Precise radial velocities of giant stars

V. A brown dwarf and a planet orbiting the K giant stars τ Gem and 91 Aqr∗,∗∗

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ABSTRACT

Aims. We aim to detect and characterize substellar companions to K giant stars, to further our knowledge of planet formation and stellar evolution of intermediate-mass stars.

Methods. For more than a decade we have used Doppler spectroscopy to acquire high precision radial velocity measurements of K giant stars. All data for this survey have been taken at Lick Observatory. Our survey includes 373 G and K giants. Radial velocity data showing periodic variations are fitted with Keplerian orbits using a χ2 minimization technique.

Results. We report the presence of two substellar companions to the K giant stars τ Gem and 91 Aqr. The brown dwarf orbiting τ Gem has an orbital period of 305.5 ± 0.1 days, a minimum mass of 20.6 Mj, and an eccentricity of 0.031 ± 0.009. The planet orbiting 91 Aqr has an orbital period of 181.4 ± 0.1 days, a minimum mass of 3.2 Mj, and an eccentricity of 0.027 ± 0.026. Both companions have exceptionally circular orbits for their orbital distance, as compared to all previously discovered planetary companions.

Key words. Techniques: radial velocities - Planets and satellites: detection - Brown dwarfs

1. Introduction

Since the discovery of the first extrasolar planets more than 15 years ago, there have been over 700 confirmed extrasolar planet discoveries. Of these planets, more than 60% have been discovered using the radial velocity (RV) technique, though the Kepler space telescope has found many more planet candidates that are waiting confirmation. Due to their spectral characteristics, solar-type main sequence stars are the stars most suitable for RV measurements, and so they have been the targets of the majority of extrasolar planet searches. However, a growing number of groups are successfully searching for planets around evolved giants and subgiants (e.g. Frink et al. 2002; Sato et al. 2003; Setiawan et al. 2003; Johnson et al. 2006; Lovis & Mayor 2007; Niedzielski et al. 2007; Döllinger et al. 2007).

There are currently 48 known substellar companions orbiting these giant stars, of which 25 have been published during the past four years. These planets allow us to probe more massive stars than are accessible on the main sequence. While main sequence planet searches can typically access stars slightly more massive than our Sun, earlier type stars typically have too few absorption lines for reliable high-precision RV measurements. Evolved stars, such as K giants, have suitable absorption lines for RV measurements, but can have much larger masses. Our sample has typical masses of 1–3 M⊙. Our results show that red giant stars with masses greater than 2.7 M⊙ host very few planets (Reffert et al. in prep.). K giant RV surveys also allow the investigation of how stellar evolution affects planetary systems.

Our search for planets orbiting giant stars has collected data from 373 stars for over a decade, with several published planet detections (Frink et al. 2002; Reffert et al. 2006; Quirrenbach et al. 2011). In this paper we report sub-stellar companions detected in the RV data of τ Gem (HIP 34693) and 91 Aqr (HIP 114855). These are both single planet systems at our detection threshold, and both planets have circular orbits.

In Section 2 we will discuss our observations in detail. Section 3 contains information about the stars themselves, including various stellar parameters, and in Section 4 we derive the planetary orbits. In Section 5 we present evidence against the existence of intrinsic stellar causes of the RV variations. In Section 6, we discuss the possible multiplicity of the host stars and the notably low eccentricities of these companions. Finally, in Section 7, we summarize our findings.

2. Observations

2.1. Sample Selection

Our sample of giant stars started with the selection of 86 K giants brighter than magnitude 6 in V, showing no signs of duplicity or variability. The original selection criteria are described in Frink et al. (2001). Observations of these stars began in June 1999. In June 2000, 96 additional stars were added to the sample with less stringent criteria, such as relaxing the criteria against long-term proper motion and photometric variability. Three stars were removed from the sample when it was discovered that they were visual binaries, leaving a total of 179 stars.
After the detection of several planets orbiting stars in our original sample (Frink et al. 2002; Reffert et al. 2006; Quirrenbach et al. 2011), 194 G and K giants were added to the sample in 2004. These stars were selected for having higher masses and bluer colors on average than the original stars. The larger masses were chosen to test whether or not more massive stars host more massive planetary companions. The color criterion was chosen because bluer stars tend to have less intrinsic jitter than redder stars.

2.2. Radial Velocity Data

The radial velocity observations were taken at Lick Observatory, using the 0.6 m Coudé Auxiliary Telescope (CAT) with the Hamilton Echelle Spectrograph (Vogt 1987). Our spectra have a resolution of $R \approx 60,000$, and cover the wavelength range 3755–9590 Å (4725–9590 Å before August 2001). A cell of molecular iodine gas was heated to 50°C and placed in the light path, and the resulting stellar spectra, with iodine absorption lines, were fitted by models created from separate iodine and stellar template spectra. Only the region of the spectrum with iodine absorption lines (5000–5800 Å) is used for this procedure. For dwarf stars, this yields Doppler shifts with precisions better than $3 \text{ m s}^{-1}$. The data acquisition and reduction process is described in more detail by Butler et al. (1996).

