Cover Page for Proposal Submitted to the National Aeronautics and Space Administration

NASA Proposal Number

15-ASTRO15R-0012

NASA PROCEDURE FOR HANDLING PROPOSALS

This proposal shall be used and disclosed for evaluation purposes only, and a copy of this Government notice shall be applied to any reproduction or abstract thereof. Any authorized restrictive notices that the submitter places on this proposal shall also be strictly complied with. Disclosure of this proposal for any reason outside the Government evaluation purposes shall be made only to the extent authorized by the Government.

SECTION I - Proposal Information

Principal Investigator	E-mail Address	Phone Number
Jason Wright	jtwright@astro.psu.edu	814-863-8470

Street Address (1)	Street Address (2)
525 Davey Laboratory	

City	State / Province	Postal Code	Country Code
University Park	PA	16802	US

Proposal Title : **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

Proposed Start Date	Proposed End Date	Total Budget
09 / 01 / 2015	08 / 31 / 2016	No budget required

SECTION II - Application Information

NASA Program Announcement Number	NASA Program Announcement Title
NESSF15R	NASA Earth and Space Science Fellowship 2015 Renewal

For Consideration By NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*

Earth Science

Date Submitted	Submission Method	Grants.gov Application Identifier	Applicant Proposal Identifier
03 / 16 / 2015	Electronic Submission Only		

Type of Application	Predecessor Award Number	Other Federal Agencies to Which Proposal Has Been Submitted
New		

International Participation	Type of International Participation
No	

SECTION III - Submitting Organization Information

DUNS Number	CAGE Code	Employer Identification Number (EIN or TIN)	Organization Type
003403953	7A720		8H

Organization Name (Standard/Legal Name)	Company Division
Pennsylvania State University	

Organization DBA Name	Division Number
PENN STATE	

Street Address (1)	Street Address (2)
201 OLD MAIN	

City	State / Province	Postal Code	Country Code
UNIVERSITY PARK	PA	16802	USA

SECTION IV - Proposal Point of Contact Information

Name	Email Address	Phone Number
Jason Wright	jtwright@astro.psu.edu	814-863-8470

SECTION V - Certification and Authorization

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in this solicitation.

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name	AOR E-mail Address	Phone Number
Melissa Gensimore	msr9@psu.edu	814-863-0301

AOR Signature *(Must have AOR's original signature. Do not sign "for" AOR.)*	Date

PI Name : **Jason Wright**	NASA Proposal Number
Organization Name : **Pennsylvania State University**	15-ASTRO15R-0012

Proposal Title : **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION VI - Team Members

Team Member Role	Team Member Name	Contact Phone	E-mail Address
PI	**Jason Wright**	**814-863-8470**	**jtwright@astro.psu.edu**
Organization/Business Relationship		Cage Code	DUNS#
Pennsylvania State University		**7A720**	**003403953**
International Participation	U.S. Government Agency		Total Funds Requested
No			**0.00**

Team Member Role	Team Member Name	Contact Phone	E-mail Address
Graduate/Undergraduate Student	**Sharon Xuesong Wang**	**814-321-7236**	**xxw131@astro.psu.edu**
Organization/Business Relationship		Cage Code	DUNS#
Pennsylvania State University		**7A720**	**003403953**
International Participation	U.S. Government Agency		Total Funds Requested
No			**0.00**

PI Name : **Jason Wright**	NASA Proposal Number
Organization Name : **Pennsylvania State University**	15-ASTRO15R-0012

Proposal Title : **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION VII - Project Summary

Our project is on improving the radial velocity (RV) precision of several leading RV instruments, including Keck/HIRES and the 9.2m Hobby-Eberly Telescope (HET) with its High Resolution Spectrograph (HRS), which are the leading facilities for extensive Kepler follow-up observations as well as independent large and deep RV surveys. We also work with two precise RV instruments on small telescopes: CHIRON and the upcoming MINiature Exoplanet RV Array (MINERVA), which has or will have even higher RV precision.

In our original proposal, our plans include: (1) removing the ~ 1 m/s RV systematics caused by telluric (water absorption) lines; (2) validating the calibrator: the iodine atlas for several instruments; (3) improving the wavelength-dependent statistical weighting; (4) improving data reduction and instrument modeling. We have made significant progress on all fronts, and carried out advanced studies and next-stage works for all items above. To be specific:

(1) We went beyond our original plan and created, for the first time, stellar spectral templates that are free of telluric contamination, and we are also implementing forward modeling of telluric lines. These two advances improved even further the removal of RV systematics caused by telluric lines. We are in the final step of completing this work, and will re-analyze data for low-mass Kepler systems and dynamically rich planetary systems and publish our work.

(2) We have successfully carried out the promised echelle spectrograph observation of iodine cells and validated the iodine atlas of McDonald 2.7m iodine cell, and ready for validation of MINERVA cell. More importantly, we have found evidence, for the first time in precise RV work, for changing cell properties for the HET/HRS iodine cell, for which we turn to theoretical code for further analysis and potentially production of even more accurate iodine atlases.

(3) & (4): We have found a better spectral PSF model for HET/HRS, which could be applied to other fiber-fed next-generation RV instruments as well. We are working towards better fitting of HET/HRS data, which will potentially bring >10 years of archival data to a higher RV precision and more planet discoveries or better characterization.

We are building the next-generation RV analysis code in Python for current and future RV surveys. The code is public, highly modular, and will incorporate modern numerical and statistical package for more robust RV estimate, using advanced packages with MCMC and Gaussian processes.

