1 Objectives and Expected Significance

The 9.2-meter Hobby-Eberly Telescope (HET) is poised to have comparable power to Keck in its capabilities of exoplanet search. With multiple upcoming upgrades for the telescope and its High-Resolution Spectrograph (HRS), the throughput and radial velocity (RV) precision of HET/HRS will be improved to the same level of Keck, which will enable HRS to discover and follow up planets and *Kepler* candidates around relatively faint stars that are far away.

Meanwhile, bright, nearby stars are very important targets for finding Earth- or super-Earth-size planets in the Habitable Zone and/or with large transit probability to enable potential studies on their atmosphere. This is the primary science goal of project *Minerva*, an array of four small telescopes that will perform dedicated RV monitoring on a carefully-selected ensemble of nearby stars.

It is the broad theme of this proposal **to develop data reduction and Doppler pipelines for HET/HRS and *Minerva* with the ultimate goal to find exoplanets around stars near and far**. We will

- Develop data reduction and Doppler (RV extraction) pipeline for the upgraded HET/HRS and *Minerva*.

Upon upgrade, the throughput of HET/HRS will be improved by a factor of $\sim$5. HET will become the second telescope, besides Keck, that is suitable for RV follow-up on the stars hosting planet candidates discovered by *Kepler*. This will make the *Kepler* follow-up programs more efficient. It will also benefit other planet search programs on HET/HRS such as surveys on long-period planets and multiple-planet systems.

As a dedicated RV survey project, *Minerva* is expected to discover $\gtrsim 10$ Earth- to super-Earth-size planets with orbital period of 1–100 days around nearby stars, with 3–5 expected to be in the Habitable Zones of their host stars (Bottom et al. 2013; Hogstrom et al. 2013). The similarity between the spectral data products of the upgraded HET/HRS and *Minerva* provides us the opportunity to develop a single pipeline that will work equally well for both.

- Improve the RV precision of the current HET/HRS.

By simply implementing the California Planet Survey (CPS) Doppler pipeline without tailoring and refining it for the fiber-fed HRS, we have already achieved $\sim$3 m/s (Johnson et al. 2011; Wang & Wright 2011; Wang et al. 2012). As some essential parts of HRS will remain the same after the upgrade, understanding the current bottleneck of its RV precision is essential for ensuring a high-precision new HET/HRS. It will also make the $\sim$10-year baseline HET/HRS archival data a very valuable asset for detecting multiple-planet systems and long-period planets, e.g. the Solar system analogs and Jupiter analogs.

- Maintain and improve the Exoplanet Orbit Database (EOD; Wright et al. 2011)[1] as a statistical study tool and an orbital information database for exoplanet research.

We plan to incorporate the up-to-date *Kepler* catalog of planet candidates into EOD. **This will put the *Kepler* planet candidates in the context of all confirmed planets**

[1]This database (at exoplanets.org) is a compilation of all exoplanets that have quality peer-reviewed orbital measurements.

discovered by other programs and methods. EOD will also be the venue to keep close update on the additional or refined orbital parameters of the *Kepler* planets that are acquired through follow-up programs. This provides the community with a complete and up-to-date collection of the reliable exoplanets (and candidates) and their orbital parameters, and it is a powerful statistical tool for studies on planet occurrence rate and so on.

2 Methodology

2.1 Developing Data Reduction and Doppler Pipeline for the Upgraded HET/HRS and Minerva

The current HET/HRS, with its long term RV precision around 3–5 m/s (Baluev 2009; Wang & Wright 2011), has made several discoveries of exoplanetary systems (e.g., Wittenmyer et al. 2009; Gettel et al. 2012; Wang et al. 2012). The key factor limiting its science capabilities and preventing it from performing extensive *Kepler* follow-up is its low throughput.

However, the 2013 upgrade will greatly improve the throughput and will enable HET/HRS to perform extensive *Kepler* follow-up. The telescope will gain a factor of 1.4 in throughput as a result of better tracking, better dome temperature control, and a better prime focus optics. The throughput of HRS itself will also see an improvement of a factor of 1.5–2 thanks to an added image slicer, a new cross disperser, and a new optical configuration. Together, all the upgrades on HET/HRS will improve its throughput in the wavelength range of the iodine region by a factor of $\sim$5.

