Precise Stellar Radial Velocities
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Precise Radial-velocity Measurements with a Cassegrain Spectrograph, II: Radial-velocity Determination and Applications

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Abstract. We present our measurements of radial velocities of two stars suspected to have a substellar companion by using observations made with a cassegrain échelle spectrograph. The stability issues and details of the data reduction are discussed in Ilyin & Duemmler (paper I, these proceedings). The results obtained here show that relatively high accuracy of radial velocity determinations is also attainable for cassegrain spectrographs.

1. Observations

Spectra of τ Boo (HR 5185; F7V) and υ And (HR 458; F8V) were recorded with the spectrograph SOFIN mounted at the cassegrain focus of the alt-azimuth 2.56-m Nordic Optical Telescope, La Palma, Canary Islands. The spectrograph is equipped with an R2 échelle and a cross-dispersion prism to separate spectral orders. A thorium-argon lamp is used for the comparison spectrum. One of the three optical cameras, which provides the highest resolving power of about 160 000 (930 $\mathrm{m\,s^{-1}}$ per one CCD pixel), was used for the radial velocity measurements. The spectral region was chosen around 6437 Å which gives 17 spectral orders, with a length of about 22 Å each, recorded simultaneously in one échelle image ranging from 5400 Å to 9400 Å.

Sixteen observations of τ Boo with the average signal-to-noise ratio of 360 were obtained in April and June 1997. Forty-four observations of υ And with the average signal-to-noise ratio of 180 were obtained in December 1997 and March 1998.

2. Radial-velocity determination

The wavelength calibration was done with the dispersion curve defined by the three-dimensional model, whenever it was possible, to reduce the instrumental effects (see paper I). The remaining small offsets were determined by cross-correlation of the telluric lines with an artificial spectrum for different spectral orders. The artificial telluric spectrum was created by computing lorentzian profiles around the given wavelength (from Pierce & Breckinridge 1973) and by adjusting the intensities to the observed spectrum. The average offset was applied to all spectral orders of the same image.

The radial velocities were measured for each order with respect to the spectral orders of the same star having the best signal-to-noise. The whole spectral order is used for cross-correlation with the template with possible exclusion of intervals disturbed by telluric lines.

The dependence of the radial velocities on the order number is corrected by a weighted linear fit across the orders. The fitted value of the radial velocity and its error for a given image are taken from that central order where the error of the linear fit is minimal.

The error of the measurement is obtained by adding two terms in quadrature: the error of the mean of the telluric correction and the error of the above fit. The error of the zeroth term of the wavelength solution is canceled by the telluric correction, the errors of the other terms are included in the linear fit across the orders.

The internal accuracy of the radial velocities can be 2 $m\,s^{-1}$ from 20 lines in a sharp-lined K-star and is not better than 20 $m\,s^{-1}$ from 5 lines in a F-star with $v \sin i > 10$ $km\,s^{-1}$. The major uncertainty in the final radial velocity comes from the telluric correction which ranges from 10 to 100 $m\,s^{-1}$ per spectral order, depending on the line strengths and the number of unblended lines.

3. Orbital solution

A keplerian orbit (Heintz 1978) was fitted to the weighted relative radial velocities by using the Marquardt method for non-linear least-squares. The orbital solutions and their functions for both stars are given below. The errors of functions of the orbital parameters incorporate covariances between the parameters. The mass of the secondary component is estimated assuming that the mass of the primary is $1.2\,M_{\odot}$ consistent with the spectral types.

An F-test gives the significance level of the elliptical fit of τ Boo of only 52% which implies that our data are not sufficient to make the conclusion. The excess of the reduced χ^2_ν above 1 could imply that the data are not adequate for a keplerian orbit. The minimal mass of a brown dwarf (20 $M_{\rm Jup}$) as the maximal mass of the secondary constrains the inclination of the orbit to 10°. The inclination $i < 10°$ would occur in 1.5% cases of randomly oriented orbital planes, which implies that, apart from the selection effects, the companion could be a substellar object with a probability of 98.5%.

