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Monitoring the Planetary Transits of HD 209458b

A. B. Schultz, M. Kochte, W. Kinzel, F. Hamilton, I. Jordan (CSC/STScI)

G. Henry (TSU), S. Vogt (UCSC), F. Bruhweiler (CUA), A. Storrs (TU)

H. M. Hart (CSC/JHU), D. Bennum, J. Rassuchine, M. Rodrigue (UNR)

D. P. Hamilton (UMD), W. F. Welsh, R. Wittenmyer (SDSU), and D. C. Taylor (STScI)

Abstract. Portions of four planetary transits of HD 209458 were observed using the Fine Guidance Sensors (FGS) onboard the Hubble Space Telescope (HST). The combined data were fit with a transit model, yielding a determination of the stellar radius $R_* = 1.17 \pm 0.03$ $R_\odot$, the planetary radius $R_p = 1.43 \pm 0.04$ R_J, and the orbital inclination $i = 86.1^o \pm 0.1^o$.

1. Introduction

The detection of over 100 Jupiter-size planets orbiting solar-like stars has provided new insight into the formation and diversity of planetary systems. A few of these extrasolar planets orbit within ~ 0.1 AU of their host star, and have been classified as "51 Peg-like" after the first extrasolar planet detected, or "roasters" due to their high effective temperatures ($900K < T < 1500K$). Of the dozen or so roasters detected, only the planet about HD 209458 transits its star (Henry et al. 1999). The Doppler technique used to detect extrasolar planets provides only the minimum mass ($M_p \sin(i)$). Knowledge of the stellar mass combined with modeling the precise photometric transit measurements provides estimates of the basic system parameters such as the orbital inclination and planetary radius. Determining the orbital inclination removes the $\sin(i)$ dependency in the planetary mass estimate. Henry et al. (2000) observed HD 209458b transits from the ground and reported $\sin(i) > 0.993$ and a planetary radius of ~ 1.42 R_J. Charbonneau et al. (2000) reported a radius of ~ 1.27 R_J. The resulting mean density of ~ 0.27 g cm^{-3} confirms that the planet is a gas giant.

2. Observations and Data Reduction

The three FGSs onboard the HST are used for astrometry, photometry, and pointing control. An FGS contains four standard photomultiplier tubes (PMTs), two for the x-channel and two for the y-channel (Nelan and Makidon 2001).

FGS1r with filter F550W (5100-5875 Å) was used as a photometer in counting mode to observe transits of HD 209458b with a sample rate of 40 Hz, yielding $\sim$ 6,500 counts per 0.025 s sample per PMT (S/N $\sim$ 80). A transit duration ($\sim$ 186 min) is slightly shorter than two consecutive HST orbits (each $\sim$ 96.5 min). The Earth occults the target for a large fraction of each HST orbit, so it is impossible to obtain data over an entire individual transit. Four transits were observed: June 11, 2001, September 11, 2001, November 10, 2001, and January 16, 2002.

We discovered that there is a time dependent sensitivity change when observing a bright source with the FGS PMTs. This sensitivity change was not observed previously since most FGS observations are short, a few seconds of integration time rather than the typical 30 minutes of integration time used to observe the transit.

Data reduction consisted of correcting for the FGS dead time and removal of the time-dependent FGS response. The out-of-transit data were fit with a fifth order Chebyshev polynomial and this fit was divided into the in-transit data, normalizing them to the mean of the out-of-transit counts. Finally, the data were placed into 80-second bins to match the STIS sampling time (Brown et al. 2001). The reduced data for the 4 transits are presented in Figure 1.