We plan to have the data reduction and Doppler (RV extraction) pipelines for the upgraded HRS ready when it is back online, which can be late 2013 or early 2014. We will use the new HET/HRS to:

- Follow up the *Kepler* Earth or super-Earth candidates to look for non-transiting gas giants further out in the system. The *Kepler* Earth or super-Earth candidates, especially the ones in Habitable Zones, are precious examples for answering questions such as the occurrence rate of the Solar system, the architecture of planetary systems with rocky planets, and the role that gas giant may have played in 'fostering' the habitability of the inner rocky planets through dynamical evolution (Wetherill 1994; Horner & Jones 2008).

- Follow up the *Kepler* systems that show transit timing variations (TTVs), which are signposts of additional planets in the system (e.g. Steffen et al. 2013). RV follow-up will reveal the full picture of the architecture of these systems, and is crucial for understanding occurrence rate of multiple-planet systems, the dynamics of planetary systems, as well as planet formation history.

- Use RV follow-up to validate/confirm the *Kepler* planet candidates, which will greatly increase the efficiency of RV validation/confirmation of *Kepler* candidates as HET joins Keck in this enormous and important task.

To be able to work with the upgraded HET/HRS, we need to make adjustments and new developments on our current pipelines. The upgraded HRS will produce spectral data in a different format. The newly added image slicer will slice the fiber image into four parts, place them in parallel, and feed them into the slit. Therefore, each of the spectral orders will have four traces that are parallel and imaged close to each other. This requires modifications and additions to the existing spectral data reduction pipeline from bias correction and flat fielding all the way to spectrum extraction. New elements will also be needed for sky subtraction as a sky fiber is added, and for combining four traces together to generate the final spectrum for each order. Since we have set up the data reduction pipeline for the current HRS (by adopting and modifying the REDUCE package; Piskunov & Valenti 2002), we are confident about developing a reliable new pipeline for the upgraded HRS.

The upgrades of HRS will enhance its stability and make it a better instrument for precise RV measurements in general. We will modify our current Doppler pipeline so that it is compatible with the new spectral format and the new instrumental properties such as the instrumental profile (IP; also called the point/line-spread function or the instrumental response function). We will also be actively improving the Doppler pipeline to make sure that it is of $\leqslant 1$ m/s precision once the upgraded HET/HRS is in action (see the next section for more details). This work will be greatly aided by our experience of implementing the CPS Doppler pipeline for HET/HRS (Johnson et al. 2011; Wang et al. 2012) and our close collaboration with the CPS group.

The data reduction and Doppler pipelines we develop for the upgraded HET/HRS can also be applied to the spectral data produced by *Minerva* (PI: John Johnson, Co-I: Jason Wright, Phil Murihead, Nate McCrady). *Minerva* is a dedicated RV monitoring project on nearby stars at Palomar Mountain to look for Earths and super-Earths that are in the Habitable Zone and/or with high transit probability. It consists of an array of four 0.7 meter telescopes with a vacuum-sealed fiber-fed spectrograph, and it is designed to have $\leqslant 0.8$ m/s RV precision (Bottom et al. 2013). The spectral images will also have four parallel traces for each spectral order, and our pipeline will be able to combine these traces and measure their RV shift just like for HET/HRS, or extract the four spectra and their RVs independently for each telescope. Project *Minerva* has finished the preliminary design review phase, and the first telescope is expected to be installed on Palomar Mountain by the end of 2013.

2.2 Improving the RV Precision of the Current HET/HRS

To fully exploit the advantages brought by the upgrades of HET/HRS, it is crucial to understand what is limiting its current RV precision, how the upgrades would solve its current problems, and if more hardware improvements are needed. The archival HET/HRS RV data with a ∼10-year baseline provides a valuable and unique opportunity to study the RV performances of fiber-fed spectrographs and their long-term RV stability in general. A higher RV precision for the current HET/HRS will also enable more science return on its archival data, such as discovering long-period planets (Jupiter analogs) and Solar system analogs.

