THE THIRD WORKSHOP ON

EPRV

EXTREMELY PRECISE RADIAL VELOCITIES

AUG 14-17

STATE COLLEGE, PA, USA

Following the tradition of previous workshops, participants will dig into the "nuts and bolts" of exoplanetary discovery and orbit characterization via Doppler velocimetry, and discuss challenges, lessons learned, and the details of their work, "warts and all".

This edition of the workshop will focus on:

- specific hardware challenges
- lessons learned from the newest generation of EPRV instruments
- new statistical and computational methods for signal extraction, signal analysis, and jitter mitigation
- physical models and spectral diagnostics of stellar granulation, activity, and other sources of jitter

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Motohide Tamura (National Astronomical Observatory of Japan)	
Johanna Teske (Carnegie Observatories)	
Sharon Wang (Carnegie Institute of Washington, DTM)	

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3 Abstracts

Thomas Beatty Pennsylvania State University
Model Independent Stellar Masses and Radii via Gaia and Exoplanet Transits
Using Spitzer transit observations of the the hot Jupiter KELT-11b, we demonstrate the role that precise Gaia parallaxes, coupled with simultaneous photometric, RV, and SED fitting, can play in determining stellar parameters that are largely model-independent. By coupling the parallactic stellar radius measured using the stellar SED, and the stellar density measured using the transit observations, we are able measure the mass of the star KELT-11 essentially empirically. TESS is expected to discover 60 to 80 systems where these measurements will be possible, and the resulting parallactic mass and radius measurements have uncertainties small enough that they will provide observational input into the stellar models themselves.

Eric Bechter University of Notre Dame
Assessing the suitability of H4RG near infrared detectors for precise Doppler measurements
The first diffraction-limited Doppler spectrographs on large telescopes will operate at near-infrared (NIR) wavelengths in order to benefit from the imaging quality delivered by existing AO systems. Beyond the silicon cutoff, hybrid structured mercury-cadmium-telluride (HgCdTe) detectors show promise to provide sufficient sensitivity to enable extremely precise radial velocity (RV) measurements of late-type stars. The most advanced NIR detector commonly available is the Hawaii-2RG (H2RG) detector, manufactured by Teledyne. While the quantum efficiency (QE) of such devices has been shown to be ∼90%, the noise characteristics of these devices, and how they relate to RV measurements, have yet to be quantified. We are characterizing the various noise sources generated by H4RG arrays using numerical simulations. We present recent results using our end-to-end spectrograph simulator in combination with the “HxRG Noise Generator,” which emulates the effects of read noise, residual bias drifts, pink (1/f) noise, alternating column noise, and picture frame noise. Our results have implications for RV error budgets and instrument noise floors that can be achieved with NIR Doppler spectrographs that utilize this kind of detector.

Andrew Bechter University of Notre Dame
Single-mode fibers and precision radial velocities: Maximizing coupling efficiency while minimizing RV errors
"The capability of adaptive optics (AO) systems to deliver corrected starlight is well suited to efficiently couple light into single-mode fibers (SMFs). These fibers, which are an order of magnitude smaller than those in use in radial velocity (RV) instruments today, facilitate the design of compact, high-resolution spectrograph, leading to a highly stable RV instrument.
iLocater, a next-generation instrument under development for the Large Binocular Telescope (LBT), is based upon this design concept. The instrument is a NIR (0.971-1.304 micron), SMF fed, spectrograph (R = 150,000 - 240,000), designed to achieve sub-m/s RV single-measurement precision, a key step towards the study of Earth mass exoplanets orbiting late type stars.
As part of the development of iLocater, on-sky measurements were undertaken in Spring

2016 with the LBT AO system to measure and characterize SMF coupling. We present on-sky results, including the efficiency of SMF coupling, and the effects that limit performance. We discuss strategies to mitigate these errors and provide the expected throughput in the final instrument design. Finally, we examine the expected magnitude of RV errors arising from SMF injection."

Sagi Ben-Ami Harvard-Smithsonian Center for Astrophysics

New Features in the design of the GMT Consortium Large Earth Finder (G-CLEF)

The GMT-Consortium Large Earth Finder (G-CLEF), the first major light instrument for the GMT, is a fiber-fed, high-resolution echelle spectrograph. In the following talk, I will present the optical design of G-CLEF, with an emphasize on the unique solutions derived for the spectrograph fiber-feed, the implementation of VPH cross dispersers coupled to a pre-dispersing prism to increase efficiency at the waveband blue-end, and our novel solutions for a multi-colored exposure meter and flat field system.