The significance level of the elliptical fit of υ And is 91%. Therefore, more observations are necessary to support the issue that the orbit is not circular. For the mass of the secondary to be less than 20 $M_{\rm Jup}$ the inclination angle has to be more than 2°, which implies a probability of 99.94% that such an orbit occurs in randomly oriented orbital planes.

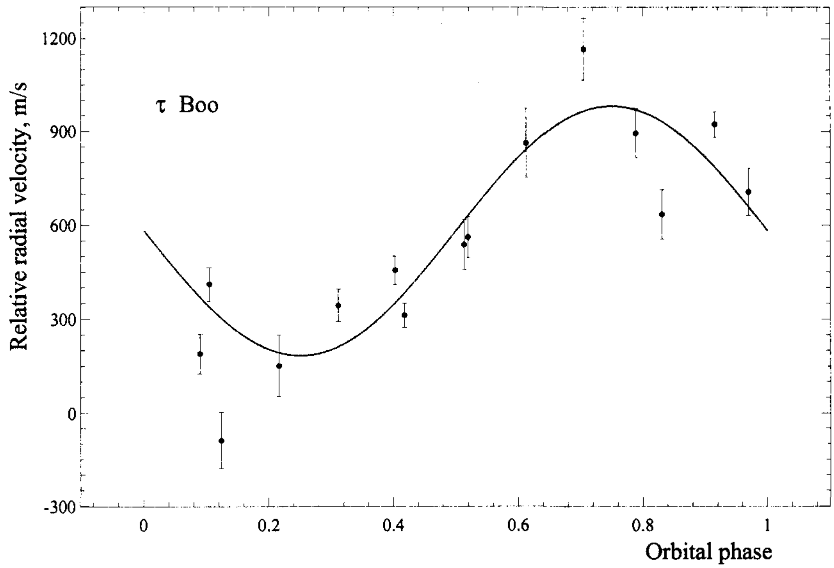

Figure 1. Relative radial velocity measurements of τ Boo and the circular orbit fit phased with respect to T_{conj}. The average error of the measurements is $71\,\mathrm{m\,s^{-1}}$.

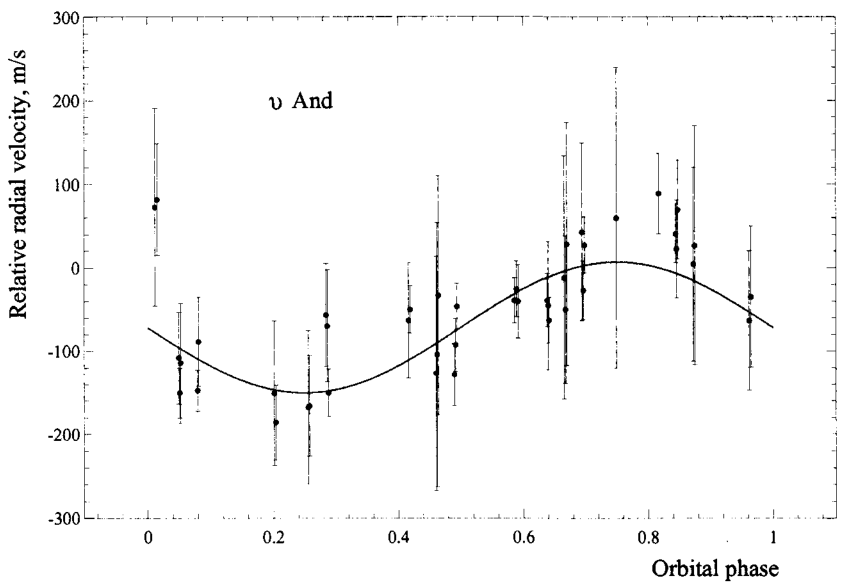

Figure 2. Relative radial velocity measurements of υ And and the circular orbit fit phased with respect to T_{conj}. The average error of the measurements is $73\,\mathrm{m\,s^{-1}}$.

