22 December 2005

NASA Center for Aerospace Information (CASI)
Attention: Accessioning Department
7121 Standard Drive
Hanover, Maryland 21076-1320

Subject: Annual Report No. 3

Reference: Cooperative Agreement NCC2-1390

Transmitted herewith is one (1) copy of the subject report for the period 1 December 2004 through 30 November 2005, in accordance with the provisions of the above referenced Cooperative Agreement.

Pursuant to the regulations applicable to the subject Cooperative Agreement, SAO hereby certifies that we have maintained a procedure for compliance with the Patent Rights/New Technology requirements and that there are no reportable inventions/disclosures.

Very truly yours,

Michael G. Griffith
Proposal & Awards Specialist

cm
Enclosure

cc: Barrie Caldwell, MS 241-1, NASA/Ames, w/encl.
Charles Sobeck, MS 244-12, NASA/Ames, w/encl.
Valarie Woodbury, ONR-Boston, w/encl.

bcc: C. Alcock, w/encl.
D. Fabricant, w/encl.
L. Feldman, w/encl.
D. Latham, w/encl.
File NCC2-1390, w/encl.

TARGET CHARACTERIZATION AND FOLLOW-UP

OBSERVATIONS IN SUPPORT OF THE KEPLER MISSION

NCC2-1390

Annual Report

No. 3
01 December 2004 to 30 November 2005

Principal Investigator

Dr. David W. Latham

December 2005

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

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TARGET CHARACTERIZATION AND FOLLOW-UP OBSERVATIONS IN SUPPORT OF THE KEPLER MISSION

This report covers work carried out at the Smithsonian Astrophysical Observatory during the period 1 December 2004 to 30 November 2005

SAO is leading the effort to prepare the Kepler Input Catalog, which will be used to select the targets actually observed for planetary transits by Kepler. In March 2004 a team led by SAO was selected to carry out a ground-based multi-band photometric survey of the Kepler target region and to use the new photometry along with other available information to estimate the astrophysical characteristics of candidate target stars for inclusion in the Kepler Input Catalog.

SAO is also active in making follow-up observations of transiting planet candidates identified by several ground-based photometric surveys. The goal is to learn how to identify stellar systems that mimic transiting planets, since this will be a major challenge for the interpretation of candidates identified by Kepler.

Kepler Input Catalog

A preliminary version of the Kepler Input Catalog was delivered to the Kepler Science Office in December 2004. It included all known stars in the Kepler field of view, based on existing catalogs such as the USNO-B1, for a total of more than 20 million stars. It also included more than 2 million stars with 2MASS infrared photometry, supplemented in many cases by new photometry from SAO's 48-inch telescope in the SDSS g, r, i, and z bands plus a custom intermediate band filter, D51, designed for luminosity sensitivity. For those stars with photometry in all the bands, the Kepler Input Catalog provided preliminary estimates of the astrophysical parameters.

Ground-Based Multi-band Photometric Survey

Production observing for the ground-based multi-band photometric survey began in May 2004, using the 4Shooter CCD camera on the 48-inch telescope at SAO's Whipple Observatory atop Mount Hopkins, Arizona. Altogether the 4Shooter was scheduled for 91 nights for this project. During the summer shutdown in August 2004 the MiniCam CCD camera, on loan from the MMT, was brought into operation on the 48-inch telescope as an interim replacement for the venerable 4Shooter. It was used for production observing during the fall 2004 and spring 2005 observing seasons. Altogether MiniCam was scheduled for 104 nights for this project. During the summer shutdown in August 2005, KeplerCam was brought into operation on the 48-inch telescope as a permanent facility instrument. It was used for production observing on all of the 47 nights assigned to this project in the fall of 2005. Time on the 48-inch telescope is under control of the CfA Time Allocation Committee, and has been provided at no cost to NASA.

In 2004 SAO undertook a project to build KeplerCam, a new state-of-the-art CCD camera for the 48-inch telescope at the Whipple Observatory. One of the advantages of KeplerCam is that it utilizes a single monolithic chip with four amplifiers, so there are no gaps in the images. In its normal mode of operation the read-out time for KeplerCam is 9 seconds. The quantum efficiency, cosmetic quality, charge transfer efficiency, and readout noise are all excellent.

