The Parent Stars of New Extrasolar Planet System Candidates

Ann Marie Cody

under the direction of
Dr. Dimitar Sasselov
Harvard-Smithsonian Center for Astrophysics

Research Science Institute
August 5, 1998

Abstract

Recent study of the stars Gliese 614, HR 7875, HR 810, and HR 5586, and Gliese 876 has found evidence of orbiting planetary companions. This research examines data on the ages and temperatures for these stars, and discusses the implications that this data have for the formation and evolution of planets. In the process of this study, it was found that Gliese 876 is a variable, suggesting the possibility of planetary eclipses. The most likely scenario determined is that the star is both an intrinsic variable and the parent of an orbiting planet.

1 Introduction

Recently, the scientific community has witnessed many major discoveries regarding the existence of planets outside of the solar system. During the last three years, Doppler techniques have allowed astronomers to infer the presence of nearly 15 planets orbiting around stars and pulsars. Among them are 55 Cancri, τ Bootis, υ Andromedae (Butler et al. 1997), 70 Virginis, 47 Ursae Majoris (Butler et al.1996), ρ Coronae Borealis (Noyes et al. 1997), 16 Cygni B (Cochran & Hatz, Butler & Marcy 1996), and 51 Pegasi (Mayor & Queloz 1995). Although each of these stars is known to be similar to our sun, the planets circling them appear to possess unusual orbital characteristics when compared to those of our own solar system. For example, the planet 51 Peg b is a Jupiter-sized object, and yet it is so close to its parent star that it completes one orbital period every 4.2 days (Mayor & Queloz 1995). Several of the other planets have also shown similar traits. Because of this, speculation has arisen regarding how such objects could have formed, and ultimately, whether conditions there could be conducive to extraterrestrial life.

Currently, a main area of study has focused not on the extrasolar planets themselves, but rather the stars that they orbit. Because the planetary candidates cannot yet be directly observed, we can only make conclusions about them by studying the parent star. Past research on 51 Peg, τ Boo, υ And, ρ^1 CnC, and ρ CrB has involved measuring and calculating such factors as stellar temperature, luminosity, radius, mass, and age (Ford, Rasio, & Sills 1998). These parameters may be used to model stellar and planetary evolution, and thus learn about a particular extrasolar system's history.

During the summer of 1998, more opportunities to study extrasolar planetary systems have surfaced with the discoveries of five new planet candidates. They orbit the stars Gliese 614 (Mayor et al. 1998), Gliese 876 (Marcy et al. & Delfosse, Mayor et al. 1998), HR 5568, HR 7875, and HR 810 (Kurster et al. 1998). Unlike the stars mentioned earlier, however, members of this group are much more diverse; many are classified as non-solar types. Therefore, the study of these new candidates will enable us to gain an even more complete picture of the conditions surrounding the existence of extrasolar planets.

Similar to the work of Ford, Rasio, & Sills (1998), this paper presents data pertaining to the five most recently discovered stars with planetary candidates. By utilizing the known values of luminosity, effective temperature, and metallicity, we calculate an entire spectrum for each star using Kurucz's opacities. This enables us to determine the temperature and predict the spectrum of the planet itself (Seager & Sasselov 1998). In the future, it is expected that the onset of more advanced technology will allow for direct confirmation of these models. In addition, the age of the parent star is determined with the Princeton Stellar Evolution Code. Finally, we discuss how all of these factors contribute to the formation and composition of the extrasolar planets.

2 Methods

To construct an accurate model spectrum for each star, it was necessary to gather observational data from many sources. Eventually, the parameters $T_{\rm eff}$ (effective temperature), $\log g$ (surface gravity), [Fe/H] (chemical composition/metallicity), $vsini$ (projected rotational velocity), and v_{macro} or v_{micro} (macroturbulent/microturbulent velocity) could be used to assemble "profiles" of the stars. However, it must be noted that few sources actually agreed on these values. Therefore, in some cases information was selected from a single source, while in others it was based on a range of observed data. For the temperature and surface gravity parameters, most values were estimated from ranges. In addition, these ranges were used to obtain an approximate error, when no other estimate of errors was available. The rotational velocity parameter was much more difficult to obtain, as only one source contained measurements. Specific information on each star is presented in Table 1 and section A1.

