Sharon Xuesong Wang

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Date: Nov. 1 2015

Dear Carnegie Fellowship Selection Committee:

I am applying to the Carnegie Fellowship beginning in September 2016. Currently, I am a graduate student in the Astronomy & Astrophysics Ph.D. program at the Pennsylvania State University (Ph.D. expected by August 2016). My thesis is titled "Weighing Rocky Exoplanets with Improved Radial Velocimetry", and my thesis advisor is Dr. Jason T. Wright.

My proposal, "Demographics of Small Exoplanets around Sun-like Stars", aims to reveal the mass and composition distribution of exoplanets with radii smaller than four times Earth's, as well as to estimate the occurrence rate of small planets with orbital periods longer than 100 days. I will use radial velocity (RV) observations to build an unprecedented large sample of well-characterized small planets, following up Kepler/K2 and TESS targets and performing independent RV surveys. I will use the Carnegie Planet Finding Spectrograph (PFS) on Magellan, as well as Keck/HIRES and the Automated Planet Finder (APF) with access through collaborations within and outside of Carnegie Observatories. I will also use the next-generation RV instruments such as the MINiature Exoplanet RV Array (MINERVA; 2016; as a team member) and NASA-WIYN Extreme Precision Doppler Spectrometer (EPDS; 2018; public time, and as a PSU proposing team member).

I am confident that I have the expertise to carry out the proposed research. I have extensive experience in diagnosing and solving problems and modeling high-resolution echelle spectra in the context of precise RV. My expertise also includes characterizing exoplanets systems using RV data and observing and raw data reduction with echelle spectrographs. I also have a solid background in statistical computing (Ph.D. Minor in Computational Sciences).

I strongly believe that my expertise and future research projects well complement the on-going research at the Carnegie Observatories. In addition to joining the PFS and the Lick-Carnegie Planet Survey team, I will bring MINERVA collaboration to Carnegie and carry on collaboration with the California Planet Survey. Moreover, my extra-galactic research projects also fit well with the current project at Carnegie, including studies on QSOs/AGNs and galaxy star formation on extreme ends.

Thank you for your consideration, and I look forward to hearing back from you.

Sincerely,

Sharon Xuesong Wang

Sharon Xuesong Wang

Department of Astronomy and Astrophysics
525 Davey Lab, Penn State University
University Park, PA 16802

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EDUCATION

PhD Candidate, Astronomy & Astrophysics, Penn State University — expected 2016
PhD Minor, Computational Sciences
Thesis: *Finding More and Lower Mass Exoplanets with Improved Radial Velocimetry*
Advisor: Dr. Jason T. Wright

Bachelor of Science, Physics, Tsinghua University, Beijing, China — Jun 2008
Thesis: *Characterizing the Luminosity-Variability Correlation in Gamma-Ray Bursts*
Advisor: Dr. Shuang-Nan Zhang

PROFESSIONAL EMPLOYMENT

Research Assistant / Fellow — May 2010 – present
Department of Astronomy & Astrophysics, Penn State University

- Jan 2013 – present, May 2010 – May 2011, with Prof. Jason Wright on detection and characterization of exoplanets with radial velocities (thesis work).
- May 2011 – Dec 2012, with Prof. W. Niel Brandt on observational studies of AGNs.
- May 2009 – May 2010, with Prof. Peter Mészáros on Gamma-ray Burst theories.

Teaching Assistant — Aug 2008 – Dec 2009
Department of Astronomy & Astrophysics, Penn State University

- including instructing and leading astronomy lab classes (Astro 11)

AWARDS

NASA Earth and Space Science Fellow — since Sep 2014
Proposal title: Finding the Lowest Mass Exoplanets with Improved Radial Velocimetry

Downsborough Graduate Fellowship — May 2013
Department of Astronomy & Astrophysics, Penn State University

- Award for senior graduate student for outstanding scholarly achievement.

Stephen B. Brumbach Fellowship in Astrophysics — May 2010
Department of Astronomy & Astrophysics, Penn State University

- In recognition of excellence in academic performance and research during the first two years.

Zaccheus Daniel Fellowship — 2009-2013
Department of Astronomy & Astrophysics, Penn State University

- Research and Travel Funding Award for current graduate student.

Teaching Assistant of the Year Award Jun 2009
Department of Astronomy & Astrophysics, Penn State University
- In recognition of outstanding teaching by a graduate student.

