

## **Finding Warm Planets Around Cool Stars: Habitable Zone Pathfinder**

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### ***Project Summary***

The date is October 24, 2010. The front page headline in the NY Times announces that scientists have discovered the first planets outside the solar system that are capable of harboring life as we know it. This proposal is aimed at nothing less than making this a reality. The instrument we propose to build and deploy on the Hobby-Eberly telescope is focused on finding earth-mass planets in the "habitable zone" (HZ), a region where liquid water can exist, around the most numerous but least luminous stars in our galaxy.

Finding and charactering extra-solar planets is a rapidly expanding cutting edge area of modern astronomical research that also engages intense public interest. There are few, if any, areas of science that capture the public imagination more effectively. Research results in this dynamic sub-field of Astronomy & Astrophysics are frequently in the news and are regularly listed among the top 10 or 100 science discoveries of the year, decade and even millennium. We will exploit this interest with our strong outreach program in the department. Extra-solar planet research is also the nucleus for the new science of astrobiology with its unique mixture of astronomy, atmospheric sciences, biology, chemistry and geology. In the United States National Research Council's most recent decadal survey for astronomy, *Astronomy and Astrophysics in the New Millenium*, one of the highest priorities for future astronomical research should be to "study the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets." Extra-solar planetary research is now and will remain one of the leading intellectual endeavors as it addresses fundamental questions concerning the origins of our cosmic environment and the origins of life. The instrument we will build is optimized to address the fundamental question of *how common are extra-solar earth-like planets in an environment that could support life.* In addition it will also be capable of exploring other questions ranging from star, brown dwarf and planet formation processes to the nature of the black-hole powered energy engines in the centers of active nuclei galaxies and quasars.

Of the over 200 extra-solar planets discovered to date using a variety of techniques, the vast majority have been discovered using Precision Radial Velocities (PRV) techniques which measure the tiny Doppler shift signature caused by a planetary companion. Our instrument, called Habitable Zone pathfinder (HZP), will pioneer this technique into the near infrared (NIR), a realm is not currently available on 8 to 10 meter telescopes. This is fundamentally important as the NIR region of the spectrum is where the cool M-type stars that are our primary target emit most of their energy. The feeble emission of these objects in the visible spectrum put them beyond the reach of current instruments.

Our technical approach is driven by a balance between detailed modeling and experiment. We have explored the fundamental principles that limit PRV, constructed realistic models simulating likely candidates to demonstrated the ability to recover planet signals and conducted limited experiments with a brass-board instrument to demonstrate an order of magnitude increase in the PRV sensitivity. The intersection of all these considerations leads us to a fiber fed, white pupil echelle spectrograph working in the 1.0- 1.65 micron wavelength region at a spectral resolving power ( $\lambda/\Delta\lambda$ )  $\sim$  40,000. A simultaneous arc-line calibration system will allow us to achieve the  $\sim$ 1 meter/sec precision and long term stability needed to detect earth-mass planets in the habitable zone in our target stars. We plan to deploy the instrument for verification and testing 24 months after award and expect significant science results within the following year.

## 1.0 Science Drivers and Instrument Description

### 1.1) Science Opportunity

The field of extra-solar planet studies leaped from a quiet area involving a few “eccentrics” to the forefront of astrophysics beginning fifteen years ago when the first extra-solar planets were discovered by Evan Pugh Professor Alex Wolszczan who used precision timing of the regular signals from “Pulsars”. This discovery of planets around a “dead” remnant of an exploded star was startling as it was the last place astronomers expected to find planets. Four years later the first extra-solar planet around a normal solar-like star was identified, but this so-called “hot Jupiter” was unlike anything anticipated. The existence of over 200 other planet systems with properties very different than our own has brought about a historic paradigm shift and is leading an astronomical renaissance. Extra-solar planet detection using precision radial velocity (PRV) measurements is by far the most productive technique to date for discovering and characterizing extra-solar planet systems. Even when upcoming space missions such as Kepler increase the number of transit discoveries, PRV measurements will remain necessary as the only means to determine masses. Indeed the instrument we propose here can be a critical pathfinder for selecting targets for a program to characterize planet atmospheres on the next generation space telescope, JWST, scheduled for a 2012 launch

The state of the art for PRV technique is currently  $1\text{-}2\text{ m sec}^{-1}$  and relies on tracking and correcting for subtle changes in the point spread function (PSF) as well as line position at the  $10^{-3}$  pixel level in an instrument. This is nearly exclusively done by imposing an  $\text{I}_2$  absorption spectrum on the target spectrum and is limited to wavelengths in the visible spectrum.