KeplerCam was built by John Geary in his laboratory at SAO, with Dave Latham serving as the Principle Investigator, Andy Szentgyorgyi as the Project Scientist, and with the participation of Steve Amato, Kevin Bennett, and Brian McLeod. The operating software for KeplerCam was developed by Ted Groner at the Whipple Observatory, with Emilio Falco responsible for supervising the daily operations and preparing the local documentation, and Wayne Peters serving as the Instrument Specialist. The participation of Latham, Geary, Amato, Bennett, Groner, Falco, and Peters was contributed by SAO at no cost to NASA.

Two observers, Carl Hegenrother and Gil Esquerdo, carried out the actual photometric observations at the telescope. Detailed observing plans and schedules for each night were prepared by Dave Latham, who maintained a database of the target regions that had been successfully observed. Altogether 113 nights on the 48-inch telescope were scheduled for this project during the reporting period.

The reduction and analysis of the photometric observations and the preparation of the Kepler Input Catalog proceed as follows. The CCD images are processed by Mark Everett at the Planetary Sciences Institute in Tucson using a pipeline that he developed specifically for this purpose. David Monet at the United States Naval Observatory in Flagstaff, Arizona, made important contributions to the astrometric section of the pipeline.

The reduced data, in the form of instrumental magnitudes and positions, are shipped to Tim Brown in Boulder, Colorado, where the data are ingested into an archival database developed specifically for this purpose. Tim also developed codes for deriving nightly extinction coefficients from the observations of standard regions, and codes for removing the effects of atmospheric extinction.

After the instrumental magnitudes have been transformed onto the standard SDSS magnitude system, together with the 2MASS photometry they are used to estimate the Kepler magnitude, effective temperature, surface gravity, metallicity, reddening and extinction, and stellar mass and radius. The procedures and codes for this process were developed by Tim Brown.

The photometric results and astrophysical parameters are next shipped to David Monet in Flagstaff, where they are merged with existing information, such as astrometry from the UCAC and USNO-B Catalogs, to form the Kepler Input Catalog, for delivery to the Kepler Science Office on DVDs.

During the reporting period, procedures were implemented for evaluating the photometric performance of each night on which observations were obtained. At the telescope, the observers rely heavy on the movies from the GOES infrared satellite, http://www.atmo.arizona.edu/products/wximagery/azir.html, and from the MMTO SkyCam, http://skycam.mmto.arizona.edu, to monitor the conditions of the sky. In particular, the MMTO SkyCam movies are archived so that they are available for subsequent review as needed. Perhaps the most important tool for evaluating the photometric performance of a night is a website created for this purpose, http://kepler.hao.ucar.edu/cgi-bin/kepler_diag.cgi, that presents a variety of diagnostic plots.

Approximately one quarter of the scheduled nights proved to be fully photometric, while roughly half the nights proved to be unsuitable for all-sky photometry. There is promise that the observations obtained on the remaining quarter of the nights will prove to be useable, but a special effort to develop more sophisticated ways of handling the extinction corrections will be needed. This effort is underway.

By the end of June 2005, every one of the 1600 pointings in the Kepler field of view had been observed at least once, with almost half of these observations coming under photometric conditions. All of the observations up to the end of June 2005 include gaps between the CCD mosaics in the cameras used. For the fall 2005 observing season we gave highest priority to re-observations of pointings that were originally observed under non-photometric conditions. Our goal is to obtain at least two independent sets of observations under photometric conditions for every pointing, with additional observations as needed for those pointings that do not show adequate agreement. To achieve this coverage of the Kepler field of view we anticipate that observing will need to continue through the fall 2007 observing season. We believe that the SAO aspects of this additional observing can be accomplished at no additional cost to NASA.

