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PRECISION RADIAL VELOCITIES FOR THE *KEPLER* ERA

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RESUMEN

La misión *Kepler* realizará la fotometría de 100,000 enanas hasta la magnitud ~ 14 en búsqueda de exoplanetas del tamaño terrestre en un campo del norte de 107 grados cuadrados. Esta búsqueda requiere de fotometría masiva y reconocimiento espectroscópico para poder así identificar las enanas de entre un millon de estrellas en el campo y post facto poder desenmascarar a las binarias impostoras que asemejan a los tránsitos de exoplanetas del tamaño terrestre. En este artículo discutimos diversos instrumentos nuevos que ha puesto en operación o está construyendo el Smithsonian Astrophysical Observatory (SAO) y que son piedras angulares en esta búsqueda espectroscópica: el Hectochelle y el TRES.

ABSTRACT

The *Kepler* Mission will provide photometry for 100,000 dwarfs to m $\sim$ 14 in search of terrestrial-sized exoplanets in a northern field 107 degrees square. This search requires massive photometric and spectroscopic reconnaissance both to identify the dwarfs from the millions of stars in the field and post facto to weed out impostor binaries and blends that mimic transiting earth-size exoplanets. In this paper we discuss several new instruments that the Smithsonian Astrophysical Observatory has recently commissioned or is building that are cornerstones of this spectroscopic follow-up: the Hectochelle and TRES.

Key Words: **INSTRUMENTATION: SPECTROGRAPHS — TECHNIQUES: RADIAL VELOCITY — STARS: PLANETARY SYSTEMS: PROTOPLANETARY DISKS**

1. INTRODUCTION

There are now four proven methods for detecting exoplanets — precise radial velocity (PRV) measurements (Mayor & Queloz 1995), precise photometric detection of planetary transit events (Charbonneau et al. 2000), micro-lensing (Bond et al. 2004), and pulsar timing (Wolszczan & Frail 1992). While the landscape may change as each technique matures, at present PRV has produced the vast majority of exoplanet detections. A future issue for exoplanet research is that as the transit technique is refined, it becomes apparent that massive photometric surveys require similarly massive PRV spectroscopic reconnaissance to weed out impostor exoplanet systems (Latham 2003; Mandushev et al. 2005). A particularly ambitious NASA program, the *Kepler* mission (Basri, Borucki, & Koch 2005), has as its primary goal the detection of rocky, earth-sized exoplanets by photometric methods. The Harvard-Smithsonian Center for Astrophysics (CfA) has built and is building several instruments that will form the core of this reconnaissance, as well as the photometry to produce the *Kepler* Input Catalog. This catalog will be used to select the 100,000 stars for photometry by *Kepler* among the 12,000,000 possible stars in the *Kepler* field.

In this paper we describe two of the spectroscopic instruments that will be used for reconnaissance of the *Kepler* field. These are the Hectochelle, a multi-object spectrograph operated at the 6.5-m Multiple Mirror Telescope (MMT) which collects hundreds of spectra simultaneously in a single diffractive order, and the Tillinghast Reflector Echelle Spectrograph (TRES), which is a fully cross-dispersed echelle spectrograph to be operated at the F.L. Whipple Observatory 1.6-m telescope.

2. HECTOCHELLE

The Hectochelle is a fiber-fed, bench mounted echelle spectrograph that operates at the post-conversion MMT. The MMT is a 6.5-m Cassegrain telescope and the Hectochelle is designed to operate with the MMT in its f/5, wide-field mode. In this mode, a triplet wide-field corrector and atmospheric dispersion compensator (Fabricant et al. 2004) delivers a 1° field of view between zenith and two air masses (60°). The robot positioner and fiber system can be operated both with Hectochelle (Szentgyorgyi et al. 1998) and Hectospec (Fabricant et al. 2005), a moderate-dispersion spectrograph designed primarily for galactic red-shift surveys and studies of