Star	T_{eff}(K)	$\log g$	[Fe/H]	$vsini$(km/s)	v_{mac}(km/s)	$v_{mic}(km/s)$
Gl 614	5200±100	4.5±0.2	0.10±0.2	0.6±0.7	2.0	–
HR 810	6050±100	4.25±0.2	0.0±0.1	5.7±0.5	4.7±0.8	1.7±0.3
HR 7875	6000±100	4.05±0.2	−0.40±0.2	6.4±0.8	–	1.5±0.5
Gl 876	3140±50	4.7±0.2	−0.40±0.4	< 0.2	–	–
HR 5568	4550±100	4.6±0.3	−0.1±0.2	1.0±0.8	–	1.0

Table 1: Stellar "Profile" Data

The data gathered for the five stars involved in this study relates primarily to stellar atmospheric conditions (see Table 1). It is precisely these conditions which determine the overall appearance of the star's spectrum. Therefore, with the aid of the computer programs Phoenix (Hauschildt, Baron, & Allard 1997) and Atlas (Kurucz 1993), we could synthesize the spectra. Our program, which is based on Kurucz's opacities, requires the input of effective temperature, rotational velocity, surface gravity, and metallicity. When run, it produces a graph of the full stellar spectrum, plotting wavelength against flux. We could then determine the bolometric luminosity of each star.

In addition to the data extracted from the model spectra, we also independently derived the luminosities by using apparent (V) magnitudes and newly-released Hipparcos parallaxes. From the parallaxes, the distances to each star were determined. Then, combining these results with the V magnitude data, we calculated the absolute magnitude. Then, we estimated the bolometric corrections with an equation involving effective temperature (Flower 1996). Finally, we calculated the bolometric magnitude and the stars' luminosities.

After luminosities were determined, they were used in conjunction with the temperatures, metallicities, and masses to create evolutionary models for the stars. By running the Princeton Stellar Evolution Code (version 3 of Oct. 1993, based on original code by Paczinski 1983), we were able to obtain approximate ages for the stars. Since we assume that the planet and star formed at the same time, this provides the ages of the planets.

3 Results and Data

3.1 Luminosity Calculations

A major step on the way to deriving luminosities for each of the five stars involved in this study is to obtain precise absolute bolometric magnitudes. First, we must calculate the absolute visual magnitude. This is done by using their well-known apparent magnitudes and recently-determined Hipparcos parallaxes. Errors in these parallaxes range from 0.55 to 2.10 milliarcseconds, producing typical distance errors of only 0.2 parsecs. Calculated distances and their corresponding errors appear in Table 2. Next, we can easily find absolute visible magnitudes. Although distance uncertainties do propagate, the range of magnitudes is very small, on the order of 04.

Because luminosity is a measurement of energy over all wavelengths of light, it is necessary to obtain overall, or bolometric magnitudes. The Flower (1996) equation gives fairly good bolometric correction, and we note the associated errors. However, for Gliese 876 in particular, a cool temperature causes the Flower (1996) bolometric correction to have a large uncertainty. Thus, we use Tinney, Mould, & Reid's (1993) measurement of the star's apparent k-magnitude (given as 5.02) and k-band correction (2.82) to get a much more accurate bolometric magnitude. This new value is 9.48, as opposed to the previously-calculated 9.07. Finally, we convert bolometric magnitudes (M_{bol}) into the luminosities (L) listed. Uncertainties in bolometric magnitude include both the uncertainties from parallax and bolometric correction. both parallax and bolometric correction (BC) ranges.

Star	Parallax (mas)	Dist. (pc)	m_v	M_v	BC	M_{bol}	L ($L_\odot$)
HR 5568	$169.32^{+}_{-}1.67$	$5.91^{+}_{-}0.06$	5.72	6.86	$-.564$	$6.30^{+}_{-} \sim 0.1$	$0.240^{+0.023}_{-0.021}$
GL 614	$55.11^{+}_{-}0.59$	$18.15^{+}_{-}0.2$	6.61	5.32	$-.227$	$5.09^{+}_{-} \sim 0.05$	$0.731^{+0.035}_{-0.033}$
GL 876	$212.69^{+}_{-}2.10$	$4.70^{+}_{-}0.05$	10.16	11.80	-2.33	$9.48^{+}_{-} \sim 0.02$	$0.0128^{+0.0003}_{-0.0002}$
HR 7875	$41.33^{+}_{-}0.73$	$24.20^{+}_{-}0.42$	5.11	3.19	-.0454	$3.14^{+}_{-} \sim 0.05$	$4.41^{+0.2}_{-0.44}$
HR 810	$58.00^{0}.55+_{-}$	$17.24^{+}_{-}0.16$	5.40	4.18	-.0383	$4.18^{+}_{-} \sim 0.03$	$1.69^{+0.05}_{-0.06}$

