A PROGRAM TO DETECT AND CHARACTERIZE EXTRA-SOLAR GIANT PLANETS

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Final Report

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Final Report for NASA Grant NAG5-10854,

"A Program to Detect and Characterize Extra-Solar Giant Planets"

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This is the final report for NASA Grant NAG5-10854 (hereinafter: "the Grant"). Work under the first three years of the Grant (from May 1 2001 through April 30 2004) has been described in previous annual reports. Here we briefly summarize that work, and then focus on activities between May 1 2004 (the start of a 1-year no-cost extension period) and April 30 2005, the end of the Grant period.

Previous Work

1. The Advanced Fiber-Optic Echelle (AFOE) Spectrograph

   During the first two years of the Grant, we continued observations of candidate stars for hosting extra-solar giant planets, using the AFOE spectrograph, then located at SAO's Whipple Observatory. At the start of the Grant, the AFOE achieved precision of 10-15 m/s on relatively bright stars. We improved the radial velocity analysis code by allowing for asymmetry in the spectrograph point spread function, and incorporating minimization procedures to adjust model parameters. This led to model spectra matching the observed spectra to within the Poisson limit (i.e. 1%, for our typical spectral SNR of 100). With these improvements, we were able to achieve precision of 7=10 m/s, on stars brighter than about V=8.

   The above precision is limited by photon flux, which is constrained both by the small aperture of the Tillinghast 1.5-m reflector, and by the intrinsic low throughput of the AFOE in the iodine-spanned spectral region. (The AFOE was originally designed for seismology of very bright stars such as Procyon using a ThAr emission lamp as wavelength reference; it did not incorporate high-throughput optics and it did not produce complete spectral coverage in the spectral region between 5000Å and 6000Å spanned by iodine reference lines.) During the course of the Grant, we re-built the spectrograph to optimize its efficiency for planet detection and increase its throughput, by replacing the grating to provide complete wavelength coverage, incorporating higher throughput camera optics, and re-working the input optical fibers. SAO provided the major funding for this, although some co-I salary support was provided from the Grant.

   During the third year of the Grant, an invitation was received from JPL to move the AFOE from the Tillinghast telescope to the 2.5-m Hooker telescope at Mt. Wilson. The principal purpose of the upgraded AFOE at this location is to monitor candidate guide stars for the SIM mission, although time will be available for precise radial velocity monitoring of other objects. The spectrograph was accordingly moved to the Mt. Wilson

[1]Deceased

2.5-m at no cost to the Grant, and support of the AFOE project from then on has been provided by JPL.

While at the Tillinghast telescope, the AFOE achieved the detection or co-detection of several extrasolar giant planets: the planet orbiting Rho Corona Borealis (Noyes et al 1997, 1999), the three-planet system orbiting Upsilon Andromeda (Butler et al 1999, Noyes et al 1999), the planet orbiting HD 89744 (Korzennik et al 2000), and the planet orbiting GJ 777A (Naef et al 2003). The last of these incorporates AFOE data acquisition and anlysis during the Grant period.

2. Precise radial velocity measurements with the Hectochelle

   SAO's Hectochelle is a multi-object echelle spectrograph designed to record spectra of up to 250 objects within the 1-degree field of view of the MMT telescope. With partial support of the Grant we have developed an iodine cell for the spectrograph, with the expectation that, when fully operational, it can provide useful radial velocity measurements in fields with numerous candidate stars for harboring extra-solar giant planets. A prime target, for example, would be within the Kepler field, where many dozens of stars with magnitude brighter than about 13 could be monitored for the radial velocity variations characteristic of close-in giant planet companions; discovery of such stars before or during the Kepler mission would allow the mission to focus on photometric measurements of the phase-function of reflected light from these planets, which should vary at a level measureable by Kepler. The geometry of the Hectochelle requires that the iodine cell be an unusual and complex shape. During the Grant period and with partial support of the Grant, this cell was constructed and mounted at the telescope, and initial throughput tests were made.