We have already implemented the CPS Doppler pipeline for HET/HRS. This is the pipeline behind the successful CPS programs that discovered the majority of RV exoplanets at Keck and Lick Observatories. Although this pipeline was not designed to work with the fiber-fed HRS, it has achieved long-term (∼4 years) precision of 3.6 m/s on the RV standard star σ Draconis (HD 185144), where the long-term RV precision of Keck on this star is 2.3 m/s (Wang & Wright 2011). Using this pipeline and data including archival HET/HRS RVs as early as 2004, we discovered a second planet in the HD 37605 system, HD 37605*c*, the 10th

Jupiter analog in the peer reviewed literature, with a 7.5-year period and $M \sin i = 3.4\ M_{\rm Jup}$ on a circular orbit (Wang et al. 2012). Figure 1 shows the Keplerian orbital fit for the HD 37605 system and the HET/HRS RV data, with residuals plotted in the lower panel.

Temperature stability in the spectrograph room of HET/HRS was identified early on as one of the contributing factors to the RV systematic errors, and this issue was resolved since the installation of a fine temperature control system in March 2008 (J. Bean, L. Ramsey, P. McQueen private communications). We confirmed the improvement in RV precision as a result of this upgrade in our analysis with the HD 37605 data, which is illustrated in the lower panel of Figure 1. The RMS of HET/HRS velocities with respect to the best Keplerian fit of the HD 37605 system is 9 m/s for data before March 2008, and it is reduced to 6 m/s for data afterwards. Such improvement is encouraging, and a closer look at the data and the intermediate products of the Doppler pipeline reveals even more potential contributors to the RV instability of HET/HRS.

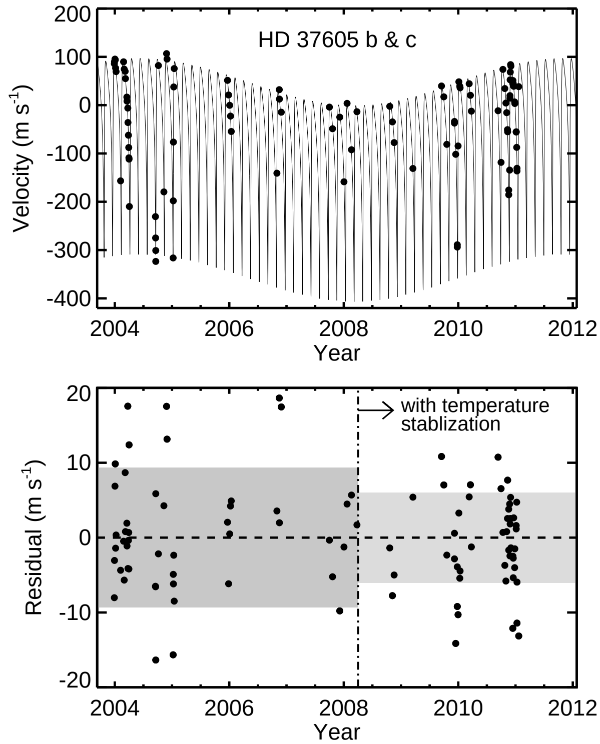

Figure 1: Best Keplerian fit for the HD 37605 system (top panel: solid line) and the velocity residuals (bottom panel). We discovered HD 37605*c* using HET/HRS data spanning ∼8 years (black dots) and also RVs from Keck and McDonald Observatory 2.1m telescope, but only HET/HRS data are shown here to highlight its precision and time baseline (Wang et al. 2012). The bottom panel shows that the amplitude of the RV residuals decreased after the fine temperature control for the spectrograph room came online (epoch marked by dash-dotted line). The heights of the two grey regions are the RMS values before and after (9 and 6 m/s, respectively).

One major issue is to model correctly the instrumental profile (IP) of HRS. IP modeling is a crucial part of the precise RV work with iodine calibration, as it affects directly several key procedures in the Doppler pipeline, such as the creation of stellar spectrum template and the forward-modeling of the observed stellar+iodine spectrum. How well the IP is being modeled can be tested by fitting an pure iodine spectrum taken by the spectrograph. The typical χ^2_ν value that we obtain for fitting iodine spectra with a generic IP model (Gauss-Hermite polynomials) is about 2.5, while for Keck/HIRES, the χ^2_ν value is typically 1.05 (John Johnson private communications). The current successful IP model for Keck/HIRES (sum of Gaussians) in the CPS pipeline is the product of careful studies and numerous trials with IP modeling. A better understanding of the IP of HRS will bring visible improvements to its RV precision. We are at the beginning of this endeavour, and we are confident that, with our experience with the Keck/HIRES IP modeling, we can well characterize the HRS IP to achieve a significant improvement in its RV precision.

