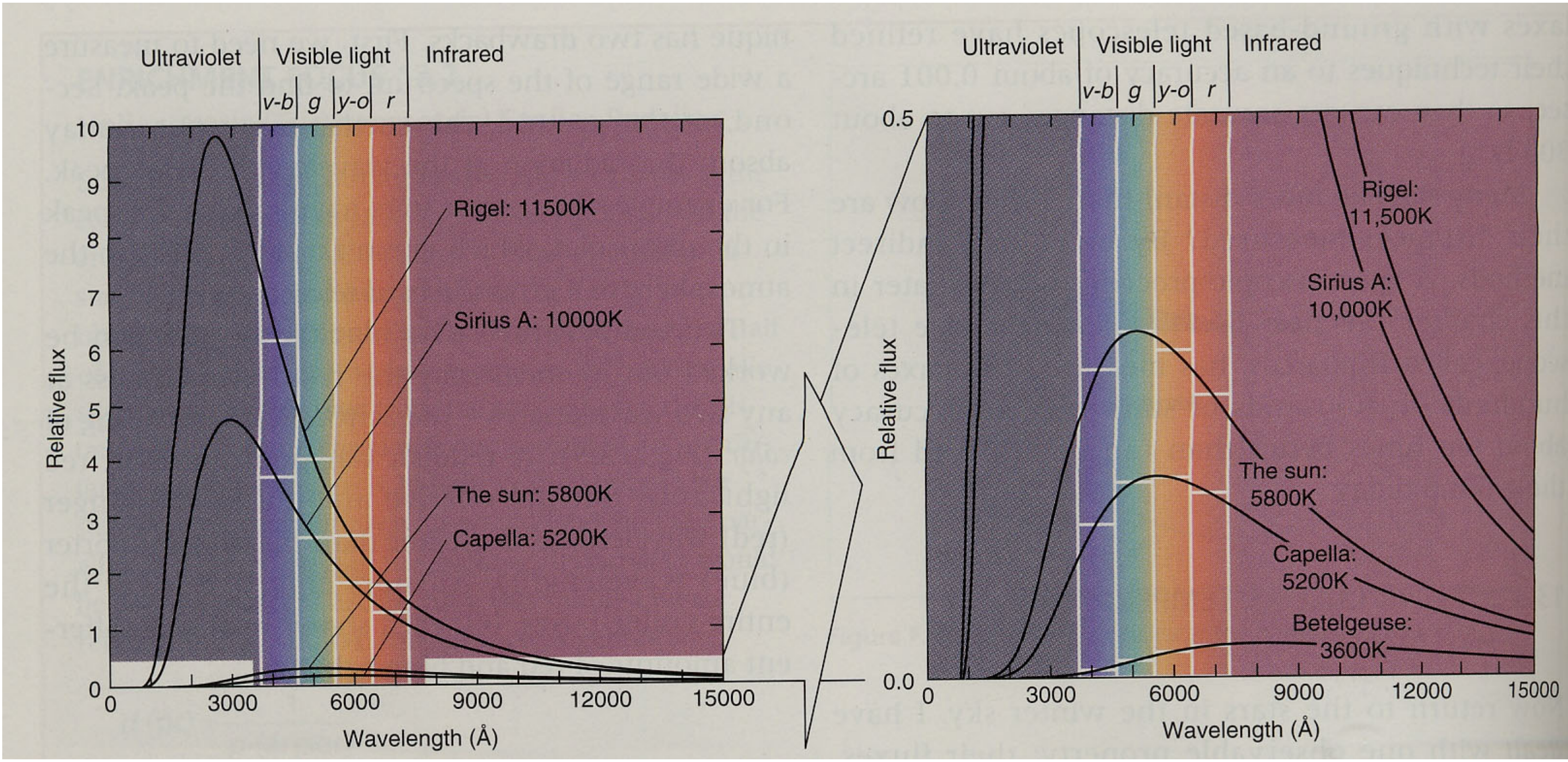


ζ Puppis:

42,000 K vs. 6000 K

10^6 L_{sun}

50 M_{sun}



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

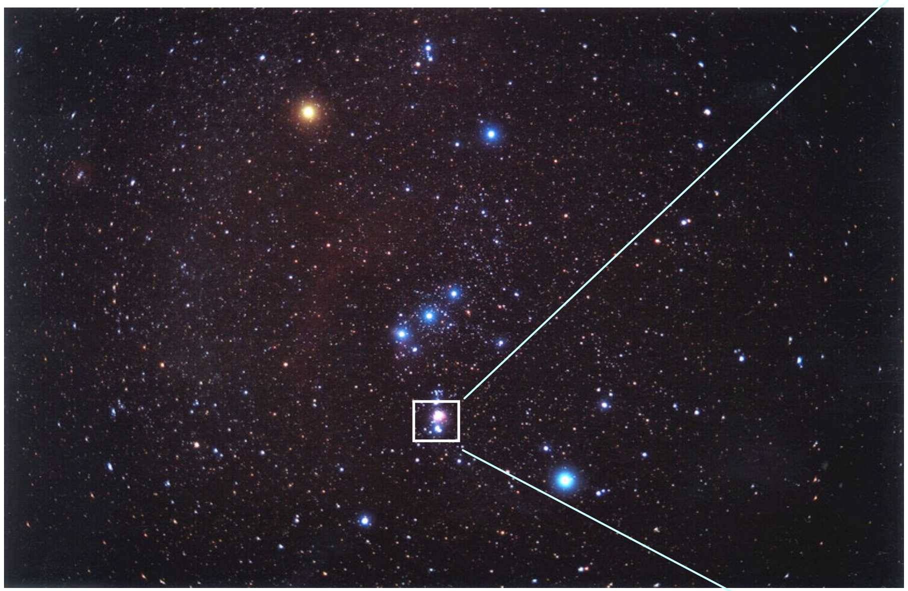
But they're not nearly hot enough to emit any significant amount of X-rays from their surfaces

Optical image of the constellation Orion

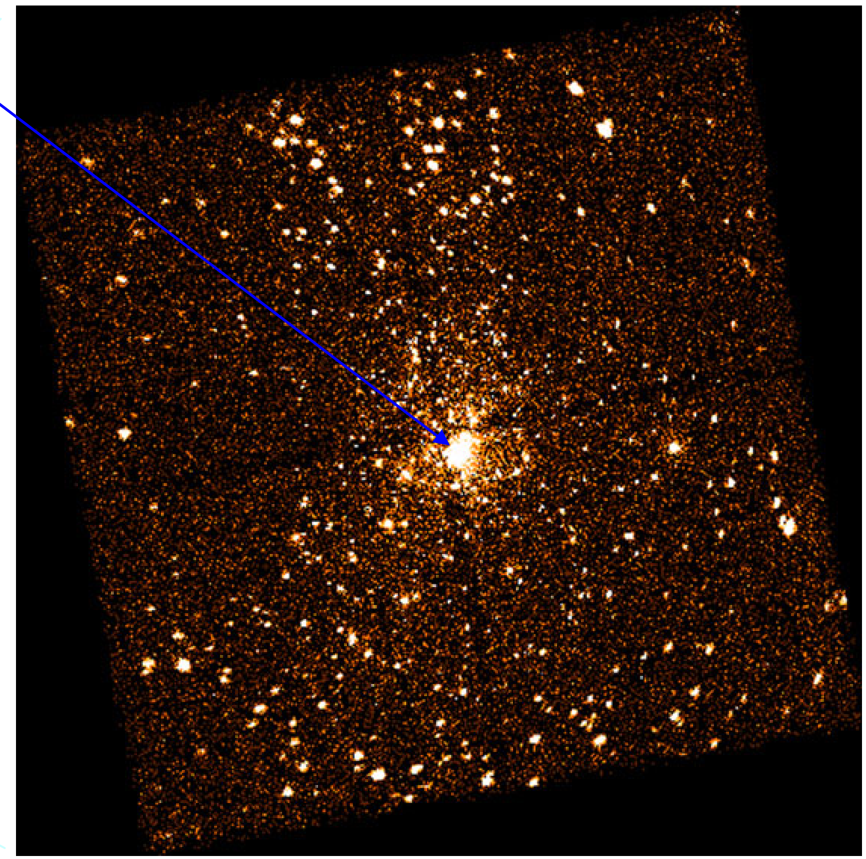
Note: many of the brightest stars are blue (i.e. hot, also massive)

