The Planet Orbiting ρ Coronae Borealis

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Abstract

Continuing precise radial velocity observations of ρ Coronae Borealis have allowed the determination of updated parameters of the 40-day orbit of its Jupiter-mass companion. This confirms the near-zero eccentricity of the orbit, and provides improved predictions for the times of possible transit of the companion in front of the star. The new data provide some upper limits to the mass of a possible second companion to the system. The orbital parameters are discussed in the light of several different scenarios for the origin and migration of extra-solar giant planets.

Web site: `http://cfa-www.harvard.edu/afoe`

The Instrument and Analysis

The Advanced Fiber Optic Echelle (AFOE)

- THE AFOE: A joint project of SAO and HAO. The instrument is installed at the 1.5-m telescope of the Whipple Observatory at Mt. Hopkins, AZ.
- THE GOAL: Measure stellar radial velocities to a precision of a few m/s.
- THE METHOD: Use a fiber-fed 2-D echelle spectrograph with $R \sim 50{,}000$. An I_2 cell in the beam path, covering six orders in the range 5,000 to 6,000 Å provides an accurate and stable wavelength calibration.

Current Extra-Solar Planet Research Program

- AFOE currently observes about 7 nights per month.
- Observing list consists of about 100 F, G, and K dwarfs, with $V \leq 7$, chosen to complement the observing lists of other groups capable of radial velocities measurements at 10 m/s precision or better.
- Methodology is to observe stars initially several times per observing run, on several successive observing runs. If significant (short-term) variations are seen, continue this pattern; otherwise reduce frequency to several observations per year to monitor possible long-term variations.
- Data are currently reduced the day after observation, to aid in planning immediately following observations.

Data Analysis Methodology

- We compute a model of the observed star plus Iodine spectrum (Figures 1 and 2).
- We then adjust the model parameters to best match the observations in the least-squares sense.
- From the parameterization of the Doppler shift, we obtain an estimate of the line-of-sight velocity of the star.

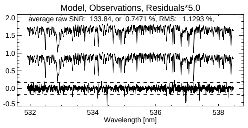

Figure 1: *(top to bottom) model, observations and residuals ($\times 5$), for a 10 minute integration on a $V = 5.4$, G2 star.*

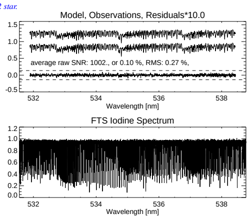

Figure 2: *(top) Model, observations and residuals for a calibration frame (i.e., quartz lamp + I_2) with very high SNR; (bottom) measured FTS Iodine spectrum ($R \approx 400{,}000$) used to build the model.*

Summary of Observations and Results

- We have continued observations of near-sinusoidal radial velocity variations of the G2 V star ρ CrB, already reported to have amplitude 66.2 m/s and period 40.0 days, (Noyes *et al.* , 1997). Figure 3 shows the radial velocity observations and the orbital fit to data through June, 1998. There are 65 AFOE observations and 14 observations from Lick (Butler, Marcy, and Fisher, 1998, personal communication) included.
- Implications: The previously reported orbit parameters for ρ CrB are not significantly changed, and imply that the star has a giant companion with projected mass $m \sin i$ of 1.1 $M_{\rm Jup}$ and a semi-major axis of 0.23 AU. There is some evidence that the eccentricity is non-zero ($e = 0.13 \pm 0.05$). Residuals to the fit show no evidence for a second companion, although a $\leq$ 1 $M_{\rm Jup}$ companion of orbital distance $\geq$ 1 AU cannot yet be formally excluded. Photometric data obtained near times of possible transits show no evidence of such transits, suggesting that we are not seeing the system nearly edge on.

Name:	HD 143761, HR 5968	π:	57./38±0.71
R.A.:	16:01:03.39	Dist.:	17.4±0.2 pc
Dec:	+33:18:51.5	T_{eff}:	$\sim$ 5800°K
Epoch:	2000.0	Vsin i:	3 km/s
V:	5.41	τ_{rot}:	20 days
B-V:	0.61	$\mathcal{L}$:	1.77 $\mathcal{L}_\odot$
$\delta(U-B)$:	0.06	$\mathcal{M}$:	1.0 $\mathcal{M}_\odot$
M_v:	4.20	$\mathcal{R}$:	1.31 $\mathcal{R}_\odot$
Sp. Type:	$\sim$ G2V	Age:	10 Gyr

