



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

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1. 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 ultraviolet wavelengths over a range of temperatures. We then compared this flux to a unique H-alpha data set for the B-star Spica to scale the model.

2. 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 dynamic magnetic field produced by the churning of charged material in a convection zone below the star's surface.

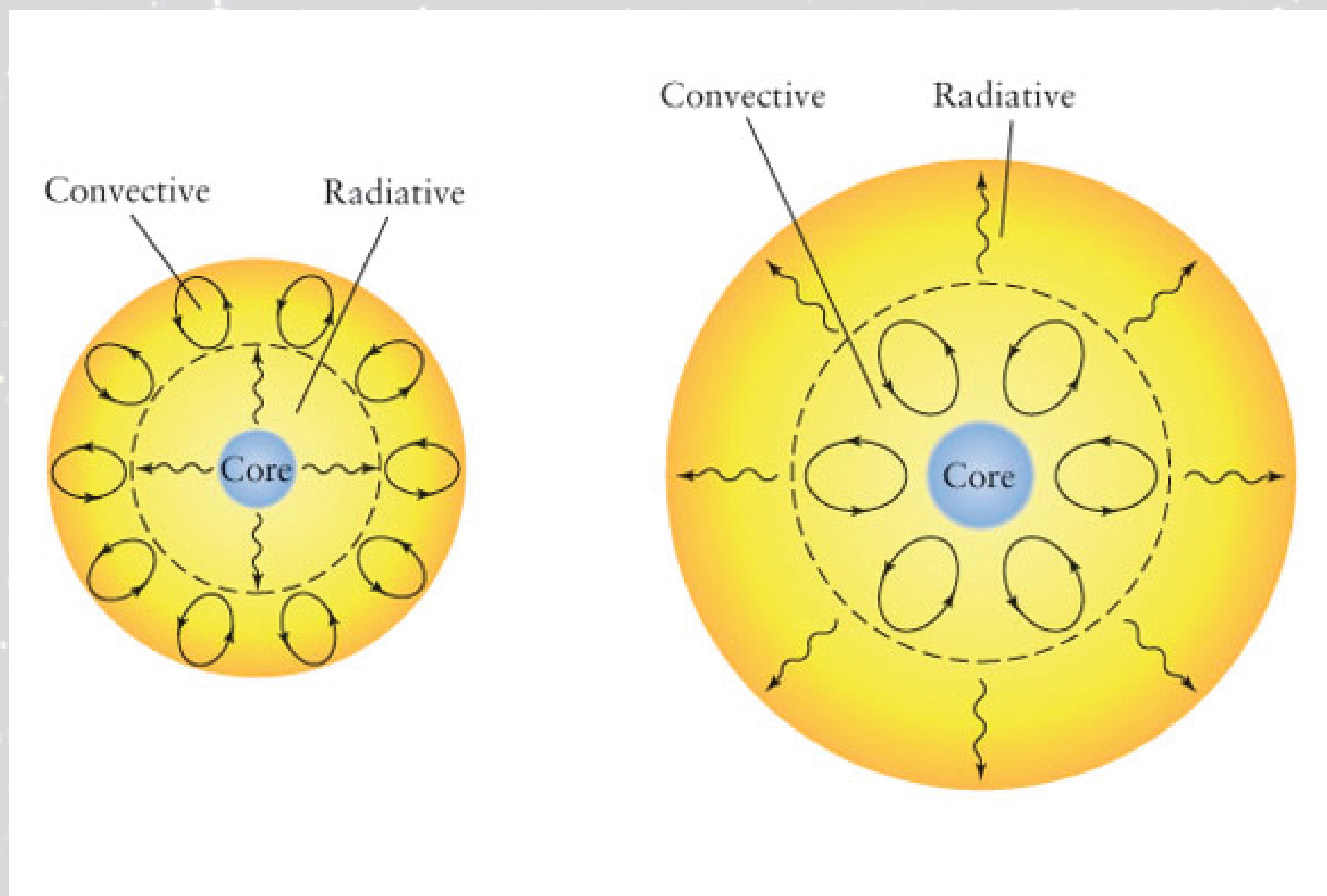


Figure 1: Low-mass stars (left) have a radiative zone near their core and a convective zone near their surface. This creates a dynamic magnetic field that serves as a mechanism for X-ray production. High-mass stars (right) have the convective zone near the core, and the radiative zone near the surface.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

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 this kind of X-ray production (Fig. 1). Intense radiation near the star's surface may accelerate gas to very high speeds. When this fast-moving gas runs into slower-moving gas, farther from the surface, shock heating occurs (Fig. 2) and the gas becomes hot enough to produce X-rays.

