UNIVERSITY of CALIFORNIA
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A COMPARISON OF SOLAR AND GALACTIC STELLAR PROPERTIES TO SOLVE THE MYSTERY OF EXCESS CHROMOSPHERIC HEAT

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Abstract

A Comparison of Solar and Galactic Stellar Properties to Solve the Mystery of Excess Chromospheric Heat

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Looking at stars similar to our Sun, I compared the projected rotational velocities, vsin(i), to the absolute visual magnitude, M_v, the B-V color index, and the calcium II emission from the chromosphere, log(RHK_c). I saw a correlation between the vsin(i) and the and the B-V color, as well as the calcium II emission and vsin(i). However, I did not see much of a pattern between the calcium II emission and the B-V color.

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To my mom,

Linda Redenbaugh,

The person who has always been there.

Acknowledgements

I would like to thank Graeme Smith for all of his help, patience and guidance throughout this process of starting and completing my thesis. I would like to thank all of my family and friends, way too many to name, for always being there and encouraging me to continue on when I didn't think I had anything left in me. Finally, I would like to thank Robert da Silva, for saving me from having to repeat 50 hours of work.

1 Introduction

1.1 The Sun

1.1.1 Sun Structure

The Sun has several layers, see Fig. (1.1). The inner most part is the Sun's core with a temperature of about 15.7×10^6 K. The visible surface of the Sun, the photosphere, is made of hydrogen, helium and small amounts of other elements, including iron, nickel, oxygen, silicon, sulfur, magnesium, carbon, neon, calcium, and chromium [1]. Beyond the photosphere is an outer layer of the Sun's atmosphere which is called the chromosphere. The chromosphere is complex and mysterious. The chromosphere lies between the photosphere and the corona and can only be seen during a total eclipse of the Sun. It is about 4×10^3 km in thickness. As you get further away from the Sun, it gets colder within the photosphere, but once you reach the chromosphere it gets a lot hotter. For example, the average temperature at the surface of the Sun is about 6×10^3 K, whereas the chromosphere can get up to 1×10^5 K. The coolest region of the Sun, approximately 500 km above the photosphere, is about 4×10^3 K. It is not understood why the Sun behaves in this manner. In this thesis we look at stars that share some of the same properties with our Sun to try and figure out why the chromosphere giving off so much excess heat.

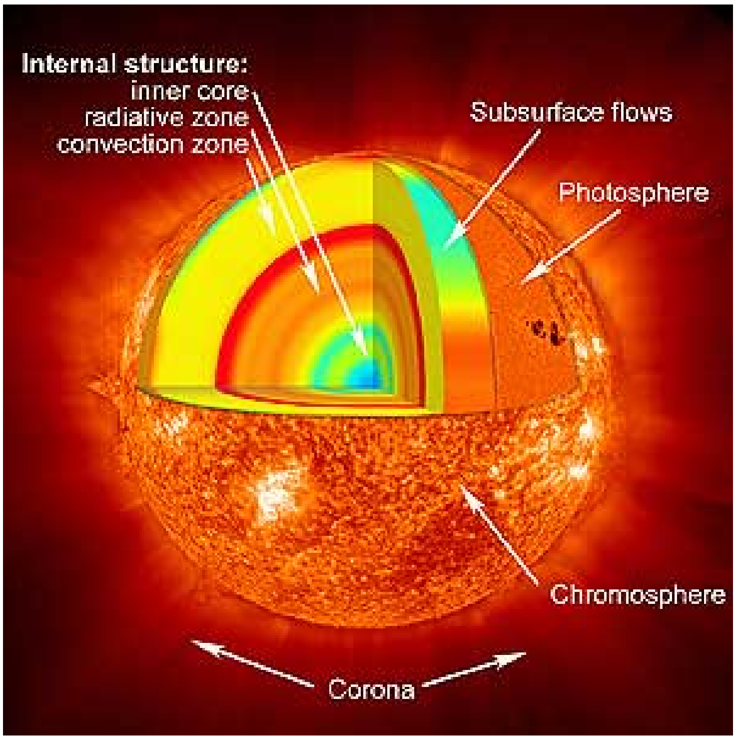

Figure 1.1: **Sun layers** A diagram of layers of the Sun [2]

1.1.2 Chromosphere

In the chromosphere of the Sun the temperatures are hot enough to singly ionize a large portion of the calcium. The temperature of the chromosphere is produced by a balance between the energy going into the chromosphere and the energy coming out of the chromosphere. The energy going in seems to be related to the magnetic field, and radiation by calcium II ions is one of the dominating sources of the energy leaving the chromosphere.

1.1.3 Calcium II Ions

We are able to look at different regions on the surface of our Sun and look at light being emitted by calcium II ions. By observing these regions, we are able to recognize that more ions are emitted in different locations of the Sun. In fact there is a direct correlation between the temperature of calcium II ions radiating into space and the magnetic field of the Sun. By looking at an image of the Sun using a violet calcium-K filter we are able to see the active regions of the Sun, which is where the magnetic field is the strongest. This is also where Sun spots occur.

