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AN UPPER LIMIT TO THE MASS OF THE RADIAL VELOCITY COMPANION TO ρ^1 CANCRI

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ABSTRACT

Doppler spectroscopy of ρ^1 Cnc has detected evidence of a companion with an orbital period of 14.65 days and a minimum mass of 0.88 Jupiter masses. Astrometric observations performed with the *Hubble Space Telescope* Fine Guidance Sensor 1r using a novel observing technique have placed an upper limit on the astrometric reflex motion of ρ^1 Cnc in a time period of only 1 month. These observations detected no reflex motion induced by the 14.65 day period radial velocity companion, allowing us to place a 3 σ upper limit of ∼0.3 mas on the semimajor axis of this motion, ruling out the preliminary *Hipparcos* value of 1.15 mas. The corresponding upper limit on the true mass of the companion is ∼30 M_J, confirming that it is a substellar object.

Subject headings: astrometry — planetary systems — stars: low-mass, brown dwarfs

1. INTRODUCTION

The Doppler spectroscopy technique has been used in recent years to detect low-amplitude, periodic radial velocity variations in ∼60 nearby stars, which have been interpreted as due to planetary-mass companions. This interpretation requires several assumptions, namely, that the root cause of the variation is Keplerian in nature, that the companion mass (M_c) is substantially less than the mass of the primary, and that one is seeing light from a single star as opposed to an unresolved, comparable-mass binary system (Imbert & Prévot 1998). The quantity determined by the radial velocity observations is then $M_c \sin i$, where i is the unknown inclination of the orbital plane to our line of sight to the star. The argument usually advanced to suggest that the masses of the companions must be small assumes that the distribution of orbital inclinations is uniform so that, on average, $\langle M_c \rangle = 4\langle M_c \sin i\rangle/\pi$ (Chandrasekhar & Münch 1950), which implies that the true companion mass cannot be much greater than the minimum mass, $M_c \sin i$. Note that this statement is true only for a large sample, and it does not preclude individual companions from having true masses that are significantly larger than their minimum mass.

Several pieces of work support the planetary mass interpretation. For example, Ito & Miyana (2001) have determined that the dynamical stability of the υ And system constrains the mass of the outer planet to be less than 1.43 times its minimum $M_c \sin i$ value. There is also one case, HD 209458, for which the companion has been observed to transit the disk of the central star (Charbonneau et al. 2000), hence giving a measure of both the companion radius and the inclination of its orbit. The companion mass of ∼0.6 Jupiter masses (M_J) is consistent with that of a giant planet. However, despite the statistical and dynamical arguments and the special case of HD 209458, doubts have persisted that $M_c \sin i$ is nearly equal to M_c for several reasons.

Using a combination of *Hipparcos* and ground-based MAP (Multichannel Astrometric Photometer) astrometry in conjunction with the orbital parameters derived from the radial velocity (RV) data, Gatewood, Han, & Black (2001) have found that the $M_c \sin i = 1\ M_J$ companion to ρ CrB is in a nearly face-on orbit with $i = 0\overset{\circ}{.}5$ and has a true mass of 115 M_J, making it an M dwarf rather than a planetary-mass object. Zucker & Mazeh (2000) have used *Hipparcos* astrometry to show that the $M_c \sin i = 6.4\ M_J$ companion to HD 10697 is actually a 38 M_J brown dwarf in an orbit with an inclination of just 5°. A similar analysis combining the *Hipparcos* and RV data extended to the 30 systems with orbital periods in excess of 10 days (Han, Black, & Gatewood 2001) suggests that at least four of the 30 stars they analyzed have stellar-mass companions, that is, $M_c > 80\ M_J$, which in turn would require $i < 1°$. If the distribution of inclinations in the sample is uniform, the probability of a system having an inclination $i < i_0$ is given by $1 - \cos i_0$. For $i_0 = 1°$, the probability would be 1.5×10^{-4}, making it unlikely that even one such system would be observed in a sample of 2000 stars. This led Han et al. to suggest that there might be a bias toward small inclination angles in the RV studies. Pourbaix (2001) also finds statistically significant astrometric orbits with low inclinations for three out of