We currently have 12–13 years of data for our original set of K giant stars, of which both τ Gem and 91 Aqr are members. We have 95 RV measurements for τ Gem, and 174 for 91 Aqr spaced over this time period. The resulting radial velocities are given in Tables B.1 and B.2 in Appendix B. Typical exposure times were 15 min for τ Gem and 12 min for 91 Aqr. The signal-to-noise ratios for these observations are typically around 120–150, and the resulting radial velocity measurements have a median precision of 4.7 m s$^{-1}$ for τ Gem and 5.2 m s$^{-1}$ for 91 Aqr. Although this is not the best possible precision available with this method, it is adequate for the requirements of this project. Giant stars typically have larger RV jitter than main sequence stars, on the order of $20 \text{ m s}^{-1}$ or larger depending on the individual star (Hekker et al. 2006), so improved precision would not be beneficial to the detection of a planetary RV signal.

3. Stellar Properties

The stellar properties of both stars are given in Table 1. Visual magnitude and parallax measurements are taken from Hipparcos observations (van Leeuwen 2007). K magnitude values are taken from 2MASS (Skrutskie et al. 2006). Hekker & Meléndez (2007) measured the metallicity of these stars, using our spectra for their analysis. τ Gem is slightly metal-rich, whereas 91 Aqr has about solar metallicity.

In order to derive stellar parameters such as mass, surface gravity, effective temperature, stellar radius and stellar age, the evolutionary tracks of Girardi et al. (2000) were interpolated onto the observed B-V color, absolute V magnitude (van Leeuwen 2007), and metallicity (Hekker & Meléndez 2007) (trilinear interpolation). In general, this approach resulted in two possible solutions, depending on the precise evolutionary status (red giant branch or horizontal branch) of the star. Probabilities were assigned to each solution, taking the evolutionary timescale (the speed with which the star moves through that portion of the evolutionary track) as well as the initial mass functions into account (Küstler 2008). More details on the method as well as the stellar parameters for all K giant stars on our Doppler program can be found in Reffert et al. (in prep).

Both of these stars were determined to be more likely on the HB by this method. τ Gem was found to have a 64% chance of being on the HB, and 91 Aqr has a 79% chance of being on the HB. If the stars are RGB stars, the masses would be $2.5 \pm 0.3 \text{ M}_\odot$ for τ Gem and $1.6 \pm 0.2 \text{ M}_\odot$ for 91 Aqr.

Absolute radial velocity measurements were taken using the CRIRES spectrograph (Käufl et al. 2004). The $v \sin i$ limit for τ Gem was measured by de Medeiros & Mayor (1999), while the value for 91 Aqr was measured by Tokovinin & Smekhov (2002).

4. Keplerian Orbit

The radial velocities of τ Gem and 91 Aqr are shown in Figures 1 and 2 along with the best Keplerian fit to the data (upper panels). The lower panels show the residual radial velocities, after subtraction of the Keplerian fits. Error bars are included in all plots, but in many cases are too small to be visible.

For each orbital solution there were six parameters fit to the data: five orbital parameters and the zero-level of the radial velocity measurements were taken using the 0.6 m Coudé Auxiliary Telescope (CAT) with the Hamilton Echelle Spectrograph (Vogt 1987). Fitting orbits with these standard orbital parameters can cause problems when the orbits have low eccentricities. For example, the periastron time has very large errors by definition, if...
the eccentricity is low. For this reason we also fitted the data using the following five orbital parameters: log $P$, log $K_1$ (where $K_1$ is the semi-amplitude of the RV), $e \cdot \cos(\omega)$, $e \cdot \sin(\omega)$, and $\lambda_0$ (where $\lambda_0$ is the sum of the longitude of the periastron and the mean anomaly). Fitting the data with these parameters resulted in no significant difference to the orbital solution or the uncertainties. We also used the revised Lucy-Sweeney test (Lucy 2013) to see whether an upper limit to the eccentricities would be more appropriate. While the derived eccentricity of $\tau$ Gem was a sufficient number of standard deviations away from zero to be accurate, this method suggests that the eccentricity of 91 Aqr is more appropriately described as less than 0.034 at the one sigma confidence level, and for the 95% confidence level, less than 0.064.

Periodograms for our data are shown in Figures 3 and 4. The top panels show the results for the RV data. Each star has a single, strong peak at a period matching the Keplerian fit to the data. 91 Aqr has several additional peaks that are weaker but significant. All of these peaks are due to aliasing effects. The two large peaks on either side of the physical peak are yearly aliases. To the left of the main peak is a peak corresponding to the physical frequency $f_0$ added to the annual frequency $f_{\text{year}}$. To the right is a double peak which combines both $f_0 - f_{\text{year}}$ and $f_{\text{year}}$ alone. These two peaks overlap because the orbital period of this companion is very close to half a year. At shorter periods there are smaller peaks at one month and at 14 and 16 days. These are due to our observing schedule. We were usually scheduled for either bi-monthly observing runs or dark time observing runs every month, thus these aliases represent our observation frequencies. All of the aliases seen here are typical for RV planet searches (Dawson & Fabrycky 2010).

The bottom panels of Figures 3 and 4 show a periodogram of the data after the Keplerian fit has been removed. Neither star has any significant periodicity in the residuals. The residual radial velocities, after subtraction of the best Keplerian fits, are consistent with the small intrinsic scatter expected from K-giant stars, at a level of around 20 m s$^{-1}$ (Frink et al. 2001).