1.1.4 Magnetic Fields

It is theorized that there is a dynamo in our Sun creating a magnetic field. The dynamo would be produced by a current of electrically conducting ionized gases within the Sun. The currents in the Sun are created by different parts of the Sun rotating at different velocities. This creates a magnetic field by Ampere's Law, which is

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_o I_{enc}. \tag{1.1}$$

The faster the Sun spins the stronger the dynamo becomes. The stronger the dynamo, the stronger the magnetic field. Likewise, the stronger the magnetic field the stronger the emission of light from Ca II ions. We are not able to measure the magnetic field directly, however we are able to measure what is called the vsin(i), the projected equatorial rotation speed, as well as the intensity of light emitted by the Ca II ions in a stars' chromosphere.

1.2 Other Stars Similar to the Sun

In this work we look at other stars similar to our own Sun in order to compare vsin(i), B-V color, M_v, log(RHK$_\mathrm{c}$) and find a correlation between them. The main properties we look for in choosing comparison stars is that they have relatively the same mass as our Sun and are main sequence stars.

1.2.1 Main Sequence

The Sun is a main sequence star. A main sequence star is one that creates energy from the fusion of hydrogen into helium. Main sequence stars have a high metallicity. The metallicity of a star is the amount of elements other than hydrogen and helium. Younger stars, such as our Sun, have a higher metallicity than older stars. When plotting stellar color against brightness, the main sequence stars stand out in a band, see Fig. (1.2). These plots are known as Hertzsprung - Russell (H-R) diagrams. H-R diagrams are important because they can tell us a lot of useful information about a star such as the temperature and luminosity.

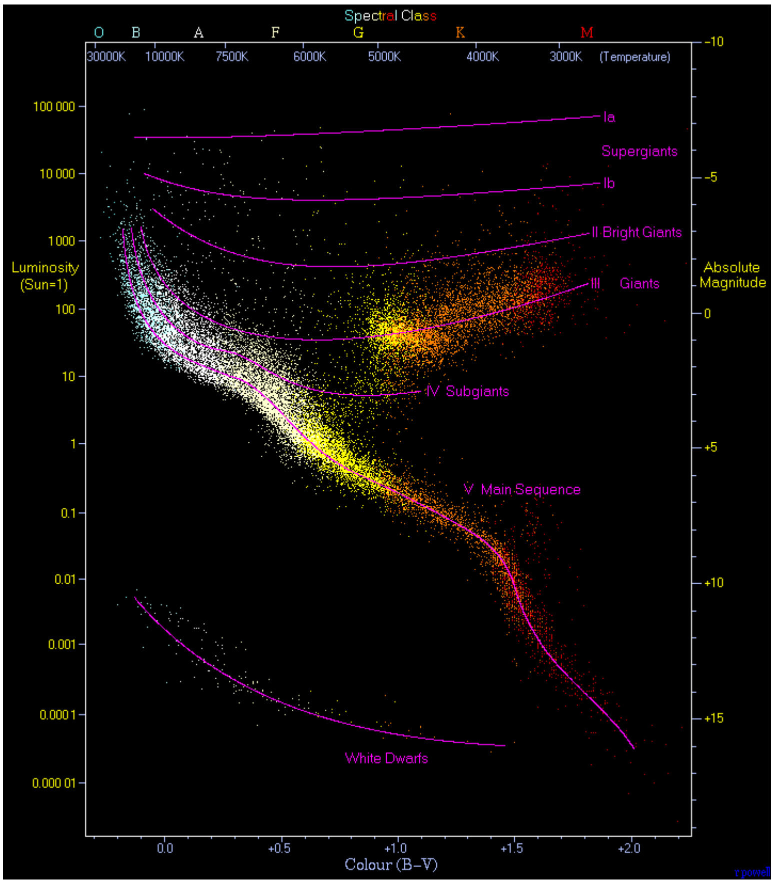

Figure 1.2: **An H-R diagram** A Hertzsprung - Russell diagram of the absolute visual magnitude, M_v versus the B-V color index [3]

1.2.2 VSin(i)

Vsin(i) is the projected rotational velocity of a star, see Fig. (1.3), where v is the equatorial velocity and i is the inclination angle from the line of sight to the Earth. It is measured from the Doppler broadening of absorption lines in the spectrum of a star.

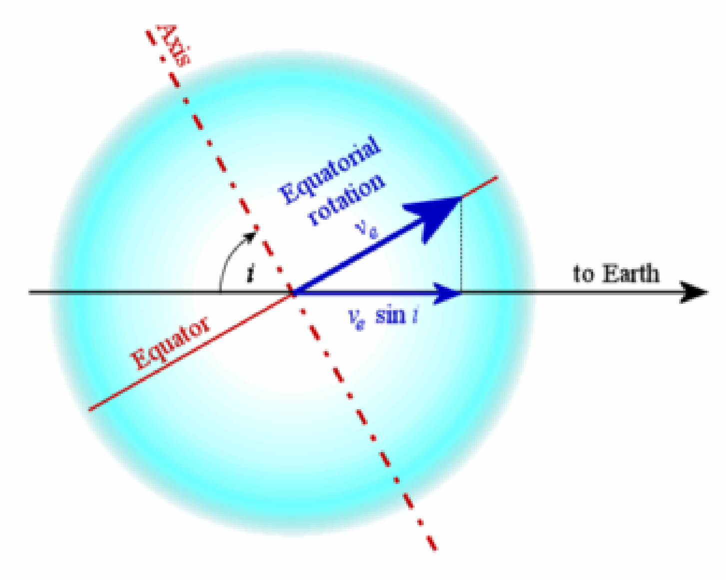

Figure 1.3: **Geometry of vsin(i)** A diagram of the geometry of vsin(i) [4]