Serena Benatti INAF - Astronomical Observatory of Padova

GIARPS@TNG

Since 2012, thanks to the installation of the high resolution echelle spectrograph in the optical range HARPS-N, the Italian telescope TNG (La Palma) became one of the key facilities for the the study of the extrasolar planets. In 2015 TNG also offered GIANO to the scientific community, providing a near-infrared (NIR) cross-dispersed echelle spectroscopy at a resolution of 50,000. The synergy between these two instruments is particularly appealing for a wide range of science cases, especially for the search of exoplanets around young and active stars and the characterisation of their atmosphere. Through ""WOW"" (the funding scheme of the Italian Ministry of the Education, University and Research promoting the research of the Italian community working in the planetary field), the Italian National Institute for Astrophysics (INAF) proposed the simultaneous use of these spectrographs with the aim to achieve high-resolution spectroscopy in a wide wavelength range (0.383 - 2.45μm) obtained in a single exposure, giving rise to the project called GIARPS (GIANO-B & HARPS-N). I will present the project and the activities required to obtain such an instrument configuration as well as the first results of the Commissioning runs. Because of its characteristics GIARPS can be considered the first and unique worldwide instrument providing not only high resolution in a large wavelength band, but also a high precision radial velocity measurement both in the visible and in the NIR arm, since in the next future GIANO-B will be equipped with gas absorption cells.

Ryan Blackman Yale University

Accounting for Chromatic Atmospheric Effects on Barycentric Corrections

Atmospheric effects on stellar radial velocity measurements for exoplanet discovery and characterization have not yet been fully investigated for extreme precision levels. We carry out calculations to determine the wavelength dependence of barycentric corrections across optical wavelengths, due to the ubiquitous variations in air mass during observations. We demonstrate that radial velocity errors of at least several cm/s can be incurred if the wavelength dependence is not included in the photon-weighted barycentric corrections. A minimum of four wavelength channels across optical spectra (380-680 nm) are required to account for this effect at the 10 cm/s level, with polynomial fits of the barycentric corrections applied to cover all wavelengths. Additional channels may be required in poor observing conditions or to avoid strong telluric absorption features.

Cullen Blake University of Pennsylvania

SIMULATIONS OF THE IMPACT OF MICRO-TELLURIC WATER LINES ON RADIAL VELOCITY MEASUREMENTS

Molecular absorption features in Earth's atmosphere present an important source of systematic error for ground-based EPRV measurements. In particular, telluric water vapor absorption poses a challenge as these features are numerous and vary in amplitude with time. Absorption features due to water vapor exist at a low level across the entire optical spectrum, and these "micro-telluric" lines can induce systematic shifts in derived stellar radial velocities. We present results of simulations of the fundamental limits imposed by micro-telluric water vapor lines and evaluate several methods for correcting stellar spectra for these lines, as well as mitigating the impact of these lines on radial velocity measurements. Our simulations incorporate realistic models of the variability of atmospheric properties, as well as the temporal variation of water vapor concentration.

Jennifer Burt MIT

COVERAGE OF THE M-R PLANE FROM A SIMULATED THREE-YEAR TESS FOLLOW-UP SURVEY ON THE APF

We forecast the ability of the Automated Planet Finder (APF) telescope to measure masses for planets from an updated prediction of the TESS planet yield. We have built a full facility simulator that takes into account the telescope and instrument performance (based on our prior years of observational data) as well as basic models for weather, atmospheric seeing and stellar activity. We simulate a three year, RV follow-up survey on the TESS planet candidates that begins after TESS surveys the Northern hemisphere. Our simulations are run using four different, time varying prioritization schemes that optimize minute-to-minute target selections with knowledge of the planets' orbital phase as derived from the transit light curves. We find that over three years, with a 40% share of the telescope, this survey will add $\sim$30 planets smaller than four Earth radii with 5? or better mass measurements to the M-R diagram. These results raise an additional, interesting opportunity to create a M-R diagram populated by planet mass measurements that all have the same systematics and instrumental uncertainties, and all of which underwent the same, retraceable decision making process to determine when they were observed. This well documented observing approach would allow us to identify the observational selection biases that influence how the M-R diagram is populated, apply a quantitative correction for them, and produce a final Bayesian inference of the M-R relation that is not distorted by observer induced effects.