5. Intrinsic stellar effects

In addition to planetary or stellar companions, intrinsic stellar activity can also cause RV variations in giant stars. This makes detections of substellar companions around K giants somewhat more challenging than around inactive stars, since one has to demonstrate that the interpretation of the observed radial velocity pattern is due to the companion and not due to intrinsic effects. This has been discussed in detail by Hatzes et al. (2004).

Features on the surface of a star, such as hot or cool spots or plages, can create asymmetries in the stellar absorption lines (Walker et al. 1992). This asymmetry is seen as a shift in the radial velocity of the star, and as the star rotates, the Doppler shift will vary periodically.
The CRIRES spectra have a resolution of \( R \approx 100,000 \) when used with the 0.2” slit. Our spectra cover the wavelength range 1.57–1.61 \( \mu m \), characterized by many deep and sharp telluric lines used as references. To determine RV measurements from these data, we followed a procedure similar to that of Figueira et al. (2010). First we reduced the data using the standard ESO CRIRES reduction pipeline. Then we obtained precise radial velocity measurements by cross-correlating a synthetic spectrum with the CRIRES spectra. Our RV measurements using CRIRES have an estimated uncertainty of 40 m s\(^{-1}\). The CRIRES data for both stars are given in Tables B.3 and B.4 in Appendix B. After collecting the RV measurements from CRIRES, a best fit orbital fit was calculated for each of the stars, to fit the IR data to the previously calculated orbital fit to the visible RV data.

During 2012 and 2013 we observed both of our stars with the high-resolution IR spectrograph CRIRES (Käufl et al. 2004) at the Very Large Telescope (VLT). CRIRES spectra have a resolution of \( R = 100,000 \) when used with the 0.2” slit. Our spectra cover the wavelength range 1.57–1.61 \( \mu m \), characterized by many deep and sharp telluric lines used as references. To determine RV measurements from these data, we followed a procedure similar to that of Figueira et al. (2010). First we reduced the data using the standard ESO CRIRES reduction pipeline. Then we obtained precise radial velocity measurements by cross-correlating a synthetic spectrum with the CRIRES spectra. Our RV measurements using CRIRES have an estimated uncertainty of 40 m s\(^{-1}\). The CRIRES data for both stars are given in Tables B.3 and B.4 in Appendix B. After collecting the RV measurements from CRIRES, a best fit orbital fit was calculated for each of the stars, to fit the IR data to the previously calculated orbital fit to the visible RV data.

Figures 5 and 6 show the CRIRES data. The top panels of the figures show the CRIRES data plotted against the Keplerian fit to the Lick data. The bottoms of the figures show the residuals of the CRIRES data after subtraction of the fit. The scatter around the fit is consistent with intrinsic jitter of the star. These plots show that the RV variations in these stars have the same amplitude and phase in both visible and IR bandpasses, confirming that the source of the variations are the companions and not intrinsic variations.
6. Discussion

6.1. Stellar multiplicity

Both of the stars discussed in this paper are listed in the literature as being multiple stars. τ Gem is indicated in the Washington Double Star catalog (WDS; [Mason et al. 2001]) as having two companion stars. The primary companion was measured to be separated by 2″, and has a visual magnitude of $m_v = 11.0$ mag. More recent observation by Hipparcos did not detect this secondary component. This component is most likely physically connected to our star, based on the very small separation. At the Hipparcos distance of 98.4 pc, the secondary star would be a K0 dwarf, separated by about 187 AU.

For a star with a companion of known mass and separation, one can find the maximum rate of change for the radial velocity of any orbit to be

$$a_{\text{max}} = \frac{2Gm_c\sigma^2}{3\sqrt{3}p^2} \tag{1}$$

where $G$ is the gravitational constant, $m_c$ is the companion mass, $\sigma$ is the parallax for the stars and $p$ is the angular separation between the stars. The derivation of this equation is given in Appendix A. If we assume that the companion here is a K0 dwarf of mass 0.8 M$\odot$, then the maximum radial velocity change would be 1.6 m/s/yr, which could be detectable with our current data. However, many orbits with RV variations below our detection threshold are also possible.

An additional companion is listed in the WDS, at a separation of about 59″, and a magnitude of $m_v = 12.4$ mag, though the physical connection of this component is dubious. This would correspond to a physical separation of well over 5000 AU, which would not be visible in our RV data.

91 Aqr is listed in the WDS as a member of a quintuple star system. The primary companion to 91 Aqr is a visual binary pair of magnitudes 10.5 and 10.7, separated from the primary component by 50″. At the Hipparcos distance of 45.9 pc, this would lead to a separation of over 2000 AU, too large to be visible in the RV data. Raghavan et al. (2006) show that the primary companion to 91 Aqr is a binary star pair by matching the proper motion and radial velocities of the two components, and by comparing spectroscopic parallaxes. Zirm (2007) derived the orbit of the BC components as having an orbital period of 83.6 yr, a semi-major axis of 0′.47, an eccentricity of 0.45, and an inclination of 87°, which is nearly edge-on. This semi-major axis corresponds to 21.5 AU.

