

### Spectral analysis for the RV Tau star R Sct:

In this section, we will take the reader through an example of the analysis we can perform using Coude Feed spectroscopy obtained as a part of our research program. We will use, as an example, the typical RV Tau star R Sct (Shown in figure 1). We will obtain spectra of additional examples of RV Tau and Semi-regular variables and detail the process of spectral line identification and analysis.

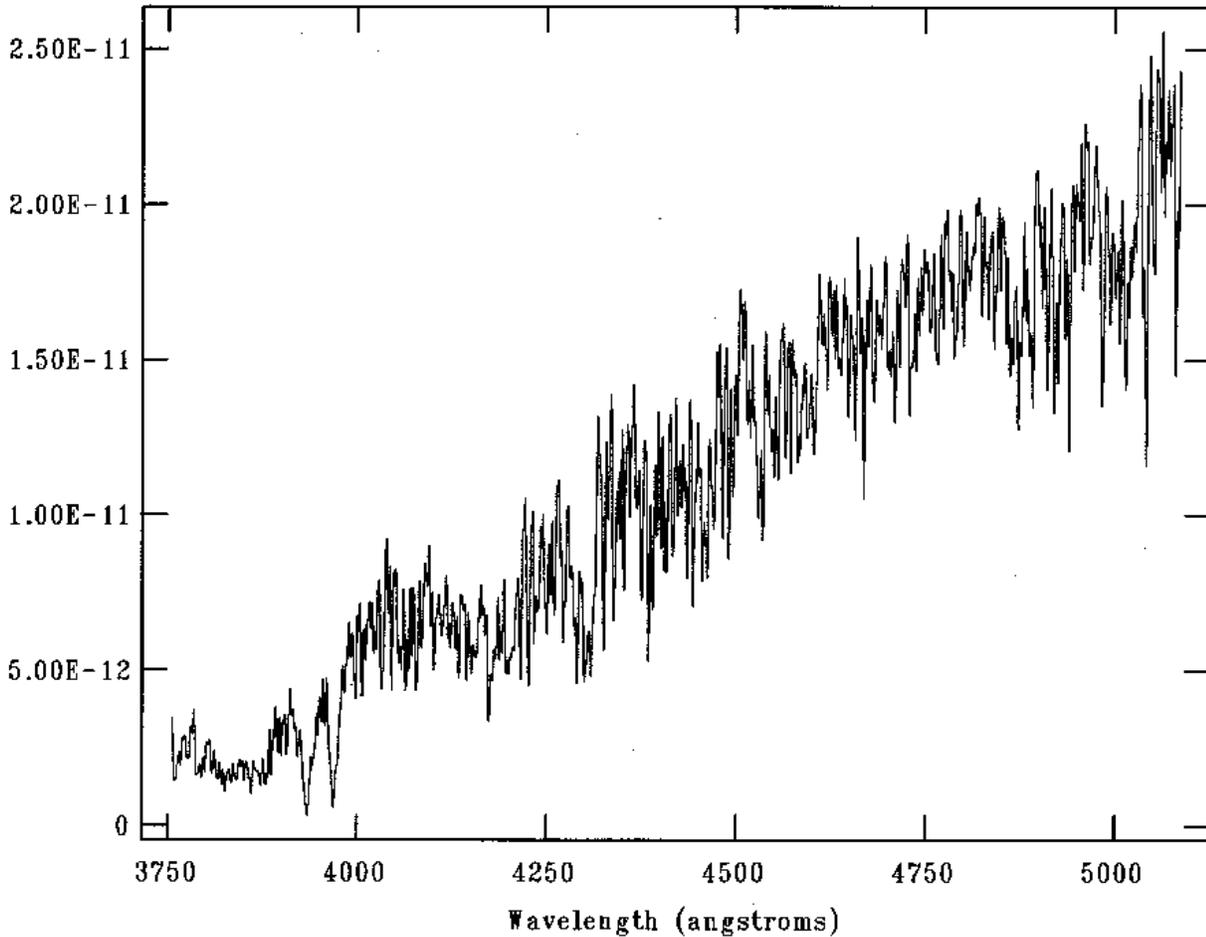


Figure 1 – a Blue region spectrum of R Sct obtained by the TLRBSE program in 2004.