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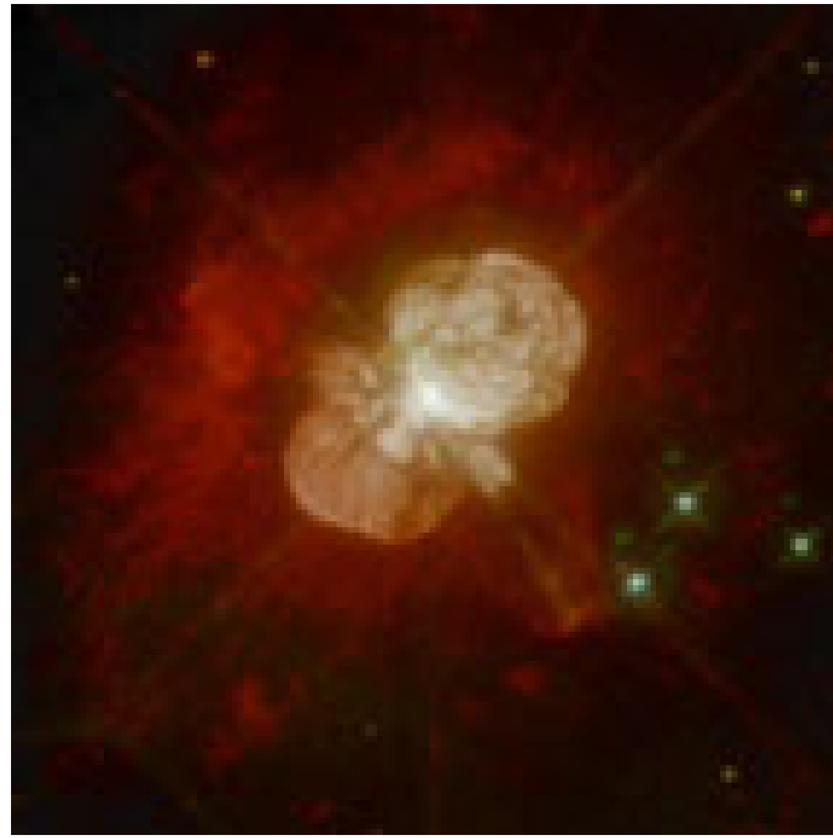
Massive stars have very strong *radiation-driven* **stellar winds**

What is a stellar wind?

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

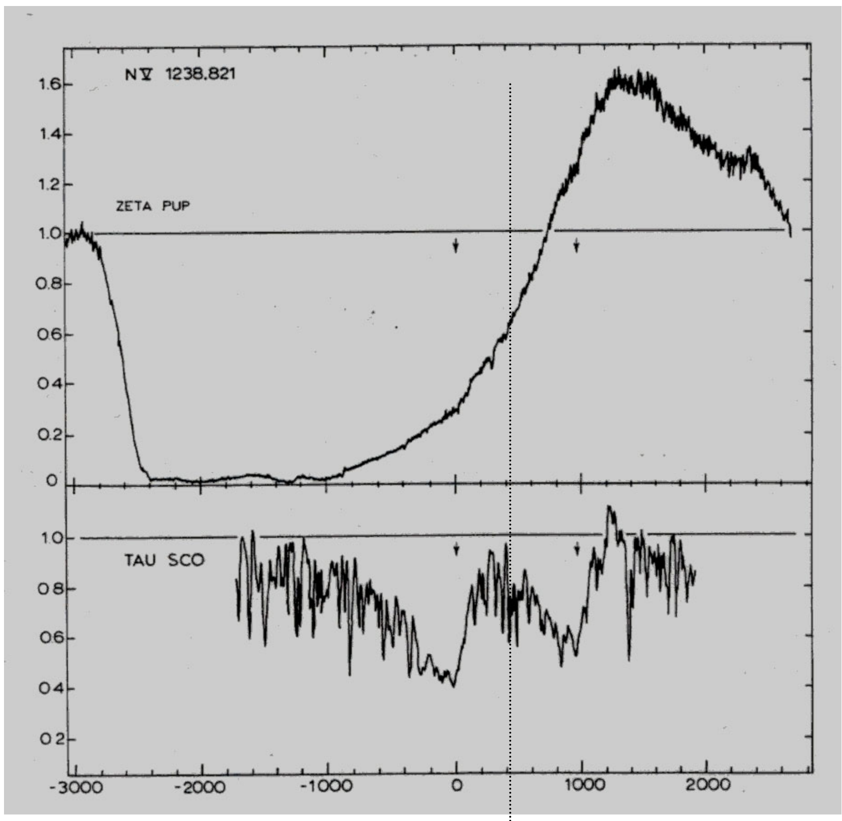
The Sun has a wind (the “solar wind”) but the winds of hot stars can be a *billion* times as strong as the Sun’s



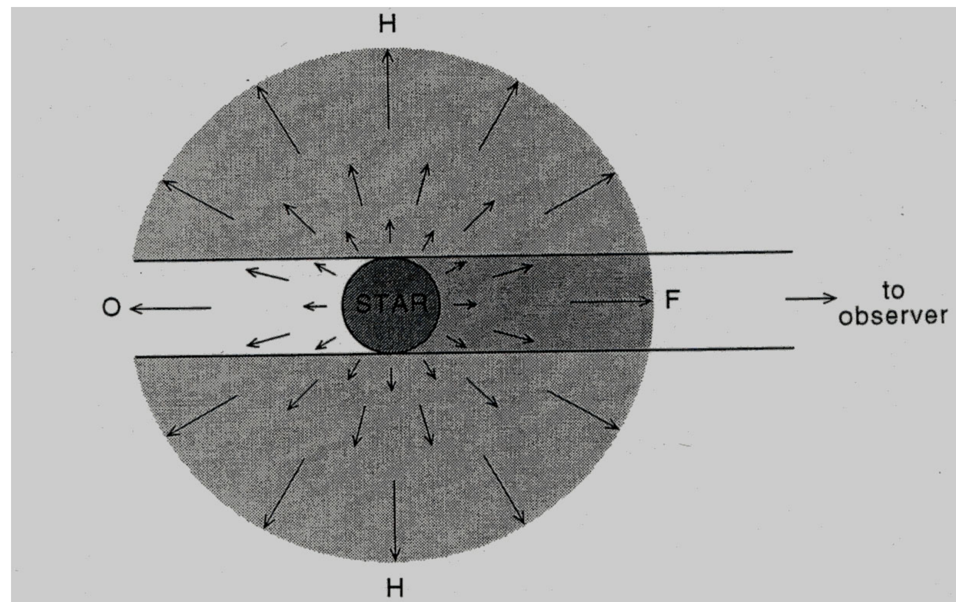
Hubble Space Telescope image of η Car; an extreme example of a hot star wind

How do we know these hot-star winds exist?

Spectroscopy! Doppler shifts change wavelengths of lines in noticeable ways.



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:

$$p=E/\mathrm{c}=\mathrm{h}\nu/\mathrm{c}=\mathrm{h}/\lambda$$

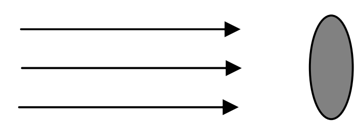
And Newton tells us that a change in momentum is a **force**:

$$F=\mathrm{d}p/\mathrm{d}t$$

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)

$$F_{rad} = L\sigma_T / 4\pi r^2 c$$

The rate at which momentum is absorbed by the electron

$$a_{rad} = L\kappa / 4\pi r^2 c$$

By replacing the cross section of a single electron with the opacity, $\kappa = \sigma / \langle m \rangle$ (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 $a_{rad} > a_{grav}$, a star would blow itself completely apart.

However, 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 can (i.e. it has a much larger cross section), but it can only be driven by light with a very specific frequency.

*The ratio of the radiation force to gravity at the Sun's surface is 10^{-5}, but remember, massive stars are up to a million times more luminous than the Sun.

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!