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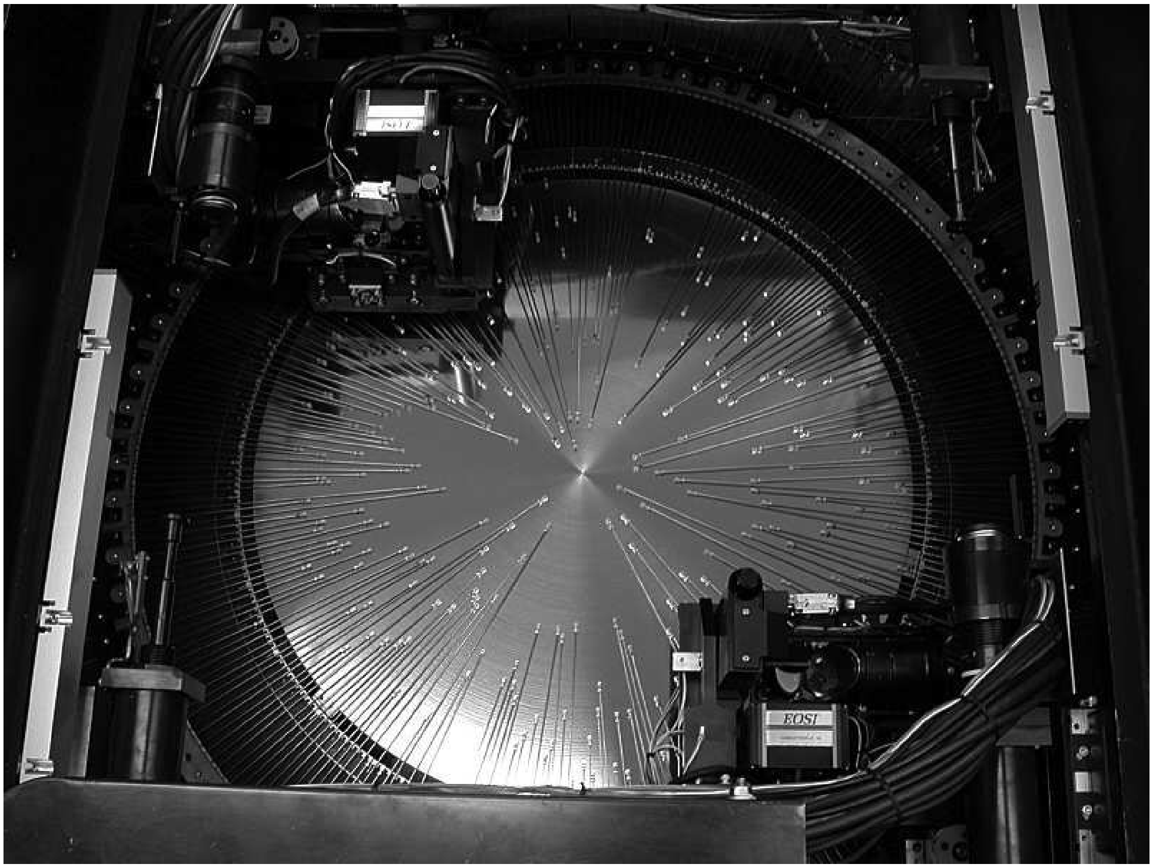

Fig. 1. The focal plane of the robot positioner used by Hectochelle and Hectospec. The two five-axis robots (x,y,z,θ, and ϕ) are at the upper left and and lower right hand corners of the figure. The optical fiber buttons have been arranged in a test configuration on the circular focal plane.

large-scale structure. The robot positioner places all 300 fiber buttons in five minutes with an accuracy of 25 μm or better. The focal plane and the two robot positioners are shown in Figure 1. The 24 inch diameter focal plane (1° on the sky) is hyperbolic, so the positioner must tilt to the local surface normal to pick and place the fiber buttons. The fiber buttons are held to the focal surface magnetically, and each fiber button contains a turning prism to direct the vertical telescope beam into the horizontally aligned optical fibers. The fiber core diameter is 250 μm, or 1.5″ at the MMT f/5 plate scale.

The optical design of the Hectochelle, by Harland Epps, is shown in Figure 2. Both the slit and the camera are internal to the beam, which introduces only slight vignetting when proper attention is paid to the cross section of the obscuring members. All surfaces are spherical. Hectochelle is a single-order instrument, where a single diffractive order is isolated with selectable order-sorting filters. The width of each order is approximately 150Å. The resolution of the Hectochelle is ∼34,000 and the efficiency is peak 5-6%, depending on which diffractive order it is operating in.

