Spectral Analysis and Grouping Be Stars: Spectroscopic analysis of Hα and forbidden lines in 6352Å-6506Å

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Introduction

I took spectra in 1874μm and 1841μm settings on the micrometer for most of my stars at Hi-Res with the spectrograph on RUCO. I used 1874nm to get H alpha, providing a wavelength range from 6506 to 6599 bounded by the wavelength calibration and 1841nm provided a wavelength range of 6352Å to 6506Å to get an oxygen line at 6360A and a multitude of iron lines. In total I got spectra on 27 stars, four of which were control stars: Alkaid, Gamma Ori, Regulus, and Spica. The control stars are B stars I intended to use to compare to the rest of my spectra. I took spectra at 1874nm to get H alpha in all objects and 3 of the 4 control stars and 18 of the 23 remaining observed stars I took spectra set at 1841nm. This was reduced with the standard Hi-Res IRAF reduction process.

Star (Notes)	Exposure Time	1874μm (Hα)	1841μm (O&Fe)
Alkaid (Control)	20s	Yes	No
Beta CMi	60s	Yes	Yes
HD58050	600s	Yes	No
HD66956	600s	Yes	Yes
HD164284	300s	Yes	Yes
HD183914	300s	Yes	Yes
HD185037	420s	Yes	Yes
HD203567	300s	Yes	Yes
HIP17851	300s	Yes	No
Kappa Dra	300s	Yes	Yes
Spica (Control)	5s	Yes	Yes
ThetaCRb	180s	Yes	Yes
HD20336	240s	Yes	Yes
HD50658	420s	Yes	Yes
HD65875	600s	Yes	Yes
HD107348	420s	Yes	Yes
HIP19343	240s	Yes	Yes
Nu Gem	240s	Yes	Yes

Omega Ori	300s	Yes	Yes
Regulus (Control)	10s	Yes	Yes
Zeta Tau	60s	Yes	Yes
Gamma Ori	10s	Yes	Yes
HD51354	600s	Yes	No
HD58647	480s	Yes	No
HR2284	300s	Yes	Yes
HD56139	300s	Yes	Yes
Rho Aur	420s	Yes	No

Table 1: Star List

After reducing my data in IRAF, given that I do not have a printer in my off-campus apartment, to be able to view all the spectra out in front of me I used Post Its, stuck them to the top of my screen and crudely sketched over the line display with splot in IRAF. I then found equivalent widths, fluxes, and wavelengths in IRAF using “splot” and wrote them in their corresponding places on the Post iT This proved to be quite helpful as I could fit a lot of information very quickly on a small piece of paper which would have taken longer to format/organize digitally. Once this was done it allowed me to move around easily my Post-Its (especially since they stick and so don't slide on their own at all) across a table to visually organize and have them all out at once. I then put all the data into a CSV file to run calculations and statistics on.