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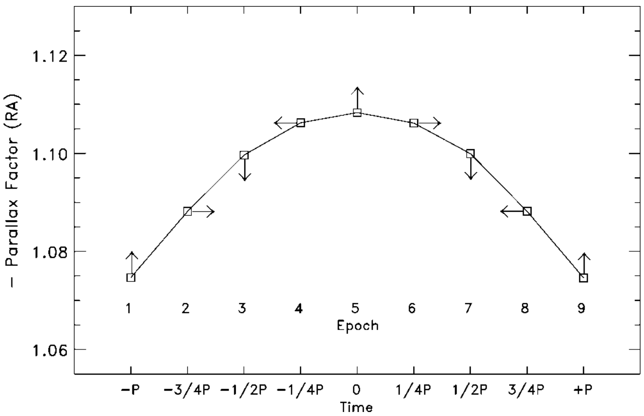

FIG. 1.—*Relative* phase of observations at each epoch is illustrated schematically on this plot of parallax factor in R.A. vs. time (in units of the RV companion period, *P*). Because we are searching specifically for a companion with a circular, face-on orbit with a period of 14.65 days, the absolute phase of the observations is not important.

four of the Han et al. potential stellar-mass companions. However, Pourbaix & Arenou (2001) argue that the trend to low inclinations is an artifact of the adopted reduction procedure and that the astrometric data are not precise enough to allow the conclusion that a significant fraction of the RV companions have stellar masses.

An independent line of evidence also raises the possibility of stellar mass companions for some of the 60 systems. Among a subset of nine of the stars of spectral type F with candidate planetary companions, Suchkov & Schultz (2001) have identified three potential binaries, HD 19994, HD 89744, and HD 169830, along with HD 114762 (A. Suchkov 2001, private communication), based on the fact that they are overly bright for their spectral type and *Hipparcos* distance. Gonzalez et al. (2001) found that two stars with RV companions, HD 37124 and HD 46375, are similarly too luminous for their spectral type and distance; they might each be unresolved binary systems. However, they also note that a wide, long-period binary cannot be ruled out, so the short-period RV companion need not be the source of the "excess" luminosity.

Another line of reasoning suggesting that the RV companions may not be planetary in nature comes from an analysis of the distribution of their eccentricities and orbital periods, which are statistically indistinguishable from those for single-line spectroscopic binaries (SB1s) (Stepinski & Black 2001; Heacox 1999). Moreover, the apparent correlation of eccentricity with orbital period for the RV companions is similar to that for SB1s (Black 1997; Heacox 1999), and their bivariate probability distribution functions are again statistically indistinguishable (Stepinski & Black 2001). The observed orbital properties also differ strongly from those of our own planetary system. The current data, interpreted as planetary systems with random inclinations, also do not lead to a simple theoretical picture (e.g., Marcy et al. 1999), and there is currently no compelling dynamical argument to support the interpretation that all of the RV companions are planets, rather than brown dwarfs or stars in low-inclination orbits. A determination of which companions (if any) are not planetary would facilitate the development of a dynamical model.

Astrometric observations of the stellar reflex motion induced by a companion can potentially remove the uncertainty in sin *i*, and thus determine the companion mass. The *Hubble Space Telescope* (*HST*) Fine Guidance Sensor 1r (FGS1r) can measure relative stellar positions to an accuracy of ∼0.3 mas, a factor of 3–5 improvement over that of *Hipparcos* and MAP data. In this Letter we present the results of a pilot program utilizing an observing technique designed to quickly search for perturbations larger than about 0.3 mas to the position of ρ^1 Cnc (HR 3522, HD 75732, 55 Cnc), a G8 V star with an $M_c \sin i =$ 0.88 M_J companion in an orbit with a period of 14.65 days (Butler et al. 1997). Han et al. report a preliminary reflex motion with a semimajor axis of 1.15 mas for this star. We discuss our rationale for selecting this target and our observing strategy in § 2 and our results in § 3.

2. OBSERVATIONS

Detection of companion-induced reflex motion is complicated by the need to determine the typically much larger proper motion (μ_α, μ_δ) and parallax (π) of the star, which normally requires observations over a baseline of at least 1 year. However, a carefully designed observing strategy can shorten this time dramatically provided an RV system with a relatively short period is chosen and provided the individual astrometric observations can be made with sufficient precision. We therefore concentrated on stars from Han et al. with the following characteristics: relatively short period, a large (>1 mas) reflex motion inferred to be present with at least moderate statistical significance, and ones most likely to have companions that are brown dwarfs or M dwarfs (their groups 2 and 3). An additional criterion was the suitability of the target for FGS1r astrometry, namely, the availability and distribution of stars in the FGS field of view, needed to define the inertial reference frame. Using these criteria, ρ^1 Cnc was determined to be the most suitable target. Its predicted reflex motion of 1.15 mas radius implies that the companion is an M dwarf of 126 M_J rather than the $M_c \sin i$ value of 0.88 M_J. However, the Han et al. result has only borderline statistical significance for this target and therefore falls into their group 2, stars for which they expect the majority of the companions to be brown dwarfs.