TELESCOPE TIME AWARDED AND OBSERVING EXPERIENCE

Exoplanet Programs

PI, 25.7 hours on Hobby-Eberly Telescope, with the High Resolution Spectrograph 2013
Improve the Radial Velocity Precision of HET/HRS
Co-I: Jason Wright, Ming Zhao

Observer, Observing Planner, Tull Spectrograph at the McDonald Obs. 2.7m Telescope 2013
TS12 arm, R$\sim$500,000, day-time runs

Observer, Keck/HIRES remote observing at Caltech and Yale ROCs 2010, 2011, 2013

Extragalactic Programs

As founding member of the MUSCEL program (MUltiwavelength study of the Structure, Chemistry and Evolution of LSB galaxies):

Co-I, 5 hours of Green Bank Telescope, 2015A with AUGUS receiver 2014
CO in Low Surface Brightness Galaxies in Tandem with Optical/UV Star Formation
PI: Jason Young, Co-Is: Rachel Kuzio de Naray, Karen O'Neil

Co-I, 9 Nights on VIRUS-P IFU on 2.7m telescope of McDonald Observatory 2013, 2014, 2015
IFU Spectroscopy of Low Surface Brightness Galaxies
PI: Jason Young, Co-I for 2014 & 2015: Rachel Kuzio de Naray

Co-I, NASA Swift Cycle 10 GI Program 2013
Anchoring the Blue End of Low Surface Brightness Disk Galaxy SEDs
PI: Jason Young, Co-I: Rachel Kuzio de Naray

Others: Co-I on one *Fermi* proposal on GRB theory (2009) and one *Chandra* Archival proposal on AGN spectroscopy (2013).

TALKS AND CONFERENCE POSTERS

Talks

Paths, Roadblocks, and Byways in Detecting Habitable Rocky Planets in Radial Velocity Data
Invited Talk, Carnegie DTM Exoplanet Seminar Nov 2015
Invited Talk, Berkeley Center for Integrative Planetary Science Seminar Sep 2015
NExScI Exoplanet Seminar Sep 2015
Contributed Talk, Bay Area Exoplanet Science Meeting Sep 2015

Co-Chair, Breakout Discussion Session on Telluric Contamination Jul 2015

The 2nd Extremely Precise Radial Velocity Workshop, Yale

Improve RV Precision through Better Modeling and Better Reference Spectra May 2015
Contributing Talk, The 1st Emerging Researcheres in Exoplanet Symposium, Penn State

Pushing the Radial Velocity Precision to 1 m/s Oct 2014
Stellar, Solar and Planet Seminar, Harvard/CfA

Accreting Supermassive Black Holes in Submm Galaxies Apr 2013
Contributed Talk at the Penn State Neighborhood Cosmology Workshop

AGNs in Submm Galaxies — Combining the Power of Chandra *and ALMA*
Contributed Talk at 2013 AAS Winter Meeting, Long Beach Jan 2013
Contributed Talk at Seyfer 2012 Workshop — Nuclei of Seyfert Galaxies and QSOs
Max Planck Institute for Radio Astronomy, Bonn, Germany Nov 2012

Resolving the 6-8 keV X-ray Background Aug 2012
Lunch Talk at Kavli Institute of Astronomy & Astrophysics
Peking University, Beijing, China

plus 6 Penn State Department of Astronomy & Astrophysics Lunch Talks and 2 invited talks at the *Swift* Mission Control Center.

Posters

Telluric Contamination: Effects and Solutions Jul 2015
Poster at the 2nd Extremely Precise Radial Velocity Workshop, Yale

Finding Extra-Solar Planet Near and Far Mar 2013
Poster Presentation at the 2013 Penn State Graduate Exhibition
First Prize Winner in the Physical Sciences and Mathematics Category

Improving the Radial Velocity Precision of HET/HRS May 2011, Jan 2014
Serial Poster Presentations at the 2011 AAS Winter Meeting in Seattle and Summer Meeting in Boston, the 1st Precise Radial Velocity Workshop at Penn State, and the 2014 AAS Winter Meeting in National Harbor.

Spectral Lags from Structured Jets
Poster Presentation at the 2010 AAS Winter Meeting in D.C Jan 2010
Poster Presentation at the Swift 5 Year Conference, **Poster Award Winner** Nov 2009

SUMMER SCHOOLS AND TRAININGS

The Dunlap Institute Summer School on Astronomical Instrumentation Aug 2013
Honorable Mention, Optical Design Challenge

The Summer School in Statistics for Astronomers Jul 2010
Pennsylvania State University

The 37th Standford SLAC Summer School Aug 2009
Revolutions on the Horizon: A Decade of New Experiments
Honorable Mention, The 37th SLAC Summer School Challenge

SERVICES AND COMMITTEE WORK

Referee, ApJ, A&A

Outreach Volunteer since Aug 2008
Given over 10 planetarium shows to local school students and general public, and over 6 public talks at various outreach events through the Penn State Astro Outreach program.