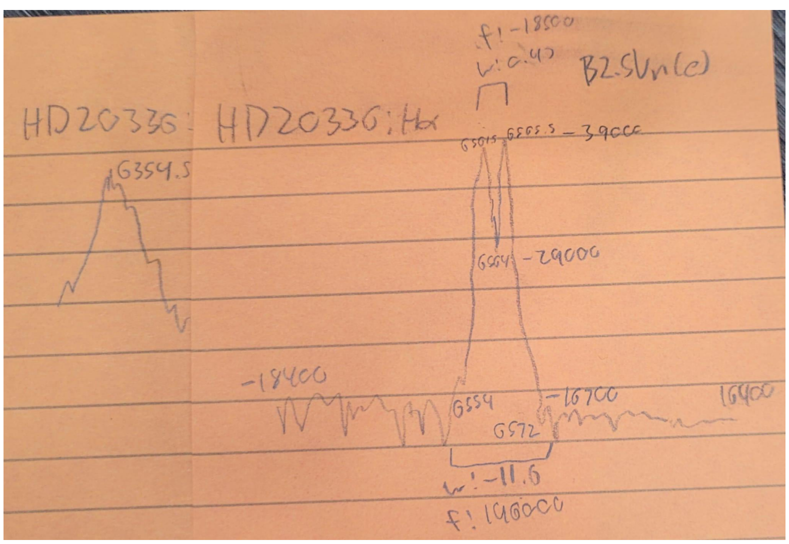


Figure 1: How values were collected

Looking at an example spectra, Figure 2 is taken from BetaCMi and is a good example of a Be star spectra. You may notice the edge of the H alpha seems to be slightly cut off, this is unfortunately for two reasons. Firstly, I originally chose this setting unfortunately with the edge near H alpha given the neon lamp we have does not have many calibration lines in that range. Due to the timing of when it was clear, I did not have time in between the back-to-back observing nights to test the data reduction to see if H alpha went past that point, which I did not expect it would, and redo it, so I stuck with what I had. While there is a fainter line at 6652 I may have been able to include in the end, binding it to 6532 Å to 6652 Å, it would have been close and without more time would not have been realistic. Given this, it did not seem to impact my data analysis that much but may have opened more routes of analysis.

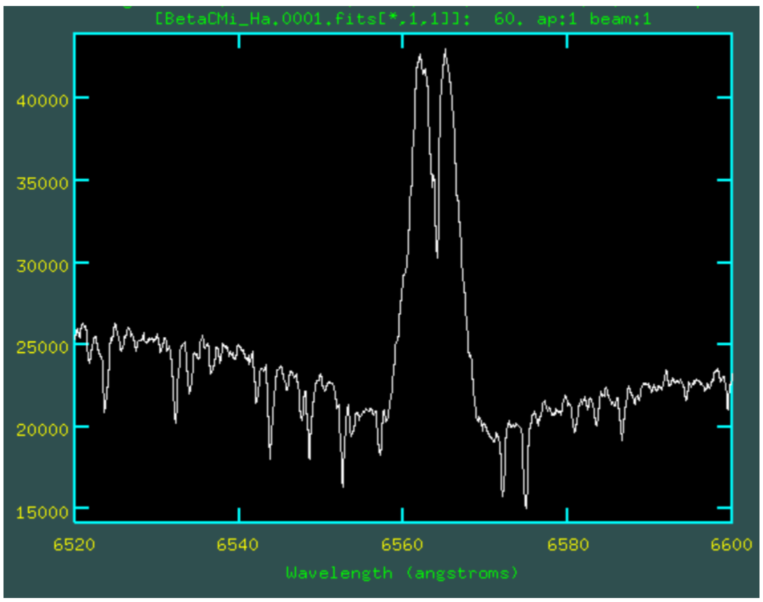


Figure 2: Example spectra (BetaCMi). The slopes from the edges show photospheric absorption, then an emission component in the center and an absorption component within the emission.

Scientific Theory

To start what causes these lines in the first place? When taking spectra we are really looking at its Black body curve, but a star, while close to a black body, has some irregularities. As can be seen in Fig. 3 you can almost trace another curve at the absorption, which would be the photospheric components with a lower temperature than the core.

Now what determines the line thickness? The convolution of a Lorenztian from natural broadening from things like the uncertainty principle with a Gaussian from the distribution of Doppler shifts in different moving particles. This results in what's called a Voigt profile which effectively has a Gausian in the center with Lorenztian wings.

Now looking back at Be star in Fig. 2. In a star accreting gas with a disk or sphere around it that hot gas adds emission lines on top of the absorption of the photosphere. Hot gas like this creates emission lines that stack over the profile of the star. However, the photosphere is often much hotter than the gas the photospheric absorption component leads to be wider than the emission line. This happens from more scatter and the wings of the Lorenztian. Moving on, as the gas cools at the edges this forms an absorption line due to the black body curve dropping down in front of the rest of the cloud, all be it much smaller due to the cooler temperature, forming an absorption line within the emission line. We will talk about extreme cases of this absorption in shell-like stars later.