Table 2: Luminosity Data

3.2 Spectral Models

In addition to calculations based on absolute magnitudes, computer models of spectra give accurate luminosities. As well as the luminosity information, the spectra of the stars feature the characteristic absorption lines and display wavelength bands of maximum light intensity. They show that, with the exception of Gliese 876, the stars emit primarily visible light and should have very small bolometric corrections. (See figures 2 through 5). Based on these spectra, errors from temperature and parallax were larger than the corrections themselves.

Therefore, we decided not to make further adjustments to the calculated luminosities.

3.3 Stellar Evolution Model

We used the Princeton Stellar Evolution Code to model these five stars. From the initial input of metallicity ([Fe/H]), the program calculated Los Alamos opacities. After setting initial conditions, the evolutionary model was allowed to run until it reached the observed temperature and luminosity (L). It should be noted that HR 5568 happens to be a triple star system; one of its companions was used in the model to help constrain results. Final data on hydrogen (X) and helium (Y) abundances, masses, and ages were obtained and are presented in table 3.

Star	[Fe/H]	X	Y	$Mass(M_\odot)$	$\log T_{eff}$	$\log L$	Age (Gyr)
Gl 614	-1.35	0.701	0.299	0.8 ± 0.1	3.71	-0.30	0.5 ± 0.3
HR 5568A	-0.45	0.721	0.279	0.65 ± 0.1	3.64	-0.70	12 ± 2
HR 5568B	-0.45	0.721	0.279	0.530 ± 0.05	3.55	-1.28	12 ± 2
GL 876	-0.45	0.726	0.274	0.29 ± 0.05	3.50	-1.89	11 ± 2
HR 810	-0.80	0.70	0.30	1.02 ± 0.08	3.78	-1.28	2.5 ± 0.5
HR 7875	-0.40	0.71	0.29	1.10 ± 0.08	3.78	-1.28	3.3 ± 0.5

Table 3: Evolution Model Data

3.4 Special Case of Gliese 876

After assembling profile data for the Gliese 876, it was found that the star has been recently designated as a BY-Draconis type variable. In an attempt to determine whether variations its brightness are due to planetary eclipses, we considered several factors. First, we calculated the magnitude decrease if a Jupiter-sized planet were to pass directly in front of the star. Using a size of 0.3 solar radii (208800 km) for Gliese 876 and one Jupiter-radius (71500 km) for the planet, the areas of their light-emitting disks were compared (as shown in figure 1). If the region of the star blocked by the planet is considered to be completely dark, light is received from only a portion of the star. The fraction of the stellar disk area remaining visible during an eclipse was computed to be approximately 0.88. This translates into an expected change in magnitude of 0.14, which is fairly consistent with the observed decrease of 0.04.

Next, we made a rough estimate of the eclipse transit times. Given a period of 61 days, semi-major axis of 0.2 AU and eccentricity of 0.27 (Marcy et al.1998), maximum and minimum orbital speed for the planet are 47km/s and 27km/s. These results imply that, depending upon the orientation of the elliptical orbit, transit times could range from 2.5 to 4.3 hours.