Astronomy beyond Academia, Founder and Group Manager since Aug 2012
A *LinkedIn* network for astronomers outside academia, endorsed by AAS Employment Committee

Mentor for First-Year Physics Major Undergraduate since Sep 2014
Penn State Physics and Astronomy Women Mentoring Program

Scientific and Logistic Organizing Committee Member May 2015
The 1st Emerging Researcheres in Exoplanet Symposium, Penn State

Graduate Council Representative Sep 2010 – May 2012
Penn State Graduate Student Association

Co-Chair and Event Organizer for Inside Scientists Studio Sep 2010 – May 2011
Graduate Women in Science, Nu Chapter at Penn State

Mentor for First-Year International Graduate Students 2009 – 2010
Penn State Global Programs

TECHNICAL SKILLS

Coding Languages:
IDL, Python, Java, C++, R

Astronomical Data Analysis Skills:
Exoplanet:

- Forward modeling echelle spectra for radial velocity (RV) extraction;
  - working with and improving the California Planet Survey Doppler code (used at Keck/HIRES, APF, HET/HRS, AAT, etc.)
  - building a Doppler code from scratch
- Diagnosing and solving problems in the context of iodine precise RV;
  - general diagnostic tests with calibration frames, standard stars frames, etc.;
  - modeling telluric contamination in reference and science spectra;
  - modeling spectrograph response function (spectral PSF);
  - modeling/characterizing iodine atlases (as calibration/reference spectra);

- Observation and raw data reduction with echelle spectrograph;
- Characterization of planetary systems with RV data;
- Modeling telluric absorption lines;
- Optical and NIR photometry;
- Solid background in statistical computing.

Extragalactic:

- X-ray: photometry, stacking, spectroscopy, and spectral modeling (CIAO tools and XSPEC)
- Galaxy SED fitting (experience with FAST, GalMC, and CIGAR)
- Metalicity estimate from emission lines (e.g. using the R23 method)

Astronomical Packages and Softwares:
California Planet Survey Consortium Doppler Code
REDUCE (optimal extraction for 2-D echelle spectrum)
TERRASPEC (software for modeling telluric spectra based on HITRAN line database)
IodineSpec5 (theoretical computation of iodine lines)
SourceExtractor (Optical/NIR photometry)
CIAO tools and XSPEC (X-ray photometry and spectroscopy)
FAST (galaxy SED fitting)
ALMA Observing and Proposal Tool

Published Code:
BOOTTRAN (in IDL, bootstrapping to compute error bars for Keplerian orbit parameters, including transit ephemeris, based on radial velocity data)

Total publications: 13, with 4 as first or second author, 9 as contributing author.
Total citations: 172 (112 citations as first or second author), h-index: 8, as of Oct 28 2015.
1 first author paper and 2 co-author papers in preperation.

First and Second Author Publications:

4. The Exoplanet Orbit Database II: Updates to exoplanets.org
Eunkyu Han*, **Sharon X. Wang**, Jason T. Wright, et al. 2014, *PASP*, 126, 813
(* Undergraduate student co-supervised)

3. The X-ray Properties of the Submillimeter Galaxies in the ALMA LABOCA E-CDF-S Submillimeter Survey
Sharon Xuesong Wang, W. Niel Brandt, et al. 2013, *ApJ*, 778, 179

2. The Discovery of HD 37605*c* and A Null Detection of Transits of HD 37605*b*
Sharon Xuesong Wang, Jason T. Wright, et al. 2012, *ApJ*, 761, 46

1. Tracking Down the Source Population Responsible for the Unresolved Cosmic 6-8 keV Background
Yongquan Xue, **S. X. Wang**, et al. 2012, *ApJ*, 758, 129

Other Publications:

9. The Distribution of Star Formation and Metals in the Low Surface Brightness Galaxy UGC 628
Young, J. E.; Kuzio de Naray, Rachel; **Wang, Sharon X.**, 2015, *MNRAS*, 452, 2973

8. Evolution in the Black Hole—Galaxy Scaling Relations and the Duty Cycle of Nuclear Activity in Star-forming Galaxies
Mouyuan Sun, and other 8 coauthors including Sharon X. Wang, 2015, *ApJ*, 802, 14S

7. The California Planet Survey IV: A Planet Orbiting the Giant Star HD 145934 and Updates to 7 Systems with Long-Period Planets
Katherina Y. Feng, Jason T. Wright, Ben Nelson, **Sharon X. Wang**, et al. 2014, *ApJ*, 800, 22F

6. MARVELS-1: A Face-on Double-lined Binary Star Masquerading as a Resonant Planetary System and Consideration of Rare False Positives in Radial Velocity Planet Searches
Jason T. Wright, Arpita Roy, Suvrath Mahadevan, **Sharon X. Wang**, et al. 2013, *ApJ*, 770, 119

5. Host Star Properties and Transit Exclusion for the HD 38529 Planetary System
Gregory W. Henry, Stephen R. Kane, **Sharon X. Wang**, et al. 2013, *ApJ*, 768, 155

4. The HD 192263 System: Planetary Orbital Period and Stellar Variability Disentangled
Diana Dragomir, and other 13 coauthors including Sharon X. Wang, 2012, *ApJ*, 754, 37

3. A Search for the Transit of HD 168443b: Improved Orbital Parameters and Photometry
Genady Pilyavsky, and other 15 coauthors including Sharon X. Wang, 2011, *ApJ*, 743, 162

2. Stellar Variability of the Exoplanet Hosting Star HD 63454
Stephen R. Kane, and other 12 coauthors including Sharon X. Wang, 2011, *ApJ*, 737, 58

1. Revised Orbit and Transit Exclusion for HD 114762b
Stephen R. Kane, and other 6 coauthors including Sharon X. Wang, 2011, *ApJ*, 735, L41

Summary of Thesis Research

Sharon Xuesong Wang

My general research interest is to find and characterize low-mass exoplanets, and eventually, Earth analogs, using precise radial velocities (RVs). My thesis work focuses on improving the RV precision of high resolution echelle spectrograph using iodine cells as calibrators.