We are preparing to publish our work in two papers, and our new Python code will also be documented in peer-reviewed literature. The work in this project was presented as part of a Solar, Stellar, and Planetary Seminar talk at Harvard/CfA in October 2014, and will be presented in future meetings such as the Extreme Precise Radial Velocity Workshop in July 2015 at Yale, where I am invited to host a discussion session addressing the topic of telluric contamination in precise RV.

PI Name : Jason Wright	NASA Proposal Number
Organization Name : Pennsylvania State University	15-ASTRO15R-0012

Proposal Title : Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry

SECTION VIII - Other Project Information

Proprietary Information

Is proprietary/privileged information included in this application?

Yes

International Collaboration

Does this project involve activities outside the U.S. or partnership with International Collaborators?

No

Principal Investigator	Co-Investigator	Collaborator	Equipment	Facilities
No	No	No	No	No

Explanation :

NASA Civil Servant Project Personnel

Are NASA civil servant personnel participating as team members on this project (include funded and unfunded)?

No

Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year
Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs

PI Name : **Jason Wright**	NASA Proposal Number
Organization Name : **Pennsylvania State University**	15-ASTRO15R-0012

Proposal Title : **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION VIII - Other Project Information

Environmental Impact

Does this project have an actual or potential impact on the environment?	Has an exemption been authorized or an environmental assessment (EA) or an environmental impact statement (EIS) been performed?
No	**No**

Environmental Impact Explanation:

Exemption/EA/EIS Explanation:

PI Name : **Jason Wright**	NASA Proposal Number
Organization Name : **Pennsylvania State University**	15-ASTRO15R-0012

Proposal Title : **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION VIII - Other Project Information

Historical Site/Object Impact

Does this project have the potential to affect historic, archeological, or traditional cultural sites (such as Native American burial or ceremonial grounds) or historic objects (such as an historic aircraft or spacecraft)?

No

Explanation:

PI Name : **Jason Wright**	NASA Proposal Number
Organization Name : **Pennsylvania State University**	15-ASTRO15R-0012

Proposal Title : **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION IX - Program Specific Data

Question 1 : Proposal Short Title

Answer: Finding Lowest Mass Exoplanet through Improved RV

Question 2 : Scientific Areas of Support

Answer: Astrophysics Research - (If you select this area, proceed to Question 4)

Question 3 : Earth Science Focus Areas

Answers :

Question 4 : Are you a U.S. citizen?

Answer: No

Question 5 : What is your citizenship?

Answer: China

Question 6 : Gender

Answer: Female

Question 7 : Are you an individual with disabilities?

Answer: No

Question 8 : Race/Ethnicity:

Answers :

Asian

Question 9 : Birth State:

Answer: Inner Mongolia Province

Question 10 : Birth Country:

Answer: China

Question 11 : Degree Program:

Answer: Ph.D.

Question 12 : Undergraduate GPA/Field of Study:

Answer: 82/100

Question 13 : Graduate GPA/Field of Study:

Answer: 3.9/4.0

Question 14 : Student Stipend:

Answer:

Sharon Xuesong Wang - Graduate Student Fellow Student Stipen - $24,000

Question 15 : Student Allowance:

Answer:

Health Insurance - $2,310

Question 16 : University Allowance:

Answer:

Tuition - $3,690

Question 17 : Total Requested (maximum of $30,000)

Answer:

$30,000

PI Name : **Jason Wright**	NASA Proposal Number
Organization Name : **Pennsylvania State University**	15-ASTRO15R-0012

Proposal Title : **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION X - Budget

Total Budget: No budget required

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SECTION I – Proposal Information

Principal Investigator	E-mail Address	Phone Number
Jason Wright	jtwright@astro.psu.edu	814-863-8470

Street Address (1)	Street Address (2)
525 Davey Laboratory	

City	State/Province	Postal Code	Country Code
University Park	PA	16802	US

Proposal Title **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

Proposed Start Date	Proposed End Date	Total Budget	Year 1 Budget	Year 2 Budget	Year 3 Budget	Year 4 Budget	Year 5 Budget
09/01/2015	08/31/2016	No Budget	Required				

SECTION II – Application Information

NASA Program Announcement Number	NASA Program Announcement Title
NESSF15	NASA Earth and Space Science Fellowship 2015

For Consideration by NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*
NASA, headquarters, Science Mission Directorate, Earth Science

Date Submitted	Submission Method	Grants.gov Application Identifier	Applicant Proposal Identifier
03/23/2015	email		OSP180313

Type of Application	Predecessor Award Number	Other Federal Agencies to Which Proposal Has Been Submitted
renewal		

International Participation	Type of International Participation
No	

SECTION III – Submitting Organization Information

DUNS Number	CAGE Code	Employer Identification Number (EIN or TIN)	Organization Type
003403953	7A720		

Organization Name (Legal Name)	Company Division
Pennsylvania State University	

Organization DBA Name	Division Number
PENN STATE	

Street Address (1)	Street Address (2)
201 Old Main	

City	State/Province	Postal Code	Country Code
University Park	PA	16802-7000	USA

SECTION IV – Proposal Point of Contact Information

Name	E-mail Address	Phone Number
Jason Wright	jtwright@astro.psu.edu	814-863-8470

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- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the two Certifications and one Assurance contained in this NRA (namely, (i) the Assurance of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs, and (ii) Certifications, Disclosures, and Assurances Regarding Lobbying and Debarment & Suspension.