1.2.3 log(RHK$_c$)

The log(RHK$_c$) is the calcium chromospheric emission index. Defined by,

$$\log_{10}(RHK_c) = \log_{10}\left(\frac{L_{Ca}}{L_{Bol}}\right) \tag{1.2}$$

it is the logarithum of the ratio of the energy radiating into space from calcium II ions per second in the chromosphere to the total energy radiating into space from a star. Since the total energy radiating into space is always greater than the energy radiated by calcium II ions in the chromosphere, this number will always be negative.

2 Procedure

2.1 Finding VSin(i) Values

Given a list of about 3,000 main sequence stars by my technical advisor, Graeme Smith, I used a database of catalogs called VizieR Service [5] to find different parameters of the stars, most notably values of vsin(i). The VizieR Service provides many different astronomical catalogs. Using three of these catalogs I was able to find most of the data I needed for comparison of the stars, see Fig. (2.1). For all of the values I collected, I set the "maximum entries per table" to be 9999, the "output layout" to be "tab-separated-values" and the "target dimension" to be 4 arc-sec. For the parameters selected, T_{eff} is the effective temperature, V_{MAG} is the absolute visual magnitude and evsin(i) is the uncertainty of vsin(i). Having described these parameters, I was able to extract vsin(i) values for 2239 stars.

Astronomical Key Words	Catalog	Sub-Catalog	Sub-Sub Catalog	Parameters Selected
Abundance	Spectroscopic Properties of Cool Stars I. (Valenti+,2005)			Teff and Vsini
Rotational Velocities	Rotational Velocities of Stars Glebocki+,2000	Catalog of Rotational Velocities		Vsini and eVsini
Velocities	Geneva-Copenhagen Survey of Solar Neighborhood (Holberg+,2007)	Recalibrated Astrophysical Data (2007 Version)	Kinimatical Parameters (From 2004 Version)	logTe, VMAG and Vsini

Figure 2.1: **Parameters used in VizieR Service** A table of parameters used in VizieR Service to obtain the set of values I used for graphs.

My first objective was to compare the different vsin(i) values from the different catalogs. I plotted the Holmberg+,2007 vsin(i) values against the Valenti+,2005 vsin(i) values in order to see the correlation between them. The plot, see Fig. (2.2), has minimal scatter, showing that the Holmberg and Valenti values of vsin(i) have good corresponding data. I then graphed the Holmberg+,2007 vsin(i) values against the Glebocki+,2000 vsin(i) values. This plot produced a larger amount of scatter, showing that the values did not correspond as well with each other. Given this information, I determined that the Holmberg values for vsin(i) are the most convincing. I put together a list of vsin(i) values with Holmberg's values as the primary velocities, Valenti's as the secondary velocities, and Glebocki's as a last resort in order to create a more complete list of vsin(i) values.