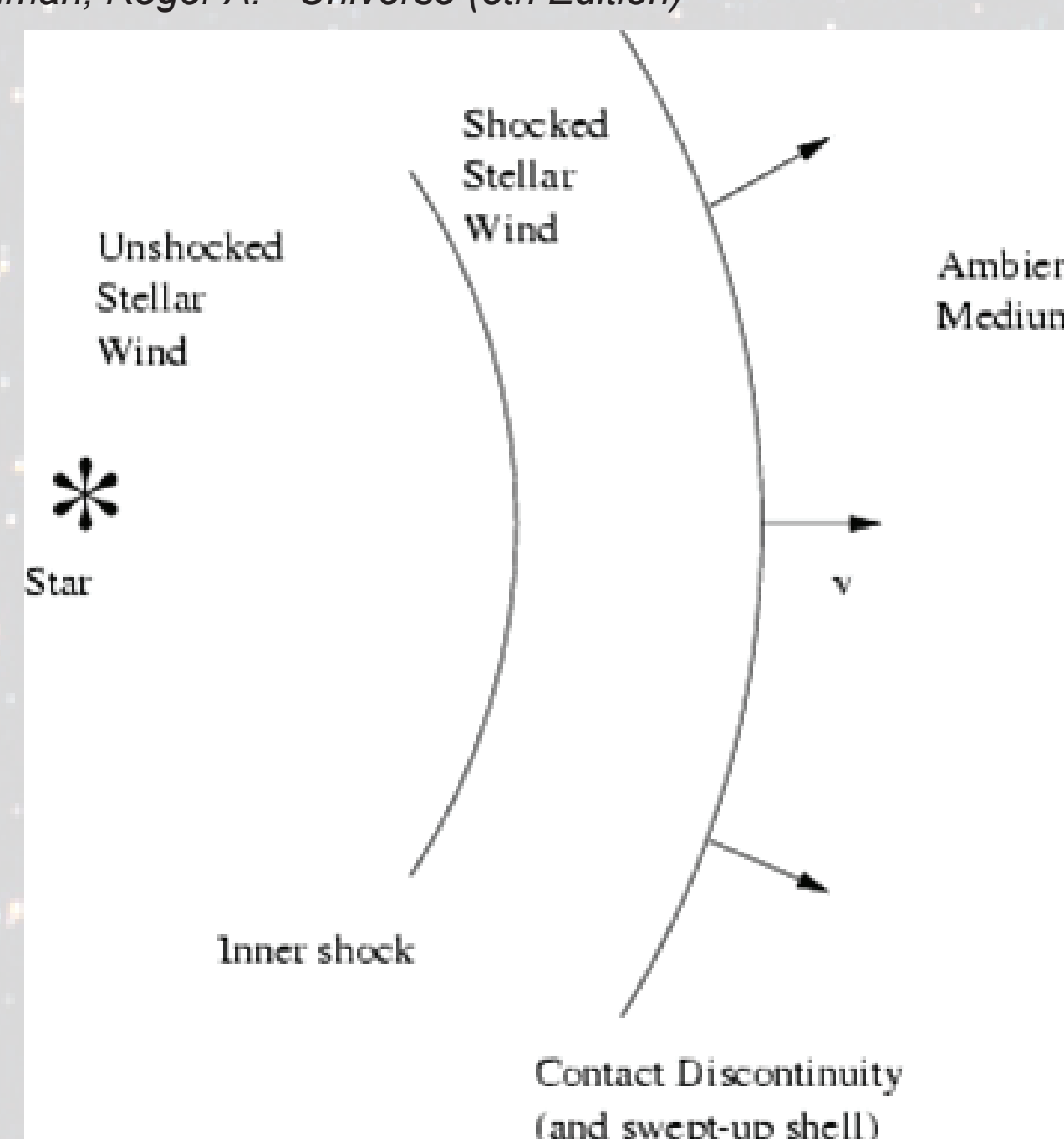


Figure 2: Intense radiation from the star leads to shock heating, allowing for X-ray production.