2.3 Maintaining and Improving the Exoplanet Orbit Database

The Exoplanet Orbit Database (EOD; Wright et al. 2011; exoplanets.org) aims to provide a complete and reliable database of exoplanets orbital information for both the scientific community and the general public. We maintain a complete collections of *peer reviewed* orbital parameters on all confirmed planets as well as the *Kepler* planet candidates. Our website is the top 2 search result on Google for keyword "exoplanets" (after *Wikipedia* page), and our site traffic is on average over 200 hits a day including 80 returned viewers.

Since most of the confirmed exoplanets today are discovered by non-transiting methods, it is important to put the *Kepler* planets/candidates into the context of all confirmed planets discovered by various programs with different target-selection strategies. In 2012, we included the first two releases of the *Kepler* planet candidate catalogs in our database, and we plan to incorporate very soon the newest releases (Batalha & Kepler Team 2013). We will update their validation/confirmation status and their newest orbital information from follow-up programs such as RV, TTV, and imaging. We will also keep their host star properties up-to-date as more spectroscopic observations and analyses become available for *Kepler* stars.

The compilation of all reliable planets/candidates with good orbital parameters and host star characterization is crucial for estimating occurrence rates of various types of planets hosted by a variety of stars. With the EOD, we maintain and improve such a compilation. We keep our database up-to-date diligently by examining the daily postings on the arXiv, and extract new or refined orbital information. In the era of *Kepler* when the number of planets/candidates are counted by thousands, such statistical power will greatly advance our understanding of the architecture and formation of exoplanet systems.

3 Relevance to NASA's Objectives and Support for NASA Missions

Broadly, our investigation addresses one of the science objectives of NASA SMD, "Discover the origin, structure, evolution and destiny of the universe and search for Earth-like planets".

More specifically, this proposal is directly and closely relevant to the Astrophysics Research Program, theme (iii) Exoplanet Exploration, in the solicitation:

- "to search for planets and planetary systems about nearby stars in our Galaxy": Our work with HET/HRS and *Minerva* is directly aimed at searching for exoplanets around nearby stars and *Kepler* targets (Section 2.1 and 2.2).
- "to determine the properties of those stars that harbor planetary systems": We will acquire high resolution spectra on planet host stars for, e.g. the *Kepler* stars, as required by the RV technique (Section 2.1). Our work on maintaining EOD also provides a database that enables statistical studies on stars that host exoplanets (Section 2.3).
- "to determine the percentage of planets that are in or near the Habitable Zone of a wide variety of stars and to measure their orbits": Project *Minerva* will find more Earths and super-Earths in or near the Habitable Zone of nearby stars. Future work with the upgraded HET/HRS will follow up potentially 'rocky' *Kepler* planets in the Habitable Zone to reveal the complete architecture of their systems (Section 2.1 and 2.2).

Our work will also support current and future NASA missions and enhance their scientific outcome: (1) **the *Kepler* mission**: The upgraded HET/HRS will directly support *Kepler* through follow-up programs, including candidate validation/confirmation, TTV follow-up, and outer planet discovery. **(2) TESS:** The array of four small telescopes of *Minerva* will be a great support for TESS by following up its transiting planet candidates, since the TESS targets are bright stars nearby. **(3) JWST:** The Earths or super-Earths with high transit probabilities discovered by *Minerva* are great targets for JWST to characterize their planetary atmospheres.

4 Relation to PI's Other NASA Grants

The PI of this proposal, Prof. Jason Wright, has received NASA Keck time to search for long-period planet and multiple planet systems. The work proposed here will continue this effort as the upgraded HET/HRS is expected to follow up some if not all of the systems in the future. The PI has also received NASA Keck time to follow up a *Kepler* planetary system with a strong TTV signal (Co-I Eric Ford). We will continue such effort with the upgraded HET/HRS to follow up and study more *Kepler* systems with TTVs (Section 2.1).

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