## The Twelve (minus three) Step Program –

### *Step 1. Determine the Spectral Type and Luminosity Class.*

We will perform spectral type and luminosity class estimation for the star by comparison with the Jacoby Spectral Atlas. This atlas includes stars of all spectral types and luminosity classes. (All the Jacoby Atlas spectra are contained on the TLRBSE Coude feed CD). We show one set of spectra from this atlas (Figure 2) covering the spectral types near early G and of luminosity class I (supergiants).

*Note – the terms early and late are used to indicate a relative blueness (hotter) or redness (cooler) in spectra. For example, an early G star might be G1 or G3 while a late G star might be G7 or G9. Similarly early spectral type stars are OBA while late spectral type stars are GKM. RV Tau and SR variables are giant and supergiant stars therefore they have luminosity classes of III, II, or I (where class II has properties in between III and I). Luminosity class V stars, like the sun, are main sequence stars and are generally used for reference as they do not vary and their intrinsic properties are well known.*

“By eye” we can see that the blue spectrum of R Sct (Fig. 1) obtained by the TLRBSE program is very near spectral type G3I. (You should examine other G stars in the Jacoby Atlas, especially of other luminosity classes and confirm this estimation). We will see that further into the analysis, we will be able to check on our initial luminosity estimation when we determine the star’s distance.

