Precise Photometry of Extrasolar Planet Transits

Program contacts:	E.W. Dunham, T.M. Brown, D. Charbonneau, J.L. Elliot, I. McLean
Scientific category:	EXTRASOLAR PLANETS
Instruments:	HIPO/BLUE, HIPO/RED, FLITECAM/CAM, FLITECAM/SPEC
Hours of observation:	50

Abstract

Precise photometric observations of transiting extrasolar planets can provide a wealth of data on the nature of these objects. Results such as planetary radius, orbital inclination, stellar limb darkening, evidence for planetary satellites or rings, and atmospheric composition can be found from the transit observation alone. When combined with high quality radial velocity data the mass and density of the planet can be determined. Infrared observations of the secondary minimum provide a means to determine the temperature of the planet and allow limits on the orbital eccentricity to be defined. Perturbations by other planets in the system can be found by variations in transit timing over a period of years.

We anticipate that very high quality transit data can be obtained with SOFIA using the HIPO and FLITECAM science instruments. At present this work is limited to the two brightest known transiting planets, but the field is so active that many additional targets will be found. The ongoing spectroscopic planet search programs and several ongoing transit search programs designed specifically to find objects bright enough for detailed follow-up work are expected to add numerous objects to this list over SOFIA's lifetime. The Kepler mission will be launched and complete its mission while SOFIA is flying, producing numerous exciting opportunities for additional work.

Observing Summary:

| Target	RA	Dec	V	Configuration/mode	Hours
HD209458	22:03:11	18:53:04	7.64	HIPO/FLITECAM, see text	25
TRES-1	19:04:10	36:37:57	11.79	HIPO, see text	25
				Grand total hours	50

Scientific Objectives

Radial velocity observations have shown that extrasolar planetary systems with giant planets orbiting near their parent stars are quite common. The field is rapidly-moving and an up-to-date catalog is maintained online by Jean Schnieder (cfa-www.harvard.edu/planets/catalog.html). Radial velocity observations alone can provide only a lower limit on the planetary mass because of the unknown inclination of the planetary orbit in space. If a planet's orbit is aligned nearly along our line of sight, the planet will transit its parent star as seen by an Earth-based observer. The uncertainty in the planetary mass derived from radial velocity observations is greatly reduced when the orbit is nearly edge-on. The transit also provides an estimate of the projected area of the planet, thus allowing its radius and density to be estimated. Precise optical photometry of the transit allows fitting for orbital parameters, the color-dependent stellar limb darkening coefficient, and the stellar and planetary radii. Small systematic deviations from the transit fit can reveal the presence of starspots, satellite(s) of the transiting planet, or planetary rings. Continued transit observations over an extended time period can reveal orbital perturbations due to other planets in the system or to satellites of the transiting planet. The magnitude of the smallest detectable perturbation is limited only by the S/N ratio of the transit photometry and the intrinsic stability of the stellar brightness on the timescale of the transit. Infrared observations of the secondary minimum can define the temperature of the planetary atmosphere and limit its orbital eccentricity. Searches for strong spectral signatures are also feasible (e.g. Charbonneau, et al, 2002; Deming, et al., 2005a).

Several transiting extrasolar planets are currently known, but only two are sufficiently bright to allow high-quality radial velocity and precise photometry observations to be made: HD209458 (Charbonneau, et al., 2000; Henry, et al., 2000) and TrES-1 (Alonso, et al., 2004). A number of search programs are underway to discover additional bright objects of this type (Horne, 2003), so further examples are expected over a period of years. The Kepler mission (Borucki, et al., 2003) will discover a wide variety of transiting planets ranging from the giant inner planets presently known to planets analogous to the terrestrial planets in our solar system. These objects will also be bright enough for excellent data to be obtained with other facilities.

Brown, et al. (2001) present an analysis of very precise photometry of the transit of HD209458 observed with STIS and the Hubble Space Telescope (see Figure 1). Recently Spitzer photometry using MIPS and IRAC has revealed the secondary minimum, to use eclipsing binary terminology, for both HD209458 (Deming, et al., 2005b) and TrES-1 (Charbonneau, et al., 2005). Even more recently Brown, et al. (2005) obtained an HST/ACS lightcurve of TrES-1 (Figure 2) with precision on the order of a few parts in 10000. We anticipate that optical photometry of similar quality can be obtained with SOFIA throughout its lifetime. Near-IR photometry of the brighter targets can also be obtained with somewhat lower S/N ratio using FLITECAM at K band and shorter wavelengths, with sufficient sensitivity to detect the secondary minimum in the L band for solar-type stars brighter than about V=10. Observations of newly discovered objects will provide basic information on the

