29 October 2007

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

Subject: Annual Report No. 5

Reference: Cooperative Agreement NCC2-1390

Transmitted herewith is one (1) copy of the subject report for the period 1 December 2006 through 30 November 2007, in accordance with the provisions of the above referenced Cooperative Agreement.

Pursuant to the regulations applicable to the subject grant, 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 Griffith
Contract and Grant Specialist

MG/rs
Enclosure

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TARGET CHARACTERIZATION AND FOLLOW-UP

OBSERVATIONS IN SUPPORT OF THE KEPLER MISSION

NCC2-1390

Annual Report

No. 5
01 December 2006 to 30 November 2007

Principal Investigator

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October 2007

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

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

This report covers the period 1 December 2006 to 30 November 2007

The Smithsonian Astrophysical Observatory (SAO) is leading the effort to prepare the Kepler Input Catalog (KIC), 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 responsible for obtaining and analyzing spectroscopic observations of many of the most promising candidate targets using HECTOCHELLE on the MMT in order to provide improved astrophysical characteristics for these stars in the KIC.

SAO is also active in making follow-up observations of transiting planet candidates identified by several ground-based photometric surveys. One 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. A second goal is to learn how to analyze and interpret the characteristics of confirmed planets in preparation for the analysis and interpretation of transiting planets found by Kepler

After the launch of Kepler, SAO will take a leading role in obtaining follow-up observations of transiting-planet candidates identified by Kepler and will participate in the scientific interpretation and publication of results.

Kepler Input Catalog

An interim version of the Kepler Input Catalog (KIC) was delivered to the Kepler Science Office in December 2006. It included all known stars in the Kepler field of view, based on existing catalogs such as the USNO-B, for a total of more than 20 million stars. It also included more than 2 million stars with 2MASS infrared photometry, supplemented in most 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 complete photometry, the KIC provided estimates of the astrophysical parameters, including the stellar radius.

Ground-Based Multi-band Photometric Survey

Production observing for the ground-based multi-band photometric survey for the KIC 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, a new state-of-the-art CCD camera, KeplerCam, was brought into operation on the 48-inch telescope as a permanent facility instrument. It is now the only instrument used with the 48-inch telescope and thus remains mounted on the telescope full time. Altogether KeplerCam has been scheduled for 315 nights for KIC and related photometry, including 138 nights during 2007. Time on the 48-inch telescope is under control of the CfA Time Allocation Committee, and has been provided at no cost to NASA.

KeplerCam utilizes a single monolithic Fairchild 486 4K x 4K CCD with four amplifiers, so there are no gaps in the images. In its normal mode of operation the read-out time for KeplerCam is 11 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.

During the reporting period, the actual photometric observations at the telescope were carried out by a professional observer, Gil Esquerdo, who was hired and trained for this work in support of the Kepler mission. In addition, some of the observing was carried out by Jose Fernandez, an SAO Predoctoral Fellow. Detailed observing plans and schedules for each night were prepared by Dave Latham, who maintained a database documenting the history of KeplerCam pointings that had been observed.

The reduction and analysis of the photometric observations and the preparation of the KIC proceed as follows. The CCD images are processed by Mark Everett at the Planetary Science 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, now at the Las Cumbres Observatory in Goleta, California, where the data are ingested into an archival database developed specifically for this purpose. Tim has 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 a system closely related to 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 have been 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 a web page was maintained by Tim Brown for monitoring the photometric performance of each night on which observations were obtained for the KIC, http://www.lcogt.net/cgi-bin/kepler_diag.cgi. At the telescope, the observers rely heavy on the movies from the GOES infrared satellite, available from the University of Arizona at http://www.atmo.arizona.edu/products/wximagery/azir.html, and on images from the MMTO SkyCam, http://skycam.mmto.arizona.edu**,** to monitor the conditions of the sky. In particular, movies from the MMTO SkyCam images are archived so that they are available for subsequent review as needed. A new web page documenting the role of SAO in support of the Kepler mission was built at http://www.cfa.harvard.edu/kepler/.

Approximately one quarter of the scheduled nights have proven to be fully photometric, while roughly half the nights have proven to be unsuitable for all-sky photometry. Our observing strategy now calls for a visit to a secondary standard region in the Kepler field of view every half hour, to monitor the atmospheric extinction. This observing protocol has been in use since fall 2005.

By the end of the reporting period, every one of the 1600 pointings in the Kepler field of view had been observed at least once, and nearly all had been observed twice. In scheduling re-observations, special attention has been given to pointings that had only one observation under photometric conditions.