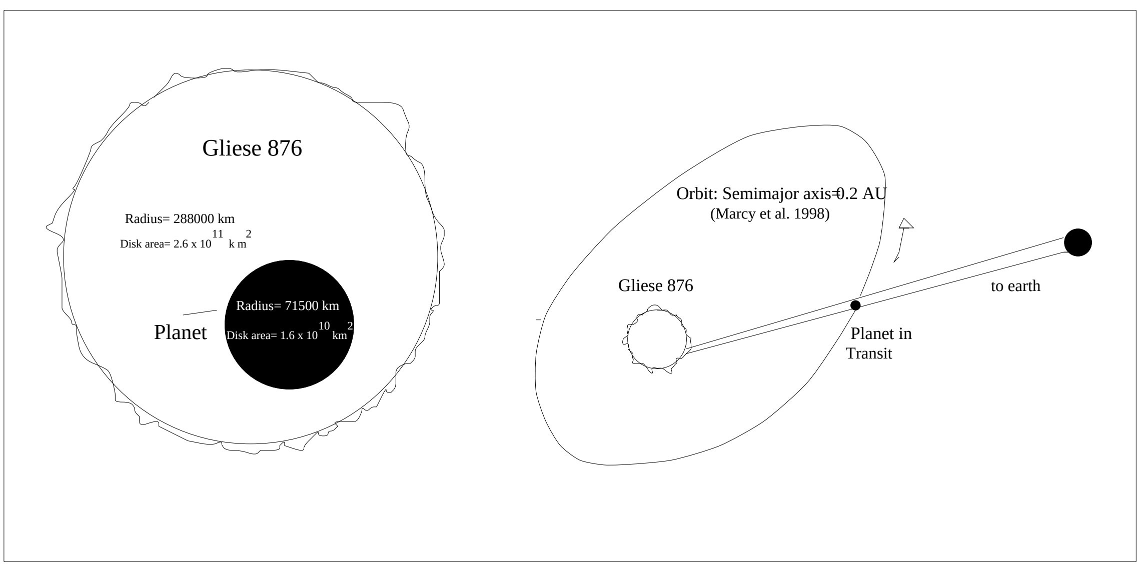

Figure 1: Eclipse diagrams.

Finally, the hypothesis that the source of Gliese 876's magnitude variation is caused by planetary eclipses suggests that a noticeable decrease in the star's brightness would occur every 61 days. Currently, the only photometric observations available are those made by Weis (1994). They are available in figure 7. In an attempt to test the suspected 61-day period, a light curve was plotted over his data. As seen in figure 8, the plotted points have a large scatter, giving no appearance of fitting to this curve. It is doubtful that the observed changes in brightness are due to any 61-day cycle of variation. Our own period analysis of Weis's data indicates that there may be a 33-day period. However, more observations will be needed to confirm the nature of Gliese 876's variability.

4 Discussion

4.1 Evolutionary Implications

Not only did the stellar evolution model derive ages for the selected stars, but it also aided in refining initial estimates of their hydrogen, helium, and metal abundances. For Gliese 614 in particular, results were quite different than expected. In addition to a high luminosity, the star appears to have low metallicity ([Fe/H]) and an unusually large helium abundance. In the past, there has been controversy over the [Fe/H] parameter, with little agreement between measurements (Xu 1991). The evolutions program's metallicity calculation of -1.35 is one of the lowest values yet determined. The high helium content is also a significant finding; it suggests that Gliese 614 is very young. Indeed, the model confirms this, determining an age of only 0.5 Gyr (giga-years) for the star and its companion planet. During this time period, it is possible that an inward-migrating planet was accreted by the star, thus changing the stellar surface and explaining the odd abundances observed.

Unlike Gliese 876, the two stars HR 810 and HR 7875 are very similar to the sun. They are each close to one solar mass and are slightly younger than the solar age of 4.6 Gyr. Finally, neither star shows signs of unusual composition. Because HR 810 and HR 7875 have so much in common with the sun, their chances of possessing earth-like planets may be greater that the other three stars examined.

The remaining stars, Gliese 876 and HR 5568 are different because of the old ages calculated by the stellar evolution model. Gliese 876 is known to be poor in metals. As with HR 5568, it has a relatively low surface temperature, making it likely that an orbiting planet would be extremely cold. Because the model for these stars shows that they have evolved very slowly over time, only slight warming could have occurred since their initial formation.

One way in which HR 5568 is different from Gl 876 is that it forms part of a triple star system. The fact that it is orbitted by two other stars (at a distance of 70 AU) has special implications for any planets that may be around it. Normally, planets perturbed by nearby stars are likely to be ejected away from their parent stars. Incredibly, though, HR 5568's planet has managed to remain in a stable orbit for nearly 12 Gyr. Perhaps this information could add to our understanding of stellar and planetary system interactions.

