On the Statistical Significance of the *Hipparcos* Astrometric Orbit of $\rho$ Coronae Borealis

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ABSTRACT

Recently Gatewood, Han & Black (2001) presented an analysis of the *Hipparcos* stellar positions and their own ground-based measurements of $\rho$ CrB, suggesting an astrometric orbit of 1.5 milli-arc-sec with an extremely small orbital inclination of 0.5°. This indicates that the planet-candidate secondary might be a late M star. We used the *Hipparcos* data of $\rho$ CrB together with the individual radial velocities of Noyes et al. (1997) to independently study the stellar orbit and to assess its statistical significance. Our analysis yielded the same astrometric orbit. However, a permutation test we performed on the *Hipparcos* measurements indicated that the statistical significance of the astrometric orbit is only 2σ. Therefore, we can expect about one out of 40 systems with a similar data set to show a false astrometric orbit.

Key words: astrometry – planetary systems – stars: individual ($\rho$ CrB) – techniques: radial velocities

1 INTRODUCTION

One of the first stars around which a planet candidate was found (Noyes et al. 1997) was $\rho$ Coronae Borealis (HR 5968 = HD 143761 = HIP 78459). The discovery was based on the detection of a small periodic radial-velocity modulation, with an amplitude of 67 m s\(^{-1}\). The corresponding minimum mass of the unseen companion was found to be 1 Jupiter mass (= $M_J$), its actual mass depending on the orbital inclination.

Recently Gatewood, Han & Black (2001) presented an analysis of the *Hipparcos* intermediate data, together with new ground-based astrometry they obtained with the Multichannel Astrometric Photometer (Gatewood 1987). Their analysis suggests an orbital semi-major axis of 1.5 milli-arc-sec (= mas) with an extremely small orbital inclination – 0.5°, indicating that the secondary might be a late M star with a mass of 0.14 ± 0.05 $M_\odot$. The extremely small orbital inclination makes this discovery intriguing, because the probability of a binary to have such a small angle, assuming an isotropic orientation in space, is extremely small – 4 × 10\(^{-5}\). Even among 50 systems, the current number of planet candidates (Schneider 2000), the probability to find one system with such an extremely small inclination is only 0.002. Therefore, the statistical significance of the Gatewood, Han & Black (2001) analysis, which might have implications beyond the study of $\rho$ CrB, should be estimated carefully.

Recently Pourbaix (2001) studied the significance of the derived *Hipparcos* orbits of many planet candidates, including $\rho$ CrB. Pourbaix fitted an orbit to the *Hipparcos* data and checked the improvement in the fit resulting from the additional parameters, using an F-test. He used the F-distribution to assess the final significance level of the derived orbit, concluding that the significance is somewhat high – 99 per cent. This use of the F-distribution assumes Gaussianity of the individual measurements. We avoid this assumption by using the permutation test, which belongs to the class of distribution-free tests (e.g. Good 1994) and thus is more robust against modeling problems of the measurement process.

We present in this paper an independent analysis of only the *Hipparcos* astrometric data (i.e. without the MAP data), with an emphasis on the assessment of the significance of the detection. On one hand, we show that the *Hipparcos* data alone,
together with the radial-velocity measurements of Noyes et al. (1997), yield, indeed, a small astrometric orbit of 1.5 mas, implying a small inclination for ρ CrB. On the other hand, we show that the statistical significance of this finding is only about 2σ. Therefore, we can expect about one system out of 40 to have shown a false astrometric orbit. Section 2 presents our analysis, while Section 3 discusses our finding.

2 ANALYSIS

2.1 Orbital Solution

The present analysis used the 38 AFOE radial velocities of ρ CrB (Noyes et al. 1997; 1999), together with the 42 astrometric measurements of Hipparcos (ESA 1997), which were analysed by the FAST and the NDAC consortia (van Leeuwen & Evans 1998). The spectroscopic and astrometric solutions have in common the following elements: the period, P; the time of periastron passage, T0; the eccentricity, e; the longitude of the periastron, ω. In addition, the spectroscopic elements include the radial-velocity amplitude, K, and the centre-of-mass radial velocity γ. The astrometric orbital elements include three additional elements – the angular semi-major axis of the photocentre, a0; the inclination, i; the longitude of the nodes, Ω. In addition, the astrometric solution includes the five regular astrometric parameters – the parallax, the position (in right ascension and declination) and the proper motion (in right ascension and declination). All together we had a 14-parameter model to fit to the spectroscopic and astrometric data. Note that we have allowed small corrections to the values of the Hipparcos reference solution of the five regular astrometric parameters.