1. Improving the RV precision of HET/HRS

I conducted diagnostic studies on the instrumental effects and data reduction problems behind the RV systematic errors of the High Resolution Spectrograph (HRS) on the Hobby-Eberly Telescope (HET). HET/HRS has an RV precision of ∼3–5 m/s (e.g. Wang et al. 2012), which is worse than that of Keck/HIRES (1–2 m/s; e.g. Howard et al. 2013), despite its hardware advantages such as being fiber-fed and temperature controlled. I set up the data reduction and Doppler pipeline (adopting the Keck pipeline) for HET/HRS. Using this pipeline, we discovered the 10th Jupiter analog in the literature (Wang et al. 2012) and refined orbital parameters for several planets as part of the Transit Ephemeris Refinement Survey (TERMS) project (e.g., Henry et al. 2013).

I first studied the spectral line spread function (LSF), which is a crucial but also the most complex component in the forward modeling process. I constructed and tested numerous LSF models, and also studied its variation across the spectral image and over time. We have found that improper modeling of the HRS LSF definitely contributes to the RV error budget, probably beyond the 1 m/s level. The problem appears to reside in both the choice of the functional form as well as the numerical algorithm employed in optimizing the > 10 free parameters for the LSF. Though crucial, LSF does not appear to be the largest driver behind the poor goodness of fit in the modeling of the HRS spectra ($\chi^2_\nu \sim 2$–4 vs. ~ 1 for Keck/HIRES).

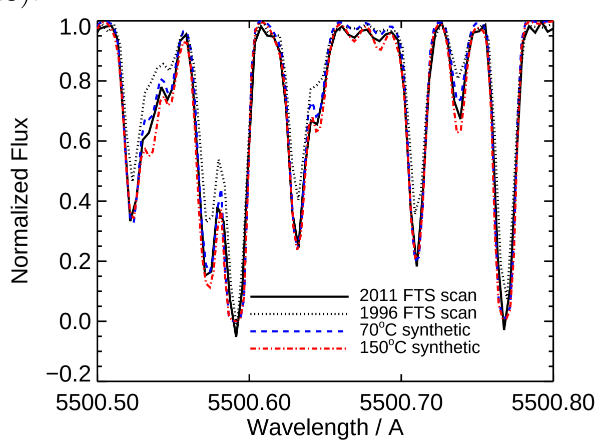
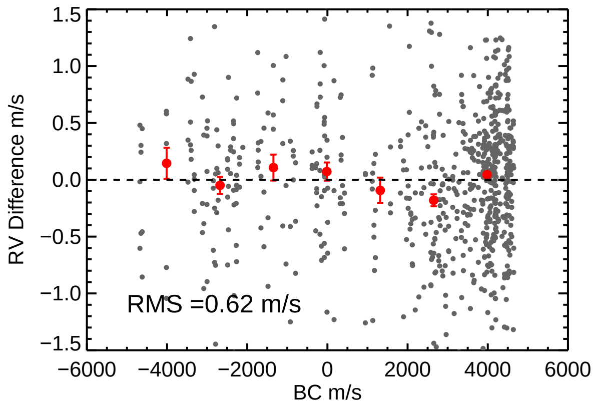
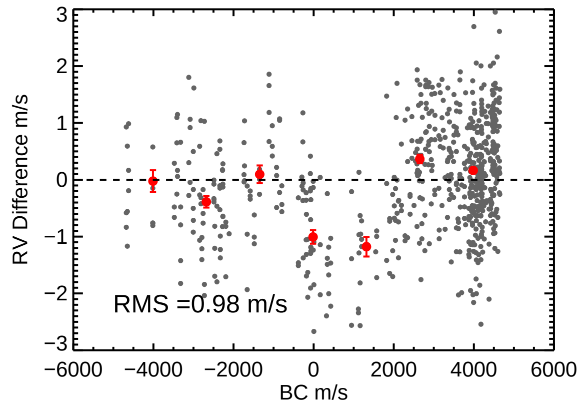


Figure 1: Comparison between synthetic iodine spectra (colored dashed and dash-dotted lines) and two FTS scans (black solid or dotted lines) of the HET/HRS cell. The synthetic spectra plotted have the best-fit column densities for the 2011 FTS scan. This is showing that the 2011 scan was taken at a temperature between 70°C (the nominal working temperature of the cell) and 150°C (the best-fit is 110°C), while the 1996 scan is at a different temperature and a different column density.

We have strong reason to believe that the main reason for an under-performance of HRS is the (lack of) knowledge of the iodine cell calibrator. Serving as both LSF and wavelength calibrators, the iodine cell needs to stay stable in terms of temperature and iodine column density. One also needs to have a precise and accurate knowledge of the "ground truth" iodine lines, which traditionally come from a Fourier Transform Spectrograph (FTS) scan. By comparing two FTS scans of the HRS iodine cell taken 20 years apart and also with a ultra-high resolution echelle spectrum of the cell, we concluded that two FTS scans were taken at different cell temperatures and/or the iodine gas column density in the



(a) effects of telluric contamination



(b) effects of deconvolution error

Figure 2: (a) Difference in RVs between a "perfect-condition" simulation and the simulation with telluric contamination injected, plotted against barycentric correction (BC) velocity of the star (∼ time of year). (b) Difference in RVs between the "perfect" simulation and the simulation where deconvolution error are introduced. Red points are RVs averaged in BC bins. The simulated data are for the RV standard star HD 185144 at Keck.

cell had changed. This is further confirmed by fitting a synthetic iodine atlas (Knöckel et al. 2004; Figure 1). We are working on introducing iodine cell temperature as an additional free parameter to better model the HRS RV spectra. Combined with a better LSF model, this will improve the RV precision of the >10-year archival HET/HRS data.

2. Effects of telluric contamination and deconvolution errors on precise RV

During my diagnostic studies on HRS, I have also identified and characterized the impact of telluric lines on the RV precision — they manifest as signals at harmonics of a sidereal year with an amplitude of ∼0.2 m/s, and it contributes to the RV error budget by 0.6 m/s (see Figure 2a). The effects would be more severe for sites at lower elevations and also for M dwarfs (Cunha et al. 2014). Our work recognized and characterized the adverse effects of telluric lines on iodine RV data for the first time. We have set up a toolbox for removing telluric contamination from the input stellar reference spectrum and incorporating telluric modeling in the Doppler pipeline.

While characterizing the effects of telluric contamination through simulations, I have also discovered and characterized the adverse effects caused by errors in the deconvolution process for deriving stellar reference spectrum. These errors cause RV aliases just like telluric contamination does, but they are more damaging as it affects the entire spectral domain. They add 1 m/s to the RV error budget and create a spurious signal with an amplitude of ∼1 m/s (Figure 2b). **This appears to be the leading terms in RV systematics for Keck at the moment.** We are now working on finding a better deconvolution algorithm in order to eliminate these RV anomalies.

References

Cunha, D., Santos, N. C., Figueira, P., et al. 2014, A&A, 568, A35

Henry, G. W., Kane, S. R., Wang, S. X., et al. 2013, ApJ, 768, 155

Howard, A. W., Sanchis-Ojeda, R., Marcy, G. W., et al. 2013, Nature, 503, 381

Knöckel, H., Bodermann, B., & Tiemann, E. 2004, European Physical Journal D, 28, 199

Wang, Sharon, X., Wright, J. T., Cochran, W., et al. 2012, ApJ, 761, 46

Demographics of Small Exoplanets

Sharon Xuesong Wang, 2016 Carnegie DTM Fellowship Proposal

NASA's *Kepler* mission has revolutionized our view of the population of exoplanets. Among the most striking discoveries is the prevalence of small planets (planets with radii smaller than four times Earth's, $R \leqslant 4R_{\oplus}$): it is estimated that $\sim 50\%$ of Sun-like stars host at least one such planet with orbital period $P \lesssim 100$ days (Fressin et al. 2013; Petigura et al. 2013; Foreman-Mackey et al. 2014). *Kepler* has discovered more than 800 small planets, with an additional 3000 candidates, opening the age of small planets and Earth analogs (exoplanets.org, Han et al. 2014; NASA Exoplanet Archive, Akeson et al. 2013).

The *Kepler* discoveries are just the beginning of understanding these small planets *as a population*, and important questions currently remain unanswered, such as the following:

(1) What are the mass and composition demographics of small planets? What is the fraction of the planets that are rocky or icy/gaseous for any given radius?

(2) What are the occurrence rates of small planets beyond $P = 100$ days? In particular, what is the occurrence rate of super-Earths inside the Habitable Zone?

I propose to address these questions with a large and well-characterized sample of small planets, enabled by precise radial velocity (RV) observations in the follow-up programs of *Kepler*/K2 and the Transiting Exoplanet Survey Satellite (TESS), as well as independent RV surveys. I will use the top RV instruments, such as the Carnegie Planet Finder Spectrograph (PFS) on Magellan, Keck/HIRES, and HET/HRS2, and improve their precision to enable more and better characterization of small planets. I will also work with next-generation RV facilities, such as the MINiature RV Array (MINERVA, 2016) and the NASA-WIYN Extreme Precision Doppler Spectrograph (EPDS, 2018). With extensive knowledge and experience in precise RV data analysis, **I am poised to bring the current RV precision (1–2 m/s) to the next level ($\sim$ 0.5–0.8 m/s) in the near future**, through advanced statistical and numerical tools and an improved understanding of stellar activity-induced RV signal, aided by the hardware advances. This work will focus on small planets around Sun-like stars (spectral type FGK), which are the best targets for the optical RV facilities I will use.[1]

1 Previous Work and Challenges

The discoveries of *Kepler* provided us with the first statistical sample of 47 small planets with both mass (M) and radius (R) measurements[2], which opened the dawn of demographic studies regarding their mass and composition. Wu & Lithwick (2013) and Weiss & Marcy (2014) derived deterministic correlations between M and R, predicting a single value of M for

[1]Notes on telescopes and access *in addition to PFS*: Keck data (>10 years) are available through public archive and through the Lick-Carnegie Exoplanet Survey team and also through collaboration with the California Planet Survey consortium. Time on HET/HRS2 (the upgraded High-Resolution Spectrograph on the 10-meter HET) is available through PSU collaboration. I am a team member on MINERVA, an array of four 0.7-meter telescopes dedicated to RV surveys. I will use WIYN/EPDS through its public time and potential institutional time as a member of the PSU proposing team.

[2]38 out of 47 are through the RV method, and 9 are via transit timing variation (TTV) analyses, which are feasible to only a small fraction of planets (dynamically active systems, $\sim 6\%$, Mazeh et al. 2013).

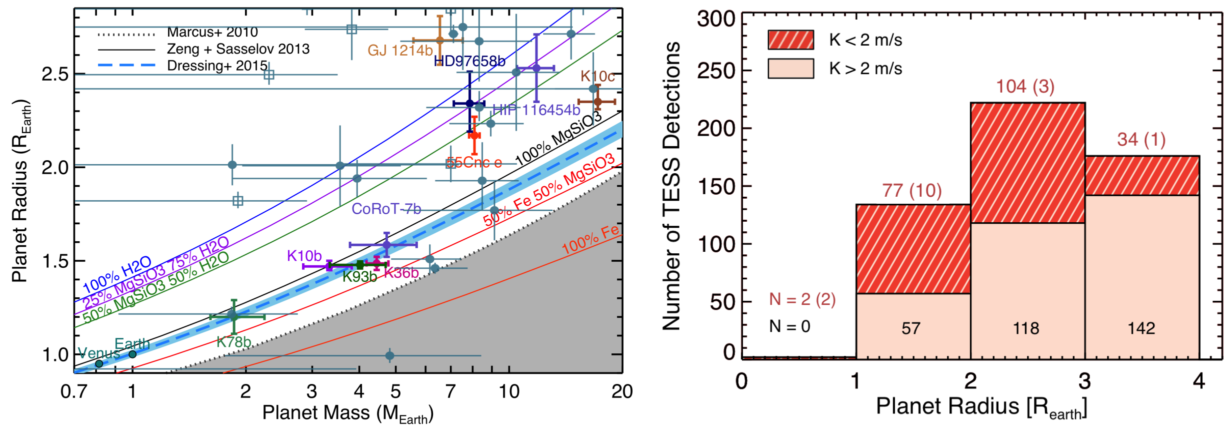


Figure 1: (a, left) Mass-radius diagram for small planets, using Figure 4 of Dressing et al. (2015) and adding exoplanets with mass uncertainties larger than 20% (gray blue). Most of the small planets have mass uncertainties too large to pin down their composition. (b, right) Histogram of radii of simulated TESS detections of small planets around Sun-like stars (Sullivan et al. 2015), grouped by RV semiamplitudes. The numbers in parentheses are for planets with $K < 1$m/s.

any given R via power-law fits. Further studies have revealed that a single equation linking M and R is highly insufficient for capturing the complete picture: Rogers (2015), Wolfgang & Lopez (2015), and Wolfgang et al. (2015) derived the intrinsic mass dispersion at given radius and quantified the mass/composition *distribution* of the small planet population.

However, the quantity and quality of this initial sample of small planets prevents more precise quantification or studies beyond the M-R plane, especially for planets with $R < 1.6R_\oplus$, which are most likely to be rocky and Earth-like (Rogers 2015). For example, Dressing et al. (2015) found that all of the exoplanets with $R < 1.6R_\oplus$ and mass uncertainty $\sigma_M/M <$ 20% appear to have the same bulk composition as Earth, but their sample size was five (Figure 1a). The situation is even worse for planets with longer periods. All of the population or occurrence rate studies mentioned above are for small planets on close-in orbits, and none of the small planets on the M-R plane has a period of longer than 80 days.

So why do we have such a limited sample, even though *Kepler* has discovered thousands of small planets? The main reasons are: (1) most *Kepler* small planet host stars are too faint for RV follow-up (90% with a *Kepler* magnitude of $K_p > 13$); (2) the detection sensitivity of *Kepler* drops greatly at $P \gtrsim 100$ days (Fressin et al. 2013); and (3) the current RV precision is not high enough for efficient and effective follow-up on systems with small planets, due to hardware and software limitations and a lack of understanding of the stellar signal at 1-2 m/s level.[3] Fortunately, the exoplanet community is equipped to overcome these challenges in the near future, the details of which, including my proposed work, are in the next section.

[3]The photon-limited precision of the leading RV instruments is ∼0.5–1 m/s for bright stars. In reality, there is almost always some extra error, i.e. the “RV jitter”, composed of systematic errors and unaccounted stellar-activity signals. For example, for Kepler-78 b (Earth mass, Earth radius, $K = 2$ m/s), the RMS of the RV residuals against the best-fit model is ~ 2.5 m/s, including an RV jitter of ~ 2.1 m/s, while the photon-limited error for the star is < 2 m/s (Howard et al. 2013; Pepe et al. 2013).

2 Moving Forward: the Proposed Work

2.1 Building up a large sample of well-characterized small exoplanets

I will follow up selected *Kepler*/K2 targets and a large sample of TESS targets, as TESS is expected to detect over 500 small exoplanets around Sun-like stars (Figure 1b), most of which are brighter than $V = 13$ (median ~ 11) and can be followed up by RV. This large sample of small planets will require an extensive RV follow-up program with high precision, as most of them induce an RV signal with semiamplitude $K < 3$ m/s, with 40% having $K < 2$ m/s (Sullivan et al. 2015; Figure 1b), essentially beyond the capability of all current RV instruments (see Figure 2a). **I propose to improve the RV precision beyond the current 1-2 m/s level, eventually to $\lesssim$0.5–0.8 m/s, within the next three years**, which will enable detection and characterization of a large sample of small planets:

(1) I will improve the precision of Keck/PFS/HET through removal of the systematic errors that I have identified and characterized *for the first time* within the iodine RV technique. The first term is errors in the deconvolution of stellar spectrum, which is *the leading systematic error term* in the Keck data. It adds 1 m/s RMS to the RV error budget (in quadrature) and causes spurious signals at periods of $\sim$1 year and harmonics with an amplitude of $\Delta \simeq 1$ m/s. I have successfully reproduced the observed pattern of the spurious signal in simulation, which enables an empirical correction, and I am collaborating with mathematicians and statisticians to find a better deconvolution algorithm. With Paul Butler (*the top* expert on iodine RV) and Magellan/PFS (built to deliver high-quality stellar template), Carnegie/DTM is the ideal place for me to tackle this long-standing problem in iodine RV. The second systematic error term comes from the telluric contamination. I will use my telluric-modeling toolbox to properly handle telluric contamination in PFS/Keck/HET data. This will remove a $\Delta \gtrsim 0.2$ m/s spurious signal and at least 0.6 m/s RMS from the RV error budget (more for instruments at lower elevations and M dwarfs; e.g., Cunha et al. 2014). These improvements are also applicable to all of the archival RV data.

(2) I will build a next-generation Doppler pipeline for current and next-generation RV instruments (in `Python` and public on `GitHub`). This new pipeline employs advanced statistical and numerical tools such as Bayesian MCMC algorithm and Gaussian processes (Figure 2b), which will model the correlated noise originated from a complex blaze function, normalization issues, CCD effects, telluric line modeling residuals, imperfect deconvolved stellar spectrum, and so on (see, e.g., Czekala et al. 2014 and Daniel Foreman-Mackey's *george* package). This new package is built to be highly modular and easily adaptable to any RV instrument. Magellan/PFS is a great instrument to implement this new package: the upgraded PFS will have the largest pixel sampling factor among all RV instruments, providing more modeling power for RV extraction.

(3) I will implement features for estimating RVs induced by stellar activity in the new package, such as bisector fitting, analysis on line depth change, and color-dependent RV estimate. This will be the first time the stellar activity and planetary RV signals are disentangled *directly from the spectral data*, instead of estimating and subtracting the effects of stellar activity "after the fact". I will take advantage of the unique high-cadence capability of MINERVA and obtain carefully designed RV time series on a sample of bench-mark stars (e.g. τ Ceti and σ Dra), thereby, tackling the problem of stellar activity-induced RVs.

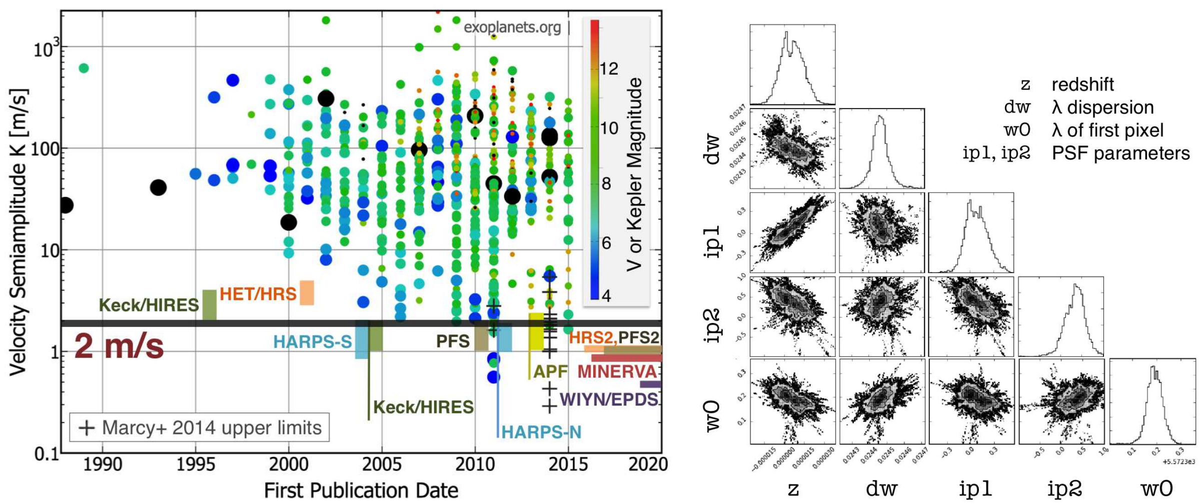


Figure 2: (a, left) The RV semiamplitude K of all RV-detected exoplanets vs. date of discovery. The planets are color- and size-coded according to their host star brightness. The RV precision has essentially stalled at ∼2 m/s level since 2005, except for a very few bright stars observed with high cadence. Current major RV instruments are plotted at their start dates, with the position and height of the rectangles indicating their RV precision. Selected future RV instruments are labeled in thick lines showing their first-light dates and target precision. The black crosses are the *Kepler* small planets with mass upper limits in Marcy et al. (2014), which will immediately benefit from the Keck precision improvements proposed. (b, right) Initial result from the new Doppler pipeline: 1-D and 2-D marginalized posterior distribution for 5 parameters (out of 17) in a fit for a 2Å spectral chunk. Final RV is derived based on a combination of RV posteriors of all chunks.

2.2 Constructing the first sample of long-period small planets

Aided by the high RV precision of the next-generation instruments, I will construct the first sample of well-characterized small planets with $P \gtrsim 100$ days, including the first statistical sample of super-Earths in the Habitable Zone (HZ) of Sun-like stars, in the next 3 years.

First, MINERVA will survey 82 nearby bright and quiet stars selected from the η-Earth sample (Howard et al. 2013) and is expected to find ∼10–20 super-Earths in the HZ of Sun-like stars (Swift et al. 2015). Second, with the upcoming upgrade promising $\lesssim$1 m/s precision (2016-2017), Magellan/PFS will become the most precise RV instrument on large telescopes, and it is poised to discover an even larger sample of long-period small planets than MINERVA. Finally, it is very likely that we will detect a sample of small planets as the "unseen" companion of TESS planets, given that ∼60% of small planets/candidates have another small planet on an outer orbit and the planet occurrence rate does not appear to drop beyond $P = 80$ days (e.g., Fressin et al. 2013; Dressing & Charbonneau 2015). Together, these samples will signal the dawn for demographic studies on small planets on longer orbits and in the HZ.

3 Relevance to Research at Carnegie DTM and Project Timeline

In order to detect and characterize small exoplanets and eventually find Earth-like planets, we need to bring the RV precision to the next level. The RV community has recognized seven components in achieving a higher precision: careful choice of stars, understanding stellar activity, stable spectrographs, stable fiber input, exquisite calibrators, eliminating tellurics, and robust data analysis (Yale EPRV2 Workshop, 2015). The community has made tremendous progress in hardware and is pushing hard in the understanding of stellar activity both theoretically and observationally. Likewise, the problems of tellurics and data analysis demand serious efforts, but such efforts are largely missing at the moment.

I am uniquely positioned to tackle these two problems, with extensive experience in both areas. Carnegie DTM is the ideal place for my research project, with strong expertise in precise RV data analysis (Paul Butler) and access to PFS. Moreover, I am poised to improve the precision of PFS and take full advantage of its scheduled upgrade in 2016-2017. The upgraded PFS will have a pupil slicer which splits each spectral order into several traces. HET/HRS2 (commissioning Jan. 2016) and MINERVA (commissioning Dec. 2015) will be *the very first* RV instruments that have this multi-trace spectral format, which poses challenges to data reduction and RV extraction. As the data person on the MINERVA and PSU HET/HRS2 teams, I will have the first-hand experience and the toolbox to tackle these challenges when arriving at DTM, well prepared for the PFS upgrade. My research project on detecting and characterizing small planets and understanding their demographics also fits in very well with the existing research at DTM, strengthening the current RV exoplanet programs and complementing the direct imaging and astrometric searches.

Timeline: *Year 1, 2016-2017*: *Kepler*/K2 target follow-up; improving the precision of PFS/Keck/HET; reprocessing archival data and publishing improved mass measurements; starting MINERVA survey. *Year 2, 2017-2018*: TESS follow-up; publishing new Doppler pipeline; data analysis commissioning with the upgraded PFS; continuing MINERVA survey and publishing initial results. *Year 3, 2018-2019*: TESS follow-up; publishing long-period small planets detected by PFS/Keck/HET and MINERVA; first year of WIYN/EPDS, RV pipeline test, and publishing initial results.

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