4.2 Gliese 876

As yet, the case for an eclipsing planetary companion around Gliese 876 is neither supported nor rejected. The idea that the star exhibits a BY-Draconis-type variability

(Kazarovets & Samus 1997) still remains open. The B-V color index changes apparent in Weis's observations point toward the existence of a cool spot on the stellar surface. If this is in fact what accounts for the magnitude changes, then the time taken for a complete cycle of variation is equal to Gl 876's rotational period, rather than the 61-day orbital period of a planet. In analyzing his observations, Weis (1994) determines possible periods of 20.2 days, 28.7 days, and 2.9 years.

However, the evidence that there is a planet around Gl 876 is also extremely convincing. Marcy et al. (1998) detect definite periodic changes in the star's radial velocity. The Keplerian nature of their velocity curve implies that the cause is the pull of a planet, and not stellar oscillations or rotating spots. Therefore, it may be likely that Gl 876 is a variable star and is at the same time orbited by a companion. Further photometric observations are necessary to rule out the hypothesis of eclipses, though. Soon, additional data could solve this problem.

5 Conclusions

During this study, we set out to gather information about Gliese 876, Gliese 614, HR 7875, HR 5568, and HR 810. Included among are results and data are metallicities, temperatures, magnitudes, luminosities, and ages. This information was applied to previous knowledge of stellar atmospheres in order to gain a greater understanding of the evolution of the orbiting planetary candidates. A major highlight of the project was the discovery of Gliese 876's variable behavior. Photometric data was examined and compared to velocity observations, in the hope that a correlation would be found. However, no conclusive results surfaced. In the future, efforts will be made to carefully track the changing magnitudes of Gliese 876. Perhaps then, the truth about this enigmatic star will finally be revealed.

6 Acknowledgements

I would like to express sincere thanks to my mentor Dr. Dimitar Sasselov, who gave up his time to guide me in this project. We also acknowledge Ed Weis for allowing the use of his observations of Gliese 876. Finally, I thank the Center for Excellence in Education for providing me with this wonderful research opportunity.

References

[1] Andersson, H., & Edvardsson, B. 1994, A&A, 290, 590

[2] Butler, P. et al. 1997, ApJ, 474, L115

[3] Butler, P. & Marcy, G. 1996, ApJ, 464, L15

[4] Cayrel de Strobel, G., et al. 1992, A&AS, 95, 273

[5] Claus, J.V. et al. 1997, A&AS, 122, 559

[6] Cochran, W.D., & Hatzes, A.P. and Butler, R.P., & Marcy, G.W. 1996, astro-ph/9611230

[7] Delfosse, X et al. 1998, A&A, 331, 581

[8] Edvardsson, B. et al. 1993, A&A, 275, 101

[9] Eggen, O.J. 1996, AJ, 111, 466

[10] Fekel, C., & Morell, O. 1997, PASP, 109, 514

[11] Feltzing S., & Gustafsson, B. 1998, A&AS, 129, 237

[12] Gratton, R.G., Carretta, E., & Castelli, F. 1996, A&A, 314, 191

[13] Flower, P.J. 1996, ApJ, 469, 355

[14] Ford, E. B., & Rasio, F.A. 1998, astro-ph/9807085

[15] Hale, A. 1994, AJ, 107, 306

[16] Hauschild, P.H., Baron, E., & Allard, F. 1997, ApJ, 483, 390

[17] Henry, T.J., et al. 1996, AJ, 111, 439

[18] Kazarovets, E.V., & Samus, N.N. 1997, IBVS, 4471

[19] Kurster et al. 1998, IAU Colloquium 170, Precise Stellar Radial Velocities, ASP Conf. Series (1999) in press

[20] Kurucz, R.L., 1993, Peculiar versus Normal Phenomena in A-type and Related Stars, eds. Dworetsky, M.M., Castelli, F., Faraggiana, ASP San Francisco, 87

[21] Leggett, S.K. 1992, ApJS, 82, 351

[22] Marcy, G.W., et al. 1998, A Planetary Companion to the M4 Dwarf, Gliese 876, ApJ Letters, in press

[23] Marcy, G.W., & Chen, G.H. 1992, ApJ, 390, 550

[24] Mariotti, J.M. et al. 1990, A&A, 230, 77

[25] Mathioudakis, M., Doyle, J.G. 1993. A&A, 280. 181

[26] Mayor, M. et al. 1998 Protostars and Planets IV (V. Manings Ed.)