We realized that we would detect a reflex motion with FGS1r only if the RV companion is more massive than about 40 M_J, which, to be consistent with the RV data, implies that the inclination of its orbit would be nearly face-on. (Inclinations larger than about 2° imply a companion mass that is too small to produce an astrometric signature large enough to measure with *HST*.) Our observing strategy was designed to optimize our ability to detect a perturbation with the known 14.65 day period and low eccentricity of the companion's orbit and an unknown value of Ω (the longitude of the ascending node).

We performed a set of FGS1r observations in the 1 month period centered around the time of maximum parallax factor in right ascension (R.A.) (hereafter α_{max}) on 2001 May 1. We observed at pairs of epochs with times that were both phased with the companion's 14.65 day period (*P*) and symmetric about the time of α_{max}. Explicitly, observations were executed in pairs occurring at the same phase from April 17 through May 16. The relative phases for each epoch are shown in Figure 1. With additional observations on May 30 (epoch 10 at $+2P$), we monitored the star's position over more than two full orbits of the companion. The star's proper motion μ_α can then be determined from the epoch pairs without a simultaneous determination of its parallax. Since the rate of change of the parallax as projected along declination, $d\pi_\delta/dt$, was constant to within 1% at the time of α_{max}, it simply added to μ_δ as a constant. Measurable reflex motion would manifest itself as a larger *dispersion* in the proper motions of the pairs. This strategy favors shorter period systems since the reflex motion is then more apparent, i.e., less diluted by the star's much larger proper motion.

TABLE 1

Proper Motion Measurements and Simulations (μ_α, μ_δ, in mas yr^{-1})

Epochs	Measured
(1, 9)	−520, −274
(2, 8)	−509, −241
(4, 6)	−520, −239
Standard deviation	5, 14

Epochs	Radius (mas) 0.3	0.5	1.0
Simulation 1: Phase = 103° (R.A.)			
(1, 9)	−520, −274	−520, −274	−519, −274
(2, 8)	−501, −241	−497, −241	−485, −241
(4, 6)	−551, −233	−571, −232	−621, −231
Standard deviation	18, 15	27, 15	50, 16
Simulation 2: Phase = 13° (Decl.)			
(1, 9)	−520, −274	−520, −274	−520, −274
(2, 8)	−508, −248	−508, −253	−508, −265
(4, 6)	−520, −203	−519, −183	−518, −132
Standard deviation	5, 25	5, 34	5, 56

Epochs 2, 4, 5, 6, and 8 each consisted of two *HST* visits, the other epochs of one visit. The data obtained in epoch 3 were severely degraded due to a loss of lock on guide stars partway through the observing sequence, so the proper-motion measurement utilizing data from the epochs 3 ($-\frac{1}{2}P$) and 7 ($+\frac{1}{2}P$) temporal pair could not be made. Each visit consisted of one *HST* orbit. All observations were obtained at a fixed *HST* roll angle and pointing, and the observing sequence for each visit consisted of four or five observations of ρ^1 Cnc interspersed with 1–4 observations of each of the seven reference stars. One of the reference stars, ρ Cnc B, is the proper-motion companion to ρ^1 Cnc. Observations of this star were unsuccessful in the first 6 epochs due to incorrect input coordinates.

3. RESULTS

In a given *HST* orbit the relative positions of the stars were determined with a precision of about 1 mas, as illustrated by the residuals for ρ^1 Cnc shown in Figure 2. Data from multiple epochs were combined by a standard six-parameter plate solution using the GAUSSFIT program (Jeffereys, Fitzpatrick, & McArthur 1987). The solution yields the proper motion of ρ^1 Cnc and ρ Cnc B and a catalog of star positions in (ξ, η) space, along with residuals to these quantities. When combining data from visits restricted to the $\pm$ temporal pairs defined above, the parallactic displacement along R.A. is not an issue since it is common to such data sets. However, when other visits are included in the analysis, the parallax of ρ^1 Cnc must be accommodated in the solution. Since it was not possible to solve for the parallax (because of the short interval over which the observations were made), we adopted the *Hipparcos* value of $\pi = 79.8$ mas for ρ^1 Cnc and ρ Cnc B, while constraining the parallax and proper motion of the remaining reference stars to zero. To determine our sensitivity to the choice of π, solutions were found using $75 < \pi < 82$ mas. The residuals in the astrometric catalog produced for each assumed value of π were essentially constant, indicating that our particular choice of π was not important provided it was correct to within a few percent.