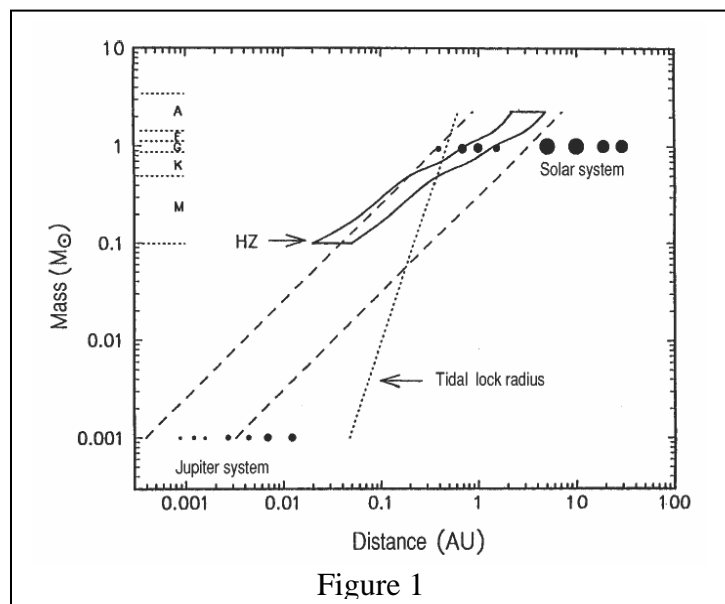


Figure 1

planets in the HZ around these stars that are well within current limits of  $1\text{-}2\text{ m sec}^{-1}$  as is illustrated in Figure 2. Planets in the HZ around more solar-like stars have radial velocity signatures significantly less than  $1\text{ m/sec}$  and are beyond reach for a variety of technical and astrophysical reasons. It is around M stars that we are targeting that it is most likely to find planets in the 1 to 10 earth mass range that are in the habitable zone using radial velocity techniques alone. It is in this range of conditions that presents the highest probability of supporting life as we currently understand it. It is here that we will focus the capability of our instrument and our effort.

The frontier for PRV work has definitely gone downscale in photon energy as we look at M stars which are the least massive and least luminous stable stars. These generally faint objects are much cooler than our sun but present the best opportunity to detect planets in the HZ around stars. Figure 1 is taken from Kasting and Catling (Annu. Rev. Astron. & Astrophys. 2003.41:429-463) and indicates that it is around these  $\sim 3000^\circ\text{K}$  stars habitable planets are possible close to the star.

The low mass of M stars, less than 0.5 solar masses, combined with close in orbits yield radial velocity amplitudes for

The standard PRV techniques that are used at optical wavelengths cannot be used on M stars because M stars are not bright enough at optical wavelengths. However, if one takes advantage of