3. 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 (Å)	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: These five Helium-like ions can be used as a diagnostic tool for determining radial location of X-ray production in an O or B type star. The UV wavelengths listed correspond to the transitions $2S1 \rightarrow 2P2$ for $J = 0$ (top), 1 (middle), 2 (bottom). These values are taken from the APED line list.

4. Line Ratios from He-like Ions

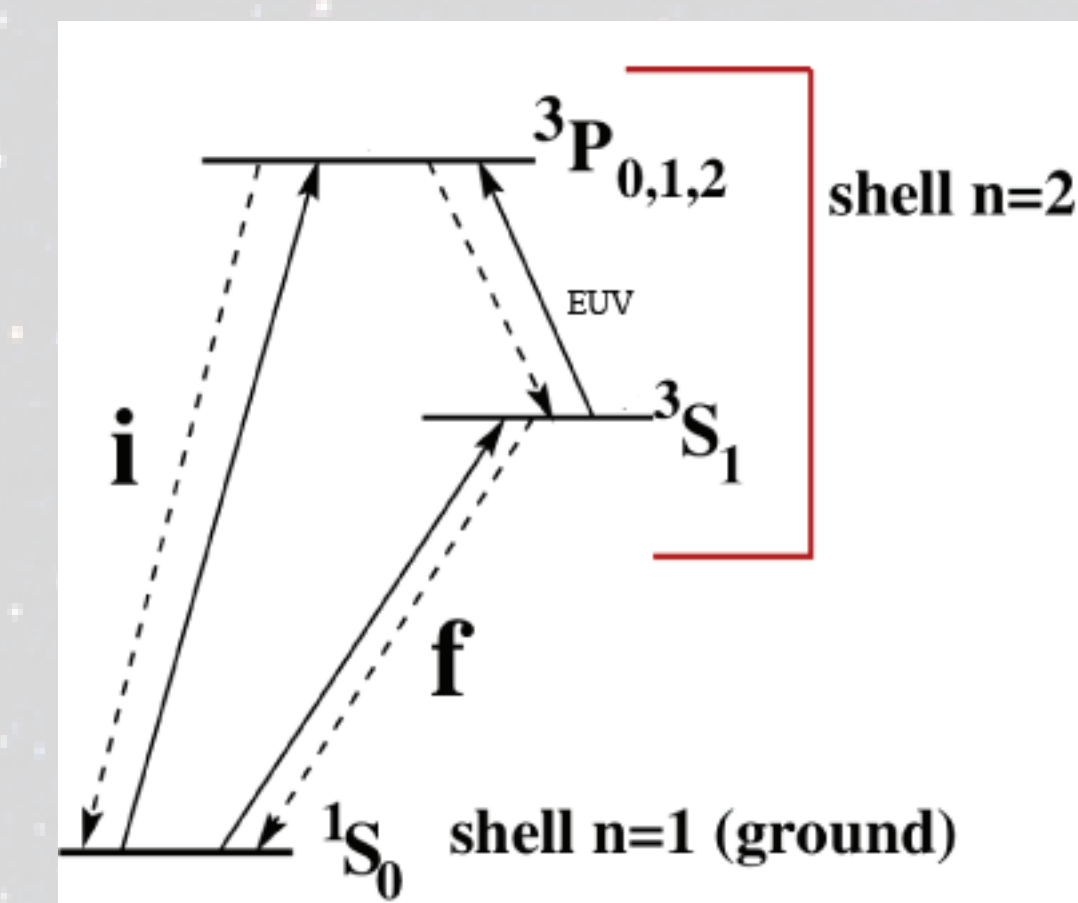


Figure 3: Energy level diagram for Helium-like ions. The forbidden and intercombination transitions are labelled as "f" and "i" respectively. Image Credit: Porquet, D. et. al.

If the ions are farther from the star, there is not as much EUV radiation, and the electron will de-excite and fall back down to the ground state, strengthening the forbidden line (Fig. 4). The ratio of f to i is therefore a useful diagnostic in determining whether X-ray production is occurring near or far from the stellar surface.

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 de-excite and fall to the ground state and strengthen the intercombination line (Fig. 3).