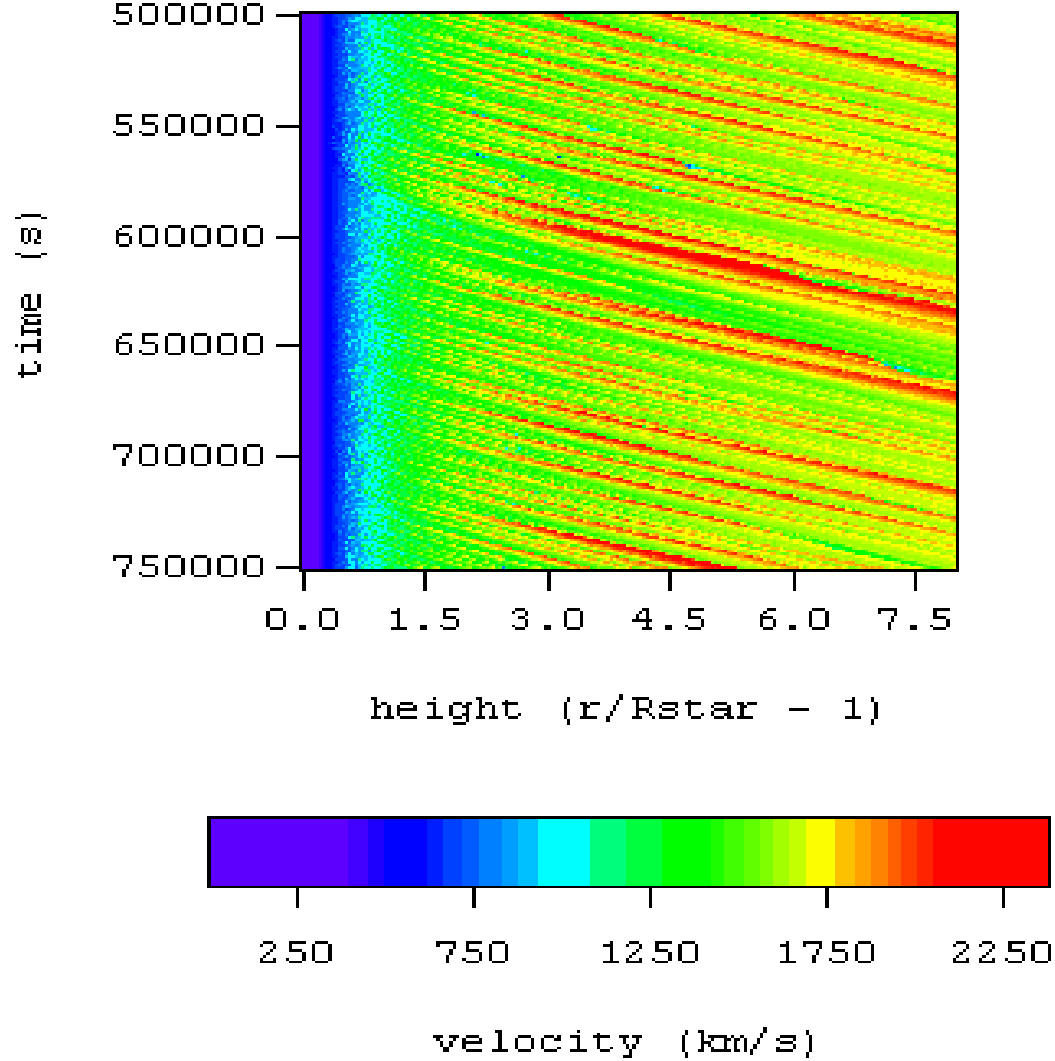
And causes the radiation force to deviate from strictly $1/R^2$ behavior: the radiation force on lines can be less than gravity inside the star but more than gravity above the star's surface.

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

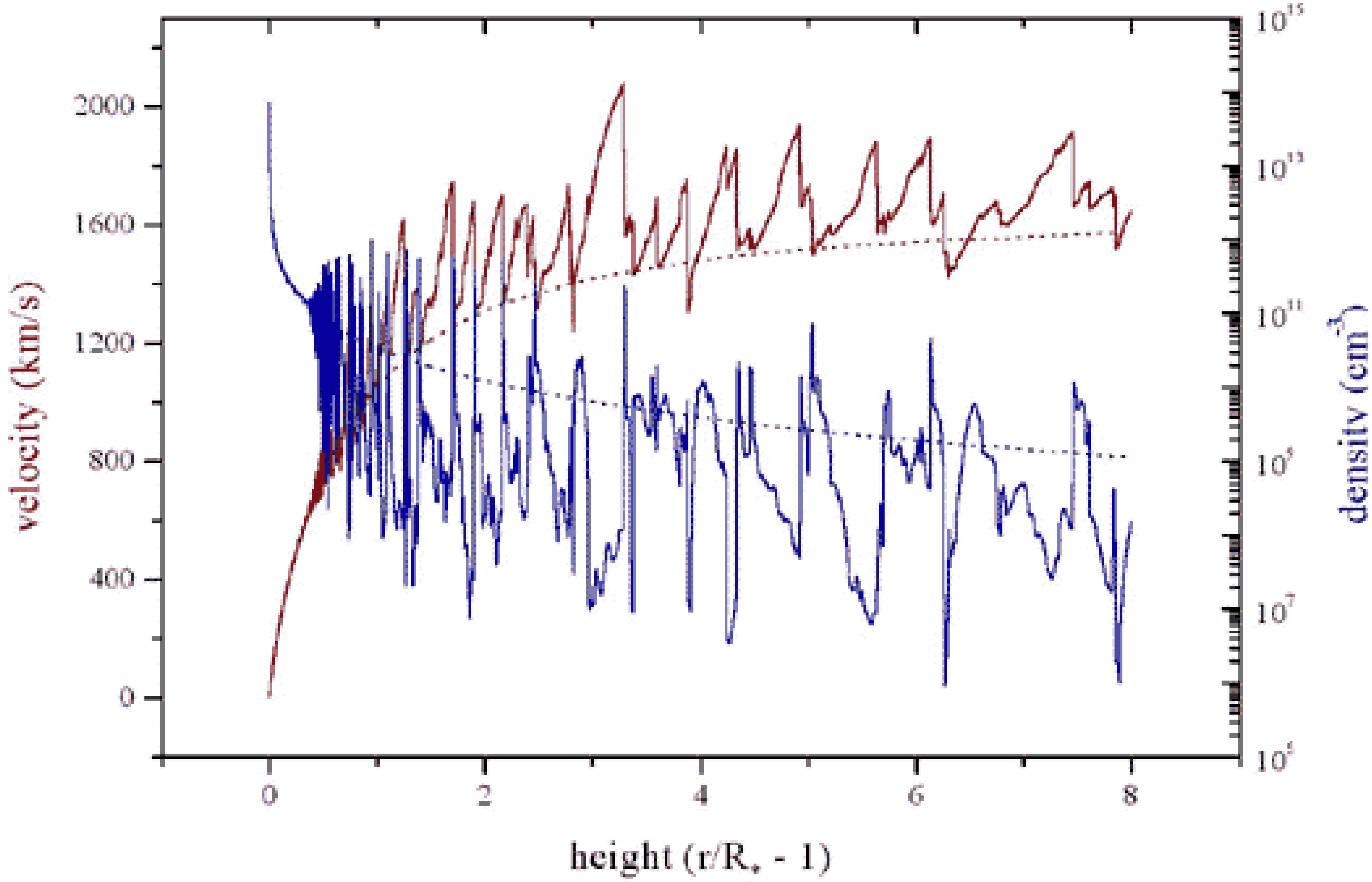
The Doppler desaturation that’s so helpful in driving a flow via momentum transfer in spectral lines is inherently unstable