3. The transiting planet HD209458

   With partial support of the Grant we continued work on the transiting planet HD209458b, originally discovered by then-graduate student David Charbonneau (Charbonneau et al 2000). We obtained a definitive light curve of the transit event using the STIS spectrograph on HST (Brown et al 2001). Based on the theoretical transmission spectrum of HD209458 during transits (Seager and Sasselov 2000, Brown 2001), and using observations with the Space Telescope Imaging Spectrometer on HST, we detected the presence of sodium vapor in the planet's atmosphere (Charbonneau et al 2002). We used stellar evolution models to obtain a definitive description of the physical parameters of both planet and star (Cody and Sasselov 2002). We also collaborated with Charbonneau on two other projects (see Charbonneau et al 2003): (1) follow-on HST STIS observation of HD 209458, designed to search for the reflected light signal from the planet via its disappearance during eclipse of the planet by the star; and (2) STIS observation to obtain photometry over an extended wavelength range from 3000 Å to 10000 Å, in order to further constrain the atmospheric properties of the planet, with particular attention to the effects of clouds and of metallicity. Publication of results of the latter two investigations is in preparation.

4. The Extra-Solar Planet Imager (ESPI) concept study.

   Under the leadership of P. Nisenson, SAO investigated and proposed to NASA a concept for direct imaging and spectral analysis of giant planets orbiting solar type stars. ESPI extends the concept suggested by Nisenson and Papaliolios (2001) for a square aperture-apodized telescope that has sufficient dynamic range to direct exoplanets. Details were published by Nisenson et al (2003).

5. The HAT project

   During the Grant period we used internal funds to initiate a program to use a small (65 mm) wide angle lens with a 2K × 2K CCD for a wide-field photometric search for transiting extra-solar planets. This telescope, which was developed originally in Hungary by a Hungarian predoctoral student at SAO (G. Bakos) and was fully automated, was named the Hungarian Automated Telescope (HAT); see Bakos et al 2002. Primarily using internal SAO funds, but also with partial support of the Grant, we expanded this project to a network of 5 somewhat larger (100 mm) and otherwise improved HAT telescopes—three of them at SAO's FLWO Observatory near Tucson Arizona and two of them at SAO's SMA installation on Mauna Kea, HI. The improved instruments were described by Bakos et al 2004. Using these instruments we initiated an intensive program of monitoring star fields for transiting planets between I magnitudes of 8 and 13.

Activities since May 1, 2004

1. The HAT Project

   During the one-year no-cost extension (NCE) the major activity was continuation of the HAT project. Support from the Grant was particularly useful during the first three months of the NCE period, as the program evolved into a new and larger HATnet program, funded by the NASA TPF Foundation Science Program under NASA Grant NNG04GN74G. Funding for the TPF Foundation Science program began on July 15, 2004, and supplied the great majority of the funding for the HAT project after that date. The remaining funding from the Grant expended during its one-year NCE was useful in enabling a smooth transition to the HATnet program. A summary of HATnet activities over the past year, supported to a small extent by the Grant and to a larger extent by the new TPF Foundation Science grant, is as follows:

   Primarily using internal funds, we completed construction of a sixth HAT telescope, which was installed at Whipple observatory in Arizona. This made a complement of four HATs at Whipple Observatory (Figure 1), plus two HATs at Mauna Kea, HI (Figure 2).

   We began operation of the HATs as a longitude-distributed network, in which nightly observations begun in Arizona were continued from Hawaii after the star fields set in Arizona (Figure 3). We also moved the two Mauna Kea HATs from their temporary location at ground level to a longer-term location on the top of the SMA assembly building.