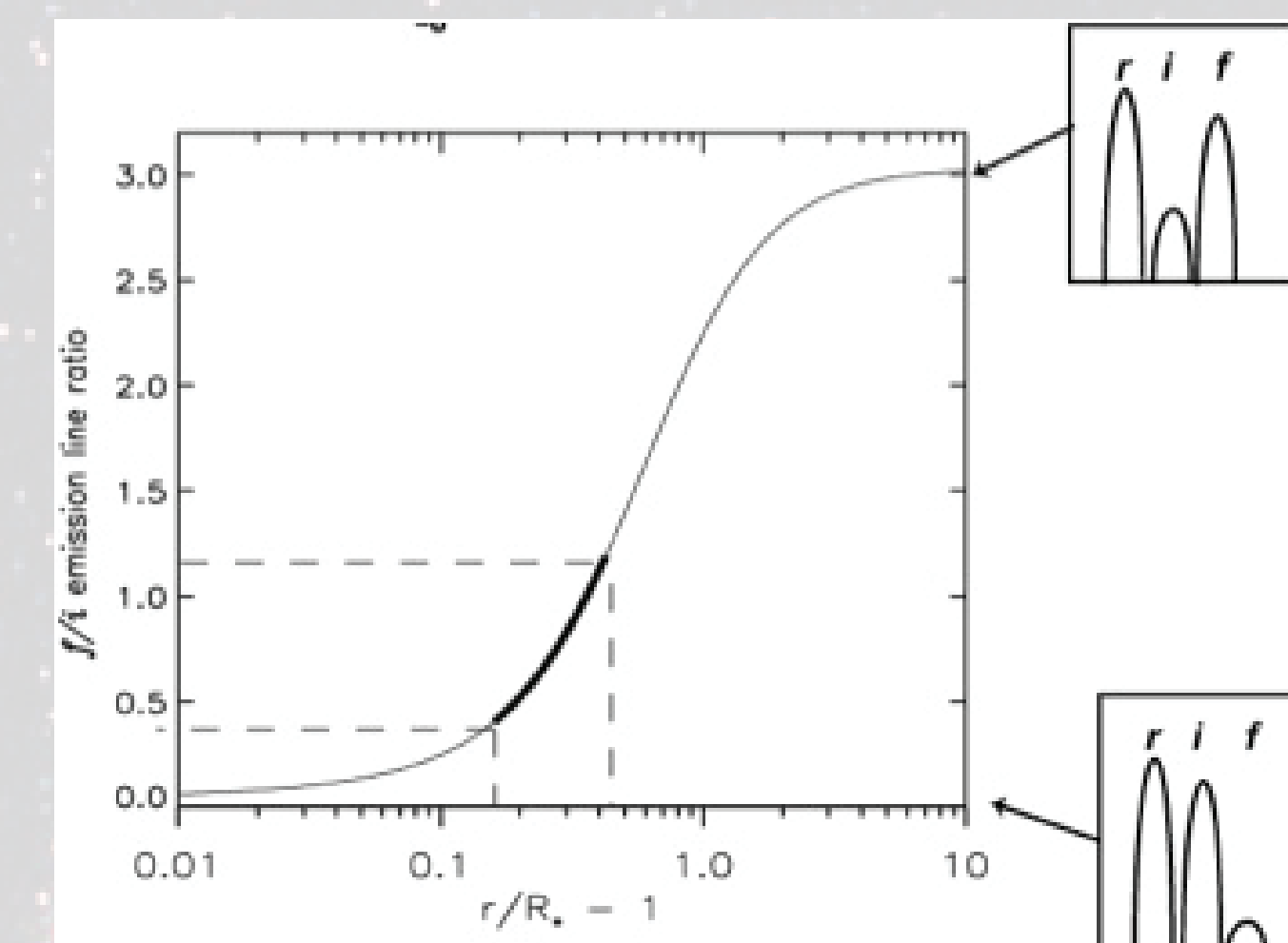


Figure 4: This plot of f/i line ratio versus radial distance from stellar surface demonstrates how the f/i ratio can be used to determine radial location of X-ray production. The boxed images on top and bottom represent the emission lines from the intercombination and forbidden transitions.

5. Computational Model Atmospheres

Computational model atmospheres simulate spectra for a star. They are presented as a grid (Table 2) based on two variables: effective temperature and surface gravity (log g).

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

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.

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. 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. We chose to use the BSTAR2006 grid, which is freely available online. The grid is shown above with each individual cell representing one model.