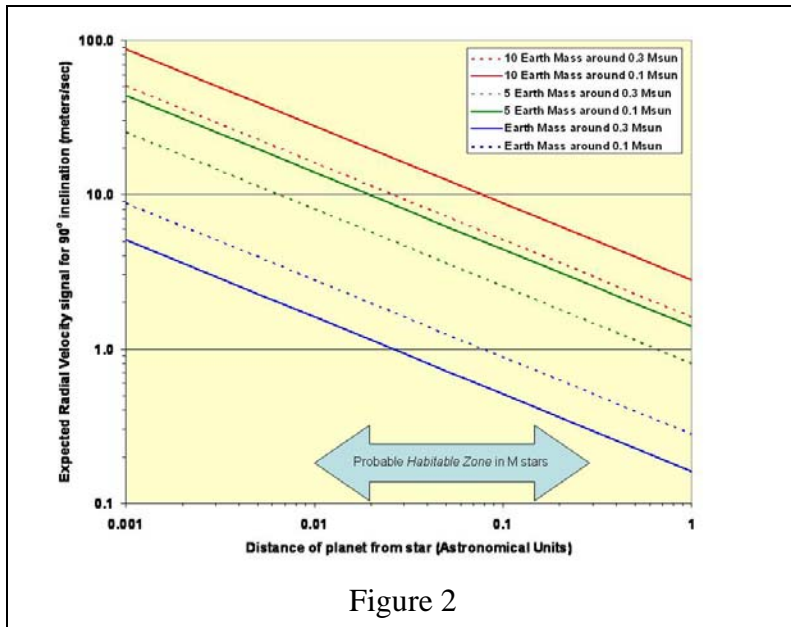


Figure 2

the fact that they emit most of their energy in the near infrared (NIR) hundreds of targets become accessible. Looking at Figure 3 from Pavlenko et al. (2006, A&A 447, 709-717), which is the energy distribution typical of our targets, it becomes clear that the 1 to 1.65 micron region is a much better region studying PRV in these objects than the visible 0.5-0.6  $\mu\text{m}$  region used by established techniques. The downside is that the earth's atmospheric absorption is more complex in this region. There are no established PRV techniques in the NIR and the best extant measurements are 100's of m/sec. We have addressed the lack of established technique in the NIR by

both modeling and testing.

## 1.2) Collateral Science

Central to our approach to HZP is that all key design issues are driven by the planet search science requirements. That said, there are numerous other forefront astrophysical observations that can be made with HZP. Indeed this instrument will allow a host of exciting research opportunities for Penn State scientists and students. We have a long and rich tradition of strong participation by undergraduates in our research and HZP will broaden those opportunities substantially.

### 1.2.1) Cosmology

A fundamental goal of modern cosmology is to map out the ionization history of the Universe and identify the sources that, over the first billion years of cosmic time, drove cosmic re-ionization. Progress here requires the ability to measure the optical depth in neutral hydrogen to objects at a range of redshifts  $z > 6$ . Observations of bright gamma-ray burst afterglows with HZP offers a potential solution to this problem. The extreme brightness of GRBs makes them beacons from the very high-redshift universe, and with the launch of NASA's Swift satellite, the promise of detecting GRBs from this epoch has finally been

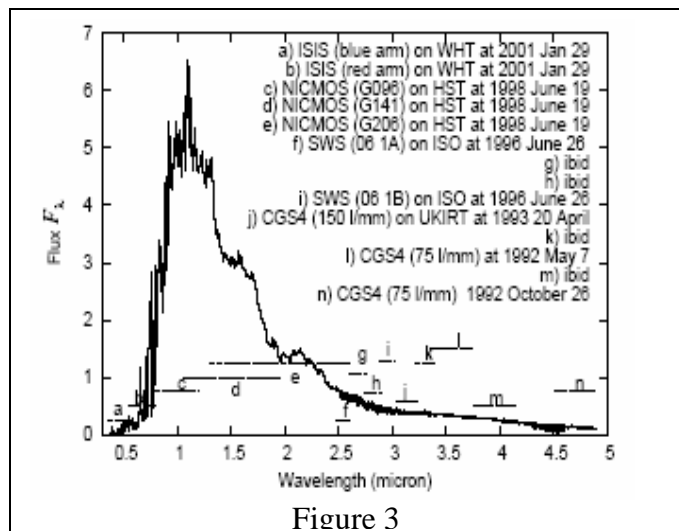


Figure 3

realized. HZP will have the resolution and sensitivity provide new insights into the properties of galaxies and the intergalactic medium at a time when the universe was less than 10 percent of its current age. Spectra of distant quasars (more than ten billion light years from Earth) will contain absorption features from material along the line-of-sight to the quasar; we can learn about the chemical composition and the dynamical state of material in the early universe. This has been one of the most active fields in astronomy for the past two decades, but almost all of the work has been confined to the ultraviolet and visible region of the electromagnetic spectrum; HZP, with its infrared capability, will provide access to the same physical features at much greater distances.

