A PLANET ORBITING THE STAR ρ CORONAE BOREALIS

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ABSTRACT

We report the discovery of near-sinusoidal radial velocity variations of the G0V star ρ CrB, with period 39.6 days and amplitude 67 m s⁻¹. These variations are consistent with the existence of an orbital companion in a circular orbit. Adopting a mass of 1.0 M_J for the primary, the companion has minimum mass about 1.1 Jupiter masses and orbital radius about 0.23 AU. Such an orbital radius is too large for tidal circularization of an initially eccentric orbit during the lifetime of the star, and hence we suggest that the low eccentricity is primordial, as would be expected for a planet formed in a dissipative circumstellar disk.

Subject headings: planetary systems — stars: low-mass, brown dwarfs — stars: individual (ρ Coronae Borealis) — techniques: radial velocities

1. INTRODUCTION

Within the past 18 months, our knowledge of low-mass companions of stars has exploded, so that it is becoming possible to carry out comparative studies of their properties such as mass, orbital period, and orbital eccentricity. This information is opening the door to a better understanding of the formation and evolution of planets and brown dwarfs, including the planets in our own solar system. However, the small number of objects with known orbital parameters does not yet permit creating a reliable picture of the origin and evolution of such objects.

For this reason it is extremely important to increase the number of known low-mass stellar companions and also gain information on their orbital properties. We have developed the Advanced Fiber Optic Echelle (AFOE) spectrograph in part for this purpose. Using this instrument we have begun an intensive program of monitoring about 100 Sun-like stars brighter than V = 6.5 with a precision of order 10 m s⁻¹; this is sufficient to detect the reflex orbital velocities of any of the substellar companions detected by precise radial velocity techniques to date. In this Letter we report the detection of periodic radial velocity variations in the star ρ Coronae Borealis, which we interpret as arising from a Jupiter-mass planet in a near-circular orbit about the star.

2. RHO CORONAE BOREALIS—AN OLD SUN-LIKE STAR

In order to understand the properties of an orbiting companion of ρ CrB (HD 143761, HR 5968), it is necessary to estimate the mass, effective temperature, and age of the parent star. The evidence argues for ρ CrB being an old, Sun-like star, with mass close to that of the Sun.

The spectral type of ρ CrB is reported to be either G0V (Jaschek, Conde, & de Sierra 1964) or G2V (Roman 1952, 1955). Reported Months ¹ V color indices average about 0.61 (Roman 1955; Naur 1955; Argue 1963), i.e., slightly bluer than the Sun, for which reported values of B − V range from 0.63 to 0.66 (e.g., Gray 1992; Cayrel de Strobel 1996; Taylor 1994). The effective temperature T_eff is about 5700 K, as determined from the infrared flux method (Gratton, Carretta, & Castelli 1996; Alonso, Arribas, & Martinez-Roger 1996), although Gray (1994) concludes from line-depth ratios that T_eff = 5868 K.

The luminosity of ρ CrB is higher than the Sun’s, suggesting that ρ CrB is more evolved and thus older. This is inferred as follows. The V-band apparent magnitude of ρ CrB is close to V = 5.41 (Rufener 1976; Naur 1955; Argue 1963; Roman 1955). The HIPPARCOS measurement of the star’s parallax is π = 57.38 ± 0.71 mas (D. Soderblom 1997, private communication), giving a distance of 17.4 ± 0.2 pc. These values imply an absolute visual magnitude M_V = 4.20. Using a Sun-like bolometric correction of B.C. = −0.07, this gives a luminosity of L = 1.77 L☉. Adopting an effective temperature equal to that of the Sun (5777 K; Cayrel de Strobel 1996), we obtain a radius of R = 1.31 R☉.

Based on the evolutionary H-R diagrams of Bressan et al. (1993), the color and luminosity of ρ CrB are consistent with a 1.0 M☉ star about 10 Gyr old. The surface gravity was determined by Künzl et al. (1997) and Gratton et al. (1996) to be log g = 4.27 and 4.11, respectively, which is also consistent within the uncertainties of the fitting procedure with an evolved solar-mass star.

G. Henry (1997, private communication) reports that four years of precise photometric data for ρ CrB show no significant periodicities between 1 and 50 days, and constant seasonal means to within 0.00017 mag. The implied absence of spot activity is consistent with an old age for ρ CrB.