Table 1: *Stellar Information for ρ CrB*

Amplitude:	66.68 ± 3.00 m/s
Period:	39.90 ± 0.08 days
ϵ:	0.13 ± 0.05
Ω:	306.9 ± 19.2
T_0:	524.1 ± 2.07 (HJD - 50,000)
RMS_{resid}:	9.34 m/s

Table 2: *Orbital Parameters for ρ CrB, from data through June, 1998*

Orbital Plot of ρ Coronae Borealis

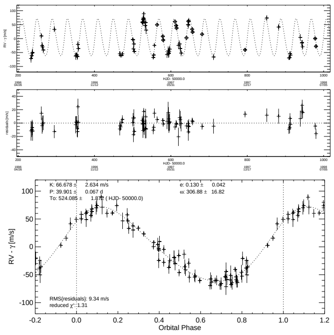

Figure 3: *Orbital fit to radial velocity observations (through June, 1998) of ρ CrB. AFOE data is indicated with crosses, and Lick data with diamonds. The residuals to the orbital fit show no evidence for a second companion. A small, but marginally significant eccentricity is also determined.*

Constraints on Second Companion

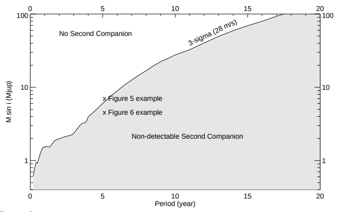

Figure 4: *Constraints on a second companion, based on the residuals (σ=9.3 m/s) to the 40-day period. A circular orbit for the second companion is assumed, with the epoch chosen to minimize the residuals. The unshaded region indicates where second companions can definitely be ruled out at the 3-σ level. In the shaded region, companions cannot yet be ruled out at the 3-σ level. Examples of orbits which can and cannot yet be ruled out are shown in Figures 5 and 6.*

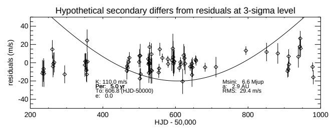

Figure 5: *A hypothetical orbit for a second companion which can be excluded at the 3-sigma level based on the velocity residuals.*

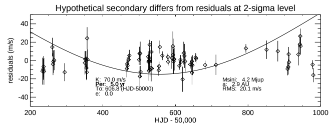

Figure 6: *A hypothetical orbit for a second companion which cannot be excluded at the 3-sigma level based on the velocity residuals.*

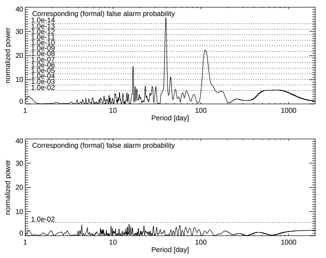

Figure 7: *Scargle periodograms for ρ CrB before (top) and after (bottom) removing the 40-day Keplerian orbit from the radial velocity data. The residuals (bottom) are consistent with random noise.*

Origin and Migration of the Companion

- The orbital period and amplitude plus the spectral type of ρ CrB imply a companion with mass m sin$i$ $\sim$ 1.1 $M_{\rm Jup}$ and semi-major axis $\sim$ 0.23 AU. In situ formation of a such a companion is unlikely (e.g. Lin and Ida 1997) but perhaps not impossible (Bodenheimer 1997, Wuchterl 1996).
- More plausible is formation of the companion at several AU by gas accretion onto a rocky core, followed by inward migration.
- Possibilities for inward migration:
  1. Interaction with another giant planet, which is ejected with decrease in semi-major axis of survivor (e.g. Weidenschilling & Marzari 1996). This seems unlikely, given the near-zero eccentricity of ρ CrB (Artymowicz 1997, Lin & Ida 1997, Rasio *et al.* 1996).
  2. Inward migration is possible through gravitational interaction with the protoplanetary gas disk (Lin *et al.* 1996, Ward 1997, Trilling *et al.* 1998). But halting of the migration near 0.23 AU is difficult: stellar tidal effects or magnetospheric clearing of inner disk do not extend out much past $\sim$ 0.05 AU. It is possible by fine-tuning of disk parameters to model a 1 $M_{\rm Jup}$ object spiraling in to 0.23 AU and stopping there (Trilling *et al.* 1998), but this requires special circumstances.
  3. Inward migration via interactions between the planet and planetesimals in mean-motion resonances (Murray *et al.* 1998) is an alternative possibility. But for a 1 $M_{\rm Jup}$ planet, migration as far inward as 0.23 AU requires a quite massive disk–of order 50 times the minimum solar nebula (for solar composition). This is at the upper range of observed properties of disks around T Tauri stars (Beckwith and Sargent 1996). This migration model does predict small eccentricities for planets with $M < 3M_{\rm Jup}$, and large eccentricities for planets with $M > 3M_{\rm Jup}$, as observed for ρ CrB, 70 Vir, and HD 114762. If the model is correct, the apparently non-zero eccentricity of ρ CrB could give information on the average size of planetesimals, since it predicts $e^2 \sim (M_{\rm planetesimal}/M_{\rm planet})$.
- CONCLUSION: We need more statistics on distribution of masses, semi-major axes, and eccentricities of low-mass companions to discriminate clearly among different formation and migration scenarios.