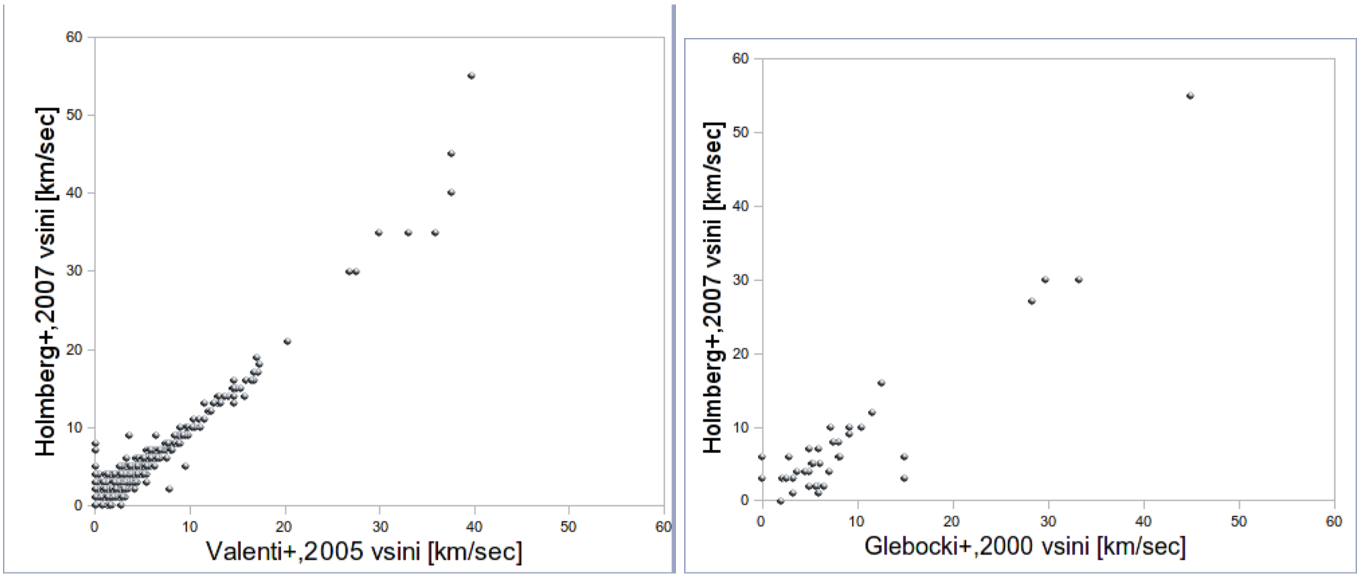

Figure 2.2: **Holmberg vs. Valenti compared with Holmberg vs. Glebocki** Values of Holmberg+,2007 vsin(i) values against Valenti+,2005 vsin(i) values compared with Holmberg+,2007 vsin(i) values against Glebocki+,2000 vsin(i) values

2.2 B-V Color, Absolute Visual Magnitude M_v and log(RHK$_c$)

Once I had this list of vsin(i) values, I was given a table of absolute visual magnitude, M_v, B-V color and log(RHK$_c$) values by Graeme Smith for my list of stars. The color index is proportional to the temperature of the star. B is the star's magnitude measured through a blue filter and V is the star's magnitude through a visible "peaking in green" [6] filter. B-V is then the color index of the star. As the star gets cooler, B-V increases. Given these data, I was able to plot M_v versus the B-V color. This plot, Fig. (2.3), is a version of the H-R diagram, and shows that the stars in my sample fall along the main sequence.

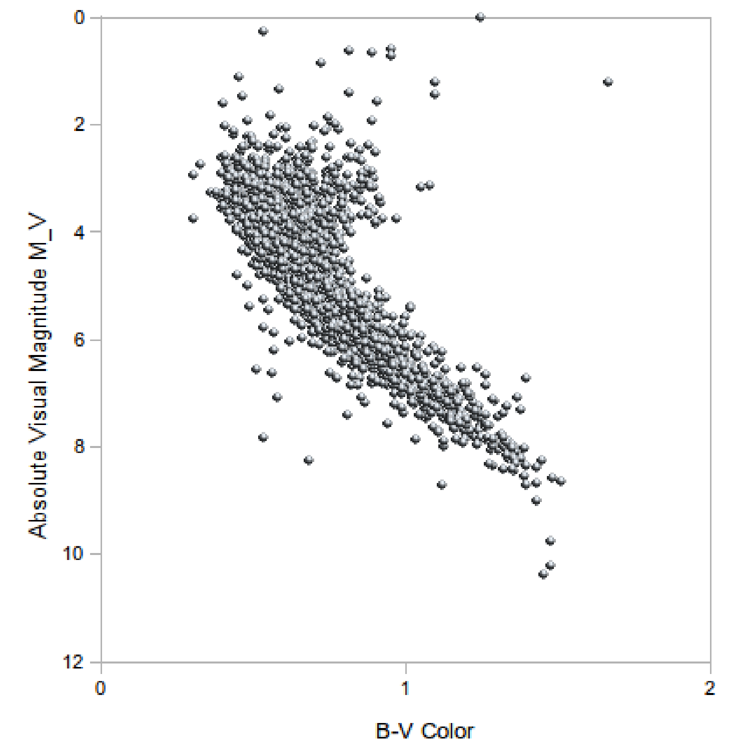

Figure 2.3: M_v **versus B-V** Absolute Visual Magnitude M_v versus B-V color of the stars in my data sample. Looking at M_v, the axis corresponds to how bright a star is, the lower the value the brighter the star. For B-V color index the larger the number, the cooler the star's temperature. A color index of 0 would be the hottest stars and a color index of 2 would be the coolest in my sample.

I then made a plot of B-V color versus the list of vsin(i) values I created, as well as a plot of vsin(i) values against the B-V color. I made these two plots in order to see if there was a correlation between the projected rotational velocities of the stars and their B-V color. The plot of B-V versus vsin(i) showed a curve that went like $-\ln(x) + c$, see Fig. (2.4). There was a trend in the highest vsin(i) values, showing the fastest rotation in the hottest main sequence stars.

I graphed the $\log(RHK_c)$ against the B-V color, see Fig. (2.5). The plot did not show much of a relation between the calcium emission index and B-V.