   Also using primarily internal funds, we designed, constructed, and installed at Whipple Observatory a larger automated photometric telescope, known as TopHAT (Fig. 4), to be

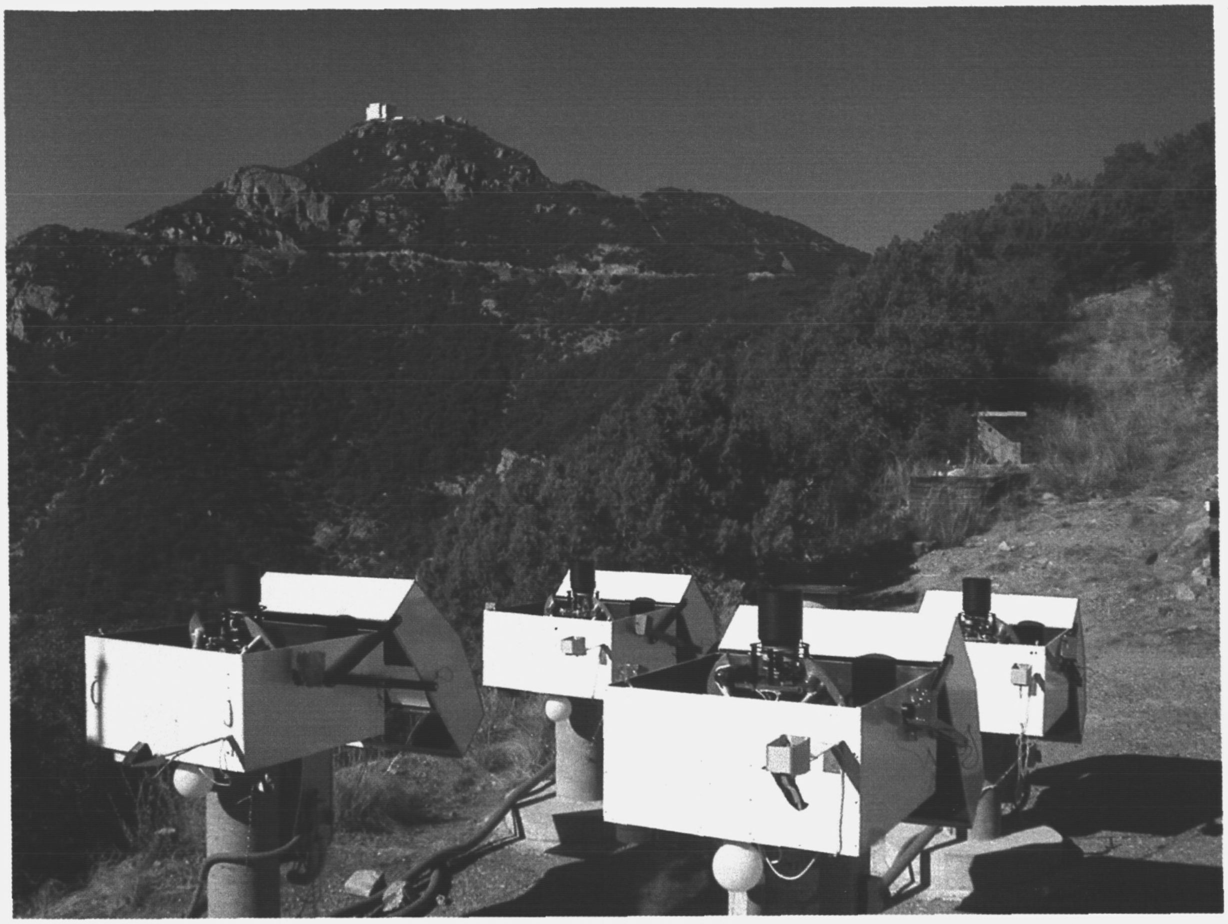


Figure 1: Installation of HAT 5, 6, 7 and 10 at the Fred Lawrence Whipple Observatory (FLWO), Arizona. Our follow-up instrument, TopHAT, was not yet on the site at the time the photo was taken.

used for follow-up of transit candidates with greater precision and with greater angular resolution (thereby facilitating rejection of "false positives" due to blending of more than one star within the 14 arcsec pixels of the smaller HAT telescopes, and also permitting near-simultaneous two-color photometry of candidate sources as a further way of filtering out false positives). The TopHAT telescope has a 10-inch aperture, and a high-quality back-illuminated 2K x 2K Marconi CCD detector. It came into full operation in April 2005, and its performance has been excellent. In fact, recent observations of the transit of the rocky-cored planet orbiting HD 149026 (Charbonneau et al 2005) show that for bright stars TopHAT can obtain photometric precision approaching 1 millimagnitude (0.1%).