[27] Mayor, M., & Queloz, D. 1995, Nature, 378, 355

[28] Noyes, R.W. et al. 1997, ApJ, 483, L111/

[29] Paczynski, B. 1983, ApJ, 264, 282

[30] Pasquini, L., Liu, Q., & Pallavicini, R. 1994, A&A, 287, 191

[31] Poveda, A. et al. 1994, RMxAA, 28, 43

[32] Reid, I.N. & Gizis, J.E. 1997, AJ, 113, 2246

[33] Saar, S.H. & Osten, R.A. 1997, MNRAS, 284, 803

[34] Seager, S. & Sasselov, D.D. 1998, astro-ph/9805335

[35] Schiavon, R.P., Barbuy, B., & Singh, P.D. 1997, ApJ, 484, 499

[36] Simons, D.A., Henry, T.J., & Kirkpatrick, J.D. 1996, AJ, 112, 2238

[37] Tinney, C.G., Mould, J.R., & Reid, I.N. 1993, AJ, 105, 1045

[38] Twarog, B.A., & Anthony-Twarog, B.J. 1995, 109, 2828

[39] Weis, E. 1994, AJ, 107, 1135

[40] Wood, B.E. et al. 1994, ApJS, 93, 287

[41] Xu, Zhou 1991, A&A, 248, 367

A Appendix

A.1 Description of the Star Sample

Because no single source contained all the necessary data for the stellar "profiles," information had to be assembled separately for each star. The following descriptions summarize information obtained, its sources, and several surprising pieces of data we found.

In the case of the star **Gliese 614**, values for T_{eff}, [Fe/H], and $\log g$ are taken from Cayrel de Strobel et al. (1992). It should be noted that the temperature parameter has a large uncertainty due to a possible reddening in the B-V index. The error on $\log g$ is based on a range of values measured by other groups. Rotational and macroturbulent velocities are obtained from Fekel (1997). In addition, a study done by Xu (1991) indicates that this star's spectrum shows several unusual metal abundances.

For **HR 7875**, the majority of information is taken from Gratton, Carretta, & Castelli (1996). However, in order to estimate uncertainties, the range of data from Andersson & Edvardsson (1994) and Cayrel de Strobel et al. (1992) is also considered. The rotational velocity parameter is given by Soderblom et al. (1989). The "profile" for **HR 810**, on the other hand, is created solely with two sources: Pasquini, Liu, & Pallavicini (1994) and Saar & Osten (1997).

HR 5568 proved to be an interesting star because it is a triple system. Two of its components orbit each other in a 309-day period. This pair in turn forms a common proper-motion system with HR 5568. The fact that this is a triple system helps to constrain the evolutionary model. Because little information was available for the B and C stars, a "profile" is only assembled for the primary (which is supposed to have the planet orbitting it). The A star is also the only member of the system which has accurate Hipparcos parallax measurements; the distance to all three stars is calculated from this number. References for this data include Mariotti et al. (1990), Rueddi et al. (1997), and Fekel (1997).

Finally, **Gliese 876** can be considered an unusual star for several reasons. First of all, with an extremely cool temperature of 3140K, it emits most of its light in the infrared (Tinney, Mould, & Reid 1993). This makes it nearly impossible to obtain an accurate absolute magnitude. Therefore, bolometric magnitudes and luminosity are calculated using this group's K-band observations. Rotational velocity, temperature, metallicity and surface gravity values are based primarily on the data of Delfosse et al. (1998) and Schiavon et al. (1997). In compiling this information, we were startled to discover that the star is actually variable (Weis 1994 and Kazarovets & Samus 1997). Samus has declared it to be a BY Draconis type variable, but the possibility remains open that the variation could actually be due to eclipses by an orbiting planet.

A.2 Figures

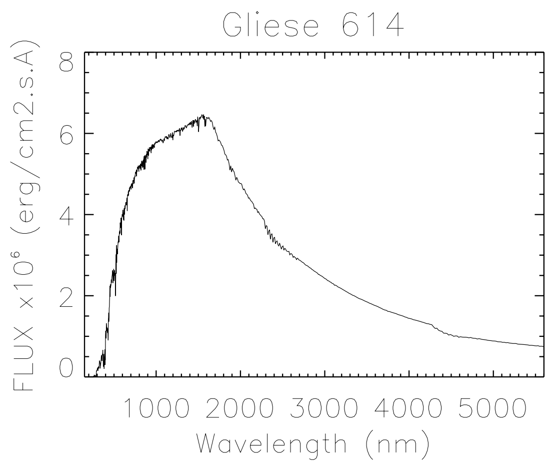

Figure 2: The theoretical spectrum of Gliese 614.