These 14 elements are not all independent. From K, P and e we can derive the projected semi-major axis of the primary orbit – a1,phys × sin i, in physical units. This element, together with the inclination i and the parallax, yields the angular semi-major axis of the primary, a1. Assuming the secondary contribution to the total light of the system is negligible, this is equal to the observed a0.

The results of our fit, which are consistent with the previous orbital solutions (Noyes et al. 1997, 1999; Gatewood et al. 2001), are given in Table 1. The small semi-major axis implies a secondary mass of M2 = 0.125 ± 0.042 M⊙, where we assumed 1 M⊙ for the primary (Noyes et al. 1997).

2.2 Significance

The semi-major axis of the derived astrometric orbit is 1.49 ± 0.46 mas. A very small semi-major axis could have been falsely “detected” even without any real astrometric motion, due to the scatter of the actual measurements (Halbwachs et al. 2000). To find out if this is the case here we performed a “permutation” test (e.g., Good 1994) by generating simulated data from the very same astrometric measurements of ρ CrB. If there is some evidence of an orbit in the measurements, it should be ruined by the permutation. However, if the derived orbit is spurious, some random permutations should be able to reproduce a similar effect. In a sense, we let the data “speak for themselves” and do not have to assume any specific distribution for the measurements.

We used the IAD Hipparcos measurements (ESA 1997) and permuted the actual timing of the observations, modifying the partial derivatives with respect to the five astrometric parameters (ESA 1997) accordingly. We then analysed the permuted astrometric data together with the actual radial velocities, deriving a new false astrometric orbit.

For most of the original measurements there are two stellar positions, one derived from the NDAC and the other from the FAST consortia. The two positions are, obviously, not independent, but have an assigned non-vanishing correlation. In our permutation we kept the pairing of the corresponding NDAC and FAST positions, while permuting the timings among
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Figure 1. Histogram of the size of the falsely “detected” semi-major axes in the simulated permuted data. The size of the actually detected axis is marked by an arrow.

A histogram of the falsely detected semi-major axes, derived from the “simulated” permuted data, is presented in Figure 1. We see that most of the artificially detected semi-major axes are at the range of 0.5–1.0 mas, with a small distribution tail beyond 1.5 mas. In 2,000 random permutations we got 46 astrometric solutions with semi-major axis larger than 1.5. This indicates that the detection significance is at the level of 0.977, which is about 2σ.

3 DISCUSSION

The analysis presented here shows that on average we expect about one out of 40 systems with a similar dataset to ρ CrB to show a false astrometric orbit with \( a = 1.5 \) mas. This implies that the statistical significance of the claimed astrometric orbit is not high enough at this point of the research.

As explained in the introduction, Pourbaix (2001) derived that the significance of the astrometric solution is at the 99 per cent level. Compared to his technique we use a distribution-free analysis and thus we feel that our assertion, of a 97.7 per cent level, is more justified.

One way to find out the true nature of the secondary of ρ CrB is to try and observe the secondary directly. If the secondary is indeed a stellar object, infrared spectroscopic observations, especially when analysed with TODCOR – a two-dimensional correlation technique (Zucker & Mazeh 1994), should detect some trace of the faint secondary (e.g., Mazeh et al. 2000a). Together with M. Simon and L. Prato, we plan such observations in the near future. Obviously, more precise astrometric
measurements, expected to come in the future from the FAME (Horner et al. 1999), SIM (NASA 1999), DIVA (Röser 1998) and GAIA (Gilmore et al. 1998) missions, will enable us to derive the secondary mass much more accurately.

We turn now to discuss the relatively low metallicity of ρ CrB. It was noted by many workers (Gonzalez 1997; Marcy & Butler 1998; Queloz et al. 2000; Gonzalez 2001; Butler et al. 2000) that most stars that were found to harbor planet candidates exhibit metallicities higher than the typical metallicity of the solar neighborhood. Queloz et al. (2000) and Butler et al. (2000) further pointed out that the host stars to the “51 peg like” planets are particularly metal rich. Mazeh & Zucker (2001) suggested a probable decrease of the stellar metallicity as a function of the orbital period of the planet candidates, a dependence which holds, according to their suggestion, up to about 100 days. To study their suggestion we plot in Figure 2 the metallicity as a function of the planet orbital period, for the stars that appear in The Extra Solar Planets Encyclopedia web site as of September 2000 (Schneider 2000). We follow the Mazeh & Zucker (2001) suggestion and therefore include in the figure only planet candidates with periods shorter than 100 days.