We have developed a Trend Filtering Algorithm (TFA, see Kovacs, Bakos, and Noyes 2005), which automatically corrects trends for each program star with the observed trends in hundreds of other stars in the field, using a least squares analysis. Removal of trends in this way can dramatically improve the signal-to-noise ratio (SNR) of the light curve, which in turn significantly improves the rate of detection of transits via the BLS (Box

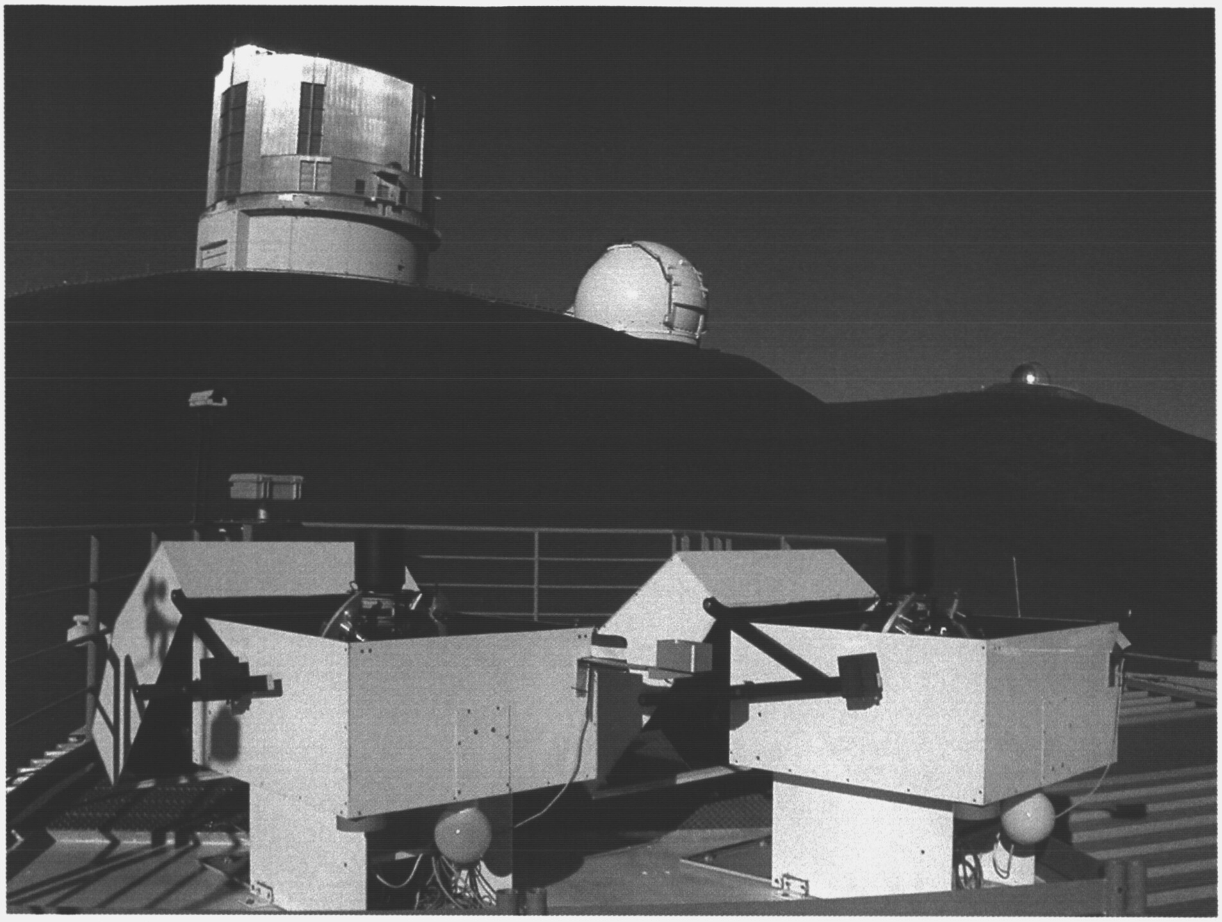


Figure 2: Installation of HAT 8 and 9 at the Submillimeter Array Site atop Mauna Kea, Hawaii. Subaru and the Keck telescopes are in the background.

Least Squares) algorithm. We have applied this methodology to some 30,000 stars observed in 12 separate HAT fields, and from this sifted out of order 120 stars with candidate transiting planets; that is about one out of every 250 stars emerges as a possible transit candidate. These 120 candidate stars have then been placed on a list for follow-up observations. By the end of the Grant period we had followed up about 70 of these candidate stars, starting with spectroscopic observations by our collaborator David Latham using the Digital Speedometers of the SAO 1.5-m telescopes at Oak Ridge Observatory in Massachusetts and the Whipple Observatory in Arizona. Figure 5 illustrates follow-up at this level for one of our more promising candidates , whose light curve exhibited a near-textbook transit shape, but whose RV curve as determined by the digital speedometers shows it is clearly a false-positive, consisting of an FV star transited by an M dwarf.

Additional photometric follow-up observations have also been performed with the 48-inch telescope at Whipple Observatory, and now that TopHAT is operational, follow-up observations are being carried out with this telescope. So far, all of the 70-odd candidates followed up have turned out to be false positives. However, we have a large body of new