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name	AOR E-mail Address	Phone Number
Melissa Gensimore	msr9@psu.edu	814-863-0301

AOR Signature (*Must have AOR's original signature. Do not sign "for" AOR.*) **Date**

Melissa Gensimore

PI Name: Jason Wright	NASA Proposal Number
Organization Name: Pennsylvania State University	
Proposal Title: Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry	

SECTION VI – Team Members

Team Member Name	E-mail Address	Phone Number
Jason Wright	jtwright@astro.psu.edu	814-863-8470
Organization Name	**Team Member Role**	**International Participation**
Pennsylvania State University	PI	No
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**
		0.00

Team Member Name	E-mail Address	Phone Number
Sharon Xuesong Wang	xxw131@psu.edu	814-321-7236
Organization Name	**Team Member Role**	**International Participation**
Pennsylvania State University	Graduate/Undergraduate Student	No
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**
		0.00

Team Member Name	E-mail Address	Phone Number
Organization Name	**Team Member Role**	**International Participation**
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**

Team Member Name	E-mail Address	Phone Number
Organization Name	**Team Member Role**	**International Participation**
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**

Team Member Name	E-mail Address	Phone Number
Organization Name	**Team Member Role**	**International Participation**
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**

Team Member Name	E-mail Address	Phone Number
Organization Name	**Team Member Role**	**International Participation**
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**

Team Member Name	E-mail Address	Phone Number
Organization Name	**Team Member Role**	**International Participation**
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**

Team Member Name	E-mail Address	Phone Number
Organization Name	**Team Member Role**	**International Participation**
U.S. Government Agency Participation	**U.S. Government Agency**	**Total Funds Requested**

PI Name: **Jason Wright**	NASA Proposal Number
Organization Name: **Pennsylvania State University**	
Proposal Title: **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**	

SECTION VII – Project Summary

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We are preparing to publish our work in two papers, and our new Python code will also be documented in peer-reviewed literature. The work in this project was presented as part of a Solar, Stellar, and Planetary Seminar talk at Harvard/CfA in October 2014, and will be presented in future meetings such as the Extreme Precise Radial Velocity Workshop in July 2015 at Yale, where I am invited to host a discussion session addressing the topic of telluric contamination in precise RV.

PI Name: **Jason Wright**	**NASA Proposal Number**
Organization Name: **Pennsylvania State University**	

Proposal Title: **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION VIII – Other Project Information

Proprietary Information

Is proprietary/privileged information included in this application?
Yes

International Collaboration

Does this project involve activities outside the U.S. or partnership with International Collaborators?
No

Principal Investigator	Co-Investigator	Collaborator	Equipment	Facilities
No	**No**	**No**	**No**	**No**

Explanation:

NASA Civil Servant Project Personnel

Will NASA civil servant personnel work on this project?
No

Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year
Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs

PI Name: Jason Wright	NASA Proposal Number
Organization Name: Pennsylvania State University	
Proposal Title: **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**	

SECTION VIII – Other Project Information

Environmental Impact

Does this project have an actual or potential impact on the environment?	Has an exemption been authorized or an environmental assessment (EA) or an environmental impact statement (EIS) been performed?
No	**No**

Environmental Impact Explanation:

Exemption/EA/EIS Explanation:

PI Name:	**NASA Proposal Number**
Organization Name: **Pennsylvania State University**	

Proposal Title: **Finding the Lowest Mass Exoplanet with Improved Radial Velocimetry**

SECTION VIII – Other Project Information

Historical Site/Object Impact

Does this project have the potential to affect historic, archeological, or traditional cultural sites (such as Native American burial or ceremonial grounds) or historic objects (such as an historic aircraft or spacecraft)?

No

Explanation:

.

*Maximum 50 characters. **

Finding Lowest Mass Exoplanet through Improved RV

Scientific Areas of Support

*This choice should match the Option for Proposal Submission chosen by your advisor when this record was created. **

○ Earth Science - (If you select this area, proceed to Question 3)

○ Heliophysics Research - (If you select this area, proceed to Question 4)

○ Planetary Science Research - (If you select this area, proceed to Question 4)

◉ Astrophysics Research - (If you select this area, proceed to Question 4)

Earth Science Focus Areas

Select at least one, but not more than two!

☐ Climate Variability and Change

☐ Atmospheric Composition

☐ Carbon Cycle and Ecosystems

☐ Water and Energy Cycle

☐ Weather

☐ Earth Surface and Interior

Are you a U.S. citizen?

*

○ Yes

◉ No

What is your citizenship?

*If you are not a U.S. citizen, please provide your country of citizenship. **

China

Gender

*

◉ Female

○ Male

*

- [ ] Yes
- [x] No

Race/Ethnicity:

Check all that apply. Furnishing the information on the application form is voluntary.

- [ ] American Native or Alaskan American
- [ ] Hispanic or Latino
- [x] Asian
- [ ] Pacific Islander/Native Hawaiian
- [ ] African American, not of Hispanic Origin
- [ ] White, not of Hispanic Origin

Birth State:
*In what state were you born?**

Inner Mongolia Province

Birth Country:
*In what country were you born?**

China

Degree Program:
*In what degree program are you enrolled?**

- [ ] Masters
- [x] Ph.D.

Undergraduate GPA/Field of Study:
*What is your undergraduate GPA/Field of Study?**

82/100

Graduate GPA/Field of Study:
*What is your graduate GPA/Field of Study? (If applicable) **

3.9/4.0

.