Follow-Up Observations

SAO first began making spectroscopic follow-up observations of transiting planet candidates identified by ground-based photometric surveys in 1999. It soon became clear that the vast majority of the candidates were actually stellar systems masquerading as transiting planets. A common false positive is an F star primary eclipsed by an M dwarf companion. Triple systems that include an eclipsing binary diluted by the light of a brighter third star are also common, usually physically bound hierarchical triples, but also chance alignments. Although triple systems that include eclipsing binaries may be intrinsically rare, the photometric surveys are very efficient at finding them. Physical triples can be difficult to confirm, because the angular separations between the components are small, and the lines in the spectra of the eclipsing stars tend to be faint and broadened by rotation due to tidal synchronization.

Over the past six years the CfA Digital Speedometers have been used for follow-up observations of transiting planet candidates identified by wide-angle ground-based photometric transit surveys, including Vulcan, TrES, and HAT. More than 2000 spectra of nearly 350 candidates have been obtained. So far, only one of these has proven to be a transiting planet, TrES-1, although several targets have survived our initial spectroscopic scrutiny and now require high-quality light curves and very precise radial velocities to distinguish whether they are truly transiting planets. Twenty-six of these candidates are located in the Kepler field of view on the Kepler CCDs (Figure 2).

SAO's 48-inch telescope has proven to be effective at obtaining high-quality light curves of transiting planets and eclipsing binaries, especially with KeplerCam. Good examples of this work are light curves with better than millimag photometric precision for the transiting planet HD 149026 (Charbonneau et al. 2005) and for the recently discovered transiting planet HD 189733 (Bakos et al. in preparation). KeplerCam has also been used to obtain exquisite light curves for eclipsing binaries with F dwarf primaries and cool M dwarf secondaries. These light curves are essentially indistinguishable from the light curves of giant transiting planets (Beatty et al. in preparation). Figure 1 shows an example for an F/M eclipsing binary identified by the HAT team.

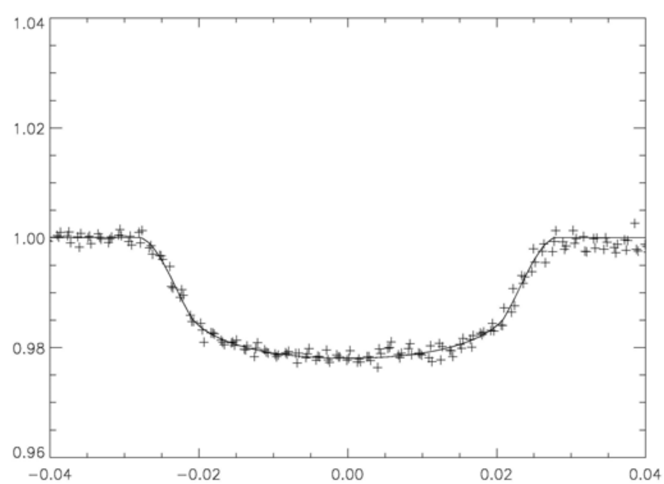

Figure 1. A light curve of an eclipsing binary consisting of an F star primary and a cool M dwarf secondary obtained with KeplerCam in the SDSS g band.