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 seven 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, HAT, XO, KELT, and WASP. More than 4000 spectra of more than 600 candidates have been obtained. So far, ten of these candidates have been confirmed as transiting planets (TrES-1, through -4, and HAT-P-1b through -6b). Papers have been published or submitted for all these confirmed transiting planets. Several more have been confirmed by follow-up observations, but the papers have not yet been submitted. More than a dozen additional candidates have survive the initial spectroscopic reconnaissance and now require very precise radial velocities and high-quality light curves to confirm whether they are planets.

KeplerCam on SAO's 48-inch telescope has proven to be effective at obtaining high-quality light curves of transiting planets and eclipsing binaries. In 15 cases (HD 149026, HD 189733, XO-1, WASP-1, WASP-2, TrES-2, TrES-3, TrES-4, TrES-4, HAT-P-1b, Hat-P-2b, HAT-P-3b, HAT-P-4b, HAT-P-5b, and HAT-P-6b) KeplerCam has been used to obtain high-quality light curves leading to the publication of much improved radius determinations for these planets.

The confirmed transiting planet TrES-2 is located in the Kepler field of view and falls on a Kepler CCD. We have obtained half a dozen additional high-quality light curves of TrES-2 with KeplerCam in order to establish a long time base for transit timings. When combined with the hundreds of transit timings that will be observed by Kepler, this will provide an unusual opportunity to search for additional planets in the system by means of timing variations.

Members of the SAO team were authors on 11 papers related to the Kepler mission that were published in major refereed journals (almost all in the Astrophysical Journal) during the reporting period, in every case with an acknowledgement to the Kepler mission for support. In addition, members of the SAO team were authors on 15 papers related to Kepler and appearing in conference proceedings or presented at scientific meetings during the reporting period.

Spectroscopic Stellar Classification

SAO is responsible for high-resolution spectroscopic classification of a significant number of target candidates in the Kepler Input Catalog. The main instrument for this work is HECTOCHELLE, a 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, including candidates for asteroseismic observations with Kepler.