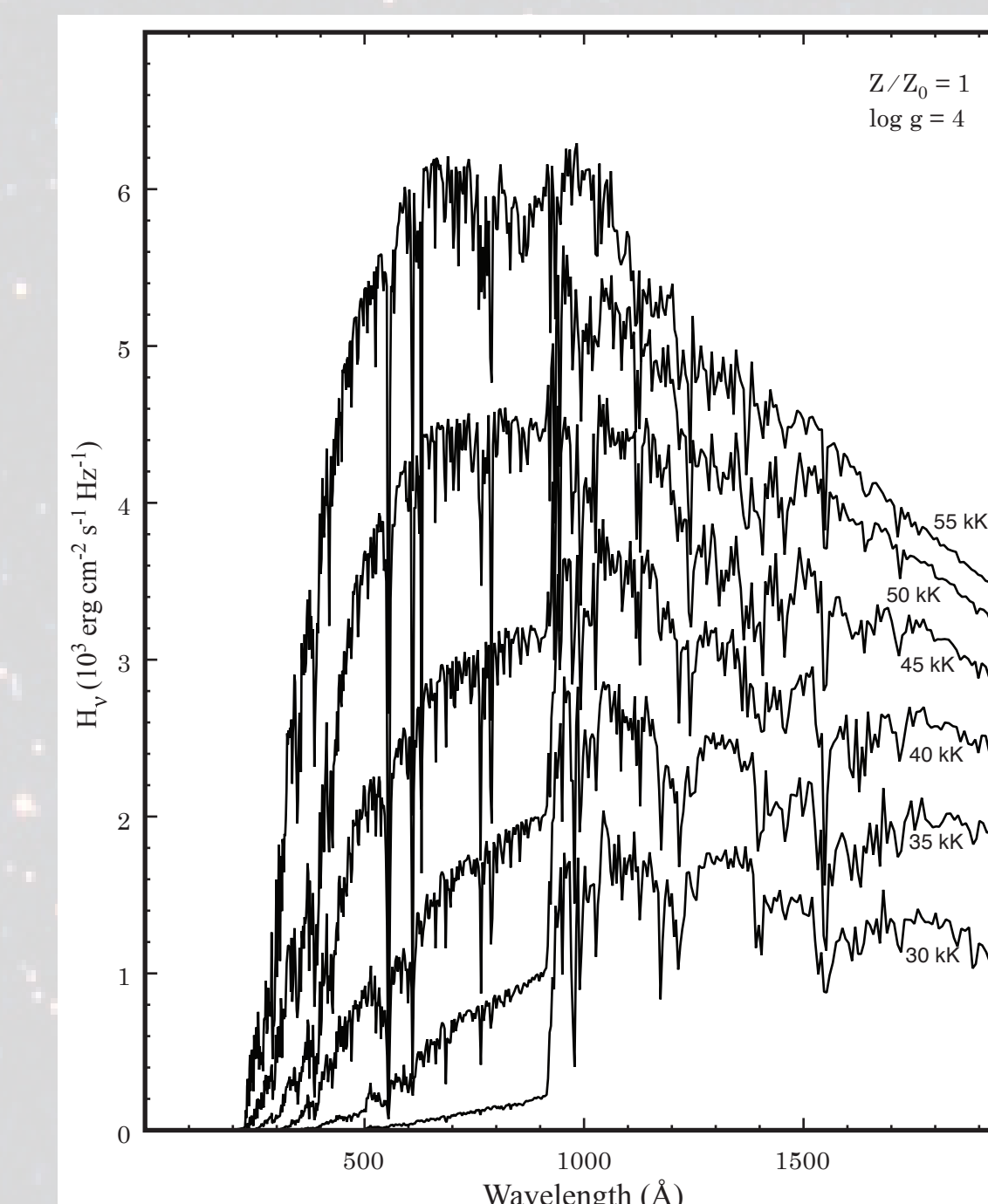


Figure 5: Spectra produced by the BSTAR2006 model grid for six temperatures.

8. References

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6. 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.