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

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

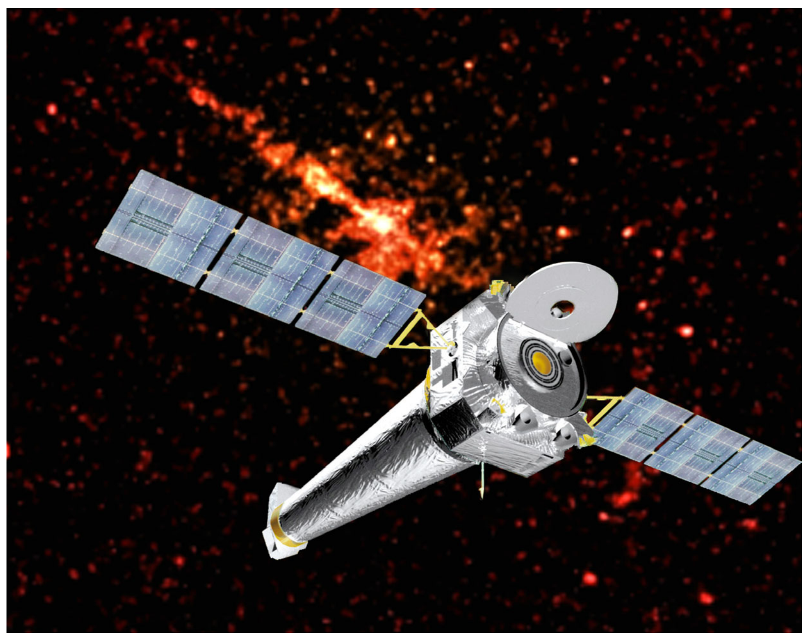
Wind-shocks : broad lines

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/dynamo (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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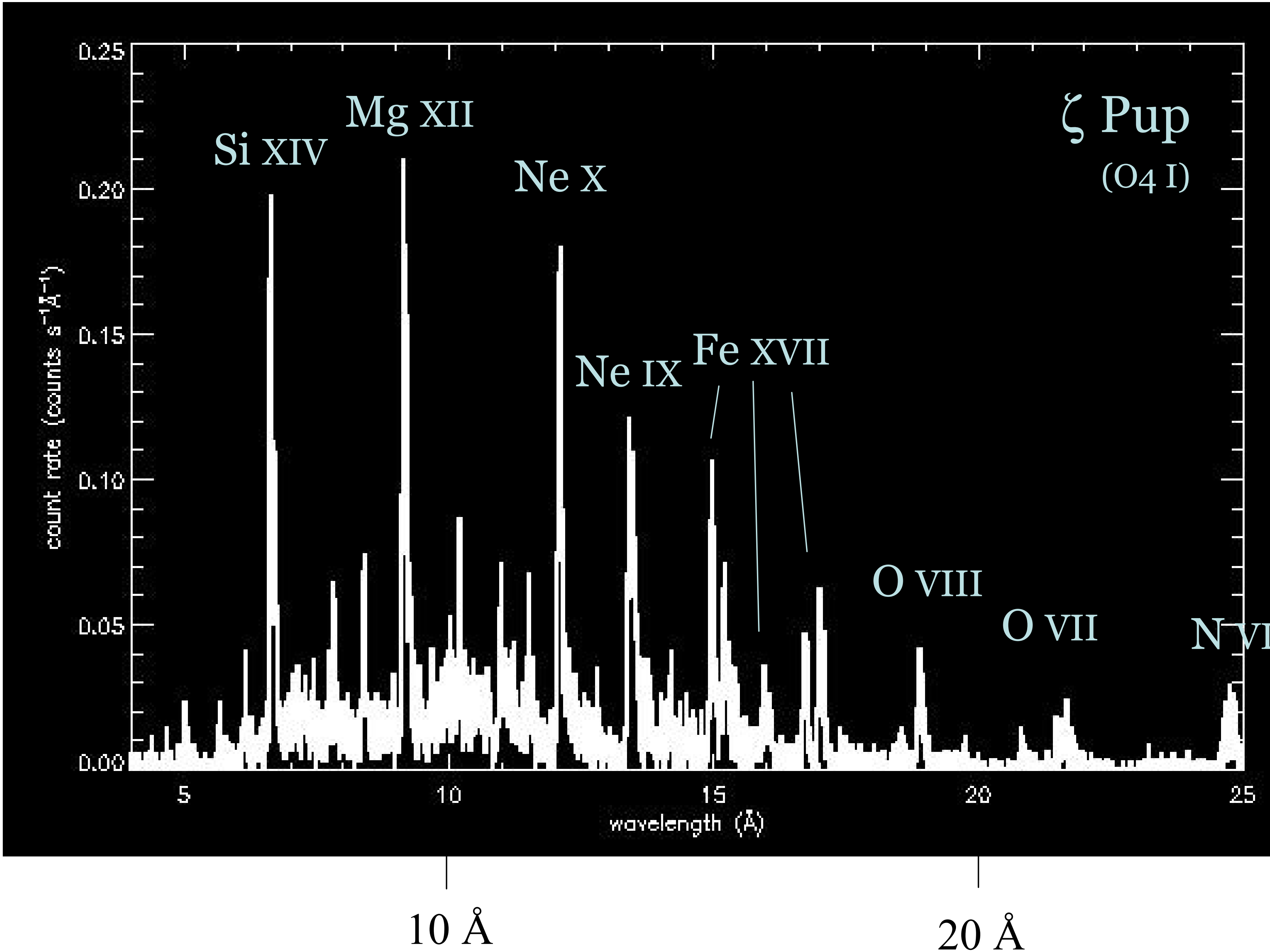
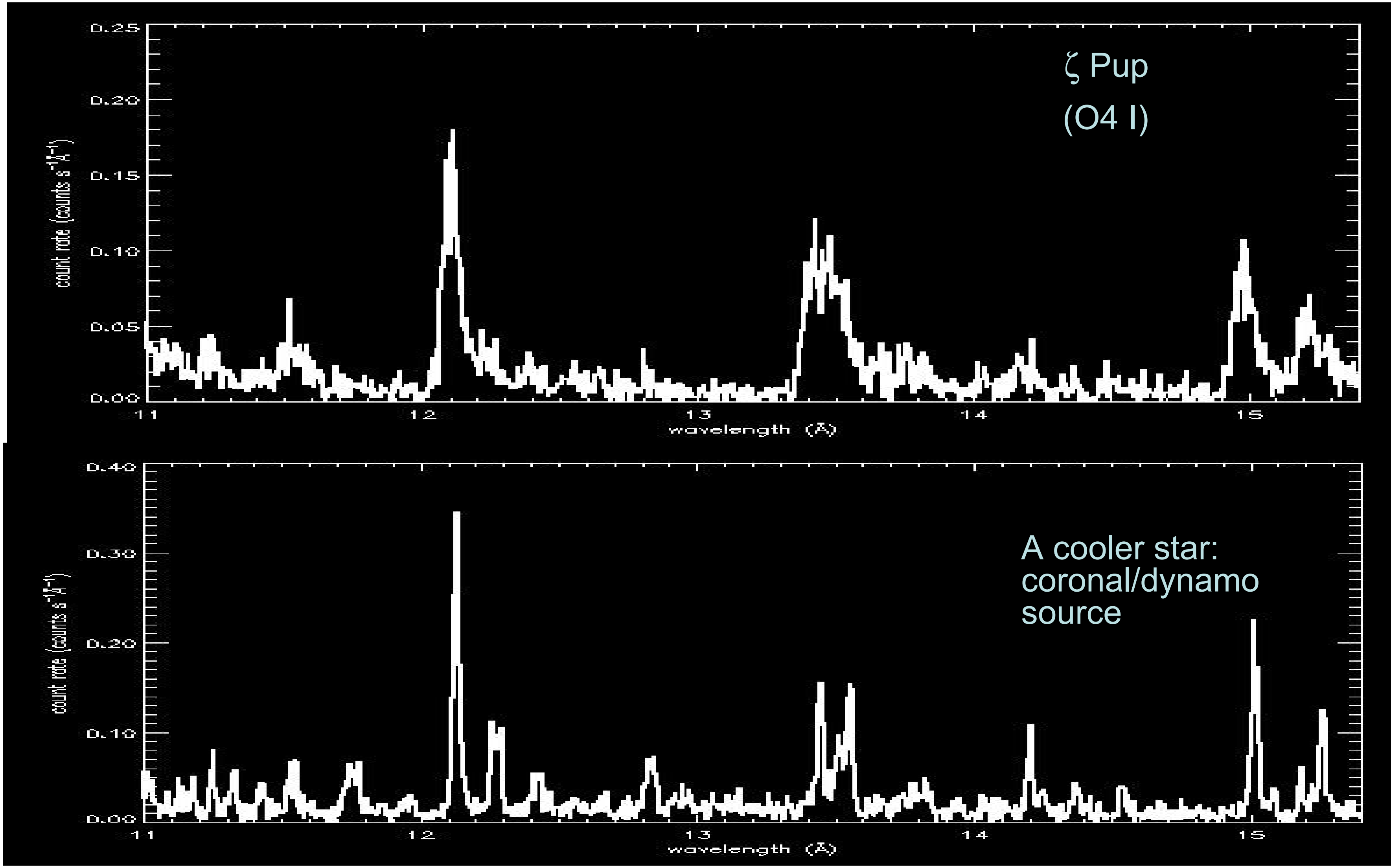