*The student stipend is $24,000 per year and should be comparable with the prevailing stipend rate on the student's campus. Clear justification must be made and approved by the Authorizing Institutional Official of the university if the amount of the student stipend requested is greater than $24,000. Students are encouraged to work with their advisor and university Office of Sponsored Research in determining the appropriate allocation in each budget category. The stipend must be prorated if anticipated tenure is less than twelve months. **

Sharon Xuesong Wang - Graduate Student Fellow Student Stipen - $24,000

Student Allowance:

*The student allowance is $3,000 and should be itemized to include anticipated use of the grant funding for, i.e., travel to conferences and seminars, health insurance policy, books, etc. Requested budget in the two allowance categories may be exchanged, as long as the total sum of the two categories does not exceed $6,000. Students are encouraged to work with their advisor and university Office of Sponsored Research in determining the appropriate allocation in each budget category. The student allowance must be prorated if anticipated tenure is less than twelve months. **

Health Insurance - $2,310

University Allowance:

*The university allowance is $3,000 and should be itemized to include anticipated use of the grant funding for, i.e., tuition and fees, etc. Requested budget in the two allowance categories may be exchanged, as long as the total sum of the two categories does not exceed $6,000. Students are encouraged to work with their advisor and university Office of Sponsored Research in determining the appropriate allocation in each budget category. The university allowance must be prorated if anticipated tenure is less than twelve months. **

Tuition - $3,690

Total Requested (maximum of $30,000)

*The maximum NESSF award is $30,000 per year. Not all awards require $30,000 per year. Enter the total of the combined items 16 through 18 above. **

$30,000

Finding the Lowest Mass Exoplanets with Improved Radial Velocimetry: 2015 Progress Report

Sharon Xuesong Wang

1 Summary of Project and Orignal Plans

Our project is on improving the radial velocity (RV) precision of several leading RV instruments, including Keck/HIRES and the 9.2m Hobby-Eberly Telescope (HET) with its High Resolution Spectrograph (HRS), which are the leading facilities for extensive *Kepler* follow-up observations as well as independent large and deep RV surveys. We also work with two precise RV instruments on small telescopes: CHIRON and the upcoming MINiature Exoplanet RV Array (MINERVA), which has or will have even higher RV precision.

In our original proposal, our plans include:
(1) removing the > 1 m/s RV systematics caused by telluric lines;
(2) validating the calibrator: the iodine atlas for several instruments;
(3) improving the wavelength-dependent statistical weighting;
(4) improving data reduction and instrument modeling.

We have made significant progress on all fronts, and carried out advanced studies and next-stage works for all items above, as detailed in Section 2. We plan to finish the ongoing work described in Section 2 before the end of this funding cycle, and we lay out our plans for the next one, starting September 1 2015, in Section 3.

2 Progress and Achievements

We describe our progress on item (1) in Section 2.1, item (2) in Section 2.2 and item (4) in Section 2.3. Our new work described in Section 2.4 address both (3) and (4).

We plan to publish the work described in Section 2.1 through 2.3 in two papers, and the work of Section 1.3 is in the form of a new code, written in *Python*, that is made available to the public and will also be documented in peer-reviewed literature. Most of the work described here was presented in a Solar, Stellar, and Planetary Seminar talk at Harvard/CfA in October 2014, and will be presented in future meetings such as the Extreme Precise Radial Velocity Workshop in July 2015 at Yale, where I am invited to host a discussion session addressing the topic discussed in Section 2.1, and also a couple of more other future meetings in 2015–2016.

2.1 Telluric-Free Stellar Templates and Forward Modeling of Telluric Lines

Earth's atmosphere creates absorption lines (telluric lines) in the observed spectra based on which we derive the RVs of the stars. These telluric lines impersonate stellar lines but do not exhibit Doppler shifts, and thus they creates a bias to the measured RV, at a level of at least ~ 1 m/s. Our original plan was to improve the mask we used for throwing out the telluric-contaminated spectral regions, and also to tune the fitter in our modeling code to adjust to this change.

However, during the past year, we have found that more elaborate solutions rather than simply "ignoring" the telluric regions would be more efficient in correcting the biases. As a result, we have made two major progresses:

(a) We have created, for the first time, stellar spectral templates (reference spectrum to measure the RV against) that are free of telluric contamination.

(b) We are incorporating a full forward-modeling module into the existing RV code to model the telluric lines in the star+iodine observations (work in final step).

Figure 1 illustrates the improvements made by these two new efforts. Similarly to Figure 1 shown in our original proposal, they show the RMS of RVs of a standard star observed by Keck before and after our telluric treatment. Different from the old Figure 1, this set of RVs were derived from a particular stellar template observation which had large amount of telluric contamination (i.e. deep water lines caused by humid observing condition). Our old approach of ignoring telluric-contaminated regions would bring only marginal improvement on these RVs. However, with our telluric-free stellar template and preliminary modeling implementation, a significant portion of the aliasing signal caused by the telluric lines is successfully removed (the trend shown in the third panel). We also see reduction of powers in the periodogram at harmonics of a sidereal year, which means that for future planet detection, successful removal of telluric-induced aliasing signal would boost detection confidence level or even reveal planet signals that otherwise would not be able emerge in the periodograms.