Raghavan et al. (2006) also show that the other two companions listed in the WDS are in fact field stars. Thus, 91 Aqr b is one of a handful of planets in a triple star system.

6.2. Brown dwarf companions

It is well established that Sun-like main sequence stars are much more likely to have planetary mass companions than brown dwarf companions (Marcy & Butler 2000). From the California & Carnegie Planet Search and the McDonald Observatory Planet Search, the frequency at which we find brown dwarf companions orbiting Sun-like main sequence stars with orbital periods less than five years is less than 1% (e.g. Vogt et al. 2002; Patel et al. 2007; Wittenmyer et al. 2009). By controlling for selection effects, Grether & Lineweaver (2006) approximate the fraction of Sun-like stars harboring giant planet companions with orbits less than 5 years to be 5 ± 2%, and the fraction of such stars harboring brown dwarf companions at close orbits to be less than 1%. Since they also calculated that 11 ± 3% of Sun-like stars have stellar companions at close orbits, this demonstrates the relative...
paucity of companions in the brown dwarf mass regime, compared to both larger and smaller masses.

It appears that giant stars may host more brown dwarfs than solar-type main sequence stars. To date, 10 companions in the brown dwarf mass regime have been found around giant stars, as compared to nine brown dwarfs orbiting main sequence stars and two orbiting subgiants. Three of the nine main sequence companions were discovered with transit observations. This is all true despite the giant stars being more massive, on average, than the stars in the main sequence samples, making RV detections more difficult due to the smaller amplitudes, and despite the giant star surveys having a smaller stellar sample. It is difficult to estimate the rate of brown dwarf detection in giant stars, due to the less complete nature of these surveys, and the large and varying amount of stellar jitter in these stars. However, it seems likely that brown dwarfs are not quite so rare around the more massive, evolved stars of the giant surveys, as these more massive stars would have had more massive protoplanetary disks from which to form companions.

6.3. Eccentricity

Both of the planetary orbits described here are extremely circular. In fact, they could be considered the most circular orbits found among planets orbiting at this distance from their host star. Figure 7 shows the orbital eccentricity of known extrasolar planets plotted against the semi-major axis of their orbits. Symbols for the different categories of planets are given in the plot. Planets with orbits greater than 3.5 AU are omitted, as are planets without properly measured values and uncertainties for the orbital eccentricity. Orbital values for the companions to Pollux and τ Oph are taken from our data, since it is the most extensive RV data set for these stars, with the best available orbital fits. There are, however, other published values (Hatzes et al. 2006; Sato et al. 2012). In particular, the alternate published value for the companion to Pollux lists an eccentricity of 0.02 ± 0.03, as opposed to our current best fit value of 0.05 ± 0.01.

From the plot it is clear that one must look at closer orbits to find planets with as circular orbits as the planets described here, with a few possible exceptions. One other K giant companion has a lower published eccentricity, (HD 32518 b, Dollinger et al. 2009), but the value for that eccentricity is questionable. The published value for HD 32518 b is e = 0.01 ± 0.03, which according to the Lucy-Sweeney test should be replaced by an upper limit on the eccentricity of 0.06 for the 95% confidence level, and at the one sigma level the upper limit would be 0.03. This is approximately the same value as the two orbits presented in this paper, but with larger uncertainty.

A more interesting planet with a more circular orbit than those presented here has an eccentricity of 0.0069 ± 0.0010 and semi-major axis of 0.65 AU (Doyle et al. 2011). This is the famous circumbinary planet Kepler 16 b. A second interesting planet with a similar orbit (though larger semi-major axis) is HD 60532 c (Desort et al. 2008). This is the outer of two planets orbiting this star, orbiting at 1.58 AU with an eccentricity of 0.02 ± 0.02. Again, using the Lucy-Sweeney test, this might more accurately be considered an orbit with an upper limit to the eccentricity of 0.05 for the 95% confidence level, and 0.03 for the one sigma confidence level. It is also interesting to note that the authors of this discovery believe there to be significant interaction between these two planets, including a possible 3-to-1 orbital resonance, with variations in the semi-major axis and eccentricity of the orbits.

Fig. 7. Eccentricities for substellar companions. Companions from this paper are shown as diamonds, all other companions of giant stars are shown with a cross. Companions to main sequence stars are shown as small plusses. Terrestrial planets from our solar system are shown as triangles.

Finally, one last notable planet is one with a semi-major axis of 2.25 AU, and an eccentricity of 0.01 ± 0.03: HD 159868 c (Wittenmyer et al. 2012). Like HD 60532 c, this is the outer planet of a two-planet system where interactions are possible, though the orbits are stable. Like HD 32518 b, the uncertainty on the eccentricity is so high that an upper limit of 0.03 (for one sigma confidence) is appropriate.

Several groups have investigated the theoretical effects of stellar evolution on the orbits of planets (Villaver & Livio 2009; Kunitomo et al. 2011). Though these studies have focused on the change in semi-major axis of the planet, and the possibility of engulfment by the RGB star, presumably planets just outside the engulfment limit will still be strongly affected by the star’s tidal forces. Effects of this interaction might include orbital circularization. Another possibility is that planets beyond a critical distance may evolve into orbits with a larger semi-major axis due to mass loss by the host star. Even though one is far more likely to find circular orbits for closely orbiting planets, either of these phenomena could explain more distant orbits, such as those described here, having very low eccentricities. It is interesting that the only planets discovered with similar orbits to the planets discussed in this paper are in multiple planetary systems that likely interact, orbit a binary star, or are orbiting evolved stars.