### **1.2.2) Extra-galactic astrophysics and cosmology**

HZP is well-suited for studying weak nuclear activity in nearby galaxies (low-ionization nuclear emission regions, or LINERs). This type of activity is extremely common, occurring in at least 40% of nearby galaxies, but its origin is not known; it could be caused by nuclear star formation or accretion onto a supermassive black hole. Understanding the nature of LINERs has extremely important implications for the evolution of their host galaxies and their connection to quasars, which are the most powerful examples of nuclear activity dating back to a time when the universe was only 1/10th of its present age. HZP can also measure the stellar velocity dispersion in the host galaxies of moderate-redshift quasars. The stellar velocity dispersions are the basis for the most reliable estimate of the supermassive black hole mass in these quasars, which in turn is the single most important parameter in understanding the structure of the quasar central engine.

### **1.2.3) Stellar Evolution**

General relativity + stellar interiors theory makes definite predictions about the rate of precession of the major axis in binary stars. Observations of high mass binaries are contrary to this prediction. It has been suggested that a third body, a G-K dwarf companion, could solve this. The NIR capability of HZP allow straightforward tests of this hypothesis. Isotopic abundances from molecular species in the NIR such as CN place constraints on convective mixing in stars. There is also the possibility of exploiting HZP to do metallicity studies (including isotopic) in cool companions to hot subdwarf stars, leading to insights about the origins and formation mechanisms of these stars

### **1.2.4) Brown Dwarfs**

Brown dwarfs are objects which connects stars to planets. They cover a mass range of a factor of 10. Current surveys including the *Spitzer* Infrared Space Observatory will find large numbers of new objects. HZP high-resolution spectra will enable compositions, temperatures and gravities to be measured. HZP spectra will also enable study of accretion processes and magnetic fields on these objects which will be key to understanding planet formation in these systems.

## **2.0) Technical Approach & Risk mitigation**

To realize HZP for the proposed cost and to meet the proposed schedule is a challenging task. We accomplish that by using a proven optical/mechanical design approach, drawing heavily on our prior experience, conducting detailed modeling to demonstrate viability and retiring major risks by experiment before final design. All these are addressed below.

### **2.0) Modeling**

No one has yet done PRV in the NIR and major reasons are the information content of the NIR spectrum and the effect of the many absorption features due to the earth's atmosphere commingled with the stellar spectrum. Using a model of a typical target star with a planet contaminated with the earth's atmosphere Dr. Wolszczan was able to "recover" the planet signal as is

demonstrated by the sinusoidal signal with a 10m/sec amplitude in Figure 4. The errors are about 1.3 m/sec. This was done for several cases which, like the one we show, are near the extreme we expect to encounter.

## 2.2) Experiment

We have build a “brass-board” experiment to address several issues of uncertainty; stability of IR detectors, calibration techniques and data extraction algorithms. Figure 5 shows the high precision NIR velocity measurements taken in our lab measuring the earth’s rotation. The residual between what is measured and predicted is ~10 m/sec. This is 10 times better than anything published to date in the NIR. While the errors are an order of magnitude higher than our goal they are consistent with predictions from the information content in the solar spectrum and calibration lines in the region observed. Extending these results to HZP yields the desired ~ 1 m/sec.