The relative chromospheric inactivity of ρ CrB also supports
its high age. Its Ca II chromospheric flux is below that of the Sun and shows no significant seasonal variations (Baliunas et al. 1995). In spite of the smaller Ca II flux, the rotation period of ρ CrB as predicted from that flux is about 20 days (Noyes et al. 1984; Soderblom 1985), which is slightly shorter than the 25.4 day sidereal rotation period of the Sun. The faster predicted rotation results from the fact that ρ CrB has slightly bluer $B-V$ color index than the Sun does. There is some observational evidence for a rotational modulation of the Ca II flux with about a 17 day period (Baliunas, Sokoloff, & Soon 1996), although that evidence is marginal (W. Soon 1997, private communication).

Further evidence that ρ CrB is older and more evolved than the Sun is provided by its metal deficiency; reported values of [Fe/H] average to $-0.19$ (Künzli et al. 1997; Hearnshaw 1974; Wallerstein 1962; Alexander 1967). The ultraviolet excess $\delta (U-B) = 0.06$ (Hearnshaw 1974) also indicates a slightly less than solar abundance. In addition, ρ CrB is a high proper motion star with a motion out of the Galactic plane of 28 km s$^{-1}$ (Cayrel de Strobel 1996), indicating that it may be a member of the old disk population.

The above information, taken all together, suggests that ρ CrB is probably of near solar mass but is older, near the end of its main-sequence lifetime or possibly already starting hydrogen-shell burning (see Cayrel de Strobel 1996, Figure 14). For the purposes of this Letter, we shall adopt a nominal mass for ρ CrB of $1.0M_\odot$.

3. OBSERVATIONS

3.1. Instrumentation and Reduction Procedure

Data on ρ CrB were taken with the Advanced Fiber-Optic Echelle (AFOE) Spectrograph located at the 1.5 m telescope of the Whipple Observatory. This instrument is a cross-dispersed, fiber-fed echelle spectrograph designed specifically to perform precise stellar radial velocity measurements (Brown et al. 1994); its construction and operation are a joint project of the Smithsonian Astrophysical Observatory, the High Altitude Observatory, and Pennsylvania State University. The spectrograph covers a wavelength range of about 150 nm between wavelengths of 392 and 665 nm, at a typical resolution $R = \lambda/\delta \lambda$ of 50,000. The combination of a fiber feed, mechanical stability, and careful thermal control minimizes drifts in the velocity zero point and also results in a very stable instrumental resolution profile. For these observations, wavelength calibration was provided by an absorption cell filled with iodine vapor (Horner 1996), which superposes a dense spectrum of molecular iodine ($I_2$) lines on the stellar spectrum in the wavelength range between 500 and 620 nm. When operated in this mode, the spectrograph can achieve Doppler precision of better than 10 m s$^{-1}$ on a 5.0 mag G star in an observation time of 10 minutes (Noyes et al. 1997).

The method of data reduction is generally similar to that described by Butler et al. (1996), although it differs in details. One-dimensional spectra are extracted from the two-dimensional echelle images, corrected for scattered light, and divided by the flat-field spectrum of a continuum lamp. The stellar radial velocity is determined independently for each of six spectral orders containing strong $I_2$ lines by modeling the observed star-plus-iodine spectrum as the product of a Doppler-shifted, high signal-to-noise reference spectrum of the star alone and a very high spectral resolution spectrum of the $I_2$ absorption cell in the laboratory reference frame; the latter

was previously measured at the McMath-Pierce Fourier Transform Spectrometer (FTS) at the National Solar Observatory. The model incorporates the desired relative wavelength shift between the spectrum of the star and that of the iodine cell, detector shifts due to instabilities within the spectrometer, and a parameterized wavelength solution and instrumental resolution profile. The instrumental profile shape is allowed to vary slowly along the order.

All of the parameters describing this model are adjusted so as to minimize the rms difference between the observed and modeled spectrum. The six independently deduced Doppler velocity shifts for each order are then combined with equal weights to provide the final velocity shift for that exposure, while the internal scatter amongst the different orders gives an estimate of its uncertainty. Each observation normally consists of three consecutive exposures, in order to correct for cosmic-ray contamination; typical exposures have continuum signal-to-noise ratio per pixel of order 100 to 150. The results of the velocity estimates for the three exposures are corrected for motion of the telescope relative to the solar system barycenter and are then combined to provide the final measure of the stellar radial velocity shift and an estimate of its uncertainty.