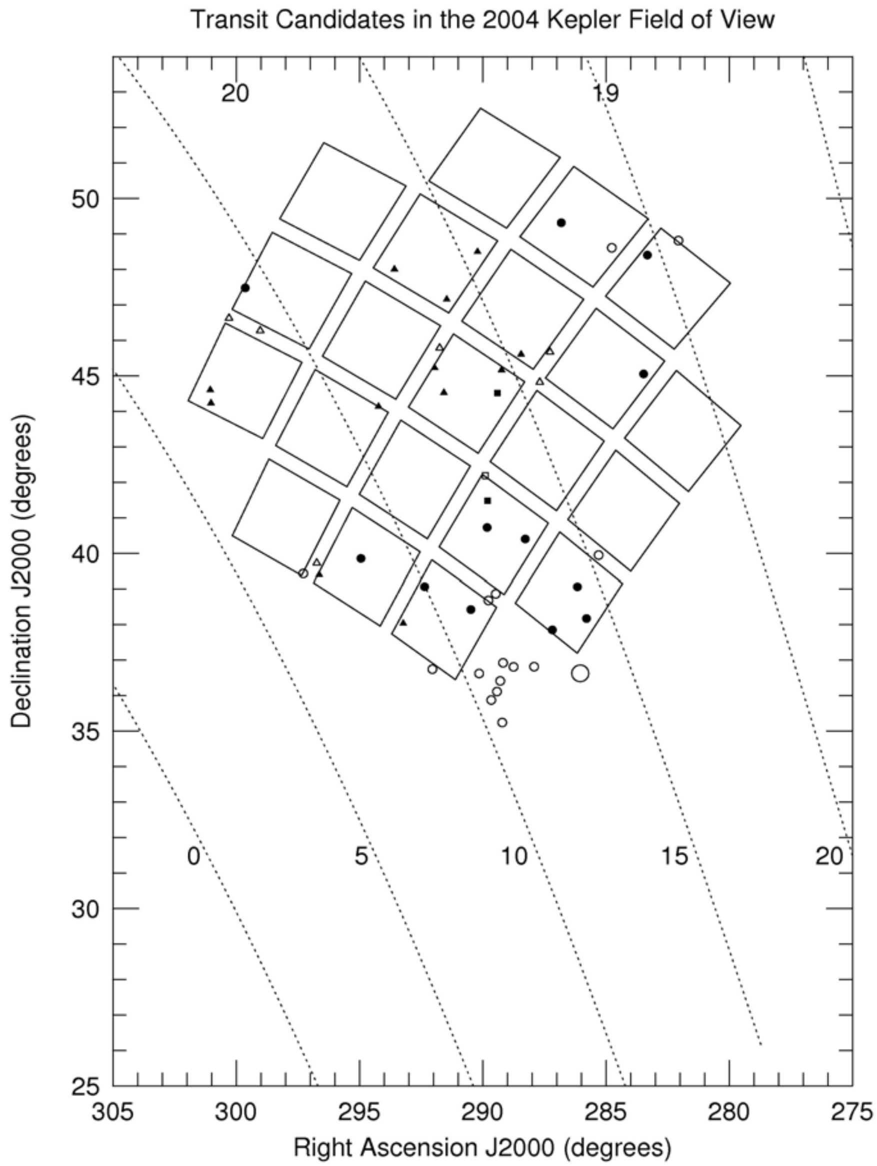

Figure 2. Transiting planet candidates in the Kepler field of view from Vulcan (triangles), TrES (circles), and HAT (squares). TrES-1 (large open circle) is just outside the field of view.

During the reporting period members of the SAO team were authors on thirteen papers (published or accepted) related to the Kepler mission, most of them reporting the results of follow-up observations of transiting planet candidates. These papers are listed in the attached bibliography. Ten of these papers are in refereed journals, seven in the Astrophysical Journal.

Spectroscopic Stellar Classification

SAO is responsible for high-resolution spectroscopic classification of many of the target candidates in the Kepler Input Catalog. The main instrument for this work will be Hectochelle, a new multi-fiber high-resolution CCD spectrograph on the MMT at the Whipple Observatory. We have also used the CfA Digital Speedometer on the 1.5-m Tillinghast Reflector at the Whipple Observatory for the classification of selected stars in the Kepler field of view.

The CfA Digital Speedometer on the Tillinghast Reflector has been in operation since 1979. It uses an intensified photon-counting Reticon detector to record 45 Å of spectrum centered at 5187 Å (including the luminosity-sensitive Mg b lines) with a resolution of 8.5 km/s. Observed spectra are correlated against an extensive library of synthetic spectra calculated by Jon Morse using Kurucz stellar models and a line list developed explicitly for this application. For solar-type stars this allows us to determine radial velocities with a typical accuracy of 0.5 km/s, projected rotational velocities with an accuracy of 2 km/s or 5% (whichever is larger), effective temperatures accurate to 125 K, surface gravities to about 0.5 in log(g), and metallicities good to about 0.2 dex if the effective temperature can be established independently using photometry. The CfA Digital Speedometers have been used to obtain more than a quarter of a million stellar spectra since 1979.

One of the goals of the Kepler mission is asteroseismology. At the request of Jurgen Christensen-Dalsgaard, leader of an asteroseismology team at Aarhus University, we undertook the characterization of 27 potential targets for their work in the Kepler field of view, all drawn from the Hipparcos Catalog. Assuming solar metallicity, we derived effective temperatures, surface gravities, and radial and rotational velocities for all these targets. Three of them proved to be spectroscopic binaries. For example, their candidate target HIP094335 proved to be double-lined. Our orbital solution derived using TODCOR is shown in Figure 3. It turns out that the Hipparcos data show that this target is an eclipsing binary.