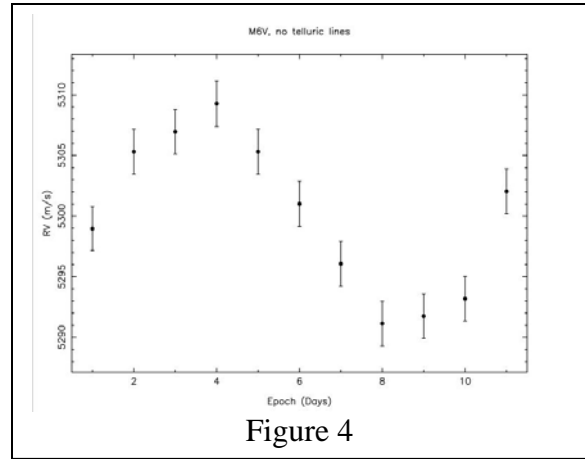


Figure 4

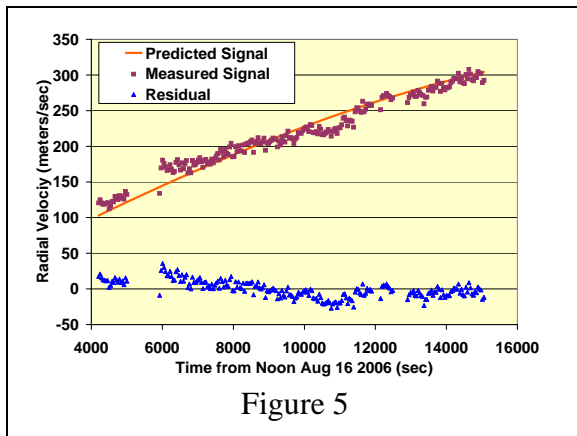


Figure 5

## 2.3) Instrument Implementation.

The instrument will be designed and constructed at Penn State. Our design is based on the highly successful planet finding instrument, HARPS at the European Southern Observatory and the Medium Resolution Spectrograph (MRS) but extended to the NIR. The MRS was built by the PI with NSF funding for the Hobby Eberly telescope at McDonald Observatory in west Texas. The HZP detector will be a new generation 2k x 2k NIR array will allow spectral coverage from 1.0 to 1.65 microns and will be procured as a system. The coverage will be complete at the short wavelength end where the

stellar information content is highest, and diminish to about 80% at the longest wavelength end. The optical design will be a white pupil design intermediate between HARPS and MRS with R3 echelle grating and a 100 mm aperture. We will use a specially designed fiber image slicer with modal scrambling as tested on our brass board. The entire system will be on an Invar optical bench in a temperature controlled enclosure. In addition the grating will be in a vacuum enclosure kept at a temperature no greater of 210 °K with a radiation shield to minimize IR background. The detector will undergo additional cooling to at least 100 °K.

Figure 6 is an optical schematic showing the layout. The collimator is an f/4.3 parabola with the fiber slicer at the prime focus. The 100 mm collimated beam is diffracted by a 31.6 line/mm 71 degree blaze echelle. There is a 50 difference between the incident and diffracted beams with the latter going to a pair of off-axis parabolic mirrors which images the “white pupil” at the echelle onto the cross-disperser (XD) grating. We show these parabolas as a single mirror with a fold inside the radiation shield in Figure 6. There is a small benefit to having this mirror cold and a more detailed trade study may show that it can be in ambient conditions on the optical bench. We have adopted

this non-Littrow in-plane geometry to avoid variable tilt of the pseudo slit along an order as would be present in a quasi-Littrow design as is used in HARPS, UVES or the HRS on HET. The XD