Because the Hectochelle and Hectospec both use the same fiber feed, but have different magnifications, only 240 fiber images fall on the Hectochelle focal plane format, while Hectospec exploits all 300 available fibers. The order-sorting filter changer inserts filters with a cam follower immediately in front of the pseudo-slit. Eleven filters are currently available for Hectochelle observations, covering diffractive orders with astrophysically interesting spectral features (Hα, [O III], Ca H and K, etc.).

The collimator is a spherical mirror with a Lawrence Livermore durable multi-layer coating on a Zerodur substrate. The diffraction grating system consists of a pair of 300 mm × 400 mm Richardson Grating Laboratory aluminum coated reflection grating ruled at 110 lpm and blazed for R2 (64.5°).

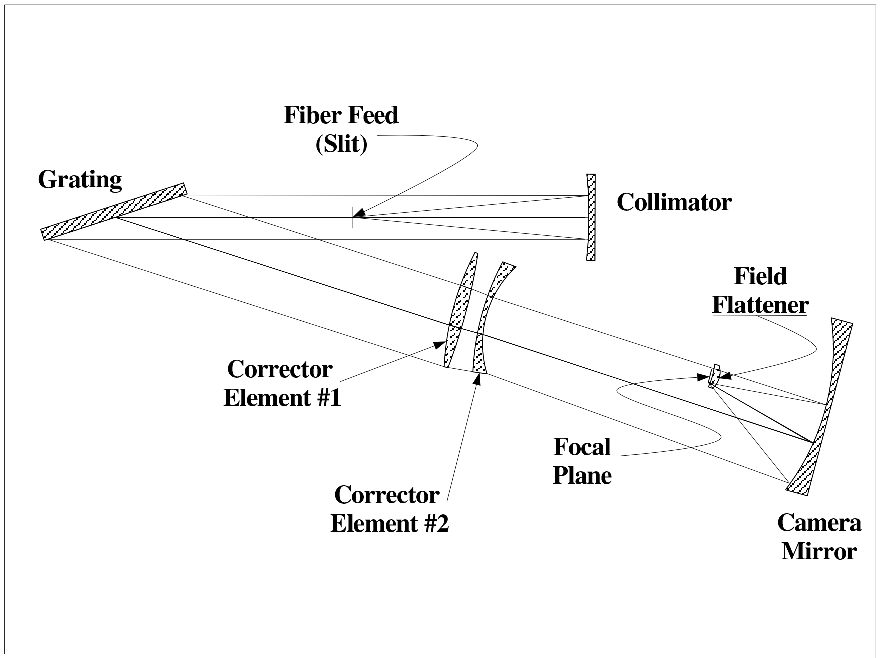

Fig. 2. The optical layout of the Hectochelle spectrograph. The order separating filters are placed just in front of the fiber feed. The iodine cell is also placed here when it is deployed.

The gratings are co-registered on a precision bonded Zerodur metering structure which matches the coefficient of thermal expansion of the Zerodur grating substrates. The angle between the incident and diffracted beams is 15°.

The Hectochelle employs a spherical doublet refractive corrector made of fused silica and antireflection coated with Sol Gel to maximize throughput. The camera mirror is a 43 inch diameter Zerodur sphere that is f/0.6 and coated with enhanced aluminum by the Flabeg Corporation.

The field flattener, an all spherical fused silica lens, also serves as a vacuum window for the cryostat. The focal plane is cooled with liquid nitrogen and the CCDs themselves are a pair of E2V 2K × 4.5K devices with 13.5 μm pixels. The readout system is an extremely flexible, high-speed architecture developed at the Smithsonian Astrophysical Observatory and now in use for virtually all its new ground-based optical and infrared instrumentation.

The Hectochelle can be operated in a PRV mode when a iodine vapor system is installed in the instrument. At present this feature of Hectochelle is under development; it is expected to provide a radial velocity precision of 30–50 m s^{-1}.

