# Determining the Radial Location of the X-ray Emitting Zones of Spica


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## Abstract


Although it is well known that O and B type stars are X-ray emitters, the mechanism driving this process is not entirely understood. Knowing the radial location of the X-ray emission is key to understanding which models of X-ray emission are correct. Emission line ratios of highly ionized, Helium-like ions can be used as a diagnostic tool for determining these radial positions, but a correct analysis relies on complete understanding of the far-ultraviolet photospheric flux from these stars. In this project, we analyzed several photospheric models to determine which should be used and reconciled discrepancies within the model with observational data of the B-type star, Spica.


## X-ray Production By Hot Stars

In cooler stars, X-rays are produced by a hot gas just outside the star's surface. This region of hot gas exists due to a dyanmic magnetic field produced by the churning of charged material in a convection zone below the star's surface. Hotter stars (O and B type) do not have a convection zone near their surface and therefore do not possess the region of hot gas required for the production of X-rays.

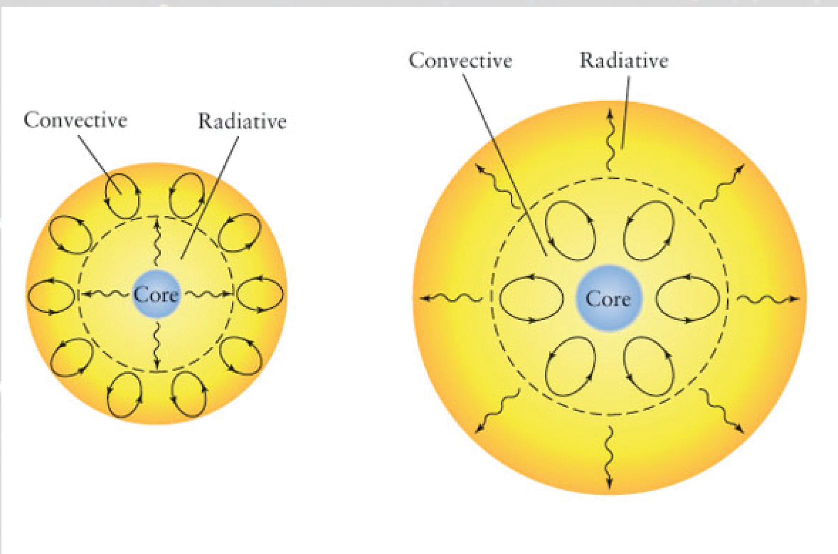


**Figure 1:** Low-mass stars (left) have a radiative zone near their core and a convective zone near their surface. This creates for a dynamic magnetic field that serves as a mechanism for X-ray production. High-mass stars (right) have the convective zone near the core, and the radiative zone near the surface. X-ray production must be caused by a different mechanism. *Image credit:* Freedman, Roger A. - Universe (8th Edition)

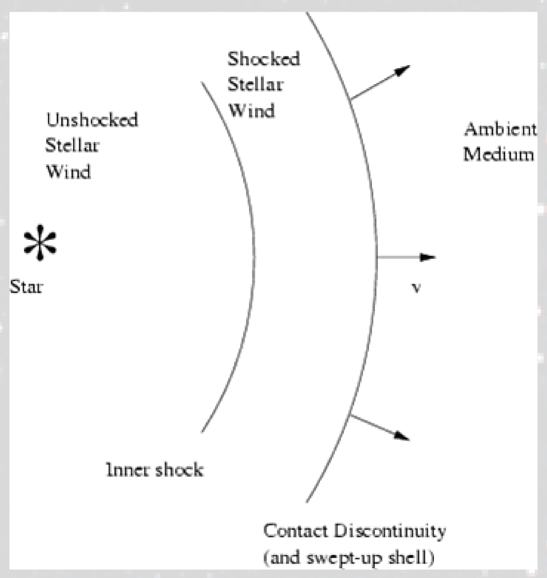


**Figure 2:** High ultraviolet flux from the star causes surrounding gas to accelerate to high speeds. This high-speed gas runs into slower, ambient gas and heats up as a result. *Image credit:* Pittard et al (2001) A&A 367,1000

It is thought that the intense radiation near the star's surface may accelerate gas to very high speeds. When this fast-moving gas runs into slower-moving gas, shock heating occurs and the gas becomes hot enough to produce X-rays.

## Helium-like Ions

Temperatures within the stellar wind are high enough to almost completely ionize atoms. Many atoms are left with only two electrons, making them He-like. Spectra of He-like ions present themselves as a characteristic 3-line complex. The complex is composed of the forbidden (f), intercombination (i), and resonance (r) lines.

| Ion | S XV | Si XIII | Mg XI | Ne IX | O VII |
|---|---|---|---|---|---|
| Wavelengths (A) | 673.9 | 815.2 | 997.7 | 1247.8 | 1623.9 |
| | 738.2 | 865.2 | 1034.3 | 1273.2 | 1634.0 |
| | 756.0 | 878.4 | 1043.3 | 1277.7 | 1638.5 |