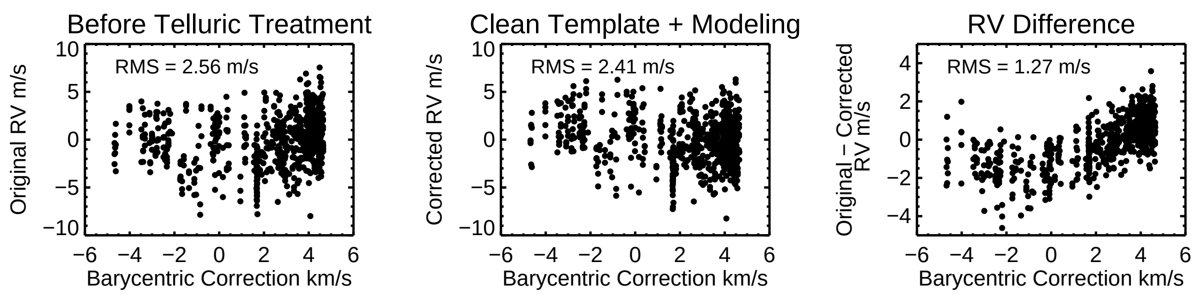

Figure 1: Measured precise radial velocities of a standard star observed with Keck/HIRES as a function of barycentric correction (i.e. Earth's radial velocity away from the target). Our treatment of telluric lines has successfully removed over 1 m/s systematic noise even for this particularly challenging stellar template (panel 3; note the change in scale on y-axis).

We have also applied our code to a couple more test targets at Keck, and we are confident that, with telluric-free templates and full incorporation of telluric lines in the forward-modeling process, we will be able improve the RV precision and accuracy for many targets at Keck, especially the stars which have low-mass, low-RV amplitude planets, such as some of the *Kepler* targets.

Here is a more detailed description of the progress, including ongoing work:

For (a): Stellar spectral templates are derived based on on-sky observations of the target star without an iodine cell and thus is also subject to telluric contamination. We have created a pipeline for producing telluric-free stellar template for Keck (also adaptable for other instruments). Using the telluric simulation package TERRASPEC (written by Chad Bender, Penn State, based on the HITRAN molecular line database; Rothman et al. 2013), we are able to determine the oxygen and water column densities based on the red portion of the spectrum near 7000Å and construct telluric line model for the bluer iodine region of the spectra. Then for each step in the process of template creation, we are able to model the telluric lines and therefore remove it form the end product.

We are now collaborating with the CHIRON group at Yale (Debra Fischer and Matt

Giguere) to provide them with a telluric-free τ Ceti template, to enhance the RV accuracy and precision on this important RV standard star for better understanding of stellar activity induced RV signal. We are also collaborating with John A. Johnson's group at Harvard to produce an even more superior stellar template which is derived based on many star+iodine observations.

For (b): For the star+iodine observations (the RV observations), we have implemented basic telluric line model plug-in function in our RV code as a first step, where the water column density would be a fixed value for all observations. We are constructing the module which would fit for the water column density for each observation and construct different telluric models. This would be the final step to fully modeling the telluric lines in RV observations, and thus provide the maximal capability of removing the biases within the frame of our current RV code (for work beyond this, see Section 2.4).

2.2 Evidence for Changes of Iodine Calibration Cells and Solutions

A "ground truth" iodine atlas is crucial for the precise iodine radial velocimetry. It is used for modeling the observed iodine lines in the stellar+iodine RV observation to anchor the absolute wavelengths and the spectrograph response function. Such a "ground truth" atlas is normally obtained through a Fourier Transform Spectrometer (FTS). Our previous work has revealed potential problems with FTS atlases, and in our original proposal, we promised to use the TS12 arm of the Tull spectrograph at McDonald Observatory to validate the qualities of the FTS iodine atlases for HET/HRS, MINERVA, and the McDonald 2.7m.

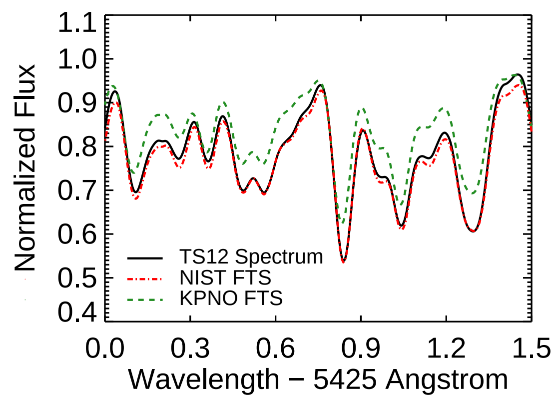

Figure 2: TS12 spectrum vs. NIST FTS vs. KPNO FTS for the HET/HRS iodine cell at 70°C, all convolved down to a resolution of $R = 60,000$ (typical RV observation resolution) for comparison purposes.

In October 2014, the TS12 observations were successfully carried out. All data are reduced and we have made comparisons between the TS12 spectra and FTS scans. For the 2.7m cell, its TS12 spectrum matches very well to its FTS atlas, again (together with the 2.1m cell data from 2013) proving that TS12 is an appropriate tool for validating FTS atlases. The TS12 spectra for the MINERVA cell is also ready, and right now we are waiting for the FTS expert on our team to reduce the MINERVA FTS data for comparison, which is expected to be done before June (first light of the proto-type MINERVA spectrograph).

Finally, for the HET/HRS iodine cell, we have taken its TS12 spectra at three different temperatures (50, 60, and 70°C; the RV working temperature for the cell is 70°C). Our main findings (both are first-time discoveries for iodine RV work) are as follows:

(a) Temperature change (5–10°C) in iodine cell matters: The long suspected temperature-induced iodine spectrum change was finally confirmed, which is seen very visibly among the TS12 spectra taken at three different temperatures. Based on our NIST FTS atlases taken at two different temperatures, temperature change on the order of 10°C should not induce visible line changes. However, we suspected issues with temperature control and data calibration with the NIST atlases, and the TS12 spectra confirmed our suspicion and proved that temperature on the order of even 5°C would have manifested as significant line changes (for precise RV purposes).