The residuals of the star positions in the derived astrometric catalog were small, 0.27–0.45 mas for ξ and 0.28–0.60 mas for η (see Fig. 2), with the exception of those for ρ Cnc B, which were ~1 mas, attributable to the fact that it was observed in only 5 of 15 *HST* orbits. The derived proper motions for ρ^1 Cnc and ρ Cnc B were (μ_α, μ_δ) = (−515.2 ± 6.6, −256.6 ± 4.7) and (−508.7 ± 18, −221.7 ± 12.6) mas yr^{-1}, respectively. The error bars include the cumulative 1 σ errors from all the fitted parameters. This compares with the *Hipparcos* values of −485.46 ± 1.03, −234.40 ± 0.72 for ρ^1 Cnc. The difference between our proper motion and the *Hipparcos* value is most likely due to the unmodeled, but small, proper motion of one or more reference stars, which cannot be accurately measured over such a short time. We emphasize that our technique and results do not depend on an accurate determination of the absolute proper motion, but rather on the differential accuracy with which we can determine it among epochs and epoch pairs, so a systematic offset from the *Hipparcos* value is not relevant.

We used three different techniques to search for reflex motion and to gauge the sensitivity of our measurements. First, we fixed the inclination at $i = 0°$ and the period of the companion to $P = 14.65$ days and solved for the phase and radius of the reflex motion, along with residuals of these values, using data

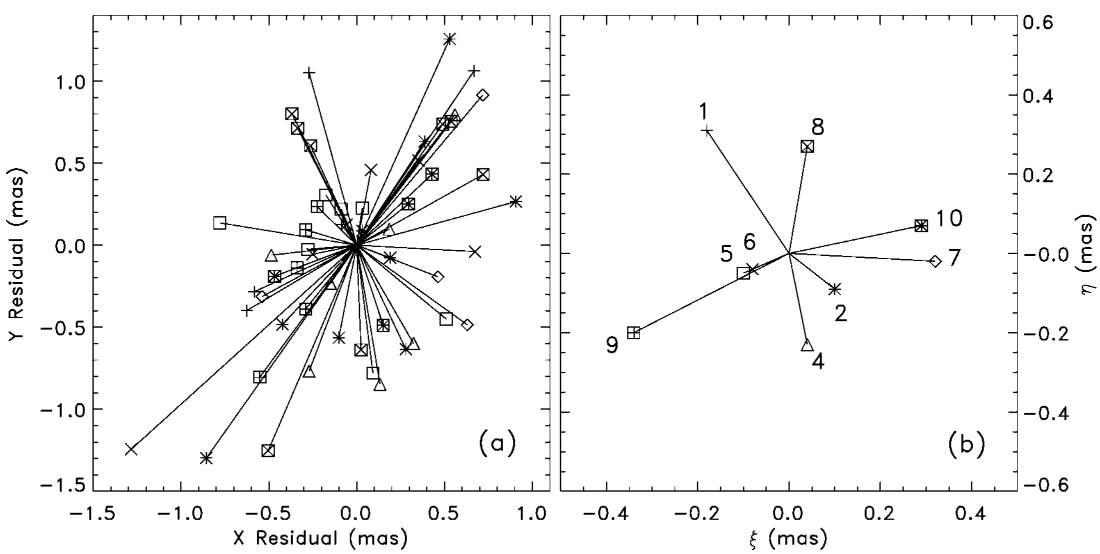

Fig. 2.—(*a*) *X* and *Y* residuals for all observations of ρ^1 Cnc relative to the best-fit six-parameter plate solution model with proper motion and parallax removed. Data from the 10 epochs, excluding epoch 3, are plotted using symbols as in (*b*). (*b*) The ξ, η position of ρ^1 Cnc at each epoch from the best-fit model, illustrating the accuracy of ~0.3 mas achieved by the observations.

from all 10 epochs. This solution yielded a reflex motion with a radius of 0.08 ± 0.2 mas, i.e., a nondetection.

Second, we again fixed the inclination and period of the companion, then in simulations imposed a range of values for the phase angle and radius of the reflex motion on the data and solved for the phase and radius (again using data from all 10 epochs) to assess how accurately we could recover them if such perturbations were present. The recovered values of (r, ϕ) matched the imposed values to within the residuals computed by the model for $r \gtrsim 0.3$ mas. From this test we concluded that our observations would have detected any 14.65 day period circular reflex motion with a radius in excess of 0.3 mas at 1.5 σ. No such motion was seen in the real data.