7. Summary

In this paper we report the detection of two substellar companions orbiting the K giant stars τ Gem and 91 Aqr, using the Hamilton spectrograph at Lick Observatory. The companion to τ Gem has a minimum mass of 20.6 M_J, putting it in the brown dwarf regime. The companion to 91 Aqr has a minimum mass of 3.2 M_J, putting it in the giant planet mass range. Both companions have extremely circular orbits, especially considering their relatively distant orbits, and the orbital characteristics have been stable over more than 12 years of observation. RV data taken in the IR match the orbital fit, confirming the presence of a companion as the source of the RV variations.

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Fig. A.1. Diagram of binary star system. The star of interest is on the right and the companion is on the left. The observer is below the system in the plane of the page, so that the separation \( r \) can be broken into the component along the line of sight, \( z \), and the projection of the separation visible to the observer, \( x \).

Appendix A: Maximum RV change for stars with companions

In the case of a visual binary star system, one might not have any information about the orbit other than the current separation. In this case, one can still calculate the maximum RV change of any orbit in that configuration, as long as the distance to the system is known.

Figure A.1 shows the orientation of our system. The star and companion are separated by distance \( r \). If we assume the observer is in the plane of the page, then we can break that distance into the \( x \) component, the projection of the separation visible to the observer, and the \( z \) component along the line of sight. We know that the acceleration of our star of interest, due to the gravitational interaction with its companion, is

\[
a = \frac{Gm_c}{r^2} \tag{A.1}
\]

where \( G \) is the gravitational constant, \( m_c \) is the companion mass, and \( r \) is the physical separation between them. Since we do not know the physical separation, but instead only have the projection of this separation, we must find the acceleration in terms of the projected separation \( x \) and the component of the separation along our line of sight, \( z \). Here we are only concerned with the acceleration along our line of sight, which is

\[
a_x = \frac{Gm_c z}{(x^2 + z^2)^{3/2}}. \tag{A.2}
\]

To find the maximum value for the acceleration we must differentiate,

\[
\frac{da_x}{dz} = \frac{Gm_c(x^2 - 2z^2)}{(x^2 + z^2)^{5/2}}, \tag{A.3}
\]

then set this equal to zero. This gives

\[
z_{\text{max}} = \frac{x}{\sqrt{2}} \tag{A.4}
\]

which is the condition at the maximum acceleration. Inserting this back into Equation A.2, and putting the projected separation \( x \) in terms of the observed angular separation \( \rho \) and the parallax \( \varpi \), gives the maximum acceleration along the line of sight

\[
a_{x,\text{max}} = \frac{2Gm_c\varpi^2}{3\sqrt{3}\rho^2} \tag{A.5}
\]

for any orbit of a star with a companion of given mass.

Appendix B: RV data

Table B.1. RV data for \( \tau \) Gem

| JD^* [days] | \( v_{\text{rad}} \) [m s\(^{-1}\)] | \( \sigma_{\text{RV}} \) [m s\(^{-1}\)] |
|-----------|-----------------|-----------------|
| 1809.039  | -277.8          | 3.6             |
| 1854.888  | -12.6           | 4.0             |
| 1898.902  | 223.8           | 6.5             |
| 1930.810  | 334.5           | 4.4             |
| 1990.659  | 167.6           | 5.6             |
Table B.1. RV data for τ Gem