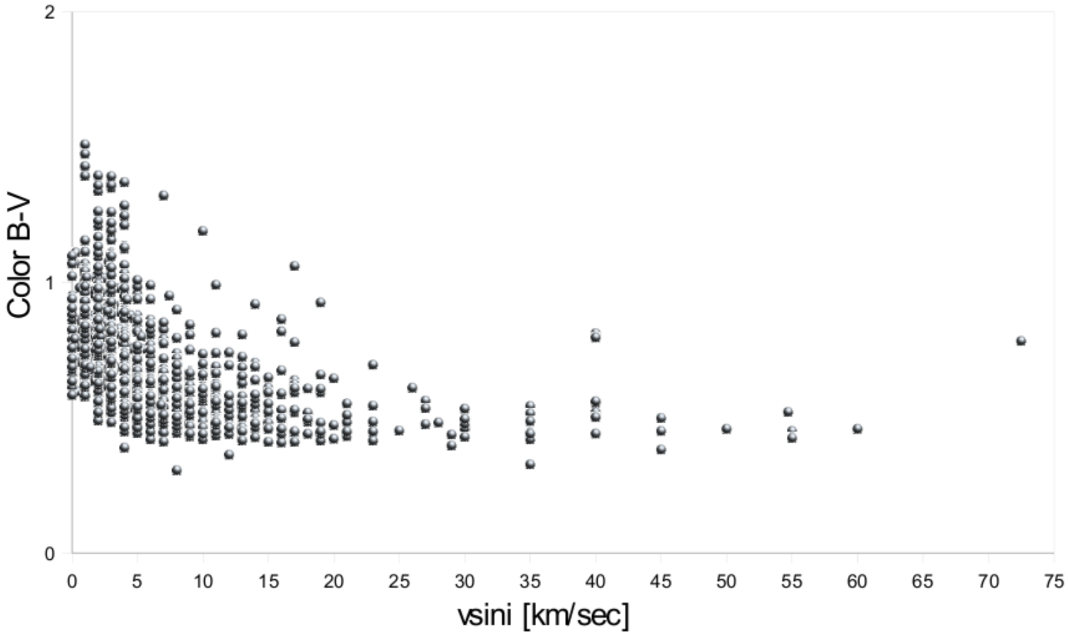

Figure 2.4: **B-V versus vsin(i)** B-V color versus vsin(i) of the stars I used in my data set.

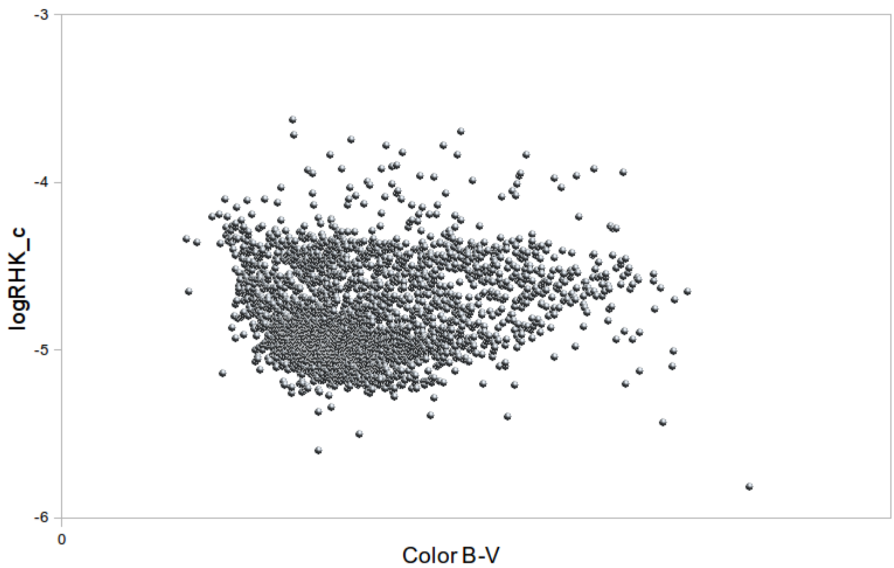

Figure 2.5: log(RHK_c) **vs. B-V color** The calcium chromospheric emission index, log(RHK_c) against the B-V color

The last to plot was the calcium emission, log(RHK$_c$), against the vsin(i) values, see Fig. (2.6). This plot suggests that there is some correlation between the values. It is this result that we want to look at in more detail. In order to see a parallel between these stars and the Sun, I was

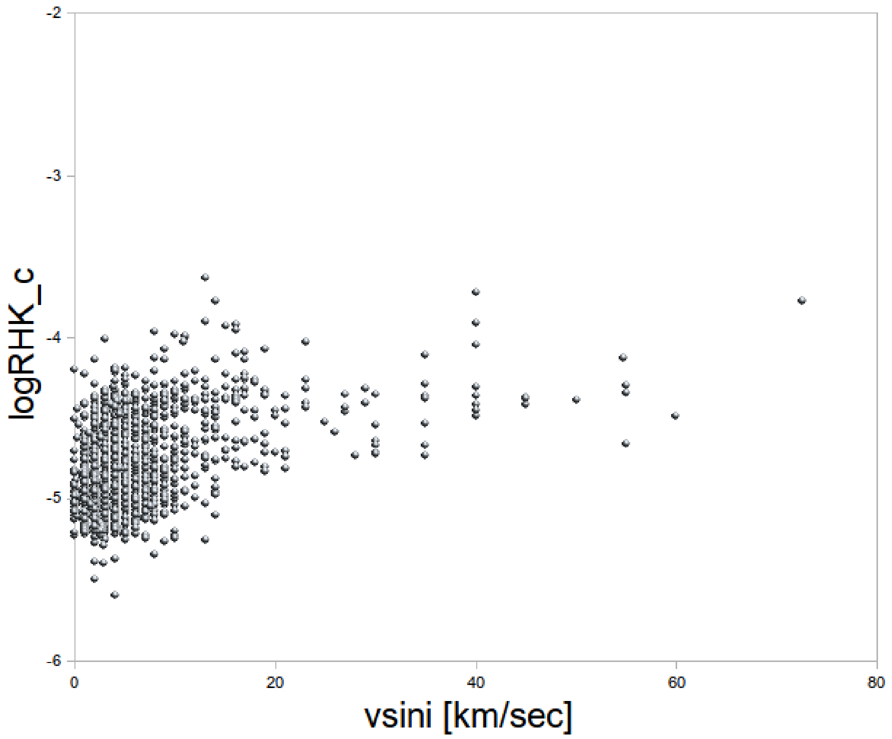

Figure 2.6: log(RHK$_c$) **vs. vsin(i)** The calcium chromospheric emission index, log(RHK$_c$) against vsin(i).