**Table 1:** Wavelengths where fir 3-line complex occurs for several helium-like ions.

## Line Ratios from He-like Ions

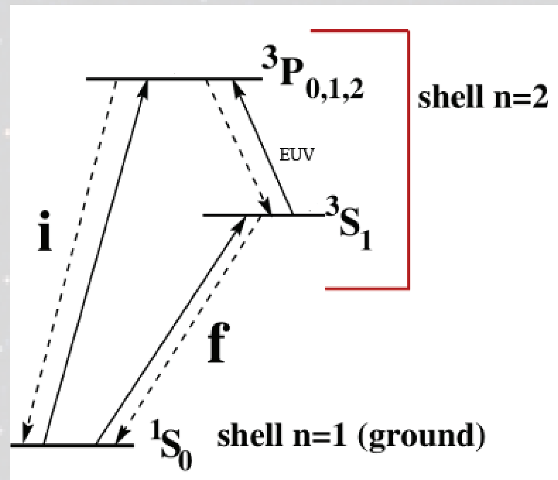


**Figure 4:** Energy level diagram for Helium-like ions. The forbidden and intercombination transitions are labelled as "f" and "i" respectively.

*Image Credit:* Porquet, D. et. al.

Electrons in the Helium-like ions excite to the $S_1$ state by the high temperatures generated by shock heating. If the ions are relatively close to the surface of the star, high extreme ultraviolet (EUV) radiation will push the electrons up further into the $P_{0,1,2}$ state where it will eventually recombine and fall to the ground state and strengthen the intercombination line.

If the ions are further from the star, there is not as much EUV radiation, and the electron will recombine and fall back down to the ground state, strengthening the forbidden line. The ratio of f to i is therefore a usefull diagnostic in determining whether X-ray production is occuring near or far from the stellar surface.

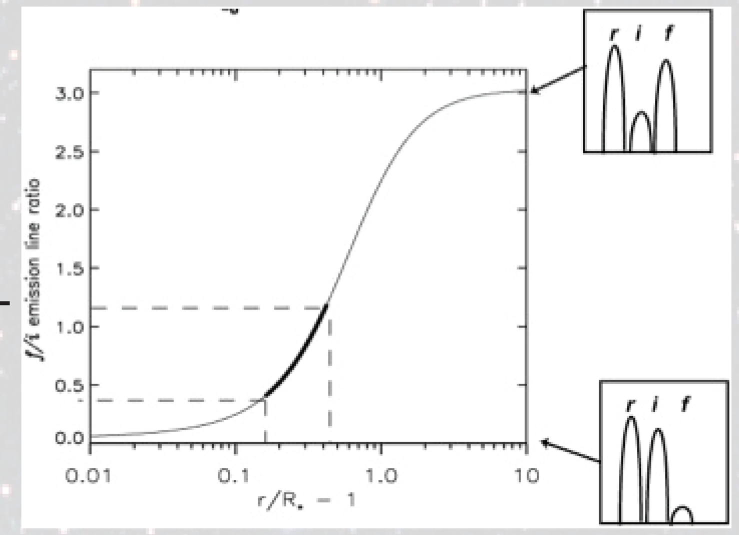


**Figure 5:** This plot of f/i line ratio versus radial distance from stellar surface demonstrates how the f/i ratio can be used to determine radial location of X-ray production. The boxed images on top and bottom represent the emission lines from the intercombination and forbidden transitions.

## Computational Model Atmospheres

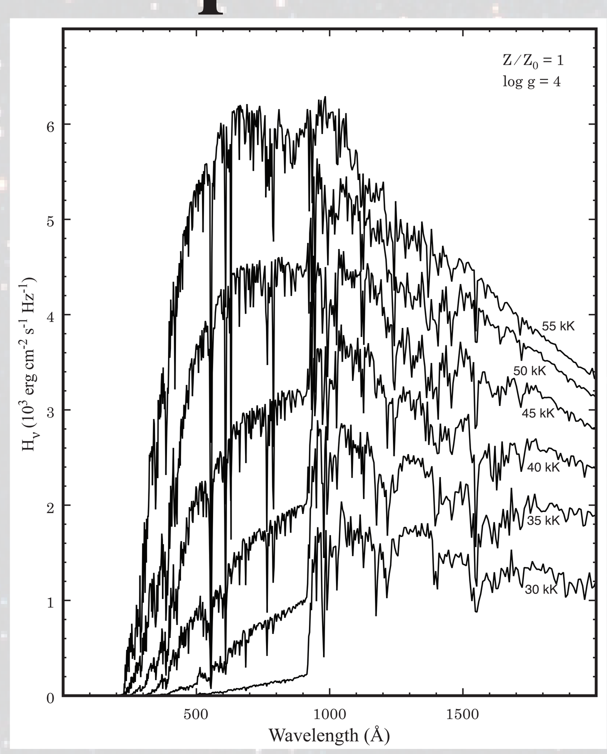


**Figure 3:** Spectra produced by the BSTAR2006 model grid for six temperatures.

Computational model atmospheres simulate spectra for a star. They are presented as a grid based on temperature and surface gravity.

| log g | Effective Temperature (kK) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 1.75 | × | | | | | | | | | | | | | | | |
| 2.00 | × | × | × | × | | | | | | | | | | | | |
| 2.25 | × | × | × | × | × | × | | | | | | | | | | |
| 2.50 | × | × | × | × | × | × | × | × | × | × | | | | | | |
| 2.75 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | | |
| 3.00 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| 3.25 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| 3.50 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| 3.75 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| 4.00 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| 4.25 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| 4.50 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| 4.75 | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |

**Table 2:** The BSTAR2006 grid. The x's indicate effective temperatures and log(g) values for which a model exists. We used the model of effective temperature 24 kK and log(g) 3.75 because it is the model that best describes Spica.