3.2. Observations and Results

Observations of ρ CrB were obtained on 41 nights between 1996 May and 1997 March. A tabulation of the data, showing times of observation, derived velocities, and estimated uncertainties, may be found in the Solar and Stellar Physics pages of the Center for Astrophysics World Wide Web site. The data, together with uncertainties, are plotted in Figure 1.

We fitted a Keplerian orbit to the data using a least-squares fitting process. The orbital parameters are given in Table 1. They result from an iterative $2.5 \sigma$ rejection fitting procedure (where $\sigma$ is the rms of the residuals to the fit); three points were rejected on this basis and are shown as crosses in Figure 1. We note that the orbital parameters resulting from a fit without any rejection, or from a $3 \sigma$ rejection procedure, which eliminated only one point, differ from the values listed in Table 1 by less than their formal uncertainty. We verified that the elements we derived are the ones providing the best fit to the data by using a $\chi^2$-minimization routine based on a genetic algorithm (Charbonneau 1995). This algorithm uses a form of directed Monte Carlo search that is specifically designed to locate the global minimum, regardless of where it lies in the
TABLE 1

| Parameter | Value |
|-----------|-------|
| $P$       | 39.645 ± 0.088 days |
| $K_1$     | 67.4 ± 2.2 m s$^{-1}$ |
| $e$       | 0.028 ± 0.040 |
| $a_1$ sin $i$ | 210° ± 74° |
| $T_{\text{periastron}}$ | 2,450,413.7 ± 8.2 HJD |
| $r_1$ sin $i$ | (36.75 ± 0.92) × 10$^3$ m |
| $f_1$ sin $i$ | (1.528 ± 0.093) × 10$^{-7}$ M$_\odot$ |
| $T_{\text{transit}}$ | 2,450,559.37 ± 0.54 HJD |
| $N$       | 38 |
| rms($O - C$) | 9.2 ms$^{-1}$ |

parameter space. The fit to the next most likely period (at 76.8 days) has residuals with reduced $\chi^2$ of 3.3, corresponding to an extremely small probability that this is the correct period.

The period and amplitude of the fit are well determined, but because of the small eccentricity, the longitude $\omega$ and epoch of periastron $T$ have large uncertainties. However, the epoch $T_{\text{periastron}}$ of passage of the companion across the line of sight to the star is reasonably well-determined, as shown in Table 1. This value is included to facilitate possible searches for evidence of a transit across the disk of the star, which should $i$ be close to unity. However, G. Henry (1997, private communication) reports that his 208 photometric data points over the past four years, when phased at the period in Table 1, make a transit unlikely.

The derived eccentricity (0.028 ± 0.040), while close to zero, has sufficient uncertainty that a value as large as 0.1 cannot be ruled out. As noted in § 4 below, it is an important question whether the eccentricity is significantly different from zero; more observations, especially with complete phase coverage, are needed to pinpoint the value of the eccentricity more accurately.

The dashed line in Figure 1 shows the Keplerian orbital fit from Table 1. Residuals from the fit are shown in the lower part of Figure 1. Figure 2 shows the same data phased according to the orbital fit. The periodic variation of radial velocity is evident.

Part of the residuals from the orbital fit may be attributable to long-term instrumental drifts of uncertain origin. In Figure 1, such drifts are suggested especially by the groupings of residuals for the four 1996 observing runs (HJD < 2,450,450); however, the smaller rms residuals (only 5 m s$^{-1}$) of the data points for the 1997 January, February, and March observing runs indicate that the problem may have largely disappeared after an instrumental realignment in early January of 1997. Here we take the conservative approach of not correcting for long-term drifts in the orbital analysis.

4. DISCUSSION

The data plotted in Figure 1 clearly indicate a nearly sinusoidal variation in the measured radial velocity of $\rho$ CrB, with a period of 39.6 days and an amplitude of 67 m s$^{-1}$. The obvious interpretation is that $\rho$ CrB is orbited by a low-mass companion, which produces a reflex motion of $\rho$ CrB itself as they revolve about their common center of mass. If the mass of $\rho$ CrB is 1.0 $M_\odot$ (§ 2), the minimum mass $m_i$ sin $i$ of the companion is 1.1 Jovian masses, and the orbital radius $a_1$ is 0.23 AU.