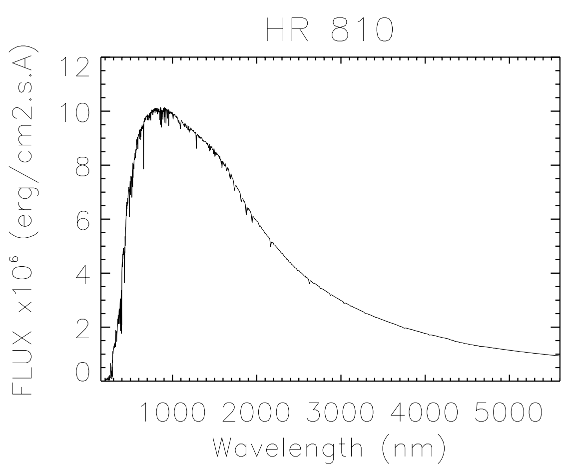

Figure 3: The theoretical spectrum of HR 810

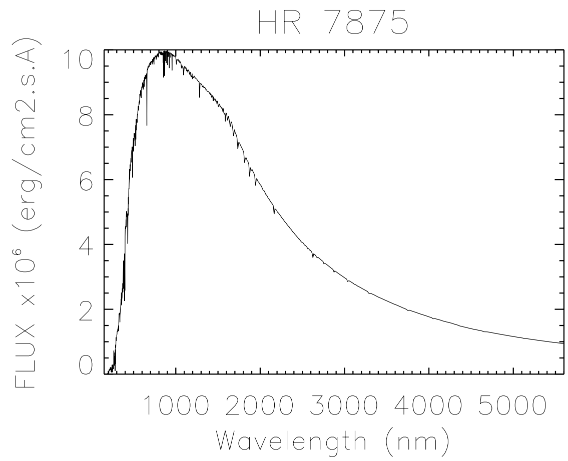

Figure 4: The theoretical spectrum of HR 7875

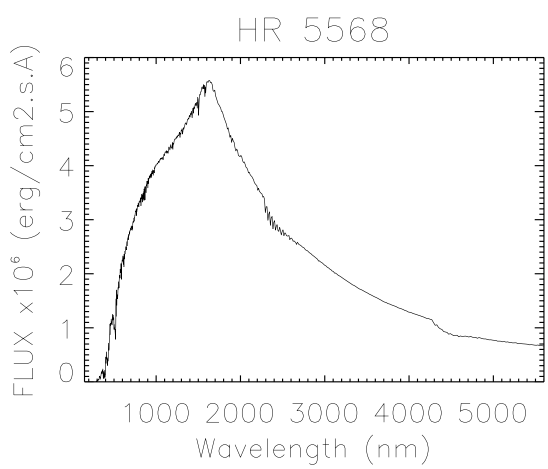

Figure 5: The theoretical spectrum of HR 5568.