Heather Cegla University of Geneva

CAUTIONARY TALES OF ROSSITER-MCLAUGHLIN ANALYSES: CONVECTIVE PROBLEMS AND NEW SOLUTIONS

When a planet transits its host star, it obscures regions of the stellar surface and induces changes in the line-of-sight (LOS) velocities, known as the Rossiter-McLaughlin (RM) effect. Since the observed velocities depend on the stellar rotation, the RM waveform is sensitive to the star-planet alignment (which provides information on the system's dynamical history). Traditional RM analyses assert that this velocity anomaly can be modelled under a few key assumptions: that the stellar surface is represented by homogenous Gaussian functions, and that rigid body stellar rotation is the sole contributor to the LOS velocities. However, these assumptions are inherently incorrect due to stellar surface magnetoconvection (and other manifestations of magnetic activity), and we have predicted that they can introduce systematic errors in sky-projected obliquities up to 20-30 degrees (Cegla et al. 2016a). To obviate these assumptions, we developed the 'reloaded RM' technique to directly measure the spatially-resolved stellar spectrum behind the transiting planet (Cegla et al. 2016b). As proof-of-concept, we determined both the sky-projected and true 3D obliquity of HD 189733, as well as constrained its level of stellar differential rotational and confirmed agreement with state-of-the-art 3D MHD simulations. More recently, we applied the reloaded RM to the highly-misaligned WASP-8 system, and identified a variation of $\sim$35% in the local photospheric profile contrast that has hitherto gone undetected in classical RM techniques (Bourrier et al. 2017). Consequently, our results indicate the system is 20 degrees more misaligned than that reported by Queloz et al. 2010 (and the star is rotating 0.3-0.9 km/s faster). Hence, the reloaded RM provides a powerful tool to probe stellar photospheres, differential rotation, determine 3D obliquities, remove sky-projection biases in planet migration theories, and validate stellar models crucial to our understanding of exoplanet host stars.

Abhijit Chakraborty Physical Research Laboratory

PARAS-2

We are going to a new modern 2.5m aperture telescope with active optics with planned first light some time in Dec 2019. The telescope site is next to our existing 1.2m telescope at an altitude of 1700m (from sea level) at Gurushikar, Mt. Abu. The site enjoys about 200 to 230 cloud free nights in a year with a mean seeing 1.3arsecs. PARAS-2 (PRL Advanced Radial-velocity Abu-sky Search-2) will be an optical fiber fed HR (R=100,000) Spectrograh under temperature control (0.003C at 25C) and Vacuum (0.001mbar). The spectrograph wavelength coverage will be 380nm to 690nm and we aim to achieve about 50cm/s precision on bright targets. The spectrograoh will be the first light instrument for the 2.5m telescope and up to 30% time will be dedicated for exoplanet related research. I will discussing in the talk about the 2.5m telescope and the spectrograph design based on what we learned during various PARAS-1 observations running with our present 1.2m Telescope.

Ryan Cloutier University of Toronto

Discovering the Closest Habitable Worlds: Simulations of the SPIRou Legacy Survey Planet Search

Small and cool M-dwarfs outnumber Sun-like stars in the solar neighbourhood by nearly 4:1. Furthermore, M-dwarfs are known to host numerous super-Earth sized planets including one potentially habitable Earth-like planet for every four M-dwarfs. To uncover this tantalizing population of planets from the ground the next generation of hi-resolution velocimeters will be optimized to observe cool M-dwarfs by operating at near-IR wavelengths rather than in the visible where the previous generation of highly successful velocimeters are currently operating. One such Canadian-led instrument is SPIRou whose first-light is scheduled on the 3.6m Canada-France-Hawaii Telescope in early 2018. Upon commissioning SPIRou will begin to conduct the SPIRou Legacy Survey Planet Search (SLSPS) in the Northern sky with an expected RV precision of 1 m/s searching for new M-dwarf planetary systems. Here I will present the results of a detailed simulation of the SLSPS. Specifically, I will report on the techniques involved in performing automated radial velocity detections of simulated planetary systems as well as the expected results from the full SLSPS. I will discuss various highlights of the planet population expected to be uncovered with SPIRou including the types of planets, how many planets, and what kinds of exciting observational follow-up opportunities these planets present. Such highlights include the study of some of the closest habitable worlds which will be amenable to high-contrast imaging with the ELTs of the coming decades.