(b) The HET/HRS cell very likely has changed over time: The TS12 spectra match better with the more recent but potentially problematic NIST FTS atlas, which had worse χ^2_ν fit than the old KPNO atlas. This is completely unexpected and suggests that: the NIST atlas was perhaps taken at the correct temperature (i.e. the KPNO atlas was at a lower and wrong temperature) but the worse fit was caused by calibration errors in the atlas; and/or the temperature or optical depth of the cell changes over the course of 20 years, and hence the differences between these three spectra (Figure 2); and further more, it is possible that the temperature/optical depth of the cell changes on a much shorter scale during the observing seasons, and most of the time it stays at a temperature/optical depth that is similar to the one when the KPNO atlas was taken (e.g. actually at a lower temperature though thought to be at 70°C).

To answer these questions and to actually resolve the issue of a changing cell, we have found a possible third venue that might provide reliable, ultra-high resolution, and wavelength calibrated iodine atlas – a theoretical code that computes iodine transmission spectrum (at any specified temperature) based on both physics and empirical calibrations (IodineSpec5; Knöckel et al. 2004). We have successfully installed and learned the code, and properly translated the code output into practical astrophysical units and to account for optical depth differences. We are now using the code to diagnose the HET/HRS cell to study whether the cell temperature or optical depth changes (as reflected by actual HET/HRS observations instead of FTS/TS12 atlas observations), and to explore the possibility of using the theoretical output as the new "ground-truth" atlas.

2.3 A Better Instrumental Profile Model for Fiber-Fed Spectrographs

One limiting factor for the current RV precision of HET/HRS is the modeling of its instrumental profile (IP, or the spectrograph response function or spectral PSF). In our original proposal, we promised to look for a better IP for HET/HRS, as a test case for future fiber-fed precise RV spectrographs, such as the upcoming MINERVA and the future fiber-fed Keck/HIRES.

The old IP model for HET/HRS is the very versatile, orthogonal, 11-parameter Gauss-Hermite polynomials (GH). However, through our analyses using calibration frames in Fourier space, we have found that although GH is probably sufficient to describe the HET/HRS IP, because of its ultra flexibility and multi-parameters, it deeply complicates the χ^2 space and very often hinders the fitter from finding the true minimal (to address the issue with the fitter, see next section and future plans). A simpler IP is therefore in great desire.

We have found a better IP function for HET/HRS, the modified Moffat function:

$$[1 + (x/\theta)^2]^{-\beta\cdot(x/\delta)^2} \tag{1}$$

It is called the "modified" Moffat function because the original Moffat function does not have the $(x/\delta)^2$ term. We added this term to add flexibility at the wings to enable change of characteristic IP width while preserving wing profile. Figure 3 illustrates the results: black line is the χ^2_ν distribution for fitting spectral chunks in an observation with GH IP; red line is for modified Moffat IP; and dashed red is for fixing the IP in the shape of a thorium line (proving that thorium line is a good proxy for IP). This 3-parameter function fits the HET/HRS data almost equally well, and it fits very well to the observed thorium line (Figure 3 inset, dots are observed thorium line).

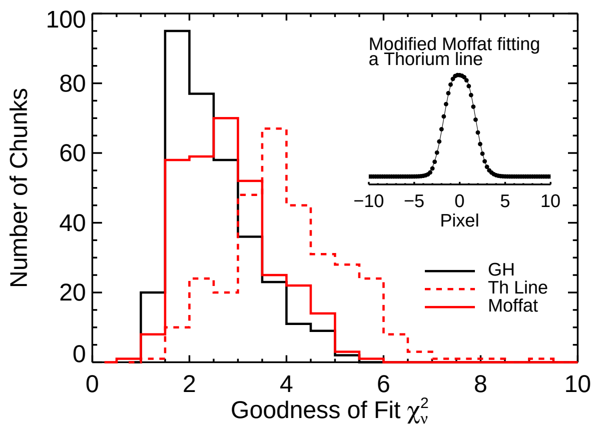

Figure 3: Histogram of goodness of fit, χ^2_ν, values for spectral chunks of a calibration frame. The modified Moffat function (red) performs almost equally well while having only 3 parameters, compared with the complicated 11-parameter GH function (black solid).

This modified Moffat function is potentially applicable to other fiber-fed instruments, since these instruments tend to have IPs with the same characteristic flat top and sharp wings.

Our ongoing work includes: adding small perturbation terms to the modified Moffat IP to account for IP asymmetry and subtle wings due to scattered light etc.; disentangling the effects of a bad IP model and bad iodine atlas (as described in previous section); and other tests with the aim to bring χ^2_ν for fitting HET/HRS data to ~ 1, which is what is achieved at Keck and enabled ~ 1 m/s RV precision.

2.4 Building the Next-Generation Data Analysis Tools for Future RV Surveys

The work described in the previous sections is all done with the California Planet Search Consortium Doppler code, which is a legacy code in IDL primarily written by John A. Johnson but with legacy parts that date back to the work of Marcy & Butler as early as 1989. It is proven to be able to produce RVs at ~ 1 m/s precision with Keck data, and is behind the discoveries and characterization of numerous exoplanets, including the first Earth-mass Earth-radius planet Kepler-78b (Howard et al. 2013; Pepe et al. 2013).

Yet, this great legacy code has many drawbacks: It is based on a simple home-constructed Levenberg-Marquardt least χ^2 fitter (LM fitter) which has high requirement on initial guesses for parameters and is terribly inefficient and inadequate in exploring the χ^2 space. It also has many legacy house keeping parts and complicated structures that makes it hard to upgrade, adopt for other instruments, and add new modules and functions.