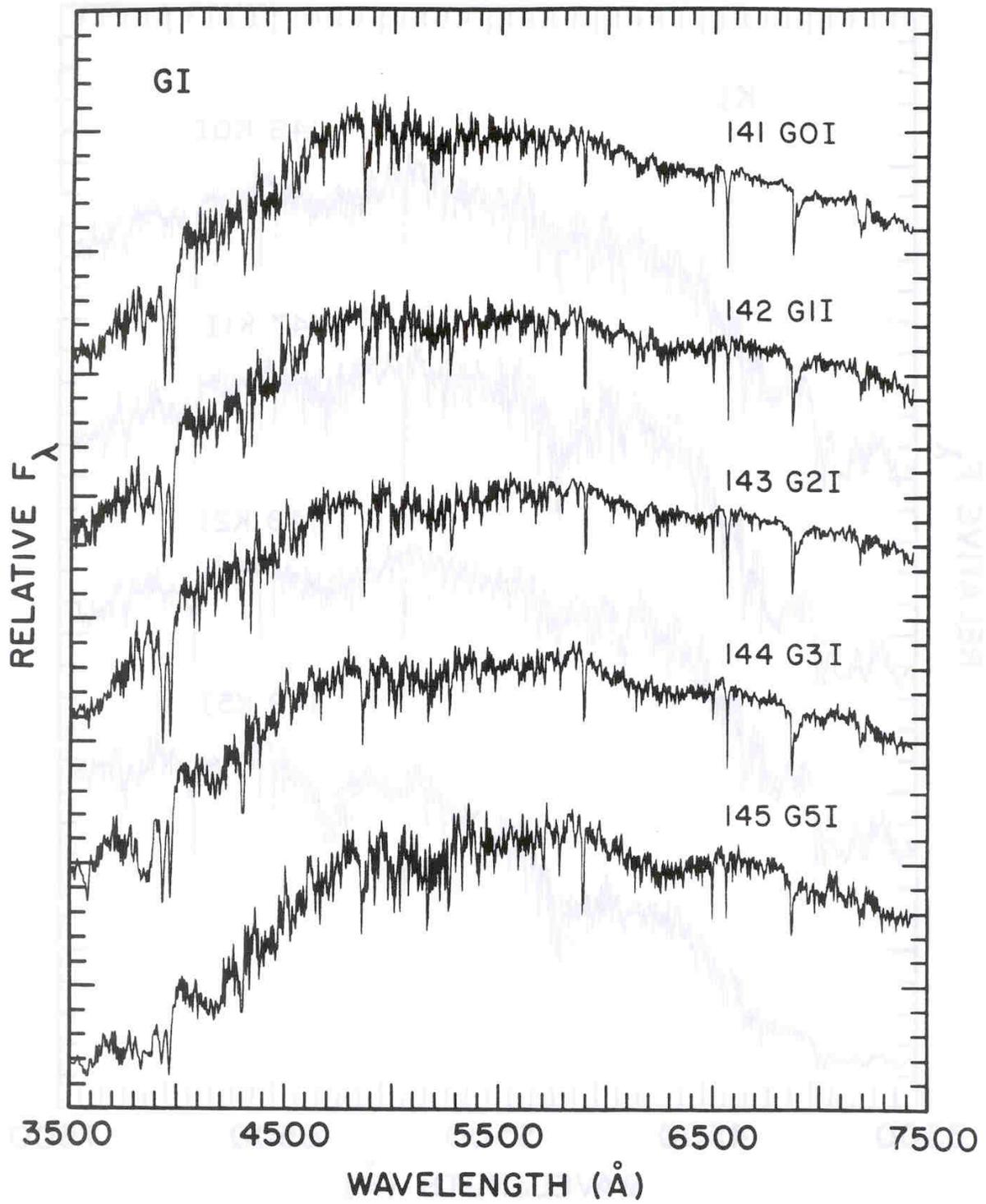


Figure 2- Some example spectra from the Jacoby Atlas near R Sct's type.

*Step 2. Determine the Star's Effective (surface) Temperature.*

Using Table 1 (at the end of this document), we can estimate the effective temperature of R Sct during this particular spectroscopic observation. If the exact spectral type is not listed, you must interpolate within the table to get an estimated value. For our G3I classification, we interpolate to estimate an effective temperature of 5190K.

*Step 3. Determine the Apparent Magnitude.*

Many of our stars are monitored photometrically by the AAVSO. Their web site (<http://www.aavso.org>) provides a light curve generator which can give (as the default) the latest few week time period or (what we usually need to do) a light curve covering the date of our specific spectroscopic observation of interest (see Fig. 3). Since these stars vary, it is important to get the apparent magnitude for the specific date of observation. The dates used by astronomers and the AAVSO web site are Julian Dates (the AAVSO web site also provides a converter from calendar date to JD).

Once at the AAVSO web site, you will see a box on the upper left labeled "Pick a Star". Type the star name (R Sct in our case) into the box, click the "Create a light curve" icon and GO. A light curve for the past 400 days will be generated and plotted. The plot will look similar to that shown in Fig. 3. The light curve for R Sct in Fig. 3 (covering a past epoch) shows that it has a normal magnitude near  $V=5.5$ , and we also see a "dip" during which time it fades by over 2 magnitudes. This type of photometric behavior is the process we are trying to study. How do the spectra change in and out of the dips? What is their cause and how does it influence the atmosphere of the star?

Choosing a light curve range of 20-40 days on either side of the date of the observation you are concerned with, usually helps place the time of spectroscopy into context as to the near-term star behavior.

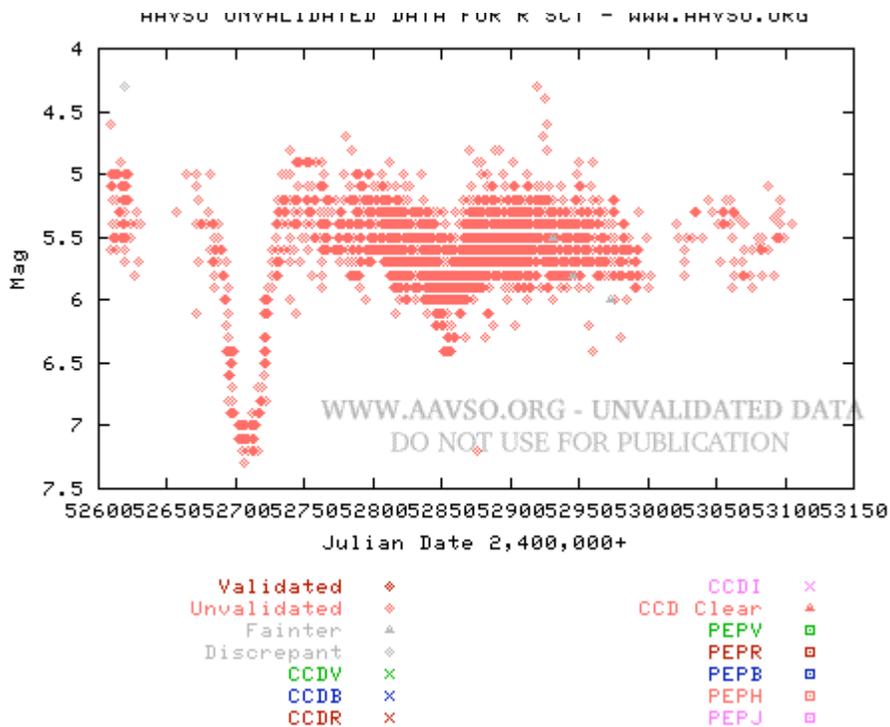


Figure 3 – Example light curve plot for R Sct obtained from the AAVSO web site.