Bill Cochran McDonald Observatory, University of Texas

An Historical Perspective on Precise Stellar Radial Velocity Measurement

We can probably trace the beginning of high precision stellar radial velocity measurement to the pioneering work of R. & R. Griffin (1973) who suggested that it might be possible to achieve a measurement precision of 10 meters/second. The application of precise RV measurement to the search for extrasolar planets began to develop in the 1980s with the pioneering program at the CFHT by Campbell and Walker. Several different interesting and innovative techniques were pursued by several early groups. One can debate whether the first successful detection of an exoplanet orbiting a main sequence star was HD 114762b by Latham et al. (1989), or 51 Peg b by Mayor & Queloz (1995). Interestingly, both of these discoveries used cross-correlation techniques. The precision of RV measurements has progressively improved due to several technical innovations. The introduction of molecular iodine absorption cells (Butler et al. 1996) improved precision to 3 m/s. The construction of HARPS, the first of a generation of fiber- fed temperature stabilized vacuum spectrographs, has now pushed the precision below the 1 m/s mark. Several new designs with sophisticated advanced calibration systems are approaching the precision levels needed to detect Earth analog systems.

Matthew Cornachione University of Utah

Optimizing radial-velocity measurement with 2D PSF spectral extraction

I describe the application of the 2D PSF spectral extraction technique (dubbed "Spectroperfectionism") to the problem of precision radial-velocity measurement. This technique was motivated and developed primarily for sky-subtraction and extraction of faint galaxy spectra, but is also applicable to high-SNR echelle spectroscopy. The 2D extraction algorithm uses knowledge of the full instrumental point spread function (PSF) to improve accuracy and precision over the commonly used row-by-row (or "optimal") extraction method. In practice, however, 2D extraction is a complex technique to implement and is subject to its own limitations. The MINERVA radial velocity pipeline has served as a real-world test of the 2D extraction method. Based upon my findings with MINERVA, I suggest guidelines for determining when 2D extraction will actually improve RV precision given the constrains of a particular study. While 2D extraction of MINERVA data compares favorably to optimal extraction, it introduces biases if appropriate calibration frames are not available, and can be difficult if the instrumental PSF is of an unusual form. New PRV spectrograph designs that incorporate frequency-comb calibration systems offer great promise for characterizing the instrumental PSF with sufficient accuracy to realize the benefits of 2D extraction. Lastly, I note that the PSF fitting portion of 2D extraction can also be applied to forward modeling efforts which may ultimately maximize RV precision. For those interested in developing their own 2D extraction pipeline, I will suggest a few resources.

David Coutts Macquarie University
Focal ratio degradation from a single microbend in a multimode circular optical fibre
"It is well known that microbends in multimode optical fibres can lead to losses, mode coupling/scrambling, and ultimately Focal Ratio Degradation (FRD) which can impact on the performance of high precision spectrographs. Usually FRD is studied by direct measurement which does not fully reveal the detailed mechanisms that give rise to FRD. In this poster, the effects of a single microbend in step index multimode optical fibres are investigated in detail both experimentally and through ray tracing. A full three dimensional ray-tracing model was developed to explore propagation of light through circular cross-section step index mulitimode fibres with a single microbend corresponding to a smooth-step lateral displacement (such as may also be produced by imperfect fibre clamping). For example, a family of rays propagating at a single propagation angle (theta) chosen to represent a high order vortex mode was traced through a microbend. The ray propagation angles are found to be systematically redistributed by the microbend to produce a distorted mode. Importantly, the propagation angles are increased for some rays and decreased for others, leading to FRD. Subsequent propagation through a short length (eg. 5-200 mm) of undistorted fibre leads to the distorted mode progressively winding up to form a helical pattern, which upon exiting the fibre tip produces a well-defined spiral pattern in the far-field. Propagation of white-light (supercontinuum) vortex modes are also studied experimentally in a variety of circular-section step index fibres (0.05-0.32 mm core diameter) with a single microbend induced by a mechanical clamp. Exactly the same spectacular spiral structures and corresponding FRD predicted by the ray trace models are observed in the far-field. Results of this study have implications for understanding key mechanisms that lead to FRD as well as the importance of avoiding mechanical distortions in fibre mounting and termination. "