The models are computed under several assumptions. One assumption is that temperatures within the star are time-independent, meaning that temperatures only vary with radial distance. This way, temperatures can be computed using the perfect gas law. It is also assumed that the stellar interior maintains hydrostatic equilibrium, meaning that pressure is proportional to radial distance. The two variables are effective temperature and surface gravity. Effective temperature is the temperature of a blackbody with the same integrated area as the spectrum. The surface gravity is the logarithm of the gravitational acceleration at the surface of the star. We chose to use the BSTAR2006 grid, which is freely available online. The grid is shown above with each individual cell representing one model.



## The Interstellar Medium

Computational models are used to analyze the spectra of these stars because observational analysis is too difficult from Earth. It is difficult to use observational spectra to benchmark model atmospheres in the EUV region because EUV light is quite easily absorbed by the interstellar medium, letting very little light pass through. It is, however, possible to measure the size of the H II region surrounding a star. This is a region of ionized hydrogen gas that's size is directly related to the ionizing flux of the star. The size of the H II region is found by looking at it's emission in H-alpha light. This light is produced when ionized hydrogen recombines to a less energetic state. This allows us to compare the observed ionizing flux of a hot star with that predicted by the model. We then scale the model accordingly. We chose the star Spica to use as our observational subject because it is relatively far from other stars, so it's H II region does not overlap with that of other stars. Spica is a B1 IV-V star with a temperature of 23,800 K.

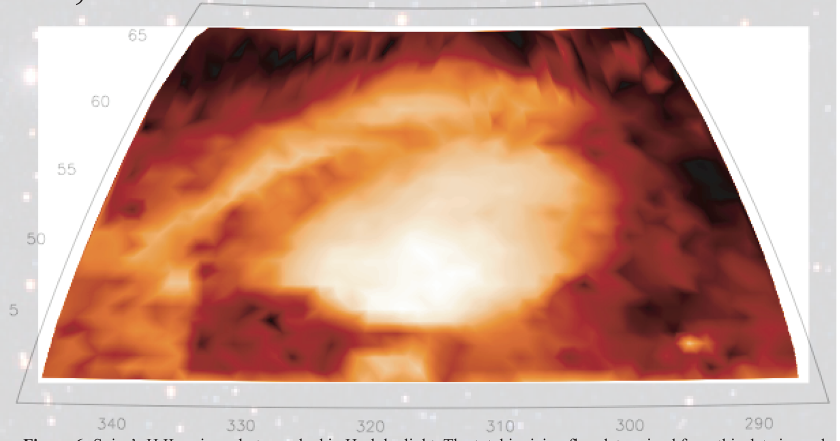


**Figure 6:** Spica's H II region, photographed in H-alpha light. The total ionizing flux determined from this data is used to scale the model. *Image credit:* Wisconsin H-Alpha Mapper (WHAM)

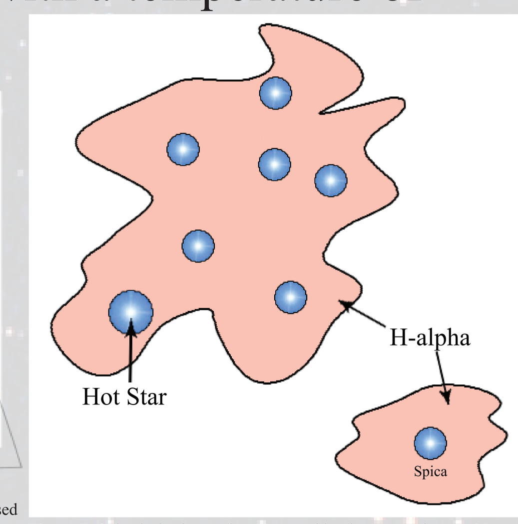


**Figure 7:** Spica is far from other stars, making it easy to observe. Not to scale

Observational data was obtained from collaborators at the Wisconsin H-Alpha Mapper at UW-Madison. The ionizing flux of Spica was found to be $2.8 \pm 0.4 \times 10^{46}$ photons/sec.

## Future Work

So far, our goal has been to match the photospheric models to the star Spica. This proved to be more difficult than predicted, however. Further research revealed that the H-alpha region surrounding Spica may be more complicated than we accounted for. For example, Spica may be surrounded by a hot ambient gas.

This possibility will need to be investigated further to assure that our scaled model is as accurate as possible. Ultimately, we would like to be able to use the scaled models to measure the f to i ratios of the helium-like ions listed in Table 1.

## Acknowledgements


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