We have set out to write a new RV code that is built in *Python*. The new code carries on the valuable successful parts of the CPS code over, and more importantly, built to be highly modular and thus will be easy to adopt for other instruments or to plug in modern numerical and statistical tools.

We have completed the structural design and built the core part of the code, where it fits one spectral chunk using any designated maximum likelihood style fitter (e.g. a better LM fitter, which yield a smaller χ^2_ν value when testing with Keck spectral chunks). We plan to make it fully functional for the commissioning of MINERVA in Summer 2015 (see Section 3 for future plans to implement more advanced tools).

Currently there is a large cry in the RV community for a public, high-precision RV code which would allow better transparency and cross checking of results. We have made our code publicly available through `gitHub`, and we plan to document the methods in peer-reviewed literature once the code is ready to be released for the greater community.

3 Future Plans

We have briefly touched on some of the future plans for the next funding cycle in the sections above. Here to summarize and elaborate:

1. After finishing implementing forward-modeling of telluric lines in the RV code, we plan to re-run RV analyses for important targets such as the *Kepler* systems with low-mass planets (e.g. the Marcy et al. 2014 targets), and dynamically interesting systems such as 55 Cancri, GJ 876, υ Andromedae, and GJ 581 (as promised in the original proposal). Publication on the telluric line treatments and any interesting science outcome from the re-analyses is among our top priorities.

2. If we can successfully improve the fitting with HET/HRS data with better iodine atlas and better IP modeling, we plan to re-run systems with low-mass planets and systems that are not among the Keck target list or not as frequently observed, to see if a higher precision will bring discoveries of more planets and better characterization of existing ones. Again, publication of the work on iodine atlas and any science outcome from the re-analyses is our top priority.

3. We plan to implement modern packages into our new RV code for more statistically robust estimates of RVs. In particular, we plan to go Bayesian by using the MCMC package, `emcee`, by Foreman-Mackey et al. (2013), which will essentially eliminate the issues of unstable/inefficient fitter, requirements on initial guesses, and unreliable/ambiguous error bars. Adopting Bayesian methods will also redefine and largely improve the wavelength-dependent statistical weighting process (which we are also currently exploring within the old code frame, in collaboration with Ben Nelson at PSU/Northwestern; as promised in the original proposal). To address the issue of stellar template uncertainties or any other persisting systematic effects in the spectra (e.g. residuals left after modeling out the telluric lines), we plan to implement the `StarFish` package by Czekala et al. (2014), which uses Gaussian processes to account for systematics in spectral modeling. These model packages will bring the Doppler analysis to the next level, and produce a truly modern code for modern RV surveys.

References

Czekala, I., Andrews, S. M., Mandel, K. S., Hogg, D. W., & Green, G. M. 2014, ArXiv e-prints, arXiv:1412.5177

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306

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

Marcy, G. W., Isaacson, H., Howard, A. W., et al. 2014, ApJS, 210, 20

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Rothman, L. S., Gordon, I. E., Babikov, Y., et al. 2013, J. Quant. Spec. Radiat. Transf., 130, 4

Project and Academic Program Schedule

Applicant: Sharon Xuesong Wang
PI: Prof. Jason T. Wright
Penn State University

September 1, 2014	Proposed Start Date of Project
August 2016	Expected Graduate Date of Applicant

Note: The applicant may graduate in August 2015 or in Spring 2016, pending postdoc application result. We will contact our program officer should any change occurs.

The applicant has already passed the qualification and candidacy exams and completed all required courses in the Ph.D. program. The proposed work is part of the applicant's doctoral thesis.

PENNSTATE

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Department of Astronomy & Astrophysics

Friday, March 20, 2015

Dr. Jason T Wright

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To the NESSF Program Managers:

I am writing to recommend renewal for Sharon (Xuesong) Wang's NASA Earth and Space Science Fellowship. Sharon has made very good progress on her project, I would say ahead of her proposed plan and schedule.

Ms. Wang is improving the radial velocity precision of the High Resolution Spectrograph at the Hobby-Eberly Telescope (HET/HRS) and the HIRES spectrograph at Keck Observatory for the purpose of detecting planets orbiting the nearest Sun-like stars. Of particular utility is using these telescopes to study the planetary systems the *Kepler* spacecraft is discovering with rocky planets in the "Habitable Zone"[1]. HET and Keck are the only two large (8–10 meter class) Northern Hemisphere telescopes capable of precise radial velocity measurements, which we use to discover and characterize the orbits of planets orbiting other stars. Sharon has also begun applying this expertise to the MINERVA project at Mount Hopkins, which employs small (0.7-meter) telescopes to find planets orbiting the nearest stars, and will perform important *TESS* followup observations.

Ms. Wang has successfully determined the power spectrum of the Keck/HIRES and HET/HRS instrumental responses, which has become a key tool for diagnosing their abilities (and limitations) in measureing precise Doppler velocities. This power spectrum reveals to us the nature of the missing components of our models of the HET/HRS instrumental response.

Ms. Wang also managed a successful visit to McDonald Observatory to use the Tull spectrograph, which is the highest-resolution astronomical optical echelle spectrograph we are aware of. This 4-day run resulted in the highest signal-to-noise ratio and resolution spectrum of our iodine calibration cells ever made with an echelle. Ms. Wang is comparing these spectra to our spectra from Fourier transform spectrographs to diagnose any inadequacies in them as references for our work.

Ms. Wang is developing a new Doppler code "from scratch" to work on the MINERVA array, and also for the new, upgraded HET/HRS. This code will be free of the inadequacies of the existing legacy code we use, with good

[1] The region around a star where an Earth-like planet or moon would have a surface temperature consistent with liquid surface water.

modularity and flexibility, proper documentation, and modern programming practices.