ζ Pup
(O4 I)
Si XIV
Mg XII
Ne X
Ne IX
Fe XVII
O VIII
O VII
N VI
0.25
0.20
0.15
0.10
0.05
0.00
count rate (counts s⁻¹Å⁻¹)
5
10
15
20
25
wavelength (Å)
10 Å
20 Å

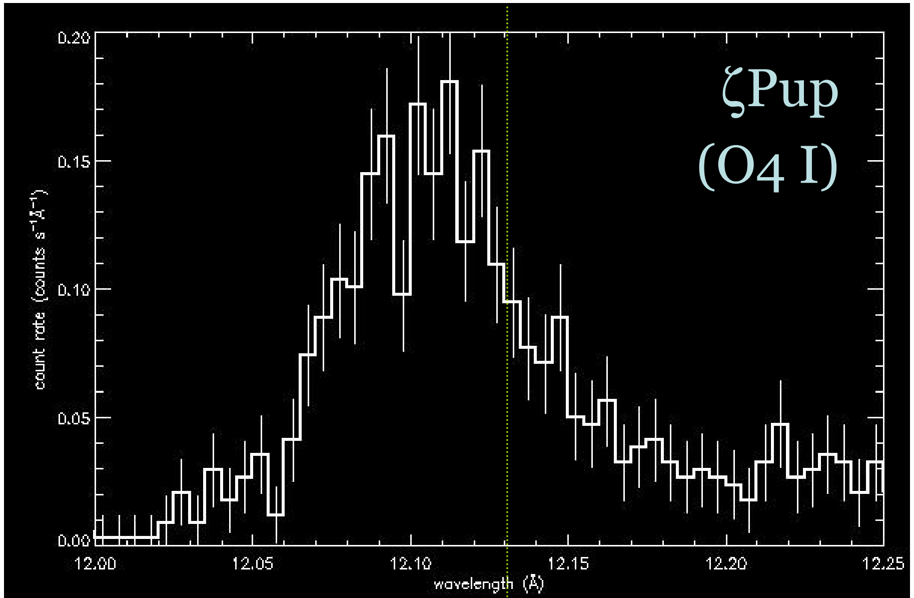
Focus in on a characteristic portion of the spectrum

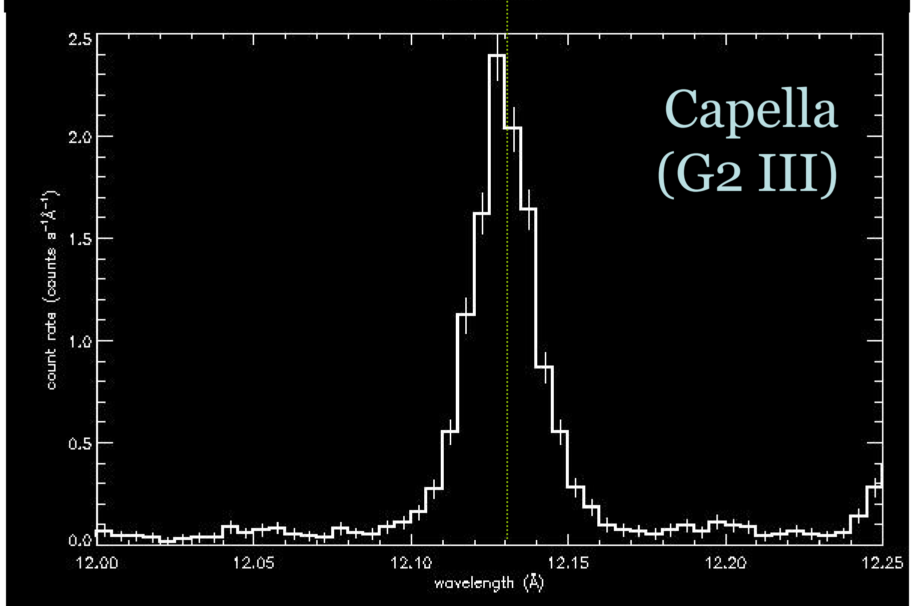
12 Å 15 Å



Ne X Ne IX Fe XVII

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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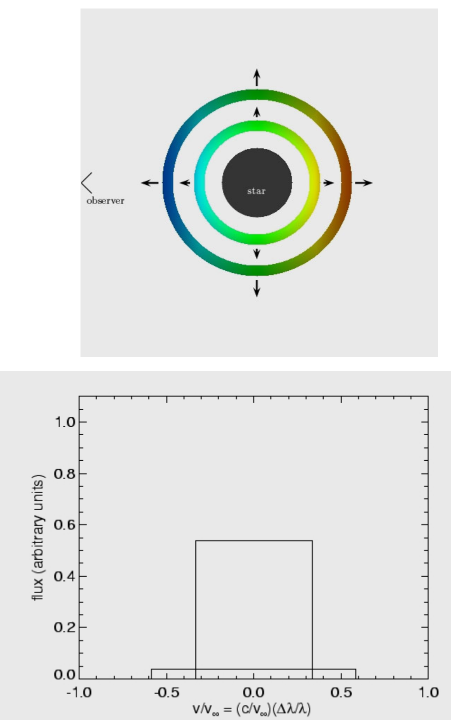
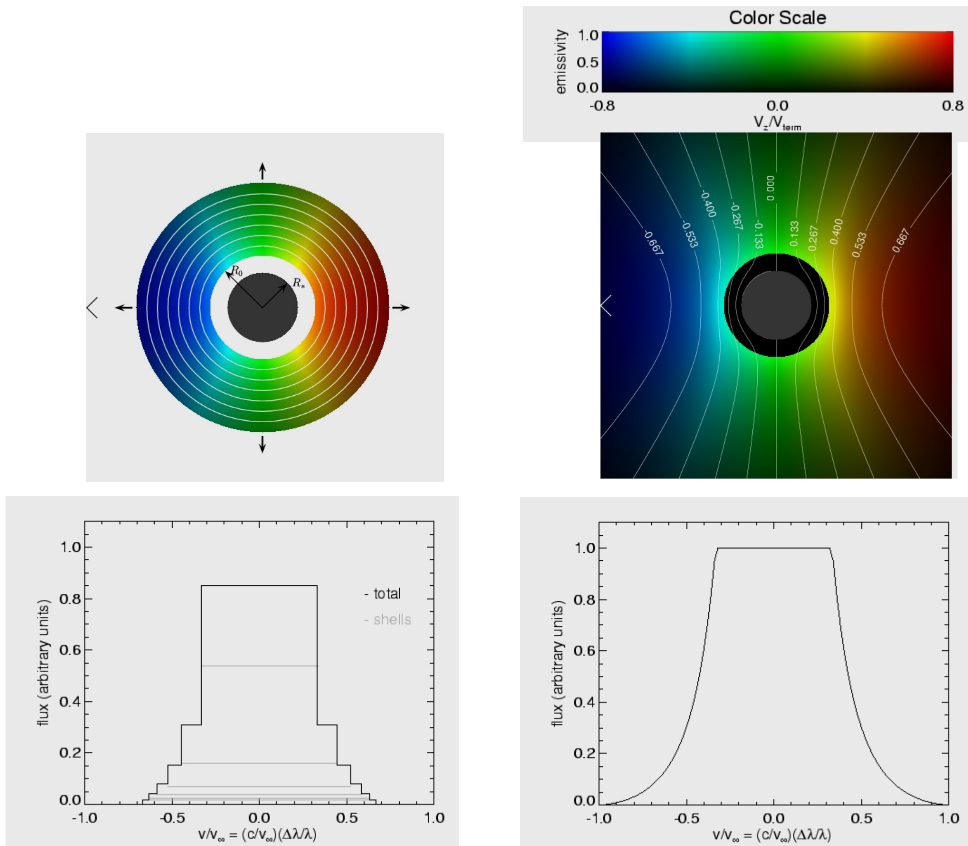
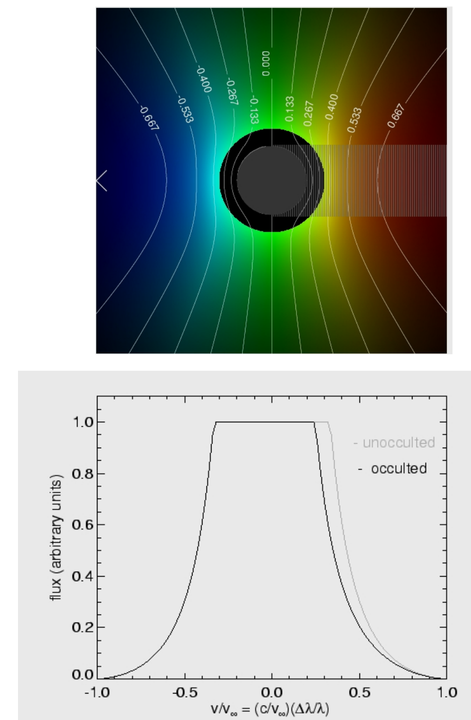
Emission Profiles from a Spherically Symmetric, Expanding Medium



A uniform shell gives a rectangular profile.

