The STARE Project: A Transit Search for Hot Jupiters

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Abstract. The STARE instrument is a small aperture, wide-field, CCD-based telescope that delivers high cadence time series photometry on roughly 40,000 stars in a typical field centered on the galactic plane. In a two-month observing run on a field, we obtain sufficient precision on roughly 4,000 stars to detect a close-in Jupiter-sized companion in an edge-on orbit. We also used this instrument to detect the planetary transits across the Sun-like star HD 209458. The project is now in its third season, and we have acquired a large dataset on several fields. Given the frequency of close-in extrasolar planets found by the radial velocity surveys, and the recent confirmation that at least some of these are indeed gas giants, the STARE project should be able to detect roughly a dozen Jupiter-sized planets in its existing dataset.

1. Introduction and Motivation

Radial velocity surveys of nearby F, G, K and M dwarf stars have revealed a class of close-in extrasolar massive planets that orbit their stars with an orbital separation of $a \lesssim 0.1$ AU. Prior to the transit results for HD 209458, the radial velocity method has been the only method by which we have learned anything about these planets. The radial velocity technique measures the period, semi-amplitude, and eccentricity of the orbit, and by inference the semi-major axis. It also yields a value for the minimum mass, dependent upon the assumed value for the stellar mass, but aside from this it gives no direct information on the structure of the planet itself. The search to measure the transit photometrically is motivated by fact that, for a star for which both the radial velocity and transits are observed, one can estimate both the mass (with negligible error due to sin $i$) and radius of the planet. These can then be combined to calculate such critically interesting quantities as the surface gravity and average density of the planet, and thus provide constraints on structural models for these low-mass companions. Assuming random orbital alignment for systems with $a = 0.05$ A.U. and Sun-like primaries, the chance of a transiting configuration is roughly 10%.
The left panel displays the achieved time series rms variation for roughly 24,000 stars in a field in Auriga, as a function of $R$ magnitude, for one night. The dominant noise source is sky background for all but the brightest stars in the field. The right panel shows a selection of variable stars as observed by STARE. From top to bottom, these are: 1. an eclipsing binary with a period of 0.876 days; 2. a $\delta$ Scuti with a period of 0.078 days; 3. a $\delta$ Cepheid with a period of 18.2 days; 4. an eclipsing binary with a 4% primary eclipse and a period of 2.55 days. This small eclipse depth is approaching the level that would be predicted for a transit of a Jupiter-sized companion across a Sun-like star.

2. The STARE Instrument

The telescope is a Schmidt camera of focal length 286 mm and f/2.9. The modest 10 cm aperture images a 6 degree square field of view onto a $2034 \times 2034$ pixel CCD with 15 $\mu$m (11 arcsecond) pixels. The majority of observations are taken through a red (approximately Johnson $R$) filter, with supporting observations in $B$ and $V$ to determine stellar colors. The data are analyzed via a pixel-weighted photometry scheme, with post-photometry linear regression to account for gray and color-dependent extinction. Prior to July 1999, the main instrument was an Aero-Ektar lens. The new system has a much more Gaussian-shaped point spread function, which increased the precision and the throughput by a factor of 2.

The STARE instrument delivers high cadence (2 minute) times series photometry on roughly 40,000 stars ($9 < V < 14$) in a typical field centered on the galactic plane. As shown in Figure 1, sky background is the dominant source of noise for the majority of stars in the field, while the brightest stars are scintillation limited. In each field, we obtain sufficient precision on roughly 4,000
stars to detect a close-in Jupiter-sized companion. Since fields centered on the
galactic plane are not always available, we have also stared at some high-galactic
latitude fields. These fields are significantly less crowded and will allow us to
measure the effects of crowding on our photometry pipeline.

The telescope is currently located in Boulder, Colorado, but is portable. In
the future, it may be relocated in longitude so as to provide much greater time
series coverage when operated as part of a network with similar instruments,
such as those run by W. Borucki at Lick Observatory (Vulcan, Borucki et al.
2000) and by E. Dunham at Lowell Observatory.

A byproduct of the STARE observations is the high-cadence monitoring of
numerous variable stars, the majority of which are new detections. We have
made many of the light curves available electronically (Brown & Kolinski 1999),
and plan to continue to do so in the future.

3. The First Transiting Extrasolar Giant Planet

We have detected the first planetary transits across a Sun-like star, HD 209458,
as described in Charbonneau et al. (2000). These have also been reported by
Henry et al. (2000).