Ms. Wang has also developed a comprehensive model of the effects of the Earth's atmosphere on stellar spectrum, which she uses to produce realistic synthetic stellar spectra with known Doppler shifts, as they would actually be observed at our telescopes. By feeding these spectra to her Doppler code, she can determine the exact effects of these telluric lines, including innumerable "microtellurics" on our Doppler measurements. Her prior work has revealed that these effects are important at the 1-3 m/s level; this new work will make sufficiently precise descriptions of the effect that we will be able to remove them.

As you can see, Sharon has made outstanding use of her first year's NESSF. I am eager to see what advances her next year brings, and the planets we will discover and characterize as a result.

Jason T Wright
Assistant Professor of Astronomy

The Pennsylvania State University

Office of the Registrar

ADVISING GRADUATE TRANSCRIPT

STUDENT NAME: XUESONG WANG

ADMITTED FROM: TSINGHUA U B S 07/08
DATE OF ADMISSION: FALL 08

--FALL SEMESTER 2008 ---
College: SCIENCE Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 501	FUND ASTRO	3.0	A	12.00
ASTRO 502	FUND ASTROPHYS	3.0	A	12.00
ASTRO 602	SUPV EXP/COLL TCHG	2.0	A	8.00
ASTRO 590	COLLOQUIUM	1.0	A	4.00
ASTRO 527	COMP PHYS & ASTROP	3.0	A	12.00
	Cumulative	10.0	4.00	40.00
	Total	10.0		

--SPRING SEMESTER 2009---
College: SCIENCE Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 585	TOPICS ASTRO AP	3.0	A	12.00
ASTRO 534	STEL STRUC EVOL	3.0	A	12.00
ASTRO 602	SUPV EXP/COLL TCHG	1.0	A	4.00
PHYS 562	QM II	3.0	A-	11.01
	Cumulative	19.0	3.95	75.01
	Total	19.0		

--FALL SEMESTER 2009 ---
College: SCIENCE Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK SEM CLASS: GR

Course		Credits	Grade	Grade Points
PHYS 510	GR I	3.0	A	12.00
ASTRO 589	SEM ASTRO RES	1.0	A	4.00
ASTRO 542	ISM & STAR FORM	3.0	A	12.00
ASTRO 596	INDIVIDUAL STUDIES	3.0	A-	11.01
ASTRO 602	SUPV EXP/COLL TCHG	1.0	A	4.00
	Cumulative	29.0	3.93	114.02
	Total	29.0		

--SPRING SEMESTER 2010---
College: SCIENCE Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK SEM CLASS: GR

Course		Credits	Grade	Grade Points

ASTRO 545	COSMOLOGY	3.0	A	12.00
ASTRO 585	TOPICS ASTRO AP	3.0	A	12.00
STAT 500	APPLIED STAT	3.0	A	12.00
	Cumulative	38.0	3.95	150.02
	Total	38.0		

--FALL SEMESTER 2010 ---

College: SCIENCE   Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK   SEM CLASS: GR

Course		Credits	Grade	Grade Points
AERSP 424	ADV COMPUTER PROGR	3.0	A	12.00
ASTRO 589	SEM ASTRO RES	1.0	A	4.00
ASTRO 596	INDIVIDUAL STUDIES	6.0	A	24.00
	Cumulative	48.0	3.96	190.02
	Total	48.0		

--SPRING SEMESTER 2011---

College: SCIENCE   Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK   SEM CLASS: GR

Course		Credits	Grade	Grade Points
STAT 440	COMP STAT	3.0	A	12.00
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	51.0	3.96	202.02
	Total	51.0		

--FALL SEMESTER 2011 ---

College: SCIENCE   Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK   SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	51.0	3.96	202.02
	Total	51.0		

--SPRING SEMESTER 2012---

College: SCIENCE   Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK   SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	51.0	3.96	202.02
	Total	51.0		

--FALL SEMESTER 2012 ---

College: SCIENCE   Major: ASTRO & ASTROPHYSICS
Campus: UNIVERSITY PARK   SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 589	SEM ASTRO RES	1.0	A	4.00
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	52.0	3.96	206.02
	Total	52.0		

--SPRING SEMESTER 2013--

College: SCIENCE — Major: ASTRO & ASTROPHYSICS

Campus: UNIVERSITY PARK — SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	52.0	3.96	206.02
	Total	52.0		

--FALL SEMESTER 2013 --

College: SCIENCE — Major: ASTRO & ASTROPHYSICS

Campus: UNIVERSITY PARK — SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	52.0	3.96	206.02
	Total	52.0		

--SPRING SEMESTER 2014--

College: SCIENCE — Major: ASTRO & ASTROPHYSICS

Campus: UNIVERSITY PARK — SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	52.0	3.96	206.02
	Total	52.0		

--FALL SEMESTER 2014 --

College: SCIENCE — Major: ASTRO & ASTROPHYSICS

Campus: UNIVERSITY PARK — SEM CLASS: GR

Course		Credits	Grade	Grade Points
ASTRO 601	PH D DIS FULL-TIME			0.00
	Cumulative	52.0	3.96	206.02
	Total	52.0		

------SPECIAL ACTIONS AND NOTES--------------------------

05-14-10 ADMIT DOCTORAL CAND PH D - ASTRO

MINOR IN COMPUTATIONAL SCIENCE

01-21-11 COMPREHENSIVE EXAM PASSED

--------- END OF TRANSCRIPT ---------