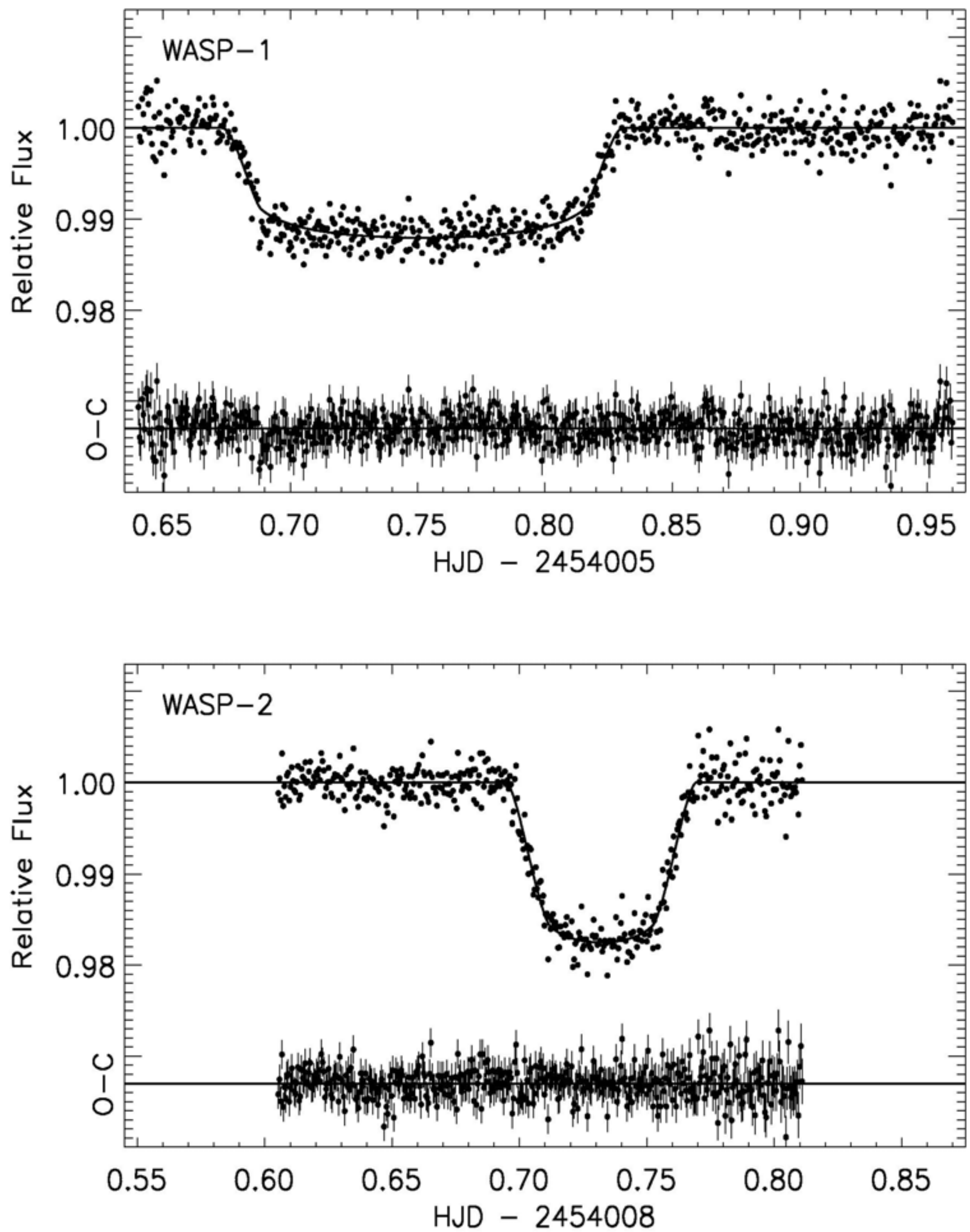

Fig. 1.— Relative z band photometry of WASP-1 and WASP-2. The best-fitting model is shown as a solid line. The residuals (observed − calculated) and the rescaled 1 σ error bars are also shown. The residuals have zero mean but are offset for clarity by a constant flux so as to appear beneath each light curve. For both time series, the median time between exposures is 42 s, and the RMS residual is 0.17%. The span of the axes is the same in both plots, permitting a visual comparison of both events. The WASP-1b transit is significantly longer and less deep, as it corresponds to an equatorial transit of a larger star than that of WASP-2b, which transits a smaller star at a greater impact parameter.

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 1 km/s, 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.

The spectral coverage in order RV31 with HECTOCHELLE is 150 Å, much wider than the 45 Å window of the CfA Digital Speedometers. Therefore we are building a new library of synthetic spectra optimized for HECTOCHELLE. Jon Morse (now Chief of the Astrophysics Division in the Science Mission Directorate at NASA Headquarters) has led the effort to fine-tune the line list for 300 Å covering the HECTOCHELLE RV31 wavelength window. John Laird (Bowling Green State University) has 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 has been convolved with the instrumental profile of HECTOCHELLE, nominally 8.2 km/s. Ultimately we expect the library to contain more than a million calculated spectra, which we will make available to the community at full resolution so that they can be adapted for use with any spectrograph. Bruce Carney (University of North Carolina) has also contributed to this effort. The participation of Morse, Laird, and Carney in this project has been support by the NSF and by their home institutions, at no cost to NASA.

Numerical simulations with the new library of synthetic spectra suggest that we should be able to use HECTOCHELLE spectra to determine surface gravities for stars on the main sequence and the subgiant branch to an accuracy better than ±0.2 dex, and metallicities to ±0.15 dex in [Fe/H] and ±0.25 in [alpha/Fe]. The reduction and analysis of the spectra of more than 200 stars in the Kepler field observed on five consecutive nights in May 2007 has demonstrated that the precision is at least this good. In addition, the systematic floor error in the radial velocities for this same set of spectra is less than 100 m/s with our present reduction pipeline, which is still being developed. Sky subtraction has not yet been implemented, but the development of this capability is underway with support from another project.

To test our ability to classify stellar spectra with HECTOCHELLE, we obtained multiple exposures of the old open cluster M67, which has an age and metallicity similar to the sun and has been very well studied by a wide variety of techniques. Figure 2 shows a comparison of the effective temperatures and surface gravities that we derived