| JD^a [days] | \( v_{\text{rad}} \) [m s\(^{-1}\)] | \( \sigma_{\text{RV}} \) [m s\(^{-1}\)] |
|-------------|-----------------|-----------------|
| 2012.653    | −4.7            | 4.0             |
| 2013.651    | −37.5           | 4.7             |
| 2014.656    | −20.8           | 4.0             |
| 2175.047    | 94.1            | 3.7             |
| 2176.055    | 136.4           | 4.3             |
| 2177.035    | 124.9           | 3.6             |
| 2192.995    | 200.7           | 4.5             |
| 2193.967    | 220.5           | 3.8             |
| 2205.938    | 280.7           | 4.5             |
| 2206.949    | 270.7           | 4.6             |
| 2222.898    | 329.3           | 4.5             |
| 2258.811    | 332.9           | 5.1             |
| 2259.853    | 299.8           | 5.1             |
| 2295.773    | 115.8           | 5.8             |
| 2297.842    | 131.0           | 6.3             |
| 2307.730    | 98.9            | 5.0             |
| 2336.741    | −129.0          | 4.8             |
| 2361.708    | −300.2          | 4.4             |
| 2362.721    | −271.6          | 4.5             |
| 2363.688    | −293.6          | 4.8             |
| 2384.667    | −327.7          | 4.3             |
| 2393.654    | −354.9          | 6.1             |
| 2529.039    | 336.2           | 4.4             |
| 2531.009    | 317.8           | 4.6             |
| 2532.039    | 326.1           | 4.3             |
| 2542.018    | 330.5           | 4.7             |
| 2543.981    | 339.0           | 4.7             |
| 2560.013    | 334.8           | 6.8             |
| 2562.004    | 322.0           | 4.6             |
| 2571.969    | 284.3           | 4.6             |
| 2574.010    | 265.6           | 4.9             |
| 2589.975    | 201.6           | 4.8             |
| 2590.892    | 205.7           | 4.5             |
| 2603.925    | 149.2           | 5.3             |
| 2604.916    | 115.8           | 5.1             |
| 2605.867    | 99.1            | 5.1             |
| 2615.842    | 47.0            | 4.5             |
| 2616.858    | 48.9            | 4.5             |
| 2627.816    | −63.7           | 3.8             |
| 2665.755    | −290.7          | 5.2             |
| 2667.815    | −328.3          | 4.9             |
| 2699.687    | −375.4          | 5.1             |
| 2717.691    | −314.8          | 4.1             |
| 2765.676    | −49.3           | 18.3            |
| 2900.034    | 178.6           | 4.6             |
| 2932.987    | −87.4           | 4.2             |
| 2934.975    | −105.0          | 4.3             |
| 2964.028    | −314.4          | 5.2             |
| 2966.896    | −321.8          | 4.3             |
| 2985.944    | −350.6          | 5.3             |
| 3022.849    | −358.7          | 5.6             |
| 3089.704    | 81.9            | 4.8             |
| 3111.665    | 229.1           | 4.1             |
| 3271.015    | −263.2          | 3.6             |
| 3357.929    | −164.1          | 4.2             |
| 3400.811    | 131.6           | 4.6             |
| 3424.711    | 254.7           | 4.3             |
| 3444.674    | 322.0           | 5.5             |
| 3651.003    | −227.0          | 4.1             |
| 3701.974    | 103.2           | 5.1             |
Table B.1. RV data for τ Gem

| JD$^a$ [days] | $v_{\text{rad}}$ [m s$^{-1}$] | $\sigma_{\text{RV}}$ [m s$^{-1}$] |
|---------------|-------------------------------|-------------------------------|
| 3741.888      | 268.5                         | 4.1                           |
| 3790.746      | 310.0                         | 4.7                           |
| 3857.654      | −124.8                        | 4.8                           |
| 4054.935      | 344.2                         | 4.4                           |
| 4057.940      | 315.3                         | 4.6                           |
| 4123.835      | 126.0                         | 4.5                           |
| 4182.662      | −250.5                        | 5.3                           |
| 4227.649      | −373.4                        | 4.6                           |
| 4392.004      | 353.7                         | 6.6                           |
| 4419.958      | 231.7                         | 4.9                           |
| 4480.917      | −210.0                        | 4.6                           |
| 4504.767      | −317.3                        | 4.9                           |
| 4754.975      | 41.5                          | 3.8                           |
| 4807.924      | −266.5                        | 4.6                           |
| 4882.830      | −217.6                        | 6.3                           |
| 4911.674      | −8.9                          | 5.7                           |
| 5102.055      | −243.4                        | 6.4                           |
| 5122.025      | −315.3                        | 5.5                           |
| 5154.966      | −334.6                        | 7.3                           |
| 5242.708      | 142.0                         | 6.1                           |
| 5282.681      | 348.6                         | 5.4                           |
| 5464.063      | −267.5                        | 6.9                           |
| 5569.854      | 245.8                         | 4.8                           |
| 5593.771      | 341.2                         | 4.9                           |
| 5620.740      | 331.8                         | 5.7                           |
| 5651.688      | 179.7                         | 5.1                           |
| 5830.017      | 28.2                          | 8.9                           |
| 5863.951      | 253.6                         | 4.0                           |
| 5865.031      | 267.5                         | 4.1                           |
| 5894.944      | 341.1                         | 6.1                           |

$^a$ Julian date–2450000

Table B.2. RV data for 91 Aqr

| JD$^a$ [days] | $v_{\text{rad}}$ [m s$^{-1}$] | $\sigma_{\text{RV}}$ [m s$^{-1}$] |
|---------------|-------------------------------|-------------------------------|
| 1744.976      | 72.1                          | 3.9                           |
| 1780.886      | 60.9                          | 4.3                           |
| 1807.843      | −46.3                         | 4.8                           |
| 1853.694      | −75.3                         | 4.7                           |
| 1856.737      | −76.5                         | 4.6                           |
| 1899.645      | 65.6                          | 5.0                           |
| 1932.598      | 101.3                         | 5.5                           |
| 2049.000      | −54.6                         | 5.7                           |
| 2079.999      | 50.9                          | 5.1                           |
| 2083.991      | 82.4                          | 4.2                           |
| 2098.992      | 65.9                          | 5.0                           |
| 2099.962      | 71.3                          | 4.7                           |
| 2100.982      | 71.2                          | 4.7                           |
| 2107.959      | 86.8                          | 5.2                           |
| 2109.955      | 60.0                          | 4.2                           |
| 2125.939      | 82.6                          | 4.7                           |
| 2163.837      | −10.0                         | 4.9                           |
| 2164.896      | 5.7                           | 5.1                           |
| 2165.868      | 4.5                           | 4.6                           |
| 2166.885      | −0.7                          | 5.4                           |
| 2174.843      | −45.9                         | 5.2                           |
| 2175.820      | −56.4                         | 5.8                           |
| 2176.798      | −55.5                         | 4.7                           |
Table B.2. RV data for 91 Aqr

