

τ Boo b: Not so bright, but just as heavy

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Abstract. We present new results derived from high-resolution optical spectra of the τ Boo system, secured in March-May 2000. The results do not show the same feature reported by Cameron et al (1999) as a candidate reflected-light signature from the planet. Together with earlier results from the 1998 and 1999 seasons, the new data yield a 99.9% upper limit on the opposition planet/star flux ratio $\epsilon < 3.5 \times 10^{-5}$ between 387.4 and 586.3 nm, a factor 3 deeper than the upper limit of Charbonneau et al (1999). For an assumed planet radius $R_p = 1.2R_J$, the upper limit on the mean geometric albedo is $p < 0.22$, 40% that of Jupiter. We find new evidence that the star's rotation is synchronised with the planet's orbital motion. Using a Monte Carlo analysis we infer that the planet's mass must lie in the range 5.5 to 10 times the mass of Jupiter.

1. Introduction and observations

During the last 5 years, many Jupiter-mass planets have been discovered in 3 to 5-day orbits about solar-type stars. Determining the atmospheric composition of such planets presents challenges to both observers and theorists. Theoretical models must address the equilibrium chemistry, cloud-formation physics and absorption/scattering properties of irradiated atmospheres at temperatures of order 1000 K. Several such models (Marley et al 1999; Sudarsky et al 2000; Seager & Sasselov 2000; Seager et al 2000) have been published lately, with a variety of predictions for the geometric albedo spectra. For observers, the challenge is to disentangle the optical reflection spectrum or the thermal IR emission spectrum from a stellar background that may be tens of thousands of times brighter. Charbonneau et al (1999) published a deep upper limit on the strength of the mid-optical reflection of the planet that orbits τ Boo every 3.3 days, while Cameron et al (1999) reported a candidate reflected-light signature at flux levels slightly greater than the Charbonneau upper limit.

We secured new observations of τ Boo on 2000 March 14, 15, 24, April 23, 24, May 13 and 17. We used the same instrument and detector on the 4.2-m William Herschel Telescope, as previously reported by Collier Cameron et

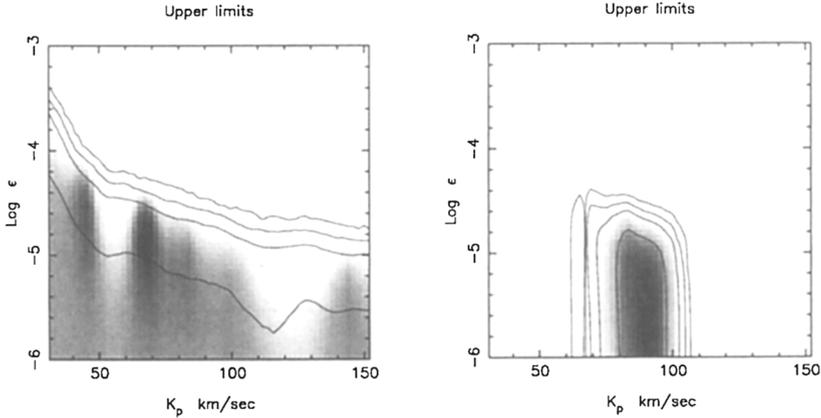


Figure 1. The greyscale gives the relative probability of the fit to the data as a function of opposition planet/star flux ratio ϵ and projected orbital velocity amplitude K_p . At left, no constraints are placed on the orbital inclination. At right, the probabilities are modified by the prior probability distribution for K_p assuming the star's rotation is synchronous (see Section 3). The contours enclose 68.3, 95.4, 99.0 and 99.9 percent of the probability.

al (1999; CHPJ99) for the 1998 and 1999 data. The observational procedures and data extraction and analysis methods were identical to those described by CHPJ99. An updated orbital ephemeris for the times at which the planet's velocity passes through the centre-of-mass velocity from red to blue, $\text{HJD} = 2451652.312 + 3.312450E$, was derived from radial-velocity data kindly provided by G. Marcy and colleagues, incorporating observations as recent as 2000 March 24. This leads to a small but significant departure from the extrapolated orbital timings used in CHPJ99's interpretation of the 1998/99 data.

2. Deep upper limit on albedo

Analysis of all three seasons' WHT data with the revised ephemeris does not reproduce the candidate detection reported by CHPJ99. Instead we find a 99.9% upper limit on the opposition planet/star flux ratio, $\log \epsilon < -4.45$, in the most likely range of orbital velocity amplitudes, $70 < K_p < 100 \text{ km s}^{-1}$ (Fig. 1). This value for ϵ assumes a wavelength-independent albedo over the observed wavelength range 387.4 to 586.3 nm, and a Lambert-sphere phase function. Given that $\epsilon = p(R_p/a)^2$ where a is the radius of the planet's orbit, the geometric albedo must be $p < 0.22$ if $R_p \simeq 1.2R_J$ as indicated by the recent models of Burrows et al (2000).

3. Synchronous rotation and orbit inclination

The HIPPARCOS parallax and Barnes-Evans angular diameter yield $R_* = 1.5 \pm 0.2 R_\odot$ (Baliunas et al 1995). The spectral type and surface gravity indi-

cate $M_* = 1.4 \pm 0.1 M_\odot$ (Fuhrmann 1998, Gonzalez 1998). The orbital radial velocity amplitude of the star is $K_* = 466.0 \pm 2.3 \text{ m s}^{-1}$ (Marcy 1999, personal communication). The projected equatorial rotation speed of the star is $v \sin i = 14.8 \pm 0.5 \text{ km s}^{-1}$ (Gray 1982, Baliunas et al 1997, Fuhrmann 1998, Gonzalez 1998, Cameron et al 1999). We performed Monte Carlo simulations with random Gaussian distributions in these 4 variables to determine the distributions for derived planet mass and projected orbital velocity amplitude.

At the > 1 Gyr age of τ Boo, the high $v \sin i$ suggests tidal synchronisation. As in 1998 and 1999, the spring 2000 data show distortions in the stellar line profiles, which drift from blue to red at the rate expected of stellar surface features if the star rotates synchronously with the planet's orbit. We therefore rejected models that yielded synchronization timescales for the star,

$$\tau_{sync} \simeq 1.2 \left(\frac{M_*}{M_p} \right)^{-2} \left(\frac{a}{R_*} \right)^6 \text{ years},$$

that were longer than the main-sequence lifetime $\tau_{ms} \simeq 10^{10} (M_*/M_\odot)^{-3}$ years. The resulting probability distribution spans the orbital velocity range $70 < K_p < 110 \text{ km s}^{-1}$ and yields planet masses $5.5 < M_p/M_J < 10$.

The new upper limit on the geometric albedo of τ Boo b, $p < 0.22$ between 387.4 to 586.3 nm, lies between the albedo spectra predicted by Sudarsky et al (2000) for "isolated" and "modified" Class IV roaster atmospheres, and suggests that substantial pressure-broadened Na I D absorption may be present. The Class V models of Sudarsky et al appear to offer better prospects for direct detection of hot Jupiters with lower surface gravities such as ν And b, for which similar observations are scheduled in 2000 October and November.

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