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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 previously reported period and amplitude, and shows a small but marginally significant non-zero eccentricity. It also provides improved predictions for the times of possible transit of the companion in front of the star. The new data provide upper limits to the mass of a possible second companion to the system. The orbital parameters are discussed in the light of scenarios for the origin and migration of extra-solar giant planets.

1. The companion to ρ CrB

Using the Advanced Fiber Optic Echelle (AFOE) spectrograph[1], we have continued monitoring the radial velocity variations of the G2 V star ρ CrB (HD 143761). This star was earlier reported to show keplerian radial velocity variations with amplitude 67 m/s, period 40 days, and eccentricity consistent with zero (Noyes *et al.* 1997). A total of 65 AFOE observations have now been obtained over a time span of 710 days (18 orbital periods). In addition, Butler, Marcy and Fischer (1998) have obtained 14 observations from Lick Observatory and kindly provided them to us. Both data sets yield orbital parameters consistent with each other, and consistent with those reported previously, with the exception that both indicate a non-zero eccentricity whereas the initial data set yielded an eccentricity consistent with zero. We have derived an orbital fit to the combined data sets, after applying an arbitrary offset between the two chosen to minimize the rms variation of the residuals, weighted by their internal errors.

[1]The AFOE is a joint project of the Smithsonian Astrophysical Observatory and the High Altitude Observatory. The instrument is installed at the 1.5-m telescope of the Whipple Observatory at Mt. Hopkins, Arizona. For instrument and observation details see Noyes *et al.* 1997.

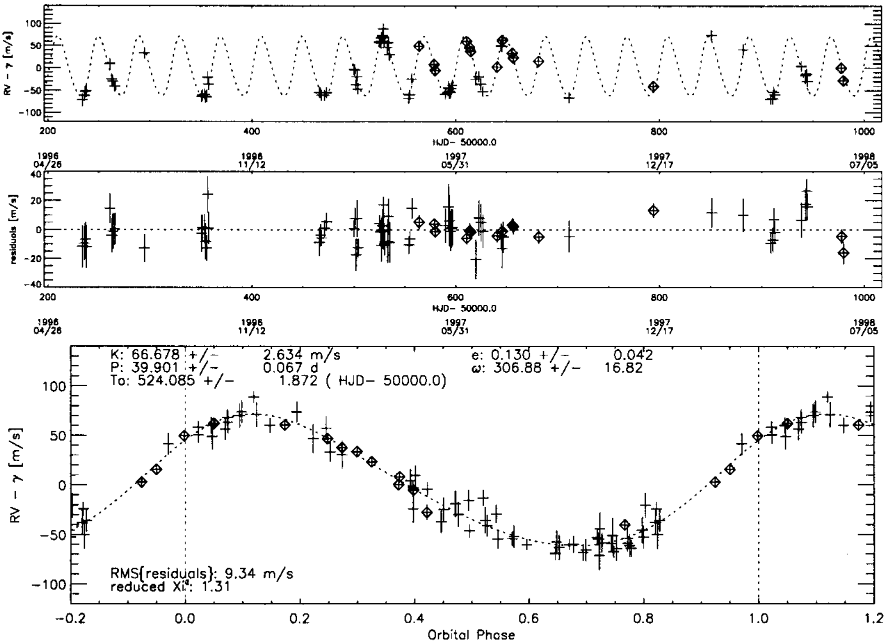

Figure 1. Orbital fit to radial velocity observations of ρ CrB. AFOE data are indicated with crosses, and Lick data with diamonds. Plotted in the upper panel are the radial velocities, the middle panel shows the residuals to the orbital fit, and the bottom panel is the phased orbit.

Figure 1 shows the combined radial velocity observations and the orbital fit, while Table 1 lists the parameters of the fit. In Table 1, the formal errors have been multiplied by $\chi = 1.14$ to reflect the small excess rms variation over that expected from the internal errors under the assumption that the radial velocity variations are strictly keplerian.

These results therefore confirm that if ρ CrB is a 1.0 $M_{\odot}$ star (cf. Noyes *et al.* 1997), it has a low-mass companion with projected mass $m \sin i \sim 1.1\ M_{\rm Jup}$, orbiting with a semi-major axis of $\sim$ 0.23 AU. It now appears that the eccentricity of the companion's orbit is non-zero at a weakly significant level of 2.6 σ.