| JD$^*$ [days] | $v_{\text{rad}}$ [m s$^{-1}$] | $\sigma_{\text{RV}}$ [m s$^{-1}$] |
|---------------|-------------------------------|----------------------------------|
| 2177.826      | −42.3                         | 5.7                              |
| 2192.772      | −75.8                         | 5.0                              |
| 2193.805      | −95.2                         | 5.0                              |
| 2194.786      | −110.7                        | 4.4                              |
| 2205.714      | −92.8                         | 5.6                              |
| 2206.754      | −103.4                        | 5.1                              |
| 2207.716      | −98.8                         | 5.3                              |
| 2222.754      | −89.1                         | 5.7                              |
| 2223.698      | −81.4                         | 5.5                              |
| 2258.635      | 31.2                          | 6.2                              |
| 2259.675      | 44.9                          | 5.8                              |
| 2295.594      | 111.2                         | 6.3                              |
| 2297.595      | 116.8                         | 7.0                              |
| 2437.985      | 45.5                          | 6.0                              |
| 2438.963      | 59.6                          | 5.7                              |
| 2439.990      | 30.8                          | 5.2                              |
| 2452.995      | 82.0                          | 5.5                              |
| 2453.944      | 55.5                          | 5.6                              |
| 2454.958      | 49.3                          | 6.2                              |
| 2464.987      | 72.1                          | 5.3                              |
| 2465.954      | 44.9                          | 5.4                              |
| 2466.975      | 80.3                          | 5.3                              |
| 2471.924      | 53.6                          | 5.6                              |
| 2483.979      | 102.5                         | 5.2                              |
| 2484.947      | 88.1                          | 5.4                              |
| 2494.978      | 94.5                          | 6.0                              |
| 2495.941      | 94.7                          | 5.8                              |
| 2496.970      | 101.0                         | 5.2                              |
| 2505.951      | 65.0                          | 6.3                              |
| 2506.919      | 62.9                          | 5.4                              |
| 2507.851      | 31.3                          | 6.1                              |
| 2517.914      | 13.5                          | 6.3                              |
| 2519.944      | −4.1                          | 5.8                              |
| 2528.862      | −18.8                         | 5.5                              |
| 2529.917      | −27.8                         | 6.7                              |
| 2530.887      | −44.4                         | 5.3                              |
| 2531.897      | −47.3                         | 5.2                              |
| 2532.858      | −34.6                         | 5.7                              |
| 2541.884      | −72.1                         | 5.5                              |
| 2542.825      | −66.1                         | 6.2                              |
| 2543.849      | −53.8                         | 5.4                              |
| 2559.876      | −91.9                         | 6.0                              |
| 2560.792      | −96.1                         | 6.0                              |
| 2571.766      | −85.2                         | 5.9                              |
| 2573.779      | −64.9                         | 6.0                              |
| 2589.758      | −75.6                         | 6.0                              |
| 2590.812      | −55.8                         | 6.1                              |
| 2603.749      | −8.9                          | 6.1                              |
| 2604.645      | −16.5                         | 5.7                              |
| 2605.685      | −34.7                         | 6.1                              |
| 2615.702      | 43.7                          | 5.7                              |
| 2616.731      | 48.8                          | 6.4                              |
| 2617.620      | 18.7                          | 6.6                              |
| 2801.984      | −2.7                          | 5.7                              |
| 2803.980      | 15.7                          | 5.4                              |
| 2837.959      | 113.0                         | 6.9                              |
| 2838.979      | 114.0                         | 7.1                              |
| 2839.976      | 71.4                          | 5.9                              |
| 2861.929      | 94.8                          | 4.4                              |
| 2863.972      | 98.8                          | 5.3                              |
Table B.2. RV data for 91 Aqr