Figure 1: HST/STIS lightcurve of the transit of HD209458b (after Brown, et al. 2001).
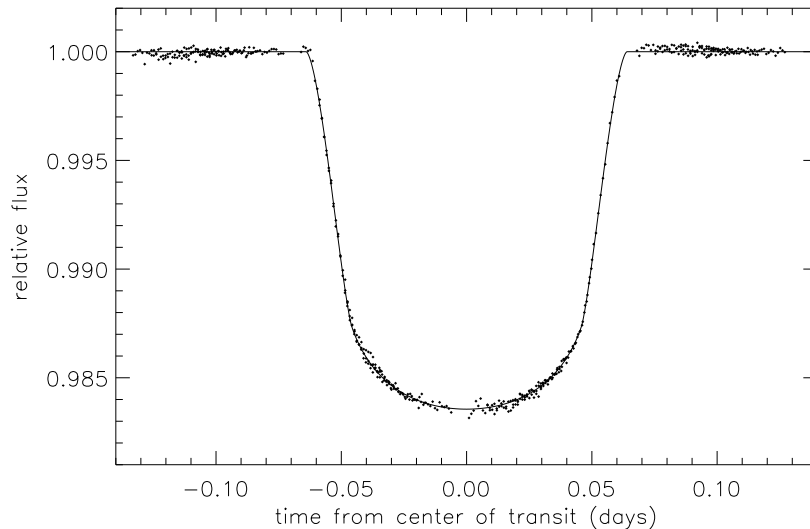
characteristics of the transiting planet. Continued precise transit timing on an occasional basis over a period of years would allow other planets in the system to be found through their perturbations on the transiting planet.

SOFIA Uniqueness/Relationship to Other Facilities

The bright stars we propose to observe will be dominated by shot noise from the object at wavelengths shorter than the thermal IR, but by background at wavelengths near or longer than the maximum of the planetary emission in the L band. At optical wavelengths, the shot noise precision will be better than 100 ppm in 10 minutes and even in the L band the precision will be approximately 500 ppm in 10 minutes for targets such as HD209458. As a result the actual precision will almost certainly be limited by atmospheric and instrumental effects.

Experience with airborne photometry on the Kuiper Airborne Observatory (KAO) indicates that scintillation is greatly suppressed compared to ground-based experience (Dunham and Elliot, 1983). It has not yet been possible to determine if this is consistent with extrapolation of tropospheric scintillation (Dravins, et al., 1998) to the high altitude of the aircraft or if, as might be expected, the scintillation is further suppressed due to the statically stable nature of the stratosphere. Extinction is very low in the stratosphere, and in some cases flight profiles can be arranged such that the object remains on the Meridian during the entire hours-long observation, an impossibility for ground-based telescopes. KAO occultation photometry was generally as good as, or better than, data obtained with 4-meter ground-based telescopes. By analogy, we might expect that a 10-meter ground-based telescope could obtain results of comparable quality to our SOFIA data. Of course, the larger apertures involved in both the airborne and ground-based telescopes drive the comparison into a regime of higher

Figure 2: HST/ACS lightcurve of the transit of TrES-1 (after Brown, et al. 2005). The small rise near the bottom of the transit could be due to a number of effects, the most likely of which is transit of a starspot.
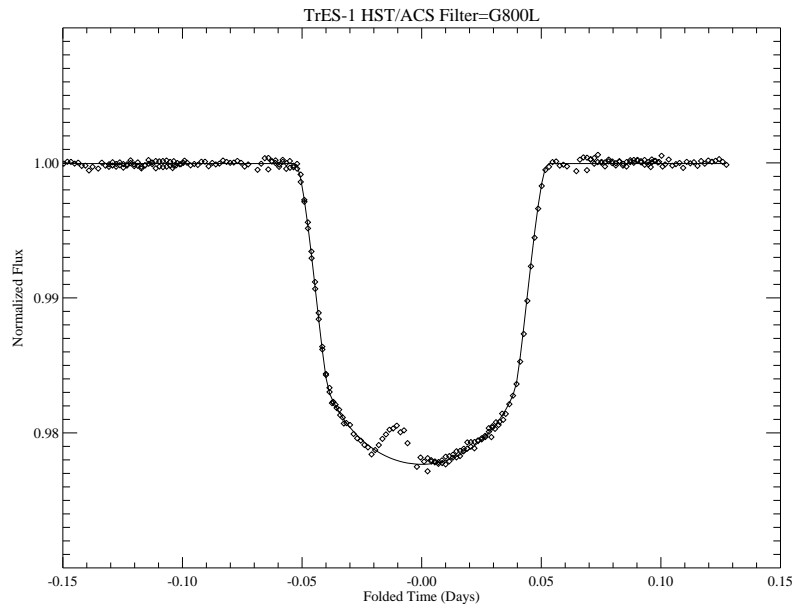
S/N ratio where other more subtle atmospheric and systematic effects will come into play. Everett and Howell (2001) report promising results for ground-based ensemble photometry. Similar airborne results await SOFIA. Ultimately the relative merits of precise SOFIA and ground-based photometry will have to be determined experimentally.