Whenever available we have used metallicities derived from spectral analysis, mostly from the seminal work of Gonzalez (2001). Mazeh et al. (2001) derived the metallicity of HD 209458. Whenever such an analysis was not available, we have used the photometric metallicity derived by Giménez (2000). The metallicities of the stars not considered by Giménez were derived by us following his prescription, based on the photometry of Hauck & Mermilliod (1998) and the calibrations calculated by Crawford (1973) and Olsen (1984).

In this figure ρ CrB has one of the lowest metallicities. The analysis presented here, which does not support the conjecture about the stellar nature of the companion of ρ CrB, strengthens the suggestion that the metallicity might depend on the period. The figure draws attention to the other two low-metallicity planet candidates. The extreme one is HD 114762 (Latham

Figure 2. The stellar metallicity as a function of the planet-candidate orbital period for planets with periods shorter than 100 days. The point representing ρ CrB is circled.
The Significance of the Hipparcos Orbit of ρ CrB et al. 1989; Mazeh, Latham & Stefanik 1996) with a metallicity of about −0.60. The nature of this secondary is not clear because it has a minimum mass of about 10 $M_J$, and even a moderate inclination can turn it into a brown-dwarf or stellar secondary. However, the other one is HD 6434 (Udry et al. 2000), with a minimum mass of 0.5 $M_J$. This small minimum mass renders the conjecture that this is a real planet safe. Therefore, even if the secondary of HD 114762 turns out to be stellar, the dependence of the metallicity on the period might still be real.

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REFERENCES

Butler R. P., Vogt S., Marcy G. W., Fischer D., Henry G., Apps K., 2000, APJ, 545, 504
Crawford D. L., 1975, AJ, 80, 955
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Gatewood G., 1987, AJ, 94, 213
Gatewood G., Han I., Black D., 2001, APJ, 548, L61
Gilmore G. F. et al., 1998, SPIE, 3350, 541
Giménez A., 2000, A&A, 356, 213
Gonzalez G., 1997, MNRAS, 285, 403
Gonzalez G., 2001 in Garcon C., Eiron C., de Winter D., Mahoney T. J., eds, Disks, Planetesimals and Planets, in press
Good P., 1994, Permutation Tests - A Practical Guide to Resampling Methods for Testing Hypotheses, Springer-Verlag, New-York
Halbwachs J. L., Arenou F., Mayor M., Udry S., Queloz D., 2000, A&A, 355, 581
Hauck B., Mermilliod M., 1998, A&AS, 129, 431
Horner S. D. et al., 1999, in Unwin S., Stachnik R., eds, Working on the Fringe: An International Conference on Optical and IR Interferometry from Ground and Space, ASP Conf. Ser. 194, p. 114
Latham D. W., Mazeh T., Stefanik R. P., Mayor M., Burki G., 1989, Nature, 339, 38
van Leeuwen F., Evans D. W., 1998, A&AS, 130, 157
Marcy G. W., Butler R. P., 1998, ARA&A, 36, 57
Mazeh T., Zucker S., 2001, in Reipurth B, Zinnecker H., eds, Birth and Evolution of Binary Stars, IAU Symp. 200, ASP Conf. Proc., in press; see also astro-ph/0008087
Mazeh T., Latham D. W., Stefanik R. P., 1996, APJ, 466, 415
Mazeh T., Prato L., Simon M., Goldberg E., 2000a in Reipurth B, Zinnecker H., eds, Birth and Evolution of Binary Stars, Poster Proc. of IAU Symp. 200, p. 22
Mazeh T. et al., 2000b, APJ, 532, L55
NASA, 1999, SIM Space Interferometry Mission: Taking the Measure of the Universe, eds. R. Danner and S. Unwin (JPL 400-811; Pasadena: NASA)
Noyes R. W., Jha S., Korzennik S. G., Kroesen G., Brown T. M., Kennelly E. J., Horner S. D., 1997, APJ, 483, L111
Noyes R. W., Contos A. R., Korzennik S. G., Nisenson P., Brown T. M., Horner S. D., 1999, in Hearne J.B., Scarfe C.D., eds, IAU Coll. 170, Stellar Radial Velocities, ASP, San Francisco, p. 162
Olsen E. H., 1984, A&AS, 57, 443
Pourbaix D., 2001, astro-ph/0102316, A&A, accepted
Röser S., 1998, in Jahrestagung der Astronomischen Gesellschaft, Heidelberg: DIVA- Beyond Hipparcos and Towards GAIA [http://www.aip.de/groups/DIVA]
Queloz D. et al., 2000, A&A, 354, 99
Schneider J., 2000, in Extrasolar Planets Encyclopedia http://www.obspm.fr/planets
Udry S. et al., 2000, in http://obswww.unige.ch/~udry/planet/hd6434.htm
Zucker S., Mazeh T., 1994, APJ, 420, 806

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