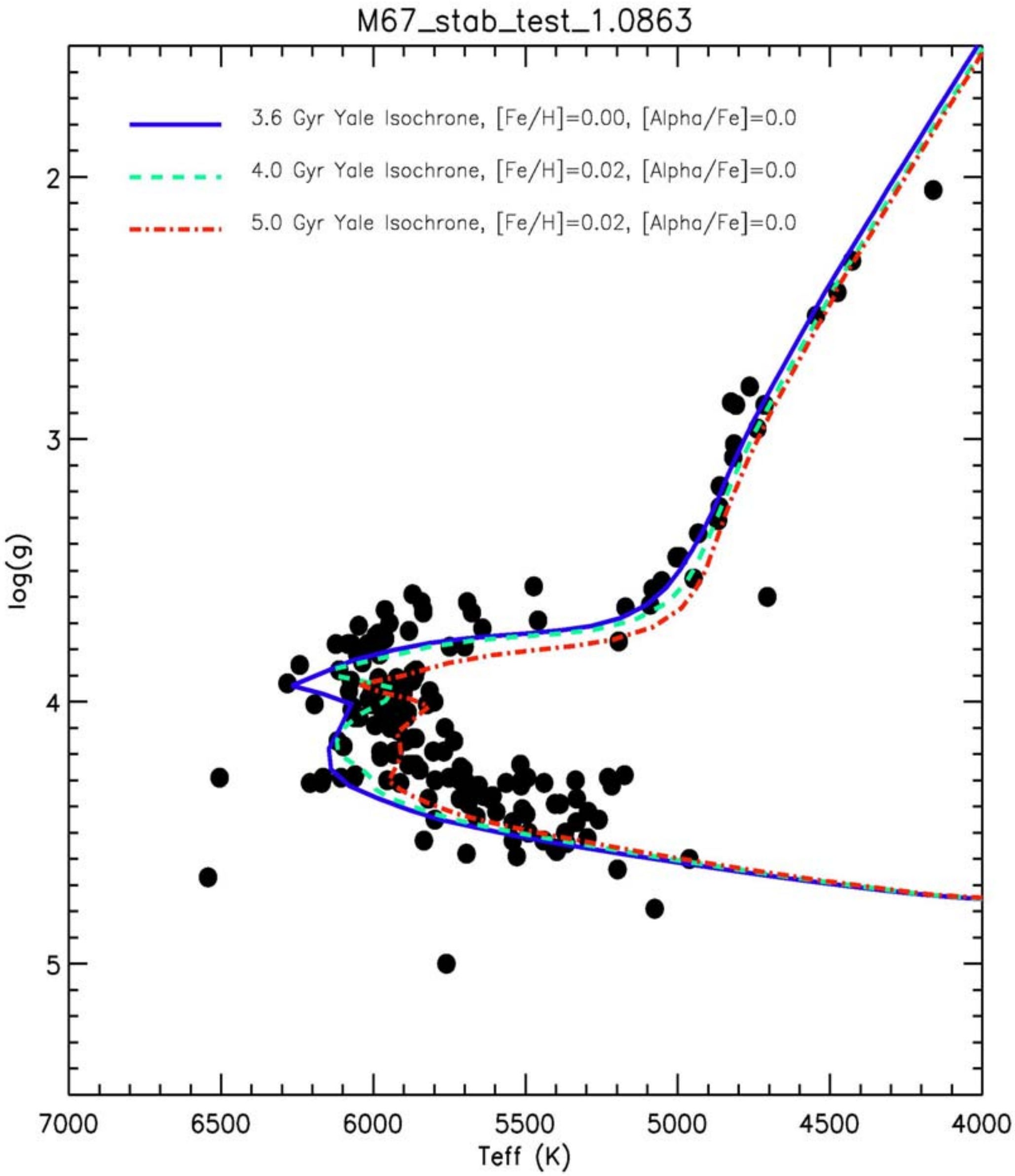

Fig. 2. The effective temperatures and surface gravities for 198 members of the old open cluster M67 derived from Hectochelle spectra using our new library of synthetic spectra. Independent comparisons of our spectroscopic temperatures against photometric temperatures from the work of Sandquist (2004) show that our temperatures are good to better than 100 K. Also plotted are isochrones from the Yale models. The canonical age for M67 is 4 Gyr, and the fit for that isochrone is very good.

from HECTOCHELLE spectra of 198 members of M67 compared to theoretical isochrones for the cluster. The agreement is very good.

During the reporting period we obtained HECTOCHELLE spectra of nearly 6000 stars in the Kepler field of view. The targets were all chosen from the interim version of the KIC to be good planet-search targets for the Kepler mission. These spectra have all been reduced and analyzed. We developed and applied new procedures for deriving the astrophysical characteristics of stars from HECTOCHELLE spectra. We now set the effective temperature to the value derived from photometry in the most recent version of the KIC. This allows us to derive metallicities, as well as surface gravities, projected rotational velocities, and radial velocities. The new procedures have been applied to all the HECTOCHELLE spectra obtained for targets in the Kepler field of view, more than 8000 spectra.

A detailed analysis of the initial follow-up observations of transiting planet candidates from the Kepler mission needed to sort out false positives led us 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 (more than 900K), and the instrument has now been brought into operation. The first commissioning run was completed successfully in September 2007. TRES is 2 to 3 magnitudes more sensitive than the CfA Digital Speedometer, as expected. It is thus well suited for follow-up spectroscopy of transiting-planet candidates identified by Kepler. The design and construction of TRES was directed by Andy Szentgyorgyi as Project Scientist, with important contributions from SAO Predoctoral Fellow Gabor Furesz. The project engineer was Mark Ordway. John Geary's CCD lab built the detector system. We are planning to use TRES as the workhorse for follow-up spectroscopy of transiting planet candidates identified by Kepler and other surveys.