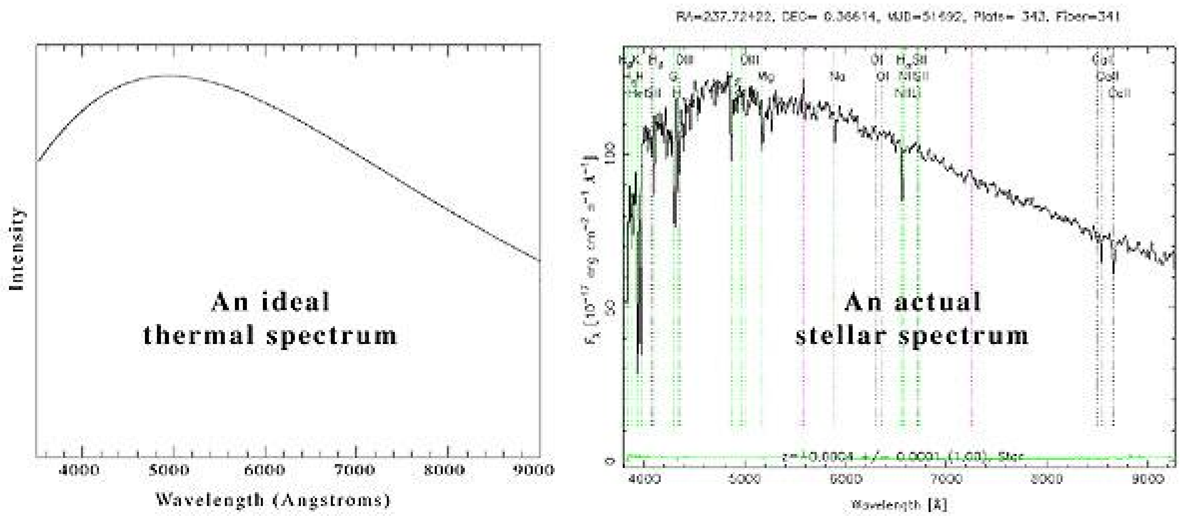


Figure 3: Comparison of ideal black body vs. steller spectrum. As you can see you can almost trace another curve at the absorption, which would be the photospheric components with a lower temperature than the core. Source: https://cas.sdss.org/dr6/en/proj/basic/spectraltypes/stellarspectra.asp

Data Analysis

Moving onto my data, I initially qualitatively grouped my lines purely on H alpha absorption, before taking any numbers or math from them the categories I ended with are only emission (i.e none/limited absorption component), significant extra peaks outside of standard absorption, "standard" (sub: absorb below continuum), emission below continuum and no emission. I chose these categories purely based on the visual aspects of the line. However, this noticeably correlates well with how Be variable stars would behave to behave. Many of them are variable in fact, behaving like B stars, Be stars, B[e] stars, shell stars, etc over time. We see a variety of different stages of Be stars. I.e starting at no emission, gradually emitting a gaseous disk, the emission taking over the absorption, and then the edges of the emission cooling, forming the baby absorption line within the emission. Other properties, such as the disk's inclination angle, which will be discussed more later, can also be variable.

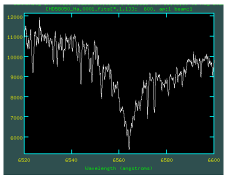
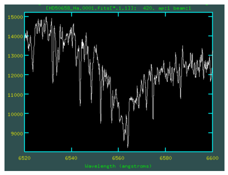
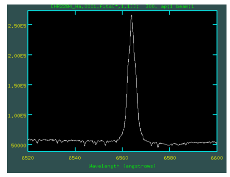
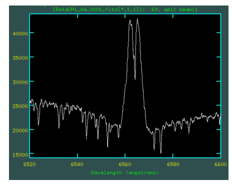
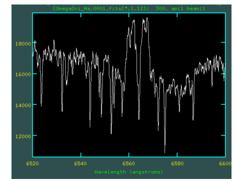
No Emission	Emission below continuum:	Zero/Minimal Absorption	Standard	Significant Absorption
HD58050 KappaDra RhoAur 	HD164284 HD50658 ThetaCRb 	HD203467 HD56139 HD65875 HIP19343 HR2284 	BetaCMi HD66956 HD20336 HD51354 ZetaTau HD107348 HD183914 HD185037 	HD58647 NuGemini OmegaOri 

Table 2: Initial qualitative categories created on first glance

Looking at the other wavelength range, only half of the 18 stars taken in the 6352A to 6506A range had related noticeable differences to me compared to the control stars. This included a variety of forbidden lines, some of which I did expect going in. I found [OI] at 6363 a variety of [Fe] lines at 6384, 6418, 6434, and 6456 as well as what I believe is a [Si] at 6354 (see Fig. 3 for examples).

I noticed a significant correlation before even doing statistical analysis. Of the 18 observed stars (excluding controls) that I took spectra in the 6352A to 6506A wavelength range, about half, 8, had an equivalent width < -9 on the emission component. All 9, HD65875, HR2284, ZetaTau, HD56139, HD107348, HIP19343, HIP17851,HD20336, HD203407 had noticeable emission in the 6352A to 6506A wavelength range. Only one other star had emission in this range, BetaCMi. However, as can be seen back up here in Fig 2, there is a significant absorption component in its emission, which would reduce the flux, and thus the equivalent width, of the emission line. Why there would be such a correlation? There are two reasons I posit. Firstly, simply a more intense emission would show smaller spectral features, like these forbidden lines we see. Secondly, wider and bigger emission lines correlate to a higher temperature as we explored earlier. This higher temperature of a gas cloud could also indicate a higher temperature of the star that accretes it. This provides an outlet to examine this in the context of spectral type. Unsurprisingly we find a noticeable correlation. 7 of the 9 with these forbidden line features were spectral type B1- B3 with HD107348 and BetaCMi at spectra type B8. Two other stars I observed in this wavelength range, Omega Ori and HD164284, were B3 or hotter, B3 and B2 respectively. However, as I explained earlier these emission stars often exhibit variability; HD164284 when observed had no noticeable emissions component in H alpha, indicating that it was in a stage where it did not have a disk or we did not see the emission, thus would not have any other emission of course. Running Fisher Exact Test on the 17 remaining stars taken in this wavelength range provides a value of 0.0152 which is very significant within a p-value of < .05.

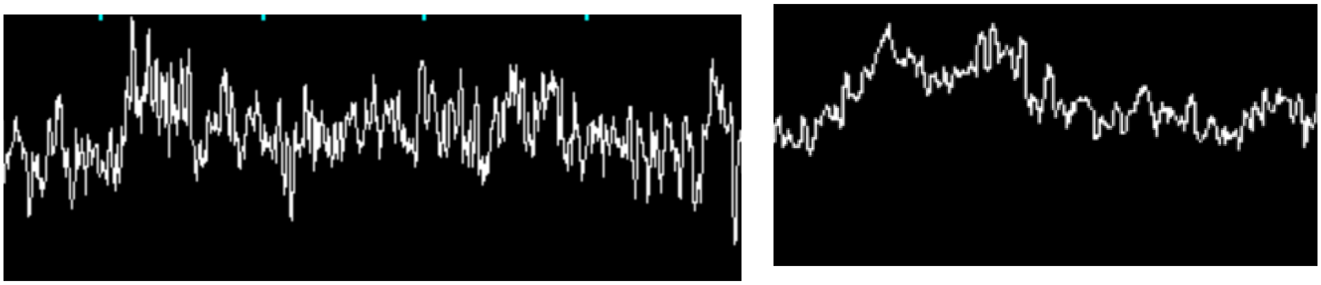
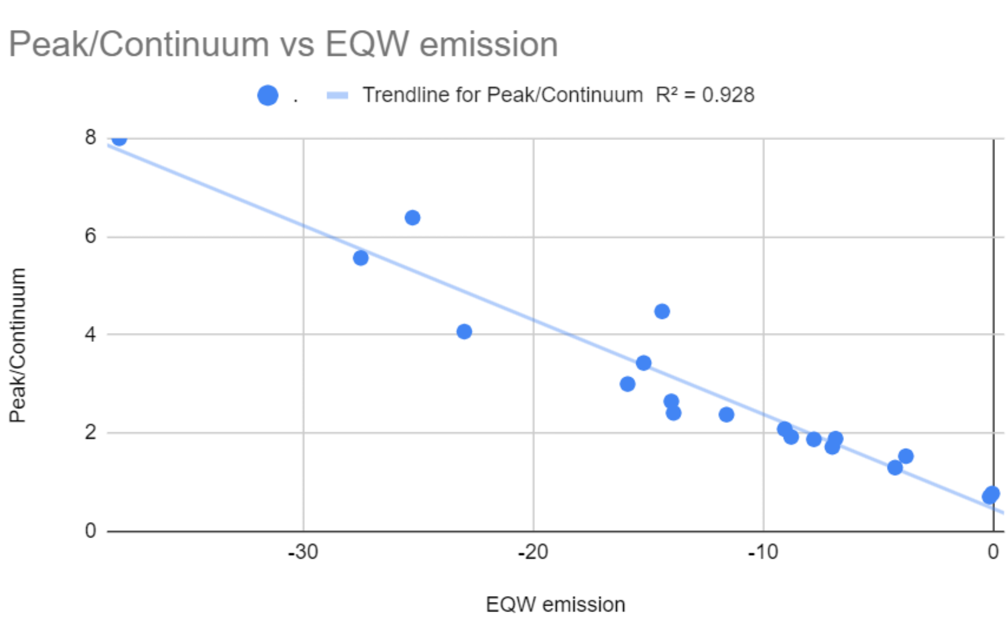


Figure 4: Left: [Fe] 6384 and 6456 emission lines in HD65875. Right: [Fe] 6384 in emission line in Zeta Tau

Pivoting to looking more at some of the actual numbers taken. If we look graph the equivalent width of the H alpha emission vs a normalization of the peak of the line to the continuum by dividing the peak by the continuum. This ratio is done to keep it consistent across observations of different exposure and magnitudes. We find a strong linear correlation R^2 value=0.928.



Graph 1: Relationship between the ratio of the peak of the emission line over the continuum to the equivalent width of the emission line. Note how it is almost perfectly linear.

This is not surprising at all, but proves what we know about lines. More flux is significant of higher temperatures due to a higher black body curve, which also causes more scatter as we discussed prior thus widening the line.

Bridging theory and quantitive analysis: Looking at stars like HD58647 you can notice the absorption component goes deep below the emission continuum. This may indicate an obscuring of photospheric light. This is indicative of shell Be stars; likely when gas is aligned to us. We often think of this as a "Shell star." We can also identify shell stars by absorption in the Fe component, such as in ZataTau shown above. Hanuschilk puts forth a crude equation to determine shell stars of (normalized to the continuum)