to plot log(RHK$_c$) versus vsin(i) of the stars with color index similar to the color index of our Sun. I have placed the following plots in the appendix. Our Sun has a B-V of about 0.65. I graphed samples for three separate ranges in the B-V color index, the first being from 0.4 to 0.5, Fig. (3.1). The following step was to plot the calcium II emission against the projected rotational velocities for the color index from 0.5 to 0.6, Fig. (3.2). Finally, the course of plotting the calcium II emission versus the projected rotational velocities for the the stars with color index between 0.6 and 0.7, Fig. (3.3).

3 Conclusion

The chart of B-V color vs. vsin(i) showed a trend for higher vsin(i) value to have a lower B-V color index which would mean a high temperature of the star would correspond to a higher projected rotational velocity. For the graph of log(RHK_c) vs. vsin(i), the image suggested an agreement between the calcium II emission and the projected rotational velocity for the higher values of vsin(i). These plots suggest that these three parameters are all related, however when plotting log(RHK_c) against B-V color, there doesn't appear to be a relation between them.

3.1 Sources of Error

While putting all of the data together, there could have been mistakes of lining up the wrong vsin(i) value with it's corresponding M_v, B-V, or log(RHK_c). There could have also been problems because the actual vsin(i) value was measured wrong. One of my main concerns is that the inclination angle, when measuring vsin(i), is unknown. This could be a large problem since the angle can vary from 0 to 90 degrees. If, for example, the inclination angle is 0 degrees, then the axis of rotation of the star would be pointing directly at the Earth and the rotational velocity would appear to be 0 km/sec. However, if the inclination angle is perpendicular to the line of sight of the Earth, then the exact rotational velocity would be known. Therefore, if the value of vsin(i) is high, then the inclination angle would be greater and a better projection, which would mean that it was close to the actual rotational velocity. If the vsin(i), on the other hand, is really low, it might be because the inclination angle is at a very low angle rotating fast, or it might be at a high angle rotating slowly The actual velocity of the star is wanted instead of the projected rotational velocity since the inclination angle is unknown.

3.2 Future Work

The rotation of the stars suggest that there is a dynamo as predicted. This dynamo creates a magnetic field, which corresponds to the heating of the chromosphere. The hotter the chromosphere is, the stronger the calcium II emission. And so it appears as though everything is related. However, because of the uncertainty in the measurement of vsin(i), there needs to be more accurate data taken for the rational velocities of stars. There needs to be more measurements taken of the actual rotational velocities instead of the projected rotational velocities. This is a very difficult and time consuming process, but also necessary in order to further the understanding of the relations of chromosphere of the stars.