| JD† [days] | \( v_{\text{rad}} \) [m s\(^{-1}\)] | \( \sigma_{\text{RV}} \) [m s\(^{-1}\)] |
|------------|------------------|------------------|
| 2879.906   | 42.9             | 5.6              |
| 2881.945   | 0.5              | 9.5              |
| 2898.891   | -19.1            | 5.2              |
| 2899.847   | -50.3            | 5.6              |
| 2900.895   | -62.0            | 5.2              |
| 2932.829   | -75.3            | 5.5              |
| 2934.777   | -103.2           | 4.7              |
| 2963.743   | -81.8            | 5.4              |
| 2966.731   | -43.3            | 6.0              |
| 3022.615   | 103.6            | 6.4              |
| 3232.884   | 24.7             | 4.1              |
| 3234.951   | 16.6             | 4.7              |
| 3265.858   | -74.9            | 3.9              |
| 3268.852   | -79.3            | 4.5              |
| 3286.776   | -90.8            | 3.8              |
| 3355.642   | 55.1             | 5.0              |
| 3546.976   | 61.2             | 4.5              |
| 3578.894   | 99.0             | 5.6              |
| 3578.929   | 80.0             | 5.4              |
| 3578.997   | 55.2             | 5.4              |
| 3579.849   | 81.1             | 4.6              |
| 3579.946   | 62.1             | 4.3              |
| 3579.995   | 63.7             | 4.1              |
| 3580.021   | 65.0             | 4.1              |
| 3580.859   | 70.2             | 4.9              |
| 3580.939   | 70.4             | 4.5              |
| 3581.021   | 73.1             | 4.8              |
| 3581.825   | 74.7             | 4.5              |
| 3581.926   | 69.7             | 4.2              |
| 3582.022   | 59.2             | 4.4              |
| 3582.849   | 55.1             | 4.6              |
| 3582.915   | 54.7             | 4.7              |
| 3583.008   | 69.1             | 4.8              |
| 3583.931   | 80.6             | 4.2              |
| 3583.939   | 74.3             | 4.0              |
| 3583.948   | 74.9             | 4.1              |
| 3584.822   | 67.7             | 4.4              |
| 3584.870   | 66.0             | 4.2              |
| 3584.943   | 59.3             | 4.1              |
| 3585.821   | 38.4             | 3.9              |
| 3585.924   | 82.6             | 4.0              |
| 3586.010   | 89.9             | 4.3              |
| 3586.825   | 70.3             | 4.1              |
| 3586.852   | 64.9             | 4.3              |
| 3587.018   | 60.7             | 4.0              |
| 3587.921   | 15.6             | 4.2              |
| 3587.985   | 35.9             | 5.3              |
| 3698.663   | -27.6            | 4.7              |
| 3702.650   | 3.4              | 5.5              |
| 3741.621   | 86.1             | 5.5              |
| 3911.975   | 107.0            | 4.3              |
| 3915.984   | 77.1             | 4.1              |
| 3934.930   | 98.3             | 4.3              |
| 3936.910   | 95.1             | 4.6              |
| 3967.907   | -20.2            | 4.5              |
| 3982.797   | -15.9            | 4.4              |
| 4054.746   | -18.9            | 5.1              |
| 4124.594   | 66.1             | 4.4              |
| 4266.991   | 74.7             | 4.0              |
| 4297.882   | 134.7            | 4.7              |
Table B.2. RV data for 91 Aqr

| JD<sup>a</sup> [days] | \( v_{\text{rad}} \) [m s\(^{-1}\)] | \( \sigma_{\text{RV}} \) [m s\(^{-1}\)] |
|----------------------|------------------|------------------|
| 4300.885             | 107.3            | 5.2              |
| 4314.872             | 92.0             | 3.9              |
| 4344.849             | −19.6            | 4.6              |
| 4348.875             | −32.3            | 4.7              |
| 4391.656             | −35.8            | 6.9              |
| 4419.688             | −3.5             | 4.8              |
| 4421.725             | −4.4             | 5.5              |
| 4482.612             | 78.9             | 6.4              |
| 4645.956             | 88.1             | 5.3              |
| 4667.963             | 75.9             | 5.0              |
| 4711.856             | −60.2            | 5.1              |
| 4756.777             | −95.1            | 4.8              |
| 4777.699             | −22.7            | 5.1              |
| 5026.951             | 110.8            | 7.3              |
| 5063.950             | 7.2              | 5.7              |
| 5097.906             | −90.0            | 6.8              |
| 5116.818             | −36.6            | 6.3              |
| 5155.655             | 60.3             | 8.1              |
| 5363.976             | 74.8             | 5.4              |
| 5420.911             | −19.9            | 4.9              |
| 5449.762             | −63.3            | 5.0              |
| 5569.617             | 73.5             | 5.1              |
| 5704.007             | −4.1             | 4.7              |
| 5732.971             | 104.9            | 4.6              |
| 5735.972             | 77.3             | 4.8              |
| 5757.920             | 43.1             | 5.7              |
| 5803.845             | −25.8            | 5.3              |
| 5806.857             | −67.3            | 5.3              |
| 5829.792             | −90.3            | 6.0              |
| 5862.718             | −66.0            | 4.8              |
| 5894.680             | 27.1             | 7.9              |

<sup>a</sup> Julian date–2450000

Table B.3. CRIRES data for τ Gem

| JD<sup>a</sup> [days] | \( v_{\text{rad}} \) [m s\(^{-1}\)] | \( \sigma_{\text{RV}} \) [m s\(^{-1}\)] |
|----------------------|------------------|------------------|
| 5859.712             | 203.0            | 40.2             |
| 5918.848             | 323.6            | 40.2             |
| 5994.624             | 2.4              | 40.2             |
| 6039.424             | −292.8           | 40.2             |
| 6244.736             | 252.1            | 40.2             |
| 6288.768             | −101.9           | 40.2             |
| 6326.400             | −316.5           | 40.2             |

<sup>a</sup> Julian date–2450000

Table B.4. CRIRES data for 91 Aqr

| JD<sup>a</sup> [days] | \( v_{\text{rad}} \) [m s\(^{-1}\)] | \( \sigma_{\text{RV}} \) [m s\(^{-1}\)] |
|----------------------|------------------|------------------|
| 5854.592             | −116.3           | 40.1             |
| 6112.896             | 98.4             | 40.1             |
| 6144.640             | 69.1             | 40.1             |
| 6239.616             | −11.1            | 40.1             |

<sup>a</sup> Julian date–2450000