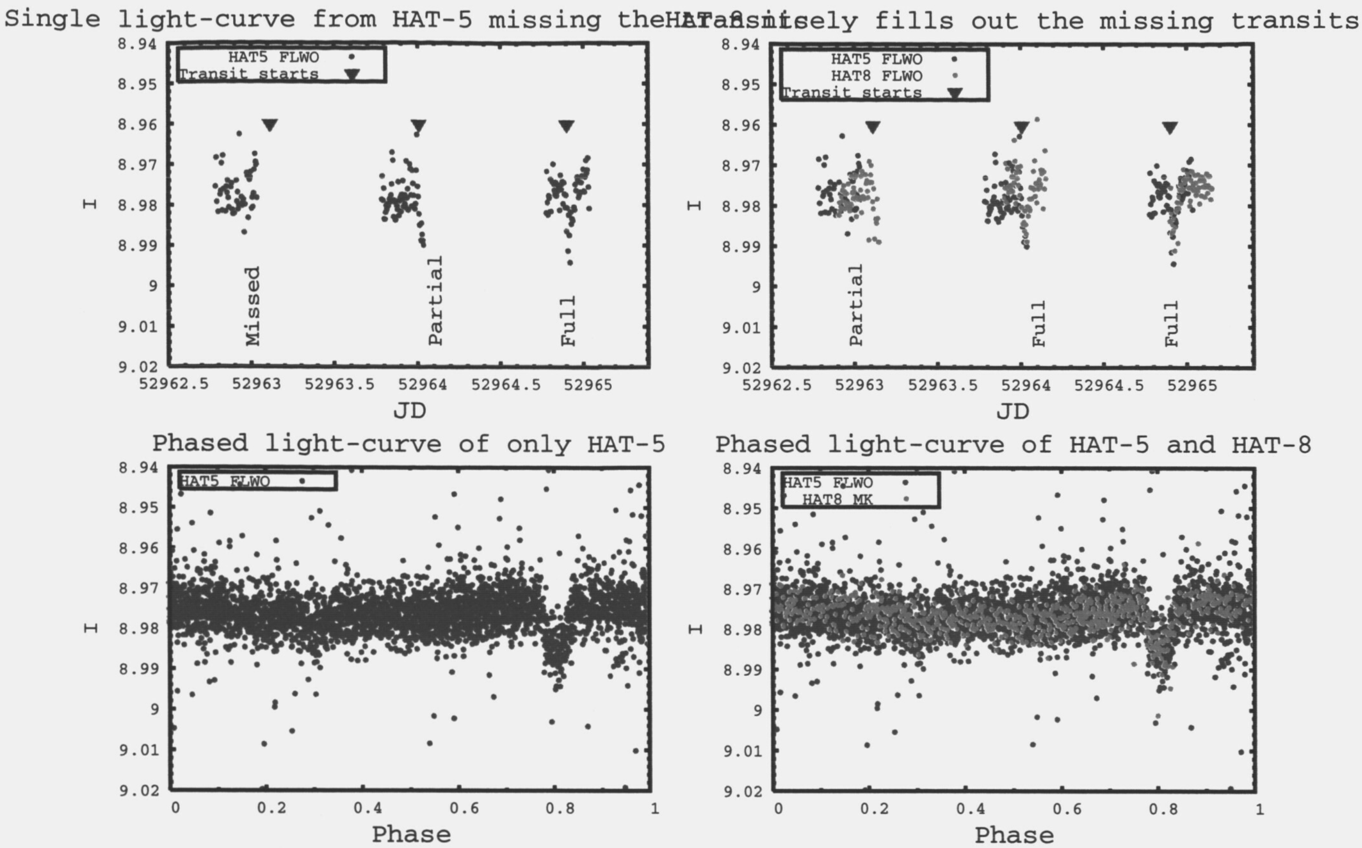


Figure 3: Combined light-curve of transit candidate number 10 in field 175 (HTR175-010) using HAT5 (AZ) and HAT8 (MK) data

data about to be run through the reduction pipeline; based on the statistics of known transiting planet detections, there should be a good probability of detection one or more transiting planets in this sample.

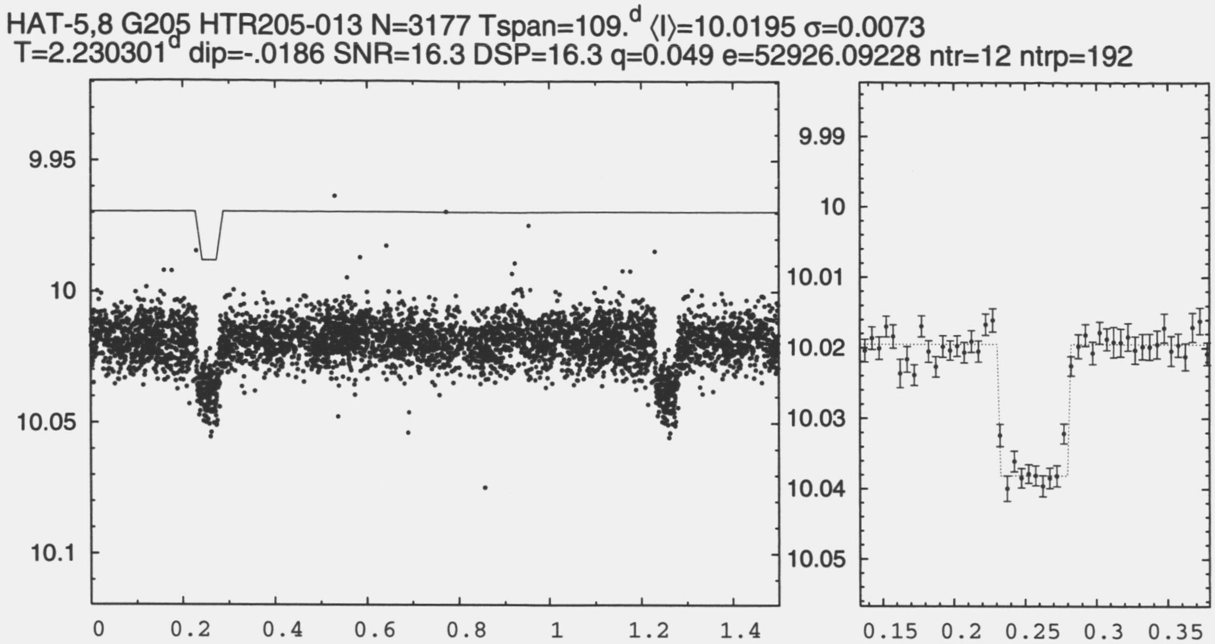
In related work, Harvard graduate student Joel Hartman has used image subtraction photometry on HATnet data on a dense star field overlapping the planned *Kepler* mission (Hartman et al 2004). Light curves were obtained for 98,000 objects and from these more than 1400 new variable stars were discovered. Some of these have variability amplitude as small as 10 mmag, i.e. in the range of extra-solar planet transits.