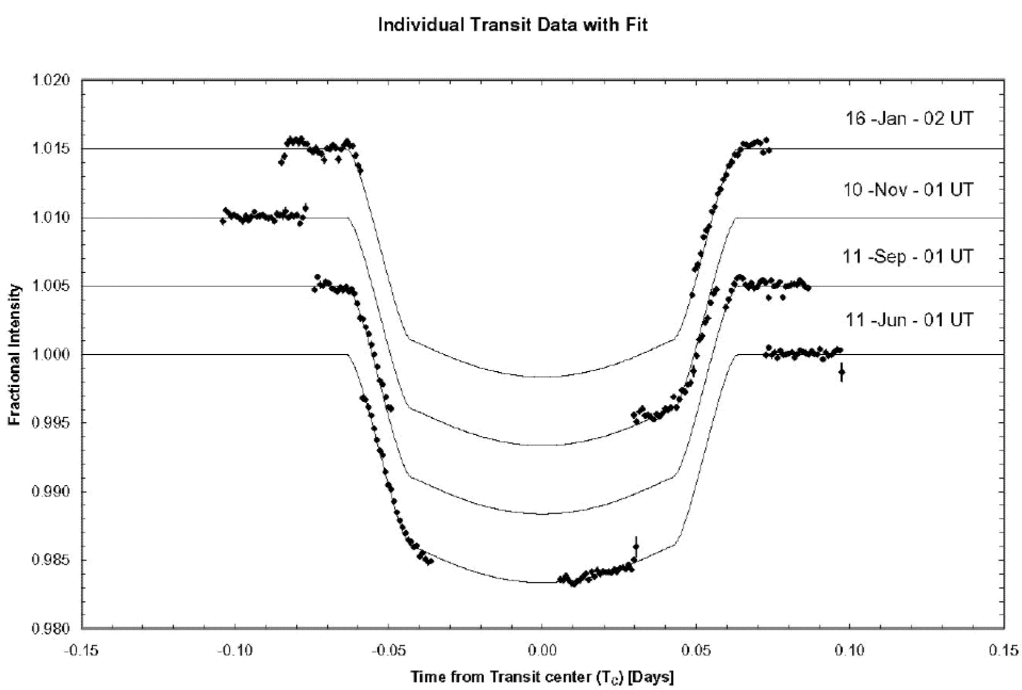

Figure 1. FGS transit observations. The model fit to the light curves is also shown.

The June 2001 observation consisted of three contiguous HST orbits, to verify the observing strategy and to capture the mid-transit point for fitting purposes. The September 2001, November 2001, and January 2002 observations consisted of two non-contiguous HST orbits, each with one non-HD 209458 orbit between the two orbits on HD 209458. The September 2001 and January 2002 observations caught the ingress and egress turn over points.

3. Light Curve Modeling

The observations were fit via χ^2 minimization to a model consisting of an opaque spherical planet in circular orbit, transiting a limb darkened star. There are seven free parameters: time of transit center T_0, stellar radius R_*, planetary radius R_p, orbital inclination, period, and the stellar limb darkening parameters u_1 and u_2. The star was assumed to have a mass of 1.1 ± 0.1 $M_\odot$ (Mazeh et al. 2000) and quadratic limb darkening of the form:

$$I(\mu)/I(1) = 1 - u_1(1-\mu) - u_2(1-\mu)^2$$

where μ is the cosine of the angle between the line of sight and the stellar surface normal. The parameters were fit to the time of transit center T_0 on November 10, 2001.

The uncertainty in each model parameter value was estimated using the technique given in Press et al. (2002). Using the parameter values obtained from the fit to the FGS data, 100 simulated FGS data sets were generated. Each simulated datum was varied from the predicted normalized flux value by the addition of random noise whose magnitude was based upon the RMS of the fit to the FGS data. Each simulated data set was then fit using the same model and free parameters as before. In addition, for each fit, the assumed mass of the star was varied based upon its uncertainty ($\pm 0.1 M_\odot$, Mazeh et al. 2000). The standard deviation of each parameter obtained from the fits to the 100 simulated data sets is used as the uncertainty for that parameter.

The only data set comparable to the FGS data set was obtained using the HST STIS (Brown et al. 2001). These data were obtained and fit using our algorithm and model. The results of this fit are listed in Table 1. The parameter fit published by Brown et al. is presented for comparison.

Table 1: Fit to the HST STIS Observations of HD 209458.

	STIS Data Fit		STIS (Brown et al 2001)	
	value	uncertainty	value	uncertainty
T_0	2451659.936935	0.000040	2451659.93675	0.00010
R_* ($R_\odot$)	1.142	0.033	1.146	0.050
R_p (R_J)	1.344	0.040	1.347	0.060
inclination i	86°.692	0°.062	86°.68	0°.14
Period (days)	3.5246735	0.0000142	3.52474	0.00007
u_1	0.289	0.037	0.2925	0.1044
u_2	0.353	0.066	0.3475	0.1044
χ^2	1.63		1.60	

For comparison, a fit to the STIS data using the same code that was used to model the FGS data, and the published STIS data results (Brown et al. 2001), are shown.

4. Analysis and Conclusions

The results of the fit to the FGS data are presented in Table 2. These are consistent with conclusions of Henry et al. (2000), Charbonneau et al. (2000), Castellano et al. (2000), Robichon & Arenou (2000), and Brown et al. (2001).

Table 2: Fit to the HST FGS Observations of HD 209458.

	FGS Data Fit	
	value	uncertainty
T_0	2452223.896173	0.000086
R_* ($R_\odot$)	1.172	0.030
R_p (R_J)	1.430	0.039
inclination i	$86^\circ.135$	$0^\circ.104$
Period (days)	3.5247542	0.0000044
u_1	0.814	0.150
u_2	-0.528	0.211
χ^2	3.85	

We have pending Cycle 10 observations of one more transit. When these observations are completed, we will redetermine the system parameters. We will also examine the data for evidence of planetary moons or rings, although these are not expected to be stable on theoretical grounds.

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