Other interpretations could be considered. It is possible, although unlikely (Soderblom 1985), that in spite of the approximately 20 day rotation period implied by the mean Ca $\Pi$ flux level, the actual rotation period of $\rho$ CrB is 40 days. In that case, an apparent periodic variation of radial velocity could, in principle, be caused by changes of the photocenter of the rotating star by periodic passage of a large spot across its disk. However, an amplitude as large as we observe would require about 3% spot coverage, which would produce a photometric modulation of order 0.03 mag. G. Henry (1997, private communication) reports an upper limit of 0.0002 ± 0.0001 mag for any variability at the period of 39.65 days. This result effectively rules out the above interpretation. A rotating magnetic region with a convective blueshift that somehow produces no photometric signature could be considered, but the more magnetically active Sun shows no spurious radial velocity variations as large as 1/10th the amplitude we observe on $\rho$ CrB (see McMillan et al. 1993). One might postulate a nonradial pulsation that does not produce any disk-integrated photometric modulation, as Gray (1997) has suggested to explain the 4.2 day periodicity observed in the radial velocity of 51 Pegasi (Mayor & Queloz 1995). However, the 40 day period of the radial-velocity variations in $\rho$ CrB is extremely long compared to the dynamical timescales characterizing acoustic-gravity modes in Sun-like stars (roughly 1 hour). Moreover, the amplitude of 67 m s$^{-1}$ is enormous compared to the 1 m s$^{-1}$ amplitude of the combined solar “5 minute” p-mode pulsations or of the (so far undetectably small) solar g-modes. Furthermore, the stringent limits on photometric variation mentioned above are extremely difficult to reconcile with radial or low-degree nonradial pulsations at an amplitude approaching the observed velocity amplitude. For these reasons, we take the view that the radial velocity variation observed in $\rho$ CrB is best explained as the result of an orbiting companion.

The companion to $\rho$ CrB may be considered to be a “planet,” where planets are taken to be stellar companions having masses comparable to the mass of the giant planets in our solar system (see Marcy et al. 1997). In addition, it is interesting to inquire if there are clues whether this companion was created like the planets in our own solar system—that is, by agglomeration of planetesimals in a circularly rotating circumstellar disk (see, e.g., Lissauer 1995)—or whether it might have been created in the manner of brown dwarfs—that is, by fragmentation within a collapsing molecular cloud, as the
low-mass tail of a binary star creation. While it has been suggested that a lower limit to the mass of brown dwarfs formed in this way is about 10 $M_{\text{Jup}}$ because of opacity effects (see, e.g., Silk 1977), it has been argued (Black 1986) that uncertainties in the binary formation process allow for brown dwarf companions with much lower mass, even overlapping the mass range of giant planets, so that, by itself, the mass of the companion to $\rho$ CrB does not determine the companion’s mode of origin.

Binary stars, and by extension stars with brown dwarf companions, typically form with significant eccentricity. If the orbital period is relatively short, the orbit may be circularized by tidal effects. However, main-sequence binaries with periods as long as the 40 day period of $\rho$ CrB generally do not have circular orbits. For example, Latham et al. (1992), in an analysis of old (10–15 Gyr) binaries in the halo, showed that only those with periods less than about 19 days were circularized. In addition, an analysis that takes into account the effect of tides on the planet itself (Rasio et al. 1996) implies a timescale for orbital circularization of the $\rho$ CrB system of more than 10$^{12}$ yr. Thus it appears unlikely that $\rho$ CrB and its companion formed in the manner of binary stars; formation of the companion by agglomeration of dust and planetesimals in a dissipative circumstellar disk around $\rho$ CrB seems more plausible (see Black 1997).

The companion to 47 UMa (Butler & Marcy 1996) is similar to the companion to $\rho$ CrB, in that they both have near-zero eccentricities and orbital periods long enough that tidal circularization should not have occurred over the lifetime of either system. However, the companion to $\rho$ CrB orbits one-ninth as far from its parent star as does the companion to 47 UMa (which lies at 2.1 AU), and 1/23rd as far as Jupiter (at 5.2 AU). The companions to both 47 UMa and $\rho$ CrB lie inside the radius of the ice condensation zone, which has been argued (Boss 1995) to be the minimum radius for formation of giant planets. The existence of a giant planet, in near-circular orbit as close as 0.23 AU to its parent star but still outside the tidal circularization radius, sharpens the question of whether such bodies could be formed in situ, or, if not, how they could migrate inward and stop in a stable orbit at their present location.

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