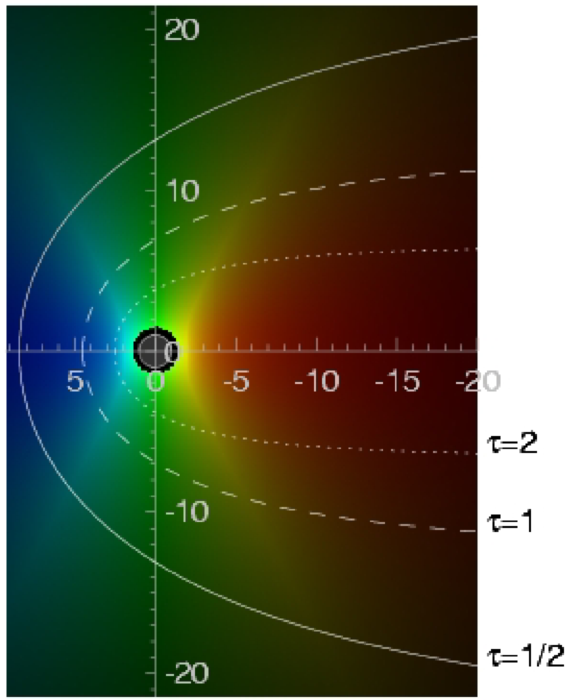


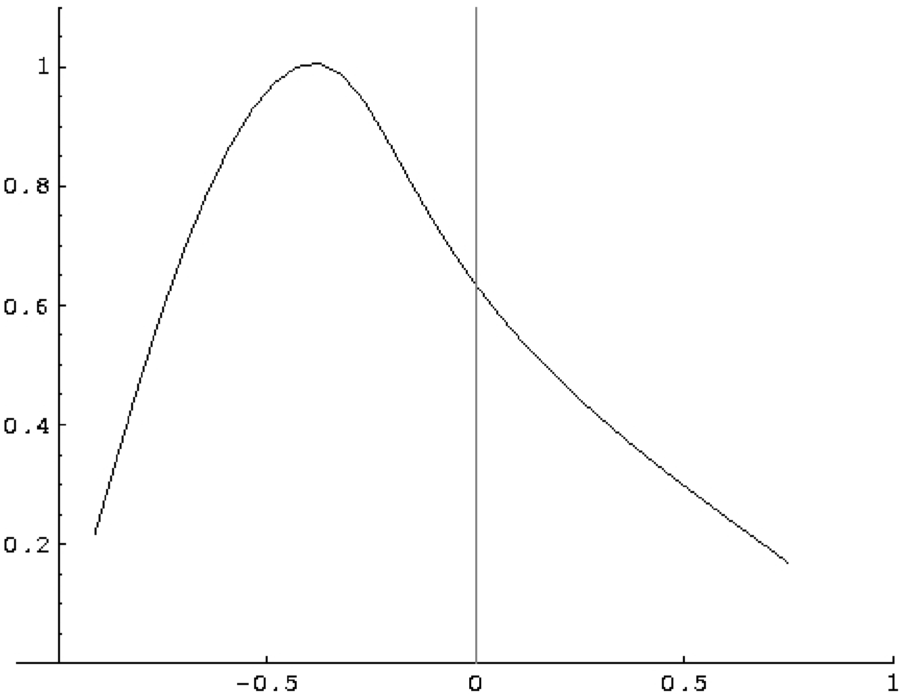
A spherically-symmetric, x-ray emitting wind can be built up from a series of concentric shells.



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

Continuum Absorption Acts Like Occultation

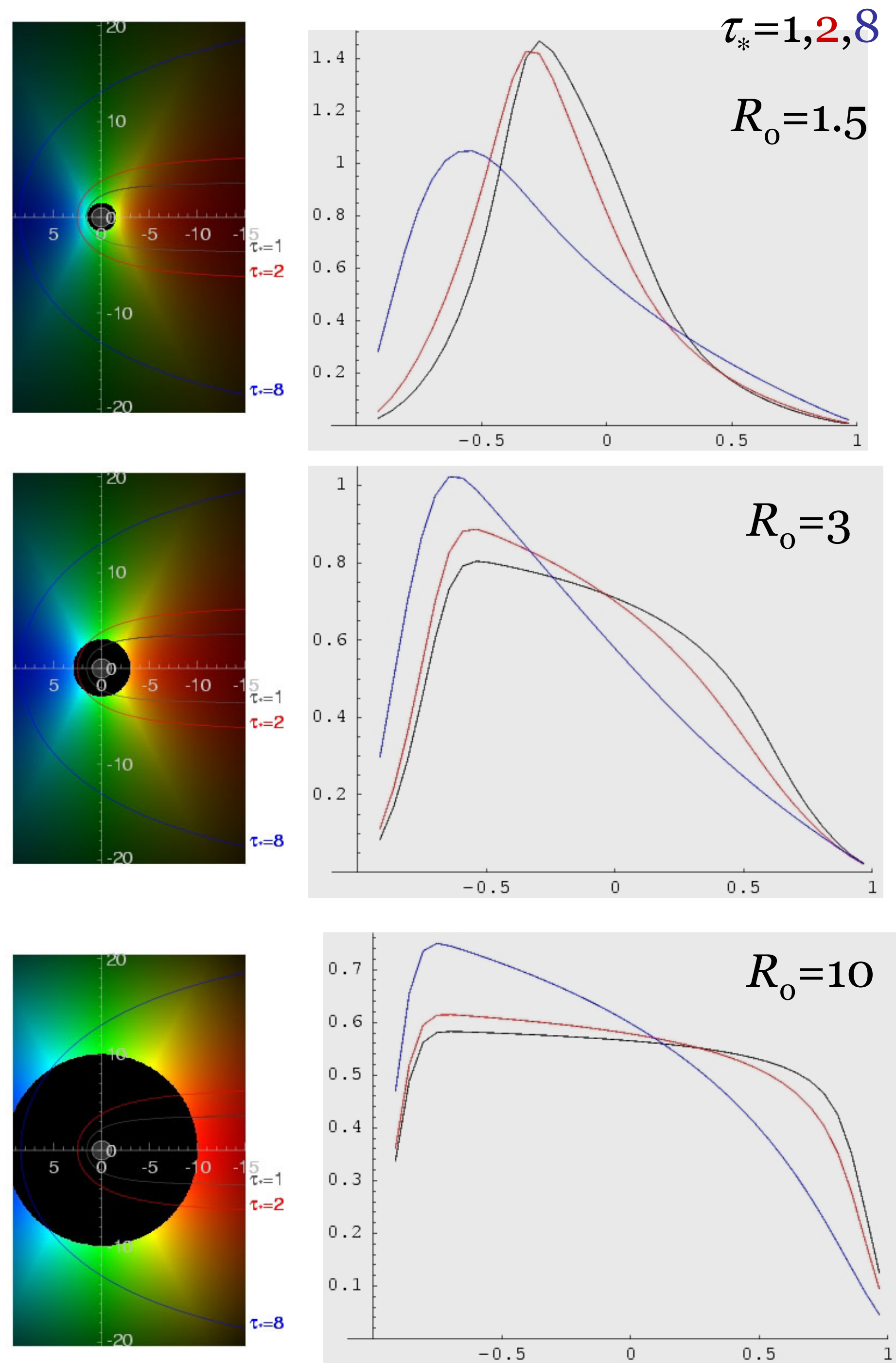




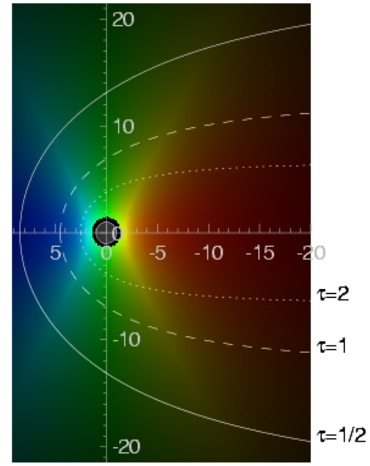
Red photons are preferentially absorbed, making the line asymmetric: The peak is shifted to the blue, and the red wing becomes much less steep.