Observing Strategy

The primary requirement of our observing strategy is to control systematic and instrumental effects to the greatest degree possible in a manner that avoids saturation due to our bright targets. It is also essential to recognize that many systematic problems common to all-sky ground-based photometry do *not* have to be solved. The task is to measure the time variation due to the transit; no particular passband is required, no calibration to standard systems is needed, time variability on timescales other than that of the transit are not important, and if necessary the observation can be differential. This is essentially the same problem that was faced by the Kepler project, and guidance can be found from their laboratory test program (Koch, et al., 2000) in which one of us (EWD) was deeply involved.

The primary problem areas in the Kepler laboratory test activity were the dependence of the differential photometry on small position changes of the image on the CCD and temperature stability of the CCD controller. The latter problem was solved by regulating the temperature of the controller and the former problem was largely also related to thermal control. Various approaches were found to compensate for residual image motion resulting in differential photometric precision of a few tens of ppm in a period of a few hours. The HIPO CCD controllers are identical to the one used in the Kepler test setup, so a similar thermal control approach will probably be needed. Similarly a different CCD temperature control system may be needed. Image motion is a particular concern for the Kepler system because

a spaceborne image (or a laboratory test image) has very sharp features. The impact of image motion is likely to be less severe in the case of SOFIA observations due to the smooth, large airborne PSF that is dominated by scattering from high-speed density fluctuations in the turbulent shear layer (Elliot, et al., 1989). If necessary an image motion compensation system can be put in place to control the photometric effects of image motion.

Our initial observing approach will be to take high-speed imaging data using in-focus images. This approach gives us the greatest resilience in the event of significant image motion early in the SOFIA operating period. Observations can be made in one or two colors simultaneously using HIPO, or in three colors using the co-mounted HIPO-FLITECAM configuration. Nearby comparison stars will certainly be required. For bright objects like HD209458 we will likely need to move the telescope to nearby comparison stars on a fixed schedule. For fainter objects like TrES-1, on-chip comparison stars will be available. Saturation can be managed by using the high-speed imaging and subframing capabilities of HIPO.

An appealing alternative approach is to use a grism to record a time-resolved low resolution spectrum rather than in-focus images. This approach would generally require a field stop to isolate the target of interest. We found on the KAO that the broad wings of the airborne point spread function combined with image motion limited the photometric precision of our aperture photometer to about 0.3% even with a 4.5 arcminute aperture (Dunham and Elliot, 1983). In those days we had no capability to measure and correct for the effects of image motion, but HIPO allows this to be done. It may be that the time-resolved spectroscopy technique will turn out to be the best observing strategy given sufficient time to understand and optimize it.

Observations of the secondary minimum in the thermal infrared have the additional problem of selecting the optimum observing wavelength. The contrast between planet and star reaches a maximum, constant value once the wavelength is on the Rayleigh-Jeans tail of the emission. This occurs at approximately 8 microns and longer wavelengths. On the other hand, background emission is lower at shorter wavelengths. This tradeoff will require study and the optimum wavelength will likely vary from object to object.

▉ Special Requirements

Depending on the observing strategy ultimately selected, there could be several special requirements related to this work. Minor changes to HIPO, and possibly also to FLITECAM, might be required. These could include addition of a grism capability in HIPO and upgraded thermal control of the HIPO CCD and its control electronics. A more significant modification would be needed if an image motion compensation system is required.

For objects where continuous observation with the object on the meridian is both feasible and desirable, deployment to foreign locations may be necessary. HD209458 can be observed in this manner. A 5-6 hour observing leg would involve at least a deployment to the east coast of the US with possible refueling in Alaska before returning to Moffett. TrES-1 and most objects in the Kepler field cannot be observed in this way due to "midnight sun"

difficulties. A long observing leg is still possible during a winter flight across Canada with the object passing under the celestial pole. At least a refueling stop would be needed for return to Moffett.

■ Precursor/Supporting Observations

These observations rely on the discovery of new objects to observe. Additional useful work can be done with HD209458 and TrES-1, but it is only when a reasonably large sample of such objects is available that the full value of the observational program can be realized. These observations are ongoing in a number of areas, including ongoing radial velocity surveys, wide-field ground-based transit searches such as the work of the TrES collaboration that several of us are involved with, and the Kepler mission. All of these will progress independently of SOFIA.

High precision radial velocity data are also essential to define the mass of the planet. Most of the planetary parameters are actually determined as ratios to the corresponding stellar parameters, so the basic stellar astrophysics needed to define the mass, distance, radius, luminosity, etc. of the star require significant attention. A number of avenues are available to obtain the requisite data.

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