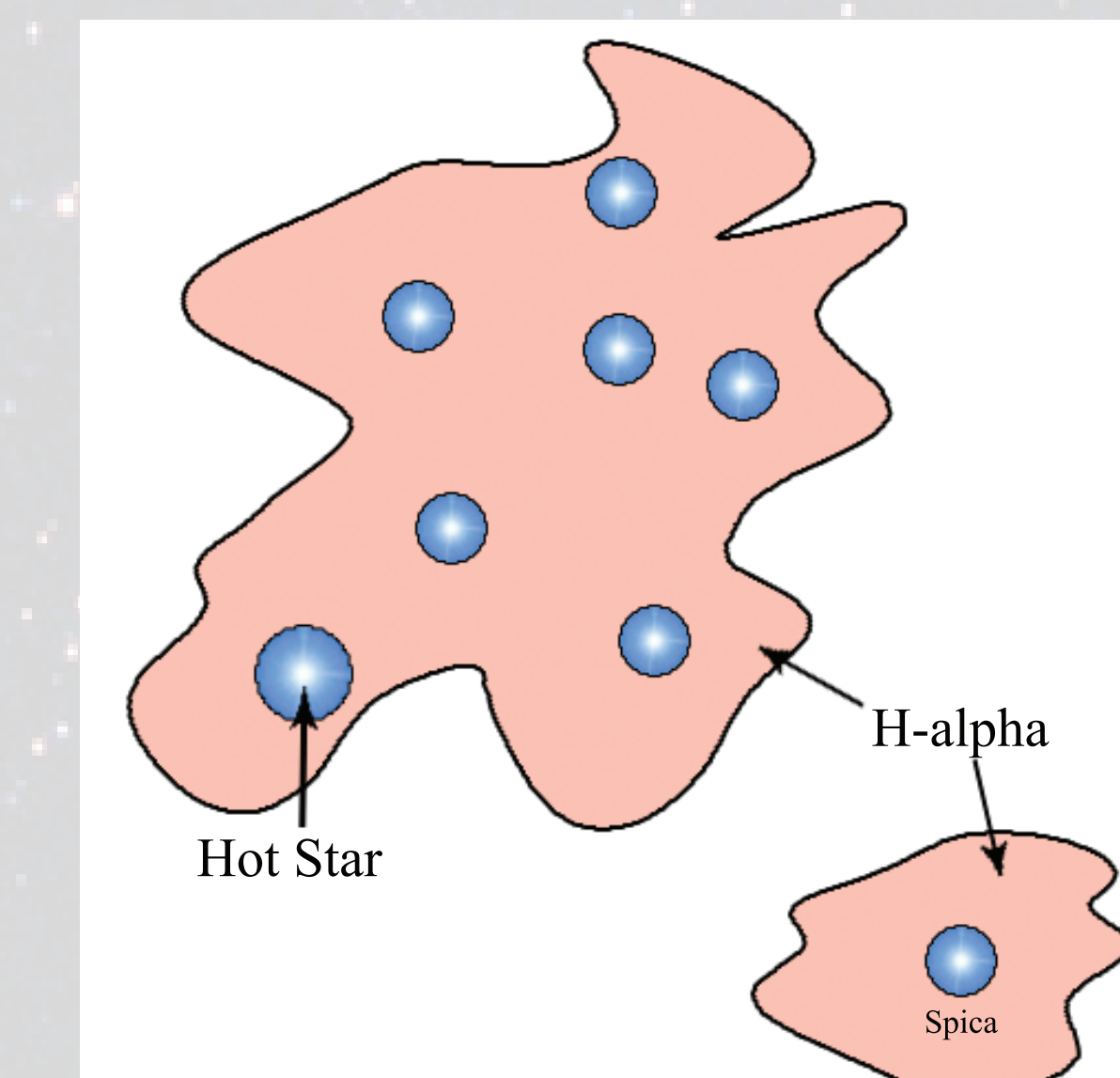


Figure 6: Cartoon diagram of Spica's H II region. Spica is far from other stars, making it easy to observe. Not to scale.