Possibilities of Transit

- Over the past six years, G. Henry has been obtaining photometric data on ρ CrB. A least-squares sin fit to the photometric data produces a semi-amplitude on the orbital period of 0.05 ± 0.09 milli-magnitudes, which places very tight constraints on any alternative photometric explanation for the observed radial-velocity variations (Henry, 1998, personal communication).

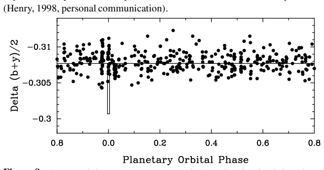

Figure 8: *Six years of photometric measurements of ρ CrB, phased to the 40-day orbit. The Solid line is the predicted light curve for transit by a companion with a radius of 1 $R_{\rm Jup}$. (Henry, Baliunas, Donahue; paper in preparation).*

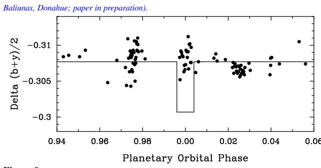

Figure 9: *Expanded view near the predicted time of conjunction.*

Radial Velocity Standards

- Figures 10 and 11 illustrate the AFOE results for two stars known to be RV constant: τ Cet and β Aql (Marcy and Butler, ApJ, 1996).

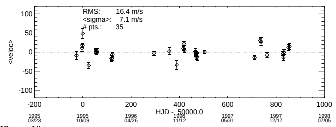

Figure 10: *Velocities for τ Cet ($V = 3.5$, G8V), a known RV constant star.*

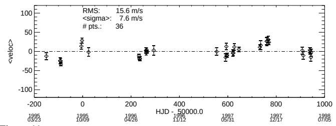

Figure 11: *Velocities for β Aql ($V = 3.7$, G8IV), a known RV constant star.*

Observations of Other Known Planetary Companions

- Other examples illustrating the current level of accuracy of our data are given in Figures 12 to 15, showing radial velocity observations and orbital fits to the following stars with known companions: 70 Vir, HD 114762, τ Boo, and ρ^1Cnc.

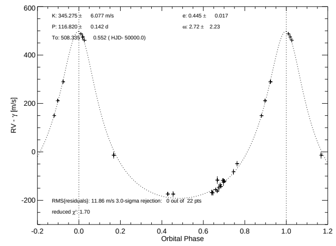

Figure 12: *Orbital fit to AFOE observations of 70 Vir ($V = 5.0$, G0V).*

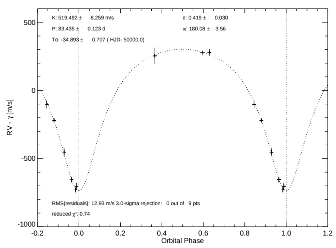

Figure 13: *Orbital fit to AFOE observations of HD 114762 ($V = 7.3$, F9V).*

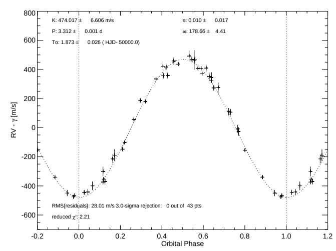

Figure 14: *Orbital fit to AFOE observations of τ Boo ($V = 4.5$, F7V).*

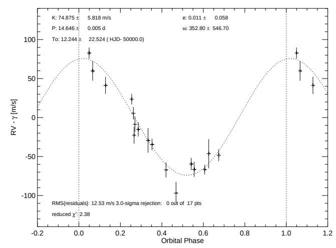

Figure 15: *Orbital fit to AFOE observations of $\rho^1 Cnc$ ($V = 6.0$, G8V).*

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