Motivation for observing HD 209458 came from D. W. Latham and M. Mayor
(personal communication) in August 1999. The times at which a potential tran-
sit could occur were calculated from the preliminary orbital period and ephemeris
from the radial velocity observations. We observed HD 209458 for ten nights
in August and September. Most of these nights occurred when no transit was
predicted, and the residuals are consistent with no variation. On the other two
nights (UT 9 Sep & 16 Sep), we see a conspicuous dimming of the star for a
time of several hours, at a time consistent with the prediction from the observed
radial velocity orbit. We attribute this dimming to the passage of the planet
across the stellar disk. Our precise measurement of two complete transits allows
us to accurately determine the planetary radius, orbital inclination, and mass,
and hence derive quantities such as the surface gravity and average density.

Assuming a value for the stellar radius and mass, and a description for the
stellar limb-darkening, we can determine the planetary radius with an accuracy
of several percent (see Figure 2). However, the dominant uncertainties in de-
termining the planetary radius and orbital inclination are the uncertainty in the
value of the stellar radius, and to a lesser extent the stellar mass and limb-
darkening. Given time series observations of the transit in a single photometric
band, it is possible to fit the data with a family of models, since a larger plane-
tary radius can be accommodated by increasing the stellar radius and reducing
the orbital inclination. In Mazeh et al. (2000), we undertook a detailed study for
of the stellar parameters, as well as the respective uncertainties. These allowed
us to measure the planetary radius to be $R_p = 1.40 \pm 0.17 \, R_{\text{Jup}}$. This value
for the radius is consistent with early predictions (Guillot et al. 1996). The
inflated value of the radius relative to that of Jupiter is a result of the slower
rate of planetary contraction due to exposure to high stellar insolation soon after
the formation of the planet (Burrows et al. 2000). We also calculated several
derived quantities, in particular the average density $\rho = 0.31 \pm 0.07 \, \text{g cm}^{-3}$,
surface gravity $g = 870 \pm 160 \text{ cm s}^{-2}$, and escape velocity $v_e = 42 \pm 4 \text{ km s}^{-1}$ of the planet.

4. Follow-Up Observations

The existence of a transiting planet suggests many fruitful follow-up observations, some of which may be accomplished within the next six months:

- High cadence, high precision photometry in other band passes would break the degeneracy shared between the stellar and planetary parameters, by exploiting the color-dependent limb-darkening of the star. Furthermore, it may be possible to observe color-dependent variations in the observed planetary radius, since the planet would appear slightly larger when observed at wavelengths where the atmosphere contains strong opacity sources (Brown 2000; Burrows et al. 2000).

- If there are other planets in approximately coplanar orbits, then the likelihood that they too will generate transits is substantially enhanced relative to that for a randomly oriented system. A central transit by a Uranus-sized planet at $0.2 \text{ AU}$ would yield a dimming some 6 hours in duration, with a depth of about 1 millimag.

- Reflected light observations such as those for the $\tau$ Boö system by Cameron et al. (1999) and Charbonneau et al. (1999) would, if successful, yield the planetary albedo directly (Charbonneau & Noyes 2000). Predicted values for the albedo are highly sensitive to the atmospheric chemistry and condensates (Marley et al. 1999; Seager 2000; Seager, Whitney & Sasselov 2000; Sudarsky, Burrows, & Pinto 2000).

- Observations at wavelengths longer than a few microns may detect the secondary eclipse (perhaps 4 millimag) as the planet passes behind the star. This would allow the planet’s dayside temperature to be estimated, and hence quantify the net energy deposition in the planetary atmosphere. Similarly, it may be feasible to measure the reduction of the primary eclipse depth in the IR relative to shorter wavelengths and hence measure the planet’s nightside temperature. If one was able to determine the dayside and nightside temperatures, then one would learn if the planetary atmosphere is effective at redistributing heat due to stellar insolation with a time scale less than the rotational period.

- If high cadence photometry with a signal-to-noise ratio of 0.1 millimag can be achieved, it would be possible to detect planetary rings and/or large rocky satellites (Sartoretti & Schneider 1999).

- By taking the ratio of high-precision spectra in and out of transit, it may be possible to see additional absorption features during transit due to the absorption of light passing through the limb of the planetary atmosphere (Brown 2000; Seager & Sasselov 2000). The amplitude of the features may be as large as 0.2% in the case of the alkali metal lines, and will be very sensitive to the height of the cloud layer in the planetary atmosphere.
Figure 2. STARE observations of the planetary transit of HD 209458, binned into 5 m averages. The rms variation at the beginning of the time series is roughly 1.5 millimag, and this precision is maintained throughout the duration of the transit. The increased scatter at the end of the time series is due to increasing airmass. The solid line is the transit shape that would occur for our best fit model. The lower and upper dashed lines are the transit curves that would occur for a planet 10% larger and smaller in radius, respectively. The rapid initial fall and final rise of the transit curve correspond to the times when the planet is crossing the edge of the stellar disk, and the curvature across the center of the transit is due to the stellar limb-darkening. These data are available electronically from the STARE project website (Brown & Kolinski 1999).
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