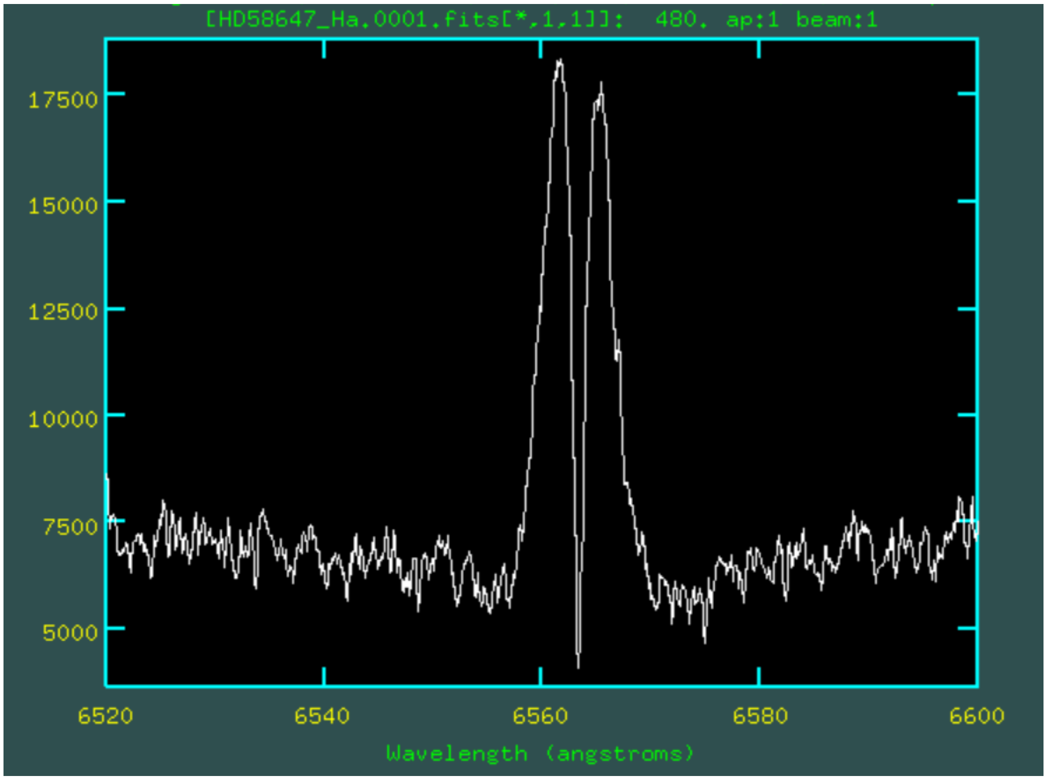


Figure 5: HD58647 strong absorption component

Bridging theory and quantitive analysis: Looking at stars like HD58647 you can notice the absorption component goes deep below the emission continuum. This may indicate an obscuring of photospheric light. This is indicative of Be shell stars; likely when gas is aligned to us. There are conflicting definitions of these shells stars so the criteria I will use is from Hanuschilk (cited in the figure below). We can also identify shell stars by absorption in the Fe component, such as in ZataTau shown above (Fig. 4). Hanuschilk further puts forth a crude equation to determine shell stars with F_p being the Flux at the peak normalized to the continuum (divided by continuum) and F_{cd} being the flux at the end of the inner absorption line.

$$
\begin{aligned}
F_{\rm p}/F_{\rm cd}({\rm H}\alpha) \; &\geq \; 1.5 \text{ for shell stars,} \\
&= \; 1.5...1.2 \;\text{ in intermediate cases,} \\
&\lesssim \; 1.2 \text{ for Be stars.}
\end{aligned}
$$

Figure 6: Relationship between the flux of the peak of the emission line to the bottom of the inner absorption line end, both normalized to the continuum as 1 (divided by continuum flux). From Hanuschik: https://articles.adsabs.harvard.edu//full/1996A%26A...308..170H/0000175.000.html

This is a metric of the amount of absorption compared to the emission peak that could indicate a shell star. Testing this we find HIP17851, a well-known shell star, HD58647 HD51359, Omega Ori, and Nu Gem to display shell-like absorption; as well as Zeta Tau based on its significant Fe absorption (Shown in Table 3).

Shell-like Stars
HIP17851 HD58647 HD51359 Omega Ori Nu Gem Zeta Tau

Table 3: Stars that show shell-like properties according to Hanuschilk's criteria

In all we have looked at a few different methods and outcomes of grouping: visual grouping of Hα that correlated to stages of variability, the existence of emission in other wavelength ranges with a posited theory of temperature, a correlation between equivalent width of emission and the peak, as well as shell vs. non-shell stars.

Next steps

In future research that could be done I would recommend shifting the current wavelength ranges to include all of Hα and the 6300 Å oxygen line as well as significant blue Fe lines would provide more insights into these processes. Having more objects observed with other emission components could also be helpful in analyzing more detailed categories. For example, I was not able to look at the difference in spectral subtypes (i.e. B1, B2, B3… etc.) due to there being only 2 or 3 in each category.