Our final and most sensitive test for detecting the reflex is to look for dispersions in the proper motions computed from the $\pm$ temporal pairs taken at epochs with identical parallax factor α. The proper motion computed from epochs (1, 9) and (3, 7), with each pair taken at the same star/companion orbital phase, should agree and be the real proper motion. Unfortunately, as mentioned earlier, the astrometry obtained in epoch 3 was compromised, so only the data from epochs (1, 9) could be used to measure a "reflex-free" proper motion. Table 1 ("Measured") shows the values of (μ_α, μ_δ) computed from the three remaining $\pm$ temporal pairs. As expected, the average value of $(\mu_\alpha, \mu_\delta) = (516, 251)$ mas yr^{-1} derived from the pairs is very close to that derived using the data from all 10 epochs. However, the dispersion of μ_δ is nearly a factor of 3 larger than that of μ_α, due primarily to the (1, 9) pair, which we attribute in part to the fact that the epoch 1 and 9 observations consisted of only a single *HST* orbit, while the epoch 2, 4, 6, and 8 observations consisted of two *HST* orbits each.

Note that the change of the star's position due to its orbit around the star-companion barycenter has a position angle that is 180° different in epochs (2, 8) relative to that in epochs (4, 6) (see Fig. 1). Therefore, any astrometric signature of the star's companion would manifest itself most dramatically in the proper motions computed from these epoch pairs. The data from epochs (4, 6) take on particular significance because they span the shortest time interval among the temporal pairs; hence, any detectable reflex motion is least diluted by the star's true proper motion computed from this pair.

To illustrate this, we conducted a series of simulations whereby we again impressed upon the data a circular reflex motion with a 14.65 day period, along with semimajor axes of 0.3, 0.5, and 1.0 mas and a variety of phase angles. The results of these simulations are shown in Table 1. As expected, because it is the "reflex-free" pair, the proper motion of epochs (1, 9) shows no change due to the imposed perturbation, while that of the (4, 6) pair has changed significantly, even for the smallest 0.3 mas perturbation. In these simulations, a reflex motion is absorbed into the proper motion computed from each $\pm$ temporal pair. Therefore, the greater the reflex, the larger the *dispersion* in the values of (μ_α, μ_δ), even though the perturbation has little effect on the average value of the proper motion computed from all the temporal pairs. For example, the measured dispersion in (μ_α, μ_δ) is (5, 14), while that from the simulation with $(r, \phi) = (0.3$ mas, 103°) is (18, 15) and that from $(r, \phi) = (0.3$ mas, 13°) is (5, 25). We take the *ratio* between the standard deviation of the measured proper motion and the perturbed proper motion as a rough (and very conservative) estimate of our ability to detect a real perturbation to the proper motion. The standard deviations in Table 1 are computed in the conventional fashion, i.e., as the square root of $\sum^{n=3} (\text{value}_i - \text{average})^2$ divided by $(n - 1)$ using the three epoch pair values listed in the table for the three cases presented. For the 0.3, 0.5, and 1.0 mas perturbations these ratios (the average for the two phases presented in Table 1) are 3, 4, and 7, respectively. Comparison of the measurements and simulations for only the (2, 8) and (4, 6) pairs would in fact be a more valid (and less conservative) measure of the sensitivity because the (1, 9) pair is unaffected by the perturbation and would give an even larger ratio. We therefore conclude that a reflex motion of 0.3 mas is conservatively ruled out at about the 3 σ level, and any reflex motion with a semimajor axis in excess of 0.5 mas is firmly ruled out at greater than 4 σ.

In summary, the strategy we chose for attempting to astrometrically detect and measure a reflex motion of ρ^1 Cnc with *HST*/FGS1r yielded the anticipated sensitivity. With just 14 orbits of *HST* time over a 30 day interval, we were able to conclusively rule out the preliminary 1.15 mas perturbation proposed by Han et al. Furthermore, we ruled out at the 3 σ level a perturbation with an amplitude greater than about 0.3 mas. This places an upper limit of ~30 M_J on the mass of ρ^1 Cnc's companion, implying that it is a substellar object. We emphasize that this observing technique is fully capable of detecting the larger and more statistically significant astrometric perturbations for, e.g., ρ Cr B and HD 195019 found by Han et al. (2001) and Pourbaix (2001) if they are real.

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