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Table 1. Orbital elements of τ Boo

Parameter	Circular fit	Elliptical fit	Butler et al. (1997)
K_1, m s^{-1}	399 ± 72	383 ± 71	469 ± 5
P, days	3.306 ± 0.025	3.301 ± 0.010	3.3128 ± 0.0002
ω, degrees		97 ± 55	254
e		0.28 ± 0.14	0.018 ± 0.016
$T_{\rm peri}$, HJD		$2\,450\,600.83 \pm 0.48$	
$T_{\rm maxRV}$, HJD	$2\,450\,599.89 \pm 0.07$	$2\,450\,600.24 \pm 0.13$	$2\,450\,235.41 \pm 0.2$
$T_{\rm conj}$, HJD	$2\,450\,600.71 \pm 0.07$	$2\,450\,600.80 \pm 0.22$	
$a_1 \sin i$, $R_\odot$	0.026 ± 0.005	0.024 ± 0.005	
$a_1 \sin i$, AU	$(1.2 \pm 0.2) \cdot 10^{-4}$	$(1.1 \pm 0.2) \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
$f(m)$, $M_\odot$	$(2.2 \pm 1.2) \cdot 10^{-8}$	$(1.7 \pm 1.0) \cdot 10^{-8}$	$3.45 \cdot 10^{-8}$
$m_2 \sin i$, $M_{\rm Jup}$	3.45 ± 0.62	3.18 ± 0.63	3.87
a_2, $R_\odot$	9.50 ± 0.002	9.50 ± 0.0008	
a_2, AU	$0.044 \pm 9 \cdot 10^{-6}$	$0.044 \pm 4 \cdot 10^{-6}$	0.0462
$\sigma_{\rm fit}$, m s^{-1}	161	159	14
χ^2_ν	6.932	6.779	
Num. of RVs.	15	15	19
Time span	80 days	80 days	450 days

Table 2. Orbital elements of υ And

Parameter	Circular fit	Elliptical fit	Butler et al. (1997)
K_1, m s^{-1}	78 ± 11	109 ± 18	74.1 ± 4
P, days	4.858 ± 0.054	4.855 ± 0.010	4.611 ± 0.005
ω, degrees		90 ± 16	314
e		0.46 ± 0.12	0.109 ± 0.04
$T_{\rm peri}$, HJD		$2\,450\,893.91 \pm 0.17$	
$T_{\rm maxRV}$, HJD	$2\,450\,892.59 \pm 0.12$	$2\,450\,893.38 \pm 0.17$	$2\,450\,088.64 \pm 0.3$
$T_{\rm conj}$, HJD	$2\,450\,893.81 \pm 0.12$	$2\,450\,893.91 \pm 0.12$	
$a_1 \sin i$, $R_\odot$	0.008 ± 0.001	0.009 ± 0.001	
$a_1 \sin i$, AU	$(3.5 \pm 0.5) \cdot 10^{-5}$	$(4.3 \pm 0.6) \cdot 10^{-5}$	$3.2 \cdot 10^{-5}$
$f(m)$, $M_\odot$	$(2.4 \pm 1.0) \cdot 10^{-10}$	$(4.7 \pm 1.8) \cdot 10^{-10}$	$2.18 \cdot 10^{-10}$
$m_2 \sin i$, $M_{\rm Jup}$	0.77 ± 0.11	0.96 ± 0.12	0.68
a_2, $R_\odot$	12.28 ± 0.001	12.27 ± 0.0002	
a_2, AU	$0.057 \pm 6 \cdot 10^{-6}$	$0.057 \pm 1 \cdot 10^{-6}$	0.057
$\sigma_{\rm fit}$, m s^{-1}	46	37	12
χ^2_ν	1.026	0.667	
Num. of RVs.	43	43	18
Time span	180 days	180 days	160 days

Discussion

Latham: Your orbital solution for υ Andromedae, where eccentricity is allowed to be a free parameter, has a high eccentricity of $e = 0.46 \pm 0.12$. Do you believe that this high eccentricity is real?

Ilyin: We do not consider that it is significant, because of the limited number of observations.

References

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