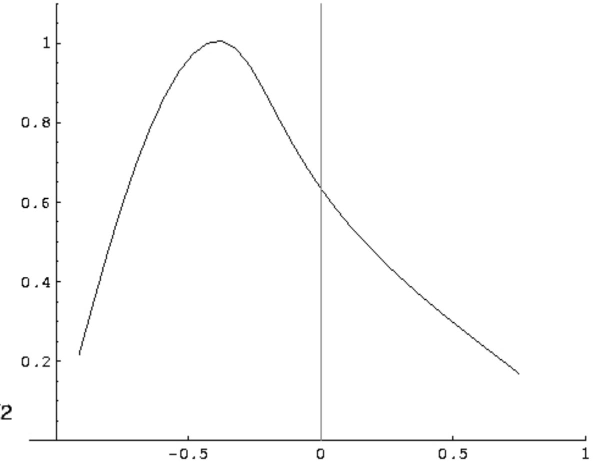
A wide variety of wind-shock properties can be modeled

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.

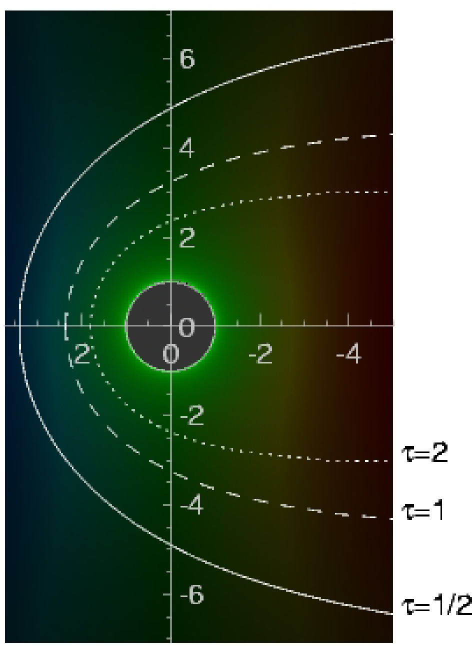


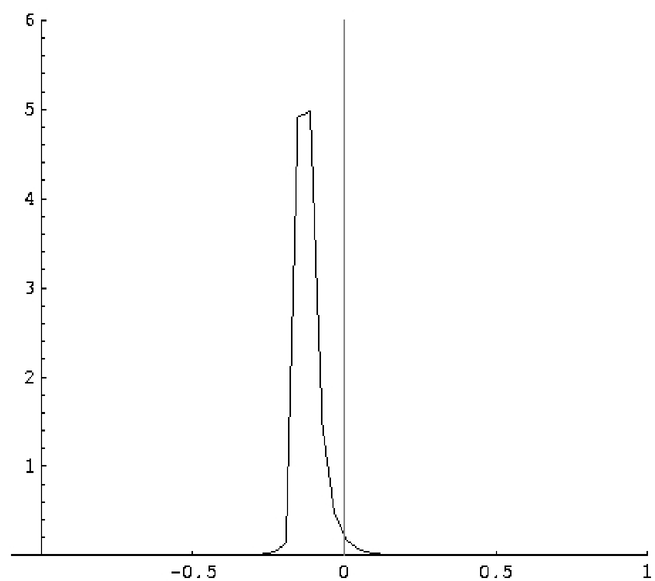
In addition to the wind-shock model,





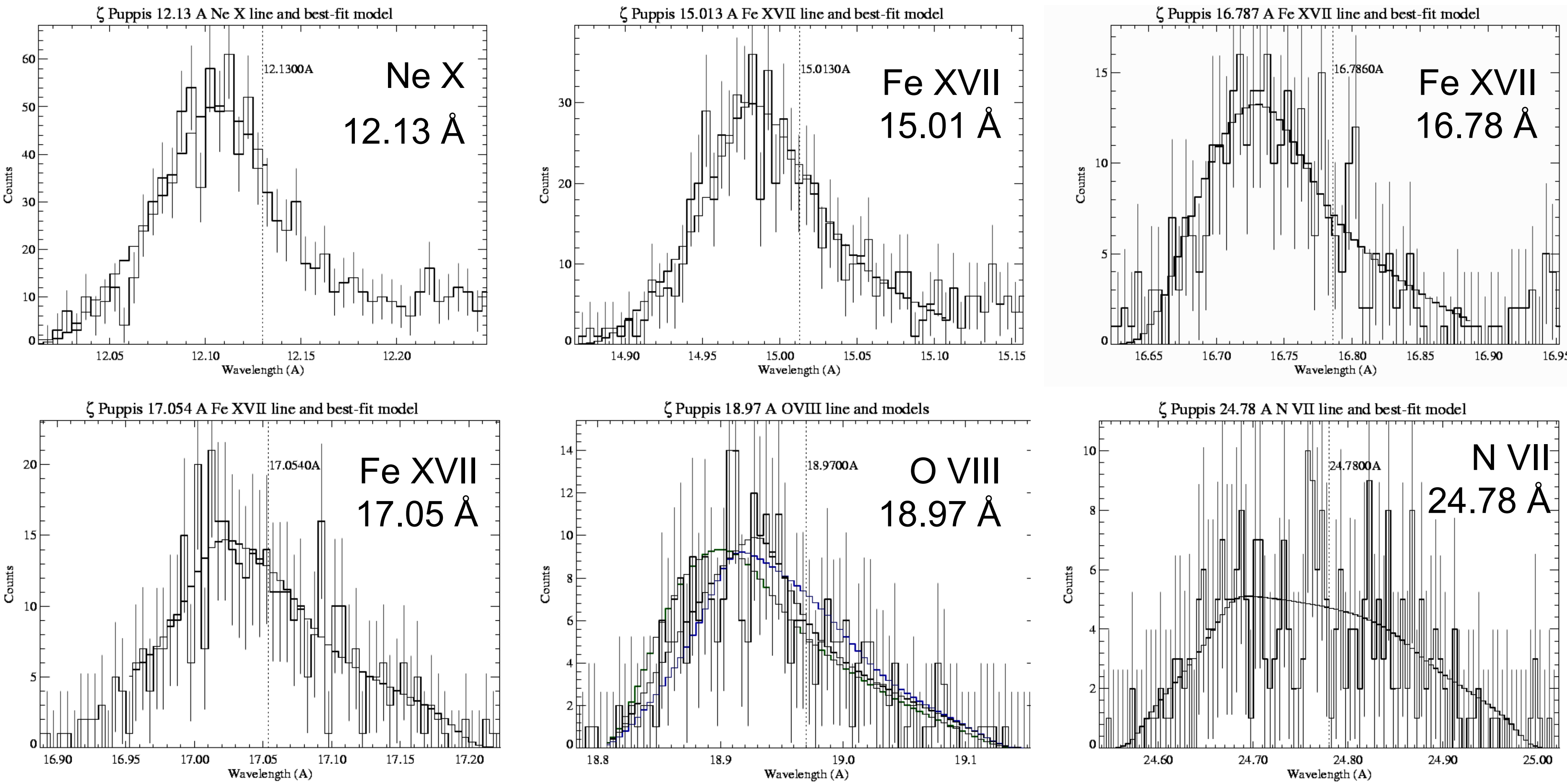
our empirical line profile model can also describe a corona