3. TRES

TRES is a fully cross-dispersed, fiber-fed echelle spectrograph that will be operated at the Mt. Hopkins 1.6-m telescope. The geometry of TRES is quasi-Littrow, so there is no anamorphism. TRES can be operated at one of three resolutions — 20,000, 30,000, and 38,000 — by changing the selected optical fibers in the optical train of the spectrograph, with diameters of 80 μm, 100 μm, & 150 μm. These fibers subtend 1.8″, 2.3″ and 3.4″ on the sky, respectively. The usable passband will be 380–890 nm, extending roughly from Ca H and K to the Ca IR triplet. Overall throughput for the spectrograph is estimated to be slightly better than 20%.

The TRES spectrograph consists of three major components:

- **A "front end"** that mounts at the Cassegrain focus of the 1.6-m telescope.
- **A bench-mounted spectrograph** that is the core of TRES
- **A fiber handling system** that runs the fiber from the front end to the spectrograph.

The front end design is shown in Figure 3. The telescope beam is folded through 90° by a piezoelectric tip-tilt system to the fiber ends. The tip-tilt system runs at 10 Hz, and corrects for guiding errors of

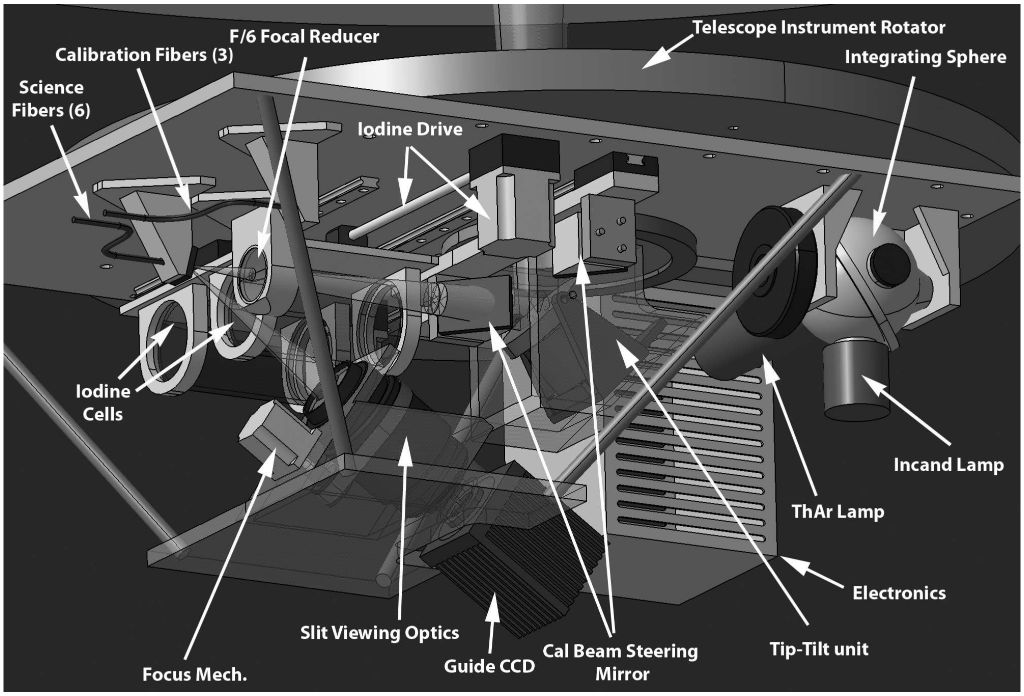

Fig. 3. The TRES Front End as mounted at Cassegrain focus of the 1.6-m telescope. In this orientation, the primary mirror is above the Front End and the telescope beam enters through a hole in the center of the Instrument Rotator and is folded to the science and sky fibers on the left side of the figure.