Appendix

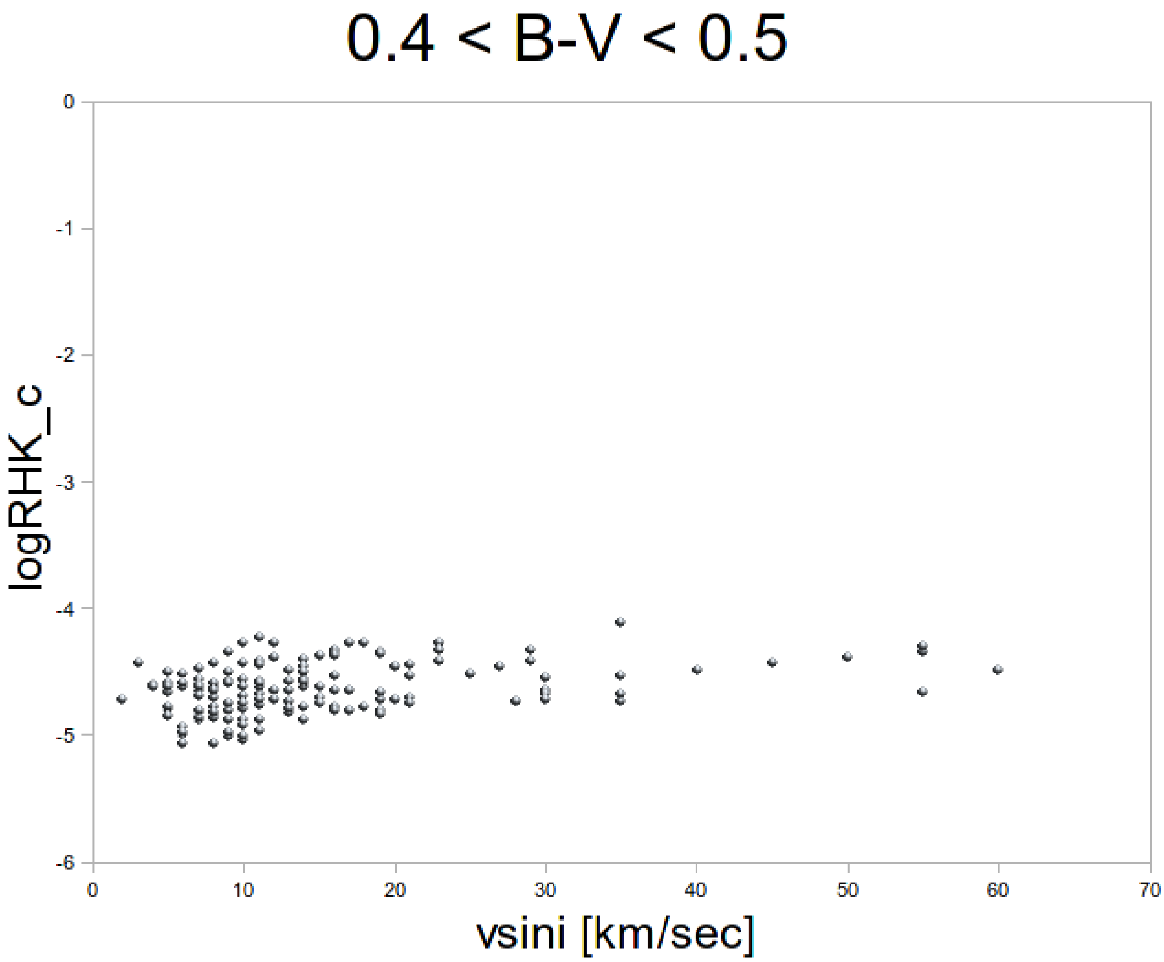

Figure 3.1: log(RHK_c) **vs. vsin(i) for B-V between 0.4 and 0.5** The calcium chromospheric emission index, log(RHK_c) against vsin(i) values for stars with B-V between 0.4 and 0.5.