2. Other Activities

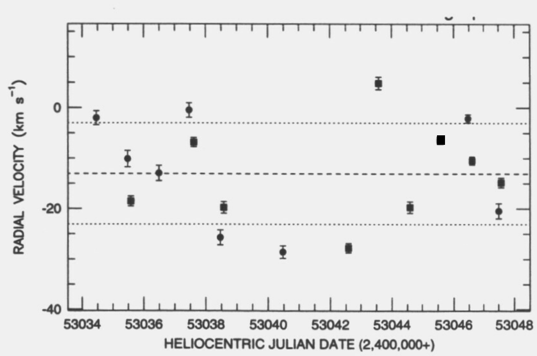
Harvard graduate student Jonathan Devor developed an automated pipeline for analyzing light curves to identify eclipsing binaries in photometric data such are produced by the HAT network or other wide field photometric data sets such as the OGLE II survey. Details of this pipeline, known as the Detached Eclipsing Binary Lightcurve fitter (DEBiL) were published (Devor 2005) with partial support of the Grant.

Figure 4: TopHAT, our 25cm diameter, 1.2m focal length follow-up instrument installed at FLWO, Arizona. The telescope has been in operation since April, 2005.

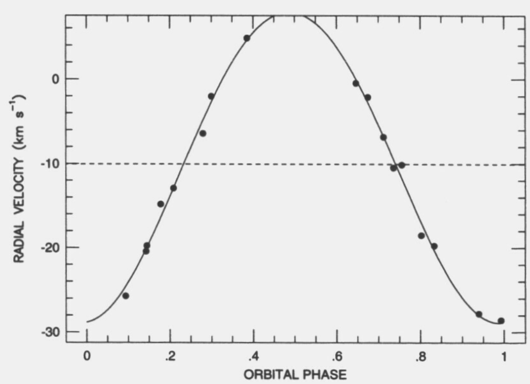
Finally, we participated in analysis of HIRES observations of the radial velocity variation of HD209458 during transit of its companion, using the Rossiter effect to gain information on the rotation rate of the star and the projected angle between the stellar rotation axis and the planetary orbital plane. The final data analysis (Winn et al 2005) shows that the projected planetary orbital plane is inclined by 4.4 ± 1.4 degrees to the projected stellar rotation axis. This is the first planetary system other than the solar system for which the relative inclination of planetary orbital axis and stellar rotation axis has been accurately measured. The small but non-zero inclination is probably a relic of the planet formation epoch, because the expected timescale for tidal coplanarization is larger than the age of the star.



(a) Box-shaped 0.018*mag* deep transit of HTR205-013.



(b) Radial velocity vs. Julian Date.



(c) Radial velocity phased with the spectroscopic period.

Figure 5: Phase light-curve and radial velocity curves for star HTR205-013, an F-dwarf primary and M-dwarf secondary. Radial velocities are determined for the single lined system by the means of correlation with a synthetic template.

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