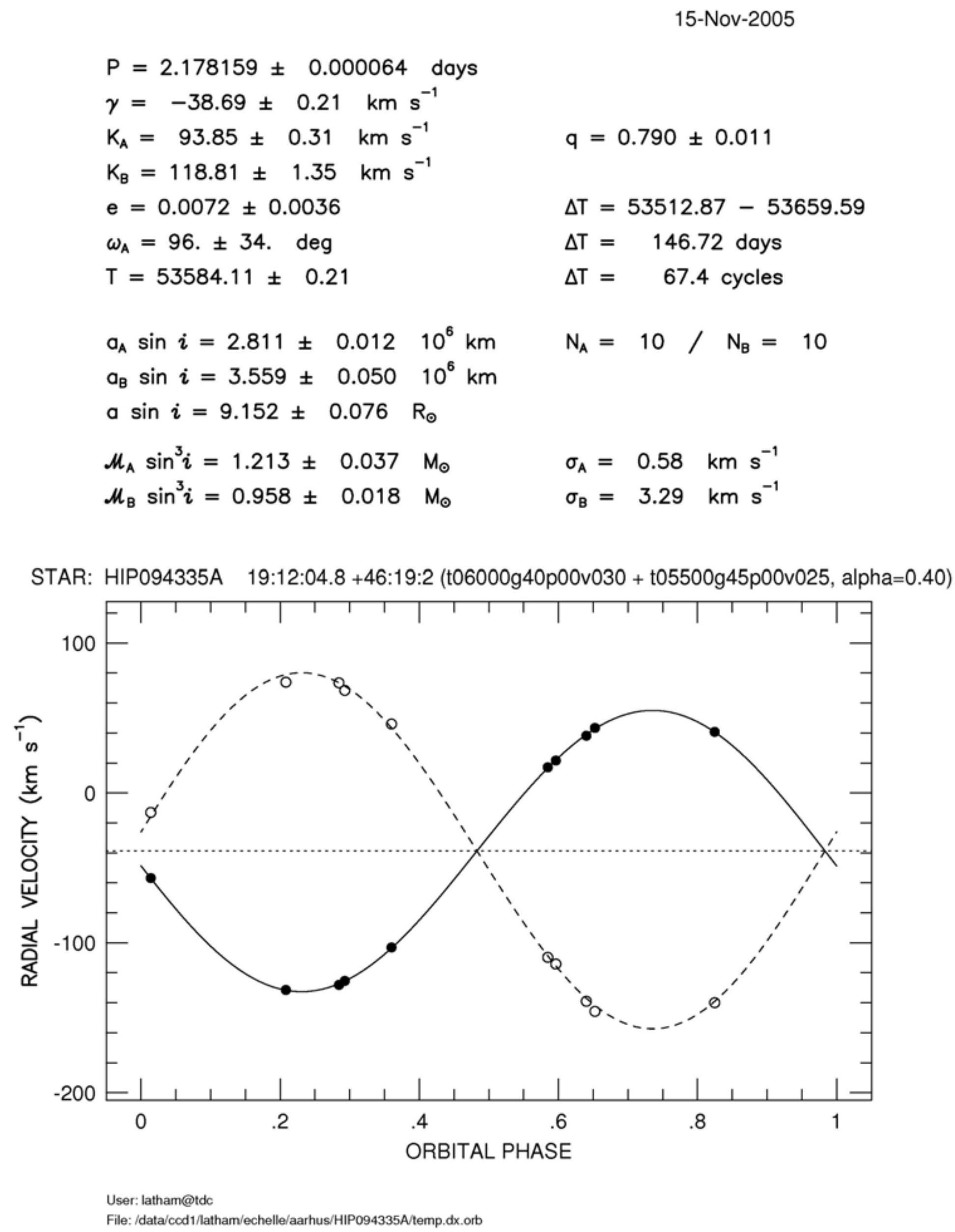

Figure 3. Double-lined spectroscopic orbit for HIP 94335, an asteroseismology candidate from Aarhus