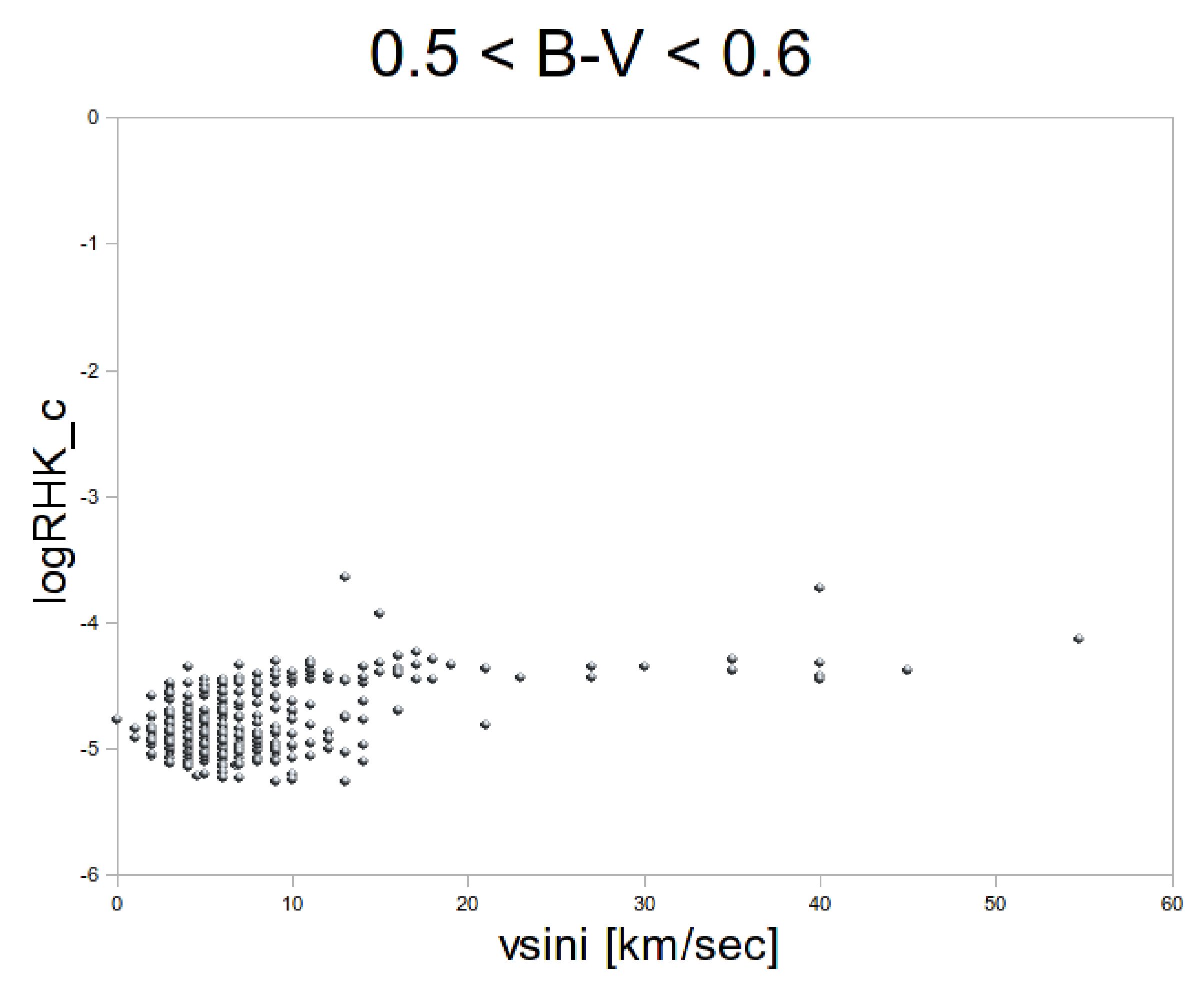

Figure 3.2: log(RHK$_c$) **vs. vsin(i) for B-V between 0.5 and 0.6** The calcium chromospheric emission index, log(RHK$_c$) against vsin(i) values for stars with B-V between 0.5 and 0.6.

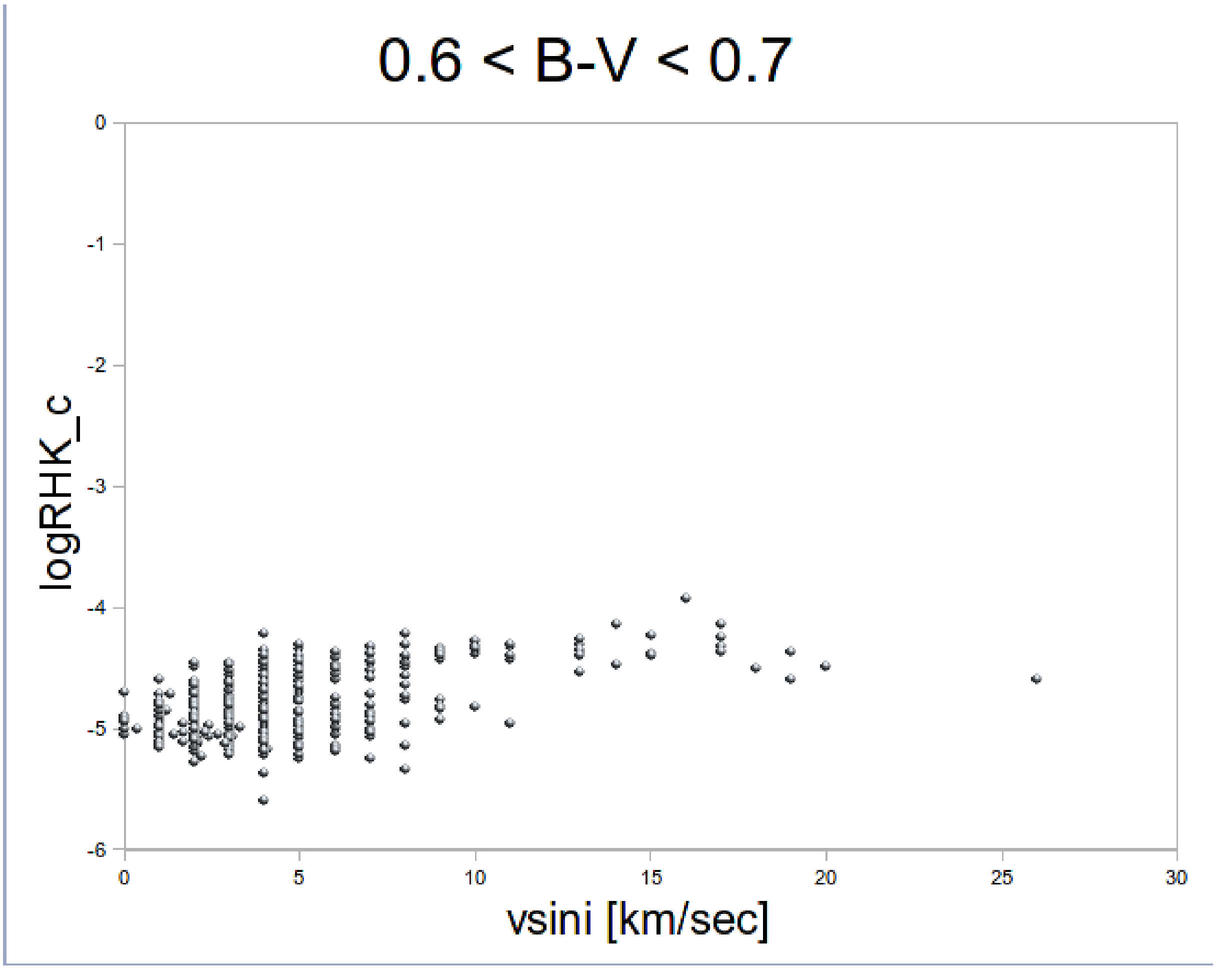

Figure 3.3: log(RHK_c) **vs. vsin(i) for B-V between 0.6 and 0.7** The calcium chromospheric emission index, log(RHK_c) against vsin(i) values for stars with B-V between 0.6 and 0.7.

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