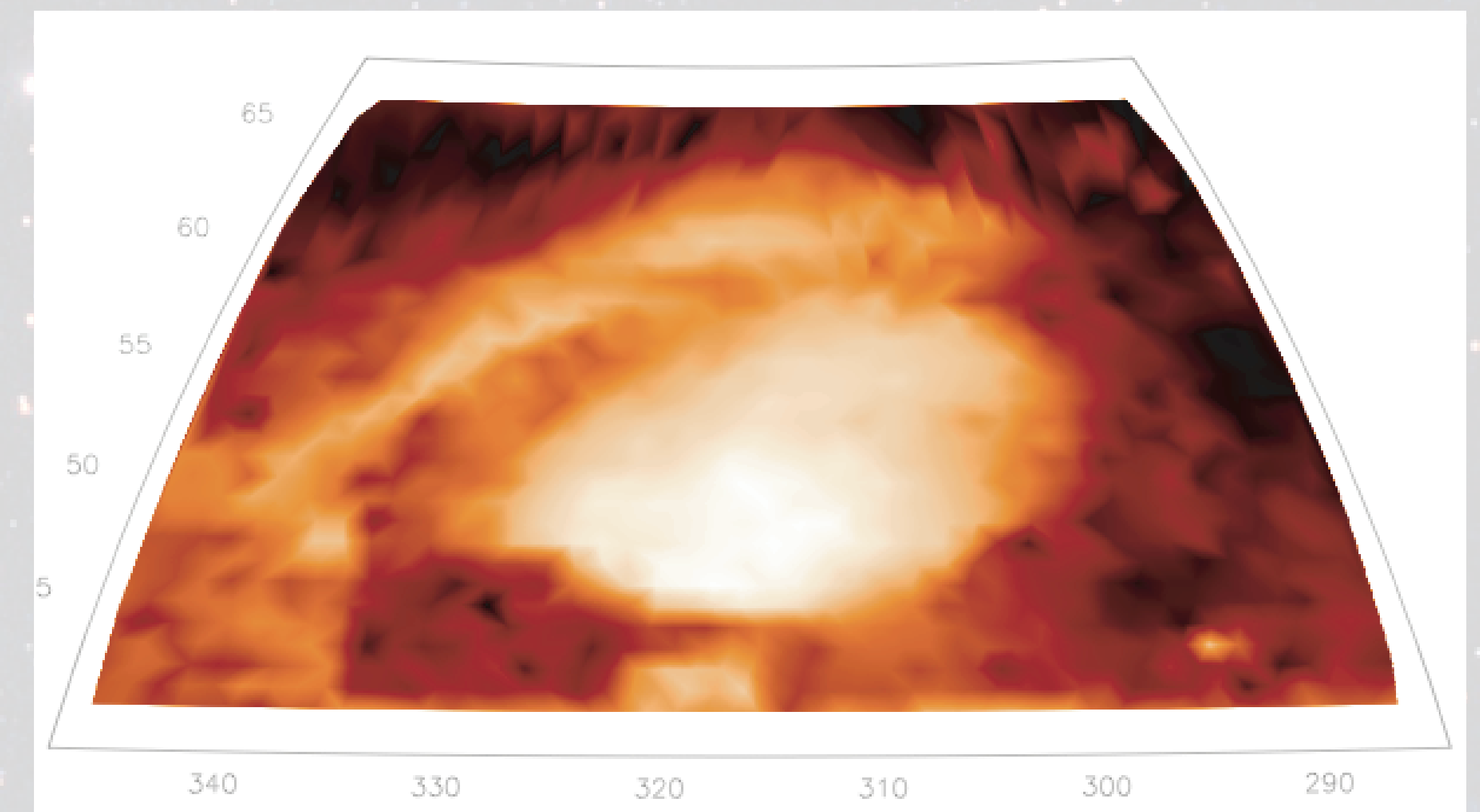


Figure 7: Spica's H II region, photographed in H-alpha light. The total ionizing flux determined from these data is used to scale the model Image credit: Wisconsin H-Alpha Mapper (WHAM).

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

7. Results

Using the computer algebra system *Mathematica* by Wolfram Research, we numerically integrated the model for all wavelengths short of 912 Å to determine the total ionizing flux. This value was then compared to the value obtained from WHAM. We found this integrated flux to be 4.93×10^{47} photons/s. This is larger than the observed flux by a factor of 18. This large difference may be a result of the model not being a perfect match for Spica. Spica's temperature is $23,800 \pm 700$ K and the model is for a star of 24,000 K. Spica's surface gravity (log g) is approximately 3.69 whereas the model is 3.75. Another explanation lies in the fact that these models are not particularly well benchmarked in ultraviolet wavelengths. This scaling factor can be used in further research to examine f/i line ratios and determine the radial location of X-ray production.

9. Acknowledgments

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