Anticipating the need for very accurate radial velocities to follow up the most interesting planet candidates identified by Kepler, in 2005 we proposed to build a new spectrograph capable of measuring radial velocities with a precision better than 1 m/s. In May 2006 this project was formally approved as part of the new Harvard University Origins of Life Initiative. We have established a collaboration with the Geneva Observatory to build HARPS-NEF (NEF=New Earths Facility), an improved copy of the HARPS spectrograph on the ESO 3.6-m telescope on La Silla that has already demonstrated the capability to measure stellar radial velocities at the level of 20 cm/s. Work on a laser comb for wavelength calibration has made excellent progress during the reporting period. If successful, this would enable a significant improvement in the velocity precision achieved with HARPS-NEF. We have chosen the 4.2-m William Herschel telescope on La Palma as the site for HARPS-NEF. Our plan is to dedicate on the order of 50 nights of telescope time per year for follow-up spectroscopy of transiting planets identified by Kepler. This project is being funded by Harvard University and SAO at no cost to NASA.

Programmatics

Latham and attended the Kepler Science Team meetings in April and November. Latham also participated in the Ground Segment Monthly Management Reviews via telephone, providing charts of the progress with the Stellar Classification Program for presentation at all of these meetings. Latham participated in the Follow Up Working Group meeting in July. Latham's Kepler funds were used to support travel by John Geary so he could participate in various review meetings for the project. The SCP team held meetings via telecons.

Latham attended meetings of the American Astronomical Society in January in Seattle and in May in Honolulu. He also participated in Nobel Symposium 135. "The Physics of Planetary Systems" in Stockholm in June (expenses paid by the Nobel Foundation), an international conference on "Extreme Solar Systems" in Santorini also in June, Bioastronomy 2007 "Molecules, Microbes, and Extraterrestrial Life" in Puerto Rico in July, and the Michelson Summer School on "Transiting Planets" at NASA Ames in July. At all these meetings he presented papers involving Kepler, and represented Kepler one way or another.

Education and Public Outreach

Latham represented Kepler on the committee to review the NASA Astrobiology Institute, organized by the National Research Council for the National Academy of Sciences, and was an active participant in the preparation of the committee report. Latham made an hour-long presentation on Kepler and related science to the committee. Latham made a presentation to the Graduate Research Forum of the Astronomy Department at Harvard University, trolling for new graduate students to get involved in research related to Kepler.

In December 2006 the NSF-NASA-DOE Astronomy and Astrophysics Advisory Committee (AAAC) established an ExoPlanet Task Force (ExoPTF) as a subcommittee to advise NSF and NASA on the future of the ground-based and space-based search for and study of exo-planets, planetary systems, Earth-like planets and habitable environments around other stars. Latham was invited to make a presentation on Kepler to the ExoPTF, and did so in April.

Publications

Eleven papers with authors from the SAO team and specifically acknowledging the Kepler mission were actually published in major refereed journals during the period 1 December 2006 through 24 October 2007. This included an invited review paper in Science. An additional five papers were submitted during the same period. We expect that one or more of these may actually be published before the end of the reporting period.

Holman, M. J., Winn, J. N., Latham, D. W., O'Donovan, F. T., Charbonneau, D., Bakos, G. Á., Esquerdo, G. A., Hergenrother, C., Everett, M. E., & Pál, A. The Transit Light Curve Project. I. Four Consecutive Transits of the Exoplanet XO-1b. ApJ, 652, 1715 (12/2006)

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Torres, G., Bakos, G. Á., Kovács, G., Latham, D. W., Fernández, J. M., Noyes, R. W., Esquerdo, G. A., Sozzetti, A., Fischer, D. A., Butler, R. P., and 6 coauthors. HAT-P-3b: A Heavy-Element-rich Planet Transiting a K Dwarf Star. ApJ, 666, L121 (9/2007)

Winn, J. N., Holman, M. J., Bakos, G. A., Pal, A., Johnson, J. A., Williams, P. K. G., Shporer, A., Mazeh, T., Fernandez, J., Latham, D. W., Gillon, M. The transit light curve project. VII. The not-so-bloated exoplanet HAT-P-1b. AJ, 134, 1707 (10/2007)

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Members of the SAO team also appeared as authors on 15 papers related to Kepler that appeared in conference proceedings or were presented at meetings or conferences during the reporting period. These papers can be identified using the ADS.