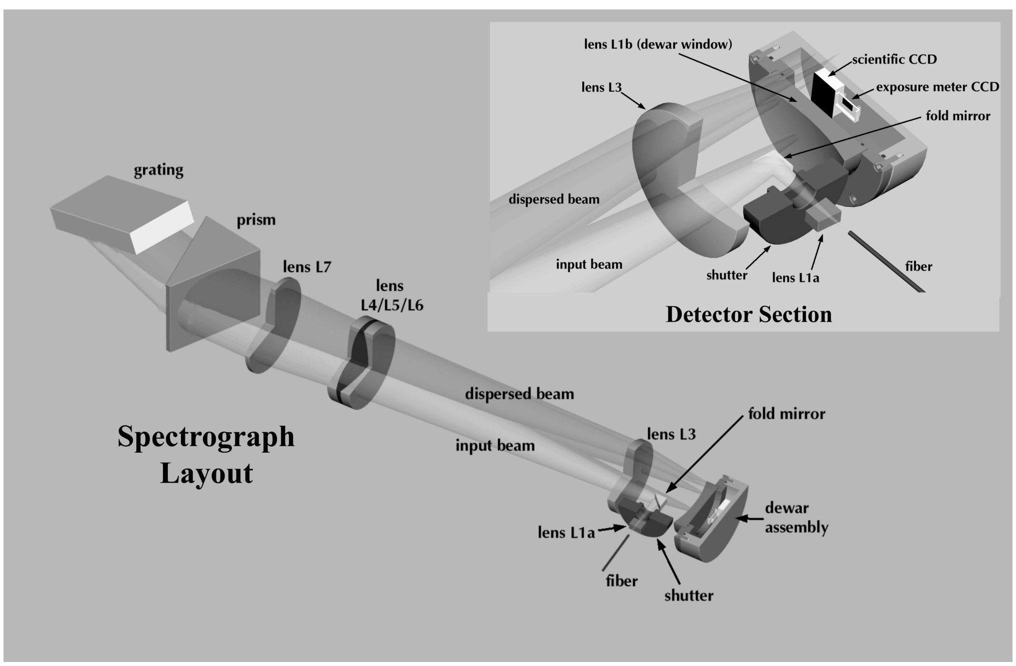

Fig. 4. The optical layout of the TRES Bench Spectrograph.The beam enters through the fiber near the lower right hand corner of the figure, and is folded diagonally upward and to the left to the diffraction grating at the upper right left corner of the figure. The beam is the diffracted back toward the science camera near the lower left hand corner of the figure.

the telescope itself. There are two fibers available at each resolution, one science fiber and one sky fiber for sky subtraction. The f/10 focal ratio of the 1.6m telescope is reduced to f/6 by a doublet lens, since f/10 is too slow a focal ratio to feed the fibers efficiently.

The calibration system consists of a pair of thorium-argon (ThAr) hollow cathode lamps and incandescent continuum lamps mounted on an integrating sphere. A periscope is used to inject the calibration beam into the science/sky fibers or to send it to a third set of fibers that may be used for continuous calibration. An iodine (I_2) vapor cell system is built into the front end as an alternative wavelength standard in addition to the ThAr system. The guide function is performed by re-imaging the reflective focal plane with an off-the-shelf Canon 100mm macro lens onto a custom CCD camera developed in collaboration with Carnegie Observatory.

The spectrograph optical layout is shown in Figure 4. It is an all-refractive, double-pass design by Harland Epps. Fiber, and hence resolution, selection is accomplished with a precision linear stage at the input of the spectrograph, which also contains the system shutter. The optical train consists of six lenses, a cross-dispersing prism, and echelle grating. The first and last lenses in the optical train are not double pass — Lens 1a and 1b are two identical lenses to permit folding the beam into the spectrograph while preserving the symmetry of the the optical design. Lens 1b is also the vacuum window of the detector cryostat. The beam diameter is 128 mm; the camera focal length is 762 mm. The grating is a Richardson Grating Laboratories catalog ruling R2 grating with a pitch of 52.7 lines per millimeter. The CCD is a E2V 2K $\times$ 4.5K, 13.5 μm pixel device. Since the beam slightly overfills the grating format, we harvest this lost light with a mirror that redirects the light to a small CCD, next to the science CCD, that is used as an exposure meter.

First light for TRES is planned for October 2006.

4. FUTURE PROSPECTS

Kepler's launch is scheduled for June 2008. By that time, we expect both Hectochelle and TRES will be well-exercised instruments with refined calibration protocols and reduction pipelines. These facilities will be powerful tools to sort among the candidate planetary systems *Kepler* will discover. The CfA continues to explore possibilities for "extreme" PRV ($<$1 m s^{-1}) as a final sieve to winnow the real earth-like planets from impostors — perhaps the greatest challenge in this search for other earths. Given the northern hemisphere location of San Pedro Mártir, there is the possibility that — with an aggressive construction schedule — a 6.5-m telescope sited at San Pedro might play a pivotal role in the search for other earths.

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