Lisa Crause South African Astronomical Observatory
SALT HRS - untapped PRV potential on a 10-m class telescope in the southern hemisphere
The 11-m Southern African Large Telescope (SALT) has a fibre-fed white pupil vacuum-echelle spectrograph – the HRS. It has a wavelength range of 370-890 nm, with a dichroic split at 555 nm. The High Stability (HS) mode has R$\sim$70000 and is equipped with an iodine cell and a simultaneous thorium-argon (Th-Ar) feed. An experimental laser frequency comb (developed at Heriot-Watt University) was temporarily coupled into the HS bench for a field-trial in mid-2016. Being able to simultaneously inject light from a Th-Ar arc lamp and the astrocomb into the same fibre helped to refine the Th-Ar wavelength solution for the

red channel of the HRS. Although designed and built to deliver precision radial velocities, SALT HRS has only really been used as a "higher" resolution spectrograph (relative to the telescope's multi-purpose workhorse, the Robert Stobie Spectrograph) to date. Extremely limited resources and other priorities have prevented the SALT Operations team from developing the necessary data reduction tools for pursuing precise RV measurements with the HRS. But with the TESS mission to look forward to, it is critical for SALT to ensure that its planet-hunting spectrograph is equal to the task – particularly as the SALT consortium is actively seeking a new partner to invest in the telescope at the 10% level.

Justin R. Crepp Notre Dame
THE ILOCATER SPECTROGRAPH
iLocater is a cross-dispersed, echelle spectrograph being developed for the Large Binocular Telescope (LBT) in Arizona. Designed to use both primary mirrors of the LBT and their respective adaptive optics (AO) systems, iLocater will provide high-spatial resolution imaging ($\theta = 41$ mas at $\lambda = 0.95$ μm) and high resolution spectroscopy ($\lambda/\Delta\lambda = 150,000$ - $240,000$) simultaneously for on-axis sources in natural guide star mode. This unique combination cannot be found at other observatories and will permit novel studies of stellar and substellar objects in the solar neighborhood including extrasolar planets. In this talk, I will present an overview of the project and describe recent results of on-sky coupling measurements using a single mode fiber with extreme AO.

Rodrigo Díaz IAFE (CONICET / Buenos Aires University)
USING MIXTURE MODELS TO ACCOUNT FOR OUTLIERS AND INSTRUMENT SYSTEMATICS IN RADIAL VELOCITY TIME SERIES
A common assumption when analysing radial velocities time series is that the velocity uncertainties are independent and normally distributed. Recent years have seen the evolution of this model towards a model including covariance between the data points. This is expected to better describe data affected by stellar activity signatures as was discussed at length at the previous EPRV meeting. In real life, however, data time series are often contaminated by other sources of "noise" as well (human errors at the telescope, instrument systematics, etc.), which appear as outliers from the assumed sampling distribution. Identifying these data points by eye is usually tricky and specially so when the amplitude of the sought-for signals are at the noise level. Here, we show how mixture models can be used to account for outliers and instrument systematics in radial velocity data sets. This represents a step forward in model realism and is therefore supposed to produce more robust results and planet detections. At the same time, mixture models have the potential to teach us about the instrument and the observational procedure. We first perform simulations to better understand the effect of mixture models on the inferred planet parameters and then apply them on real HARPS data.

Matías Díaz Universidad de Chile
DISENTANGLING DOPPLER SIGNALS AND STELLAR ACTIVITY: THE CASE OF HD26965
We report the discovery of a radial velocity (RV) signal that could be interpreted as a planet candidate orbiting the bright, metal-poor K dwarf HD26965, with an orbital period of 42.37

days, or alternatively, as the presence of residual, uncorrected rotational activity in the data. We will show why the latter is favored and makes this dataset an excellent test case for building new correlated noise models to remove the effects due to magnetic activity on Doppler measurements. Our best solution for HD26965 *b* is consistent with a super-Earth with a minimum mass of 8.10 $M_\oplus$ orbiting at a distance of 0.21 AU from its host star. Observations include data from HIRES, PFS, CHIRON, and HARPS over a timespan of 15 years. We performed the analysis using our Bayesian signal detection method including correlations between spectral activity indicators and the RVs available from each instrument. We find moderate correlations that we include in our statistical model. From this analysis, we recover a 38 day signal, which matches some literature values of the stellar rotation period. However, by analyzing the Mt. Wilson HK data for this star, