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HST/FGS High-Speed Photometric Observations of Transits of HD 209458b

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Abstract. We present preliminary analysis of new HST observations of the transiting extrasolar planet HD 209458b. Photometric observations were obtained with the Fine Guidance Sensor (FGS) on the Hubble Space Telescope (HST), providing milli-mag precision and high time resolution (40 Hz). The FGS photometry allows us to derive precise stellar/orbital parameters (ephemeris, inclination, limb darkening) and planetary radius, and also allows a search for the presence of planetary rings and satellites. We discuss preliminary results and two approaches to modelling the observations.

1. Introduction

The recent discoveries of planets around other stars carry tremendous significance for the science of astrobiology. For example, extrasolar planets that lie within the habitable zone of their host stars have already been discovered. While these are Jovian planets, not terrestrial, this is only a consequence of the strong bias in the detection methods; terrestrial–mass planets remain exceedingly difficult to find. Undetected terrestrial–size moons of these extrasolar planets could, in theory, harbor life.

More than ten times as many planets are known to exist outside the solar system than within it. However, of these 100 or so extrasolar planets, only one eclipses or "transits" its host star: HD 209458b. This chance alignment makes HD 209458b singularly important in the study of the physical properties of extrasolar planets. While spectroscopic surveys are highly successful in discovering planets (e.g., Mayor & Queloz 1995; Butler et al. 1997), spectroscopy alone cannot determine the mass or radius of the planet. Photometric observations of transits provide the missing information needed to derive the planet's mass, size, and density, as well as other system parameters. Furthermore, transits allow a far more precise determination of the orbital period and the ability to detect small objects in orbit about the planet (i.e., satellites and rings).

The planet orbiting HD 209458 was detected via spectroscopic observations of the reflex motion of its G0 V parent star (see Henry et al. 2000; Mazeh et al. 2000). The transits were discovered by Henry et al. (2000) and Charbonneau et al. (2000), who independently determined the mass and radius of the planet to be $\sim 0.63\ M_{Jup}$ and $1.4\ R_{Jup}$. This clearly established HD 209458b as a bona fide Jovian planet (or more technically, a "hot Jupiter"). At V=7.65 mag, HD 209458 is so bright that standard differential CCD photometry is problematic. Nevertheless, excellent photometry can be obtained with small ground-based telescopes (e.g., Henry 2002). HST of course does not suffer from telluric atmospheric problems and can provide very high precision spectrophotometry. The first such observations (Brown et al. 2001) revealed a beautiful eclipse and placed tight constraints on the relative radii of the star and planet. In a follow-up study, the presence of sodium in the atmosphere of the planet was measured, the first detection of an atmosphere of an extrasolar planet (Charbonneau et al. 2002). Here we present work in progress on a second set of HST observations in which the FGS was used in a novel way as a high-speed photometer.

2. Observations

The FGS on HST were used to observe transits of HD 209458b at four epochs between 2001 June and 2002 January. The photomultiplier tubes in the FGS provided a sampling rate of 40 Hz yielding ~6500 counts per 0.025 s bin (S/N~80). The light was passed through the F550W filter giving a 875Å-wide bandpass centered at 5500Å; this is crudely similar to a V-band filter. These observations were the first to use the FGS as a high-speed photometer on a bright target, and not too surprisingly, a calibration problem arose. Fortunately, this problem was stable and repeatable and therefore could be removed by dividing the light curves with an empirical FGS response curve (a polynomial fit to FGS observations of HD 209458 well away from transit). The corrected data were normalized to the out-of-transit count rate and cast into 80 s bins for analysis, providing a S/N of 5200 per bin (~0.2 mmag uncertainty). The left hand side of Fig. 1 shows the individual light curves for the four sets of observations. Because the duration of the transit (~3 hours) is much longer than the maximum uninterrupted time HST can view the source (about half the 96 min spacecraft orbit), the light curves consist of non-contiguous segments.

3. Modelling I.

The transit data were modelled as an opaque spherical planet in circular orbit around a limb-darkened star. The free parameters of the model are the orbital period P, time of a mid-transit T_o, inclination, limb darkening coefficients, and radii of star and planet. In addition to the FGS data, we also fit the previous HST/STIS observations of Brown et al. (2001). Our results (see Schultz et al. 2002 for details) are consistent with previous determinations but with considerably improved precision: e.g., the period uncertainty has been reduced from ±1.2 s (Robichon & Arenou 2000) to ±0.38 s. The revised ephemeris is $T_o = 2452223.89617 \pm 8.6 \times 10^{-5}$ HJD and $P = 3.5247542 \pm 4.4 \times 10^{-6}$ d. Improving the orbital ephemeris is one of our key goals; many interesting effects

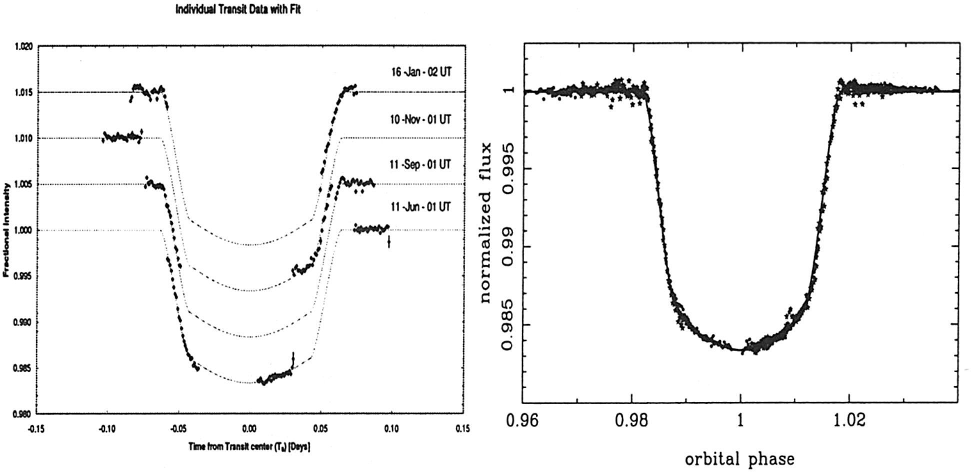

Figure 1. **Left:** FGS observations and fits using Method I. **Right:** Phase-folded FGS and STIS observations with the ELC fit.

are detectable only at this precision, e.g., orbital perturbation by another planet or GR–induced precession (e.g., Miralda-Escudé 2002). As a concrete example, the presence of a satellite with Io characteristics would reveal itself as a ~0.5 s periodic shift in the times of mid–transit (Sartoretti & Schneider 1999).

4. Modelling II.

We also modelled the data with the binary star *Eclipsing Light Curve* (ELC) code (Orosz & Hauschildt 2000). The code attempts to include nearly all relevant physical effects in modelling the star–planet system (though ELC does not yet include the effects of the planet's atmosphere). Effects such as tidal and rotational distortions in the equipotential surfaces and the resulting gravity darkening are included. Limb darkening is handled using the logarithmic prescription given by Van Hamme (1993) and the code allows the inclusion of several physical constraints while modelling the light curves: e.g., the mass of the star must agree with 1.06 ± 0.13 $M_\odot$ (Mazeh et al. 2000; Cody & Sasselov 2002) and the rotation velocity $V_{rot} \sin i$ with 3.75 ± 1.25 km/s (Queloz et al. 2000). Light curves in several bandpasses and radial velocity curves can be simultaneously fit. While details such as the non–sphericity of the bodies are completely negligible in the case of HD 209458, we stress the value of such an approach: the code produces a *single self–consistent* solution that should be able to match nearly all observations, including the remarkable "Z–wave" distortion seen in the radial velocity curve during transit (Queloz et al. 2000; Bundy & Marcy 2000). The fixed parameters in the model are the temperatures of the star and planet, 6000 K and 1400 K, respectively (Mazeh et al. 2000; Cody & Sasselov 2002; Guillot & Showman 2002). The planet is assumed to be tidally locked in a circular orbit. The parameters of interest are the orbital inclination, period, epoch of inferior conjunction, and radii of the planet and star. Three "nuisance parameters" are also included: the mass ratio, orbital separation, and rotation velocity of the star. While ELC is an exceptionally powerful tool, the extremely small ratio of planet/star radii requires a dense grid of surface tiles on the star leading to models that are computationally expensive. The results to date are based on several hundred hours of cpu time but are still very preliminary. The right hand side of Fig. 1 shows the ELC fit to *both* the FGS and STIS light curves. The parameter estimates are consistent with previous determinations, with the exception of the planet's mass which is high by $\sim$10%. This high value is an artifact of the model; we are certain of this because the model also overestimates the star's radial velocity amplitude by roughly the same relative amount. The reduced χ^2 of the overall fit is 2.6, with χ^2_ν=4.6 for the FGS data and χ^2_ν=1.85 for the STIS data. The worse fit for the FGS data is apparent in the figure: deviations from a smooth, symmetric transit are visible.

We have an additional HST observation of one more transit pending. Once the full data set is acquired, we will re–determine the system parameters and search for subtle effects that could be caused, for example, by a satellite or ring or by the transit of the planet over a starspot. We will continue to pursue the ELC modelling and will attempt to include the latest low–temperature stellar models instead of blackbodies. We will use a finer grid on the star and attempt to simultaneously fit the radial velocity curves, as well as additional photometric observations from TSU's APTs and SDSU's Mt. Laguna Observatory. Unlike the HST observations, these ground–based data can cover a full transit and thus can significantly reduce errors in phasing and the ephemeris.

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