Table 1. Orbital Parameters for ρ CrB, from data through June, 1998. Errors have been multiplied by $\chi = 1.14$.

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

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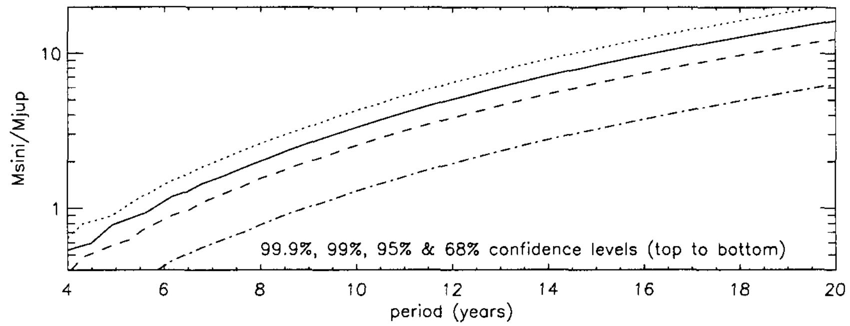

Figure 2. Constraints on a second companion, based on the residuals ($\sigma = 9.3$ m/s) to the 40-day period. Mass-period combinations above the respective lines can be excluded at the given confidence levels.

2. Constraints on a Second Companion

Residuals to the fit (middle panel of Figure 1) show no evidence for keplerian motion with amplitude K as large as 20 m/s and periods shorter than about 4 years (twice the span of the observations). This makes unlikely a second companion with projected mass $m \sin i$ as large as 0.7 or 1.1 $M_{\rm Jup}$ for orbital periods of 1 or 4 years, respectively. For longer periods, the detectability depends on the phase of the orbit during our observing span. We have calculated confidence levels that such a companion in a circular orbit would be detected in the most unfavorable circumstance; *i.e.* if minimum or maximum orbital velocity occurred in the middle of the time span. Figure 2 shows, for this most unfavorable case, the maximum values of $m \sin i$ for periods longer than 4 years which could escape detection at various confidence levels.

3. Origin and Migration of the Companion

In-situ formation of a companion with mass $m \sin i \sim 1.1$ $M_{\rm Jup}$ and semi-major axis $\sim$ 0.23 AU companion is unlikely (e.g. Lin & Ida 1997) but perhaps not impossible (Bodenheimer 1997, Wuchterl 1996). More plausible is the formation of the companion at several AU by gas accretion onto a rocky core, followed by inward migration.

Possibilities for inward migration include: interaction with another giant planet, which is ejected with decrease in semi-major axis of the survivor (e.g. Weidenschilling & Marzari 1996); gravitational interaction with the protoplanetary gas disk (Lin *et al.* 1996, Ward 1997, Trilling *et al.* 1998); or interactions between the planet and planetesimals in mean-motion resonances (Murray *et al.* 1998). Whatever the mechanism, it must allow both for "parking" the planet at 0.23 AU, and also for a non-zero eccentricity of its final orbit. Inward migration of the very close-in planets τ Boo b, 51 Peg b, and υ And b could plausibly be halted by tidal interactions with the star or clearing of the disk by the stellar magnetosphere (Lin *et al.* 1996). However, ρ CrB b is too far from its primary for such a stopping mechanism to be operative, as is also the case for the companions to ρ^1 Cnc, GL 876 (Marcy *et al.* 1998), 70 Vir, and HD 114762. All of the three very close planets mentioned above have essentially zero eccentricities, as would be expected from tidal circularization. It is perhaps significant that all of the other companions mentioned have non-zero eccentricities. Thus the migration and stopping mechanism for these companions must be one that leads to non-zero orbital eccentricities (see also Marcy *et al.* 1998).

However, the sample of extra-solar low-mass companions with known $m \sin i$, semi-major axis, and eccentricity is still very small. Our understanding of formation and migration mechanisms is bound to improve greatly as more companions are discovered in coming years.

4. Possibilities of Transit

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

Photometric data obtained near times of possible transits determined from the orbital parameters in Table I show no evidence of such transits, suggesting that we are not seeing the system nearly edge on.

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