The workhorse for spectroscopic classification of stars in the Kepler field of view will be Hectochelle on the MMT. This instrument is now operational and is being scheduled routinely for scientific observations. Our project for spectroscopic classification of Kepler candidate targets was assigned time on Hectochelle in March, May, October, and November. Altogether more than 2000 stellar spectra were obtained. Preliminary reductions of some of these spectra look very promising. We are now working on the development of a data reduction pipeline for Hectochelle spectra. Our new postdoc, Søren Meibom, is playing a leading role in this effort, with contributions from Gabor Furesz, Andy Szentgyorgyi, Dave Latham, and members of the Telescope Data Center, primarily Doug Mink and Susan Tokarz.

During the reporting period we made significant progress on the preparation of a new library of synthetic spectra for the analysis of Hectochelle. Jon Morse (Arizona State University, now at the Goddard Space Flight Center) led the effort to fine-tune the line list for a 300 Å window covering the wavelength window of the RV31 order of Hectochelle. John Laird (Bowling Green State University) calculated an initial library of 52,000 synthetic spectra, in two different versions. One is at the full resolution of 500,000, while the second is matched to the instrumental profile of Hectochelle, nominally 8.2 km/s. Numerical simulations with the new library of synthetic spectra suggest that Hectochelle should be able to determine surface gravities for stars on the main sequence and the subgiant branch to an accuracy of ±0.2 dex, and metallicities to ±0.15 dex in [Fe/H]. Bruce Carney (University of North Carolina) has also contributed to this effort. Experimental use of the new library is now underway. The participation of Morse, Laird, and Carney was supported by NSF and institutional resources, at no cost to NASA.

A detailed analysis of the initial follow-up observations of transiting planet candidates from the Kepler mission needed to sort out false positives led to the conclusion that lots of telescope time would be needed for radial velocity observations with moderate precision, typically in the range 300 to 1500 m/s. This same conclusion was reached independently by Nick Gautier and others working on the Follow-up Observation Plan. The venerable CfA Digital Speedometers, which have been in operation since the late 1970s, provide the required level of spectroscopic performance, but are limited to stars brighter than about 13th magnitude because of the limited sensitivity of the photocathodes used in the detectors.

Anticipating the need of a new state-of-the-art CCD spectrograph for follow-up of large numbers of candidates identified by Kepler, in 2004 we submitted an internal proposal for SAO funds to build the Tillinghast Reflector Echelle Spectrograph (TRES). This proposal was funded (almost 900K), and the instrument is now being built with Andy Szentgyorgyi as Project Scientist and with important contributions from Gabor Furesz. It is scheduled to come into operation by the time Kepler launches. We expect that it will be a workhorse for follow-up spectroscopy of transiting planet candidates.

We are convinced that TRES will be much more important to the success of the Kepler mission than the cross-dispersed mode of Hectochelle would have been. Thus we have redirected some of our Kepler resources from the cross-dispersed mode into the TRES development.

Programmatics

Latham and Geary attended the Kepler Science Team meetings in May and November. Latham organized a meeting of the Stellar Classification Program team in Boulder in February. Latham also participated in the Ground Segment Monthly Management Reviews via telephone, providing review charts of the progress with the Stellar Classification Program in advance for presentation at all of these meetings. Latham's Kepler funds were used to support travel by John Geary so he could participate in various review meetings for the project.

Latham attended meetings of the American Astronomical Society in January and May, the Winter Astrophysics Workshop in Aspen later that month, the May Symposium on extrasolar planets at the Space Telescope Science Institute, the international workshop on extrasolar planets to celebrate the tenth anniversary of 51 Peg in Provence in August, and Protostars and Planets V in Hawaii in October. At all these meetings he represented Kepler one way or another.

Education and Public Outreach

Latham supervised the junior thesis of Harvard undergraduate Thomas Beatty, and the senior thesis of Lucas Laursen, both on topics related to Kepler. Latham presented a public colloquium on "Kepler and the Search for Habitable Planets" at Canterbury University in March.

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