*Step 4a. Determine the Distance and Absolute Magnitude.*

Hipparcos was a European satellite observatory that determined parallax and thus a distance for stars brighter than about 8<sup>th</sup> magnitude. An instrument on Hipparcos, called TYCHO, determined parallax for stars down to about 12<sup>th</sup> magnitude albeit with greater uncertainty. Thus, if a TLRBSE program star is brighter than about 8<sup>th</sup> magnitude, it will be in the Hipparcos catalogue, otherwise it may be in the Tycho catalogue and have a poorer distance determination.

These catalogues can be accessed from the SIMBAD website under Catalogues (<http://simbad.u-strasbg.fr/Simbad>). One can also simply look up the star using the “By Identifier” query at the SIMBAD web site and the parallax from Hipparcos (or Tycho) is listed with the star entry. Remember to pay attention to the parallax uncertainties given.

For R Sct, we find a Hipparcos parallax of 2.32 mas (milli-arcseconds) when we look up the star on SIMBAD. This parallax gives a distance to R Sct of (distance = 1 / parallax in arcsec)

$$d = 1 / 2.32 \times 10^{-3} = 431 \text{ pc.}$$

We will make use of the distance to a star to determine its absolute magnitude ( $M_V$ ). The value of  $M$  along with the apparent magnitude ( $m$ ) at the time of the observation (determined from the AAVSO light curve) allows us to check on the luminosity class estimate we made in Step 1 and provides the luminosity of the star. Note, the absolute

magnitude is designated as M but at times you'll see  $M_V$  (M sub V). The latter strictly identifies the absolute magnitude as being that in the V (visual) bandpass. Absolute magnitudes can be defined in any bandpass, e.g.,  $M_B$ ,  $M_K$ , etc. General use of M (and all uses herein) implies  $M_V$ .

*Step 4b. Find the Distance to the star if the star is too faint to be in either of the above parallax catalogues.*

If no parallax is known, then we can make use a “spectroscopic parallax” to go directly to an estimate of the star’s absolute magnitude. This technique uses a model HR diagram to convert the spectral type and luminosity class estimate into an absolute magnitude (luminosity) estimate. For example, a G2V (i.e., main sequence star) has an absolute magnitude (M) of  $\sim 5$ . Knowing this, and the apparent magnitude, the distance can be estimated.

After step 4a (or directly from 4b) above, the formula

$$m - M = -5 + 5 \log d$$

can be solved to give either M (the absolute magnitude if using step 4a) or to get d (the distance if using step 4b).

For R Sct, we find (using  $d=431$  pc from step 4a and the formula given above) that its absolute magnitude is

$$5.5 - M = -5 + 5 \log (431)$$

re-arranging terms to solve for M gives

$$M = 5.5 + 5 - 5 \log (431) = 10.5 - 5 * 2.6 = -2.6.$$

We see that this value ( $M_V=-2.8$ ) for R Sct is equal to the absolute magnitude of a faint supergiant (only about 1000 times the luminosity of the sun!), but it confirms our initial (Step 1) estimation that R Sct is a luminosity class I star. An H-R diagram shows that an  $M_V$  value of  $-2.6$  is equal to a luminosity class II star, slightly more luminous than a giant (II), but not as bright as a supergiant (I). If your M value and initial estimate of luminosity class do not agree, go back to Step 1 and revise.

At this point, regardless of which step 4 you used, you should have values for your star’s spectral type, luminosity class, apparent magnitude, absolute magnitude, and distance.

*Step 5. Determine the Luminosity of the Variable Star.*

Often in astronomy, we use the sun as a comparison star. This is because we know the physics of the sun well and therefore we know its properties to high accuracy. Table 2 (at the end of this document) gives the fundamental properties for the sun. Ratios are often used as well, as all the nasty (and sometimes unknown) constants drop out of the equations.

Taking the ratio of one of our variable stars (R Sct in this example) with respect to the sun, we can relate the absolute magnitudes of the star/sun to their luminosity as follows,

$$M(\text{star}) - M(\text{sun}) = -2.5 \log (L(\text{star})/L(\text{sun}))$$

To calculate the variable star's true luminosity we take the absolute visual magnitude of the sun to be  $M_V = 4.74$  and the sun's luminosity is

$$L(\text{sun}) = 3.845 \times 10^{33} \text{ ergs/sec.}$$

Using our ratio, we have

$$-2.8 - 4.74 = -2.5 \log (L(\text{star})/3.845 \times 10^{33})$$

Solving for  $L(\text{star})$  we find that  $L(\text{R Sct}) = 1037 * L(\text{sun})$  or  $4 \times 10^{36}$  ergs/sec.