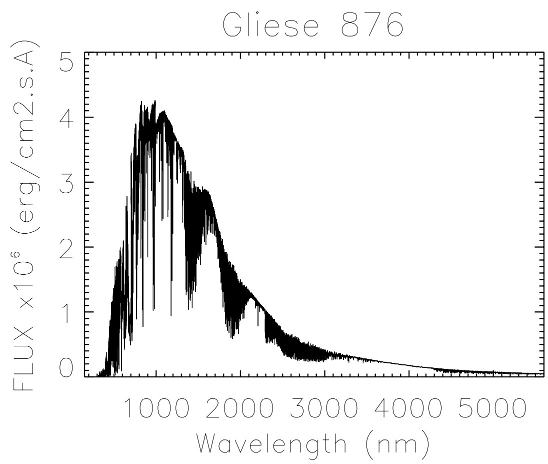

Figure 6: The theoretical spectrum of GL 876

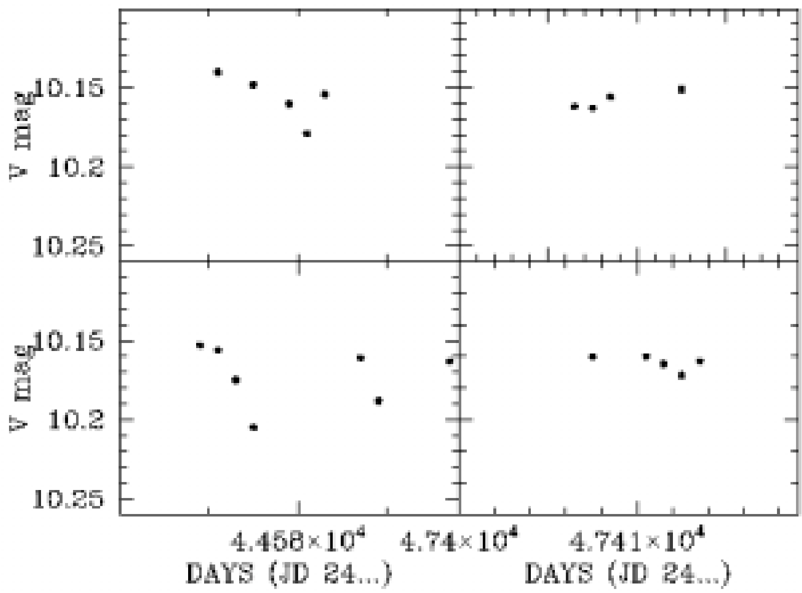

Figure 7: Plot of Weis's (1994) V-magnitude observations of GL 876

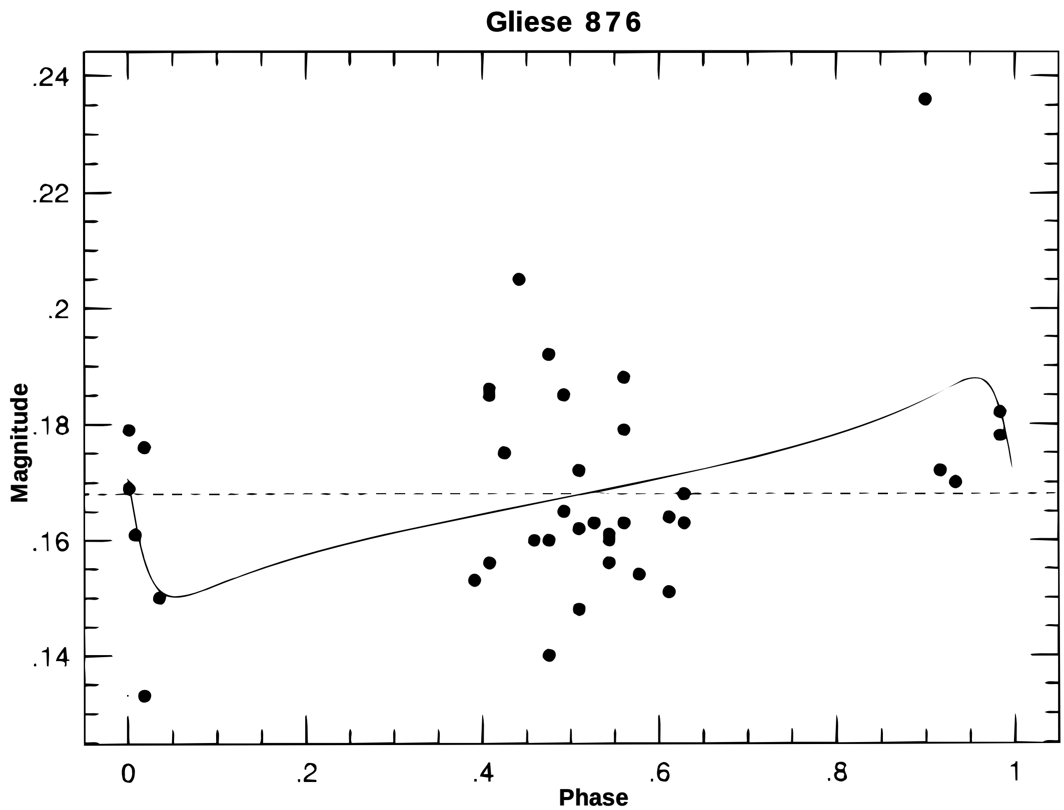

Figure 8: A light curve with period near 61 days is force-fitted to Weis's observations of GL 876.