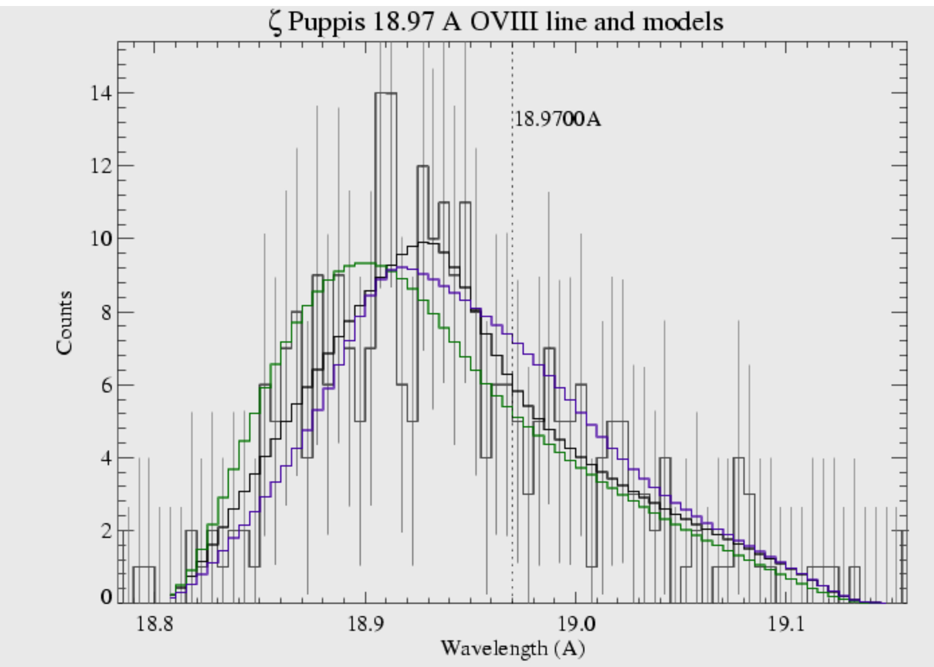
With most of the emission concentrated near the photosphere and with very little acceleration, the resulting line profiles are very narrow.

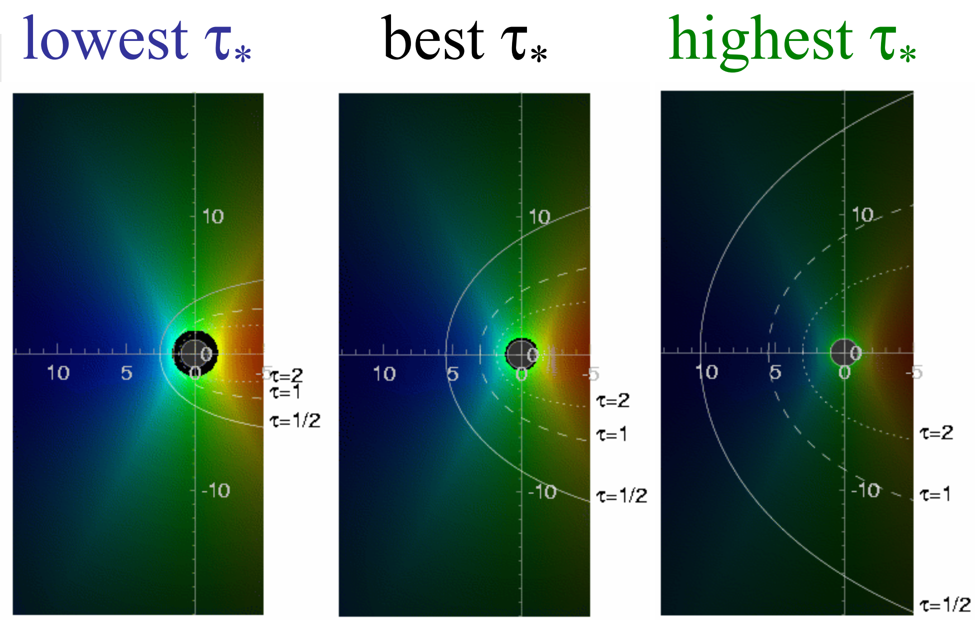
We fit all the (8) unblended strong lines in the *Chandra* spectrum of ζ Pup: all the fits are statistically good



Work done by Roban Kramer (Swarthmore ’03)

We place *uncertainties* on the derived model parameters





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.

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-shock scenario, with reasonable parameters:

$R_o \sim 1.5$

$q \sim 0$

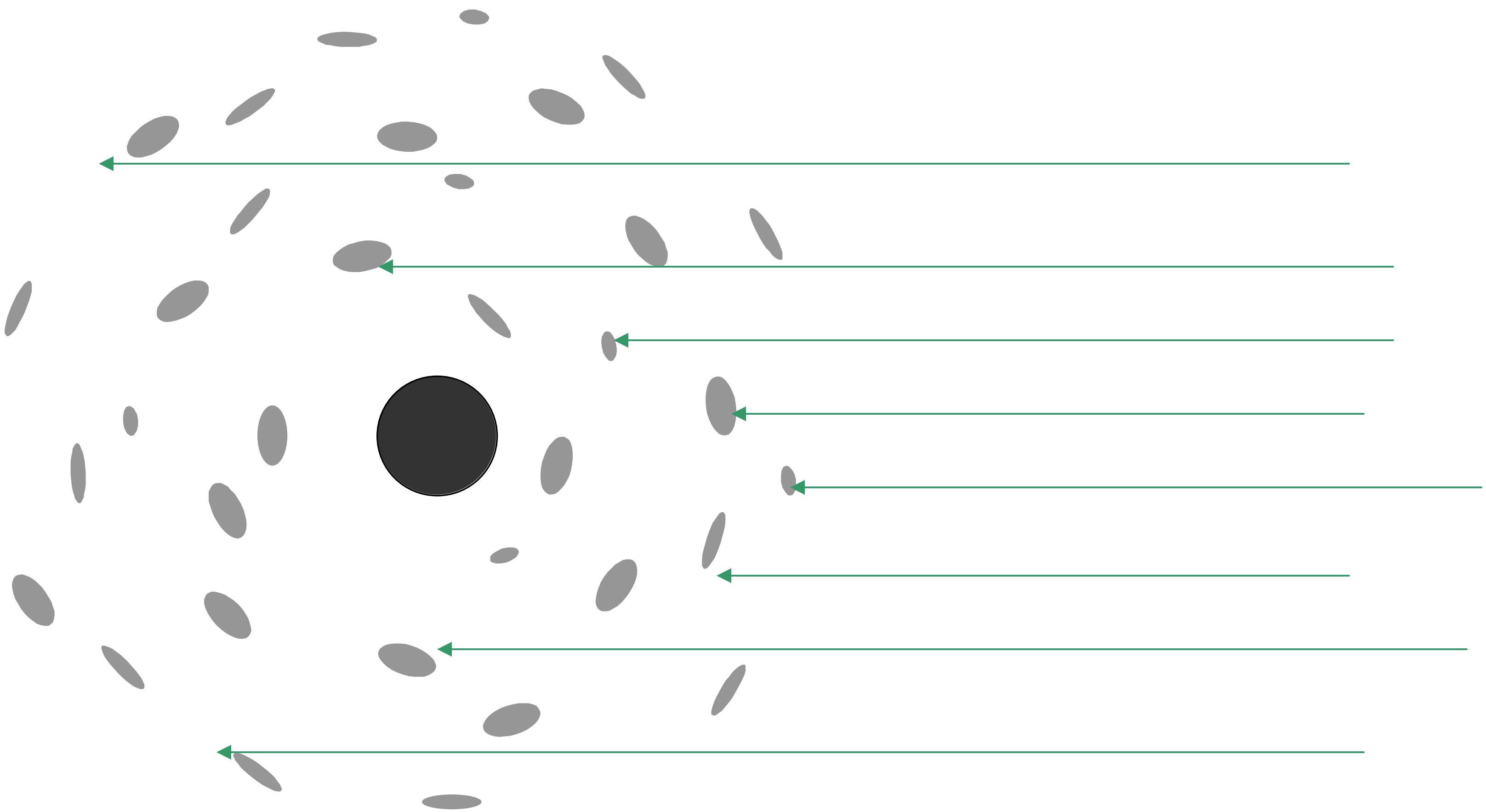
$\tau_* \sim 1$:4 to 15 times less than predicted

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).

Clumping can reduce continuum opacity in the wind

And non-isotropic clumping can also favor “sideways” escape, and thus suppression of the bluest and reddest photons, if the clumps are *oblate*



The **Venetian Blind** Model...

Conclusions

- Quantitative spectroscopy can be used to determine the relevant physical properties of the hot plasma on massive 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 and/or wind opacities overestimated? clumping?).

- Young massive stars are well explained by the hybrid magnetically channeled wind shock model.