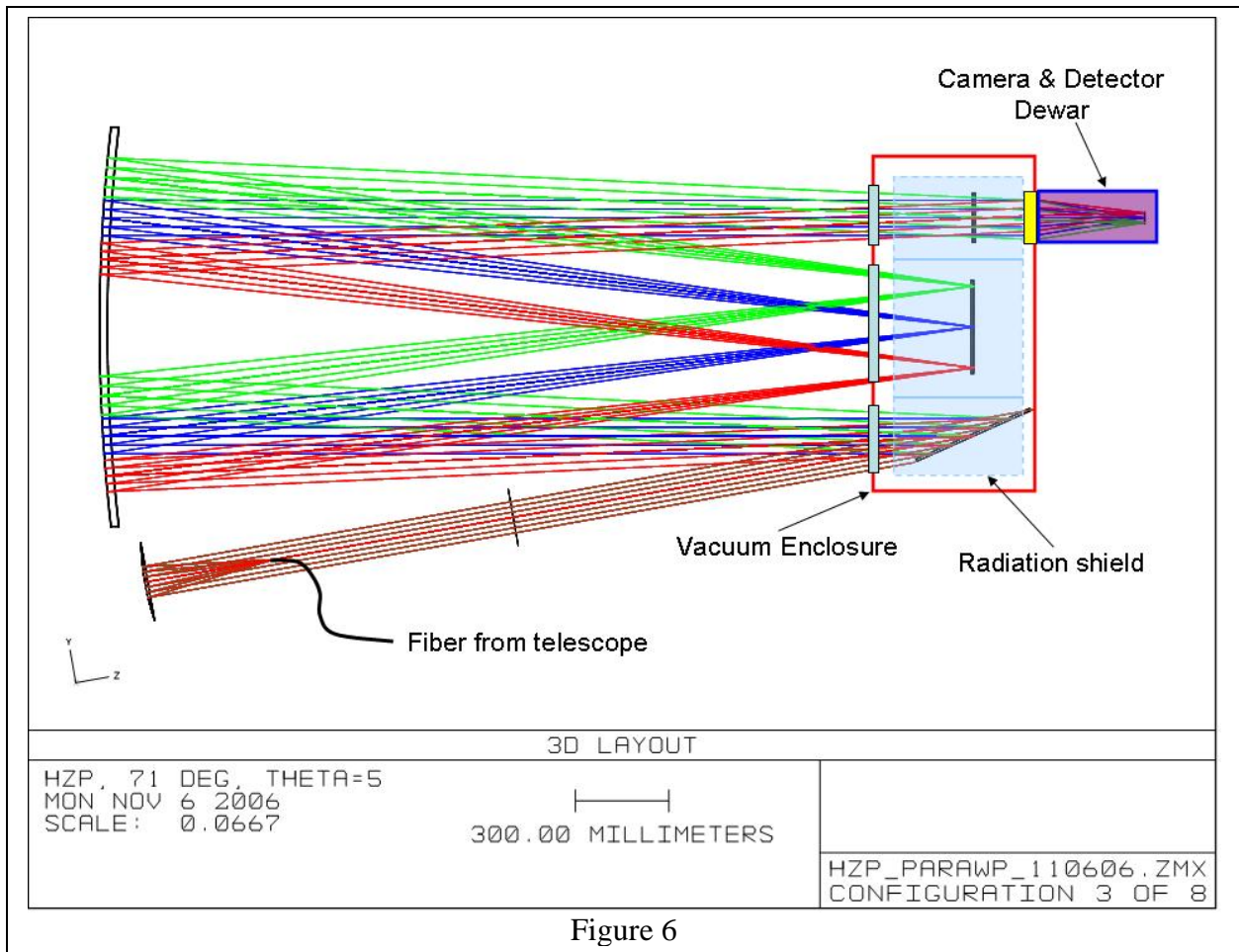


Figure 6

grating will be a VPH. All or part of the camera will be in the detector dewar which will be fully cryogenic to control IR background seen by the detector.

Critical to the performance of HZP is the calibration system. We will use a combination of Th-Ar, Ar, Ne, Kr and Xe lamps mixed in an integrating fiber that is simultaneously exposed along with the stellar spectrum. This technique is successfully used in the visible spectrum by HARPS and we have developed it for use in the NIR on our brass board at Penn State.

#### 2.4) Broader Impact

Students, both undergrad and graduate, will part of the project. This opportunity to help train the next generation of instrumental astronomers, the rarest expertise today, is a vital part of this program and will build on our strong track record in this area. The science enabled with this instrument will be a major focus of a Center for Extra-Solar Planet Research currently being planned and will be the foundation for a broad outreach and education effort to enhance science awareness and education. Finally it will also be available to scientists at the four other HET partner institutions and a small fraction of time will be available to the entire US astronomical community.