*Step 6. Determine the Radius of the Variable Star.*

Here we will make use of the equation presented above that related  $L$ ,  $R$ , and  $T$  for a star. During this step, as a further check on your work, remember that giants have radii of a few times 10 that of the sun while supergiants have radii that are ~100 up to 1000 times that of the sun

Making use of our example star, R Sct, we can use

$$\frac{L(\text{R Sct})}{L(\text{Sun})} = \frac{R(\text{R Sct})^2 * T(\text{R Sct})^4}{R(\text{sun})^2 * T(\text{Sun})^4}$$

where we have used the sun again as a reference star. Putting in numbers (and taking the sun's luminosity as 1 solar luminosity) and using the results of the preceding steps, we have

$$\frac{1037}{1} = \frac{R(\text{R Sct})^2 * 7.25 \times 10^{14}}{4.9 \times 10^{21} * 1.13 \times 10^{15}}$$

Solving for the radius of R Sct gives

$$R(\text{R Sct}) = 6.12 \times 10^{12} \text{ cm}$$

Note, we could have set the sun's radius to 1 and its temperature to 1, and solved the ratio for R Sct's values in multiples of solar units.) We see that our radius determination is again consistent with our results from above. R Sct is a small supergiant with a radius of only 87.4 times that of the sun. One can also check to see if the radius determination is in line with (but not necessarily equal to) the published values for stars with the derived mass and luminosity.

*Step 7. Determine the Star's Mean Density.*

The mean density of a star is often of use in determining its evolutionary status. Stars like the sun become denser as one gets closer to the center, but do so in well-prescribed manner. Their mean density is a sort of average density for the star. As stars move up into the giant and supergiant region they become centrally condensed (the progenitor of the end product white dwarf, neutron star, or black hole) as well as becoming very large in size.

A determination of their mean density can be used to estimate the amount of mass in their core as well as the conditions in their extended atmospheres. The mean density is also of general interest as often the value is less than the density of water and one can wax elegantly about large bathtubs and floating stars.

Getting the star's mass from published sources (once T and L class are known from above) and the star's radius (just determined) one can simply calculate the stars' *average* density. For fun, compare the density you get to that of water (= 1 gram/cm<sup>3</sup>).

$$\text{Density} = M(\text{star}) / 4/3 \cdot \pi R^3.$$

For R Sct, we find a mean density of

$$D = 2.12 \times 10^{34} / 9.6 \times 10^{38} = 2.2 \times 10^{-5} \text{ gm/cm}^3 \text{ or } 100,000 \text{ times less dense than water!}$$

Now, Step back and admire how much you have learned about this star!

Tables 1 and 2 --

Table 1 -- Spectral type and Effective Temperature as a function of Luminosity class.

Spectral Type	Luminosity Class		
	V	III	I
	Temperature (K)		
A0	9520	10100	9730
A2	8970	9000	9080
A5	8200	8100	8510

A8	7580	7450	7950
F0	7200	7150	7700
F2	6890	6870	7350
F5	6440	6470	6900
F8	6200	6150	6100
G0	6030	5850	5550
G2	5860	5450	5200
G5	5770	5150	4850
G8	5570	4900	4600
K0	5250	4750	4420
K1	5080	4600	4330
K2	4900	4420	4250
K3	4730	4200	4080
K4	4590	4000	3950
K5	4350	3950	3850
K7	4060	3850	3700
M0	3850	3800	3650
M1	3720	3720	3550
M2	3580	3620	3450
M3	3470	3530	3200

Table 2. Basic Astronomical Data for the Sun

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Mass	$2 \times 10^{33}$ gm	(1 solar mass)
Radius	$7 \times 10^{10}$ cm	(1 solar radius)
Surface Temperature	5800 K	
Luminosity	$3.83 \times 10^{33}$ ergs/sec	(1 solar luminosity)
Average Density	$1.41$ gm/cm <sup>3</sup>	
Spectral Class	G2 V	(main sequence)
Apparent visual magnitude	-26.7	
Absolute visual magnitude	+4.8	
Rotation Period (equator)	25 days	
Average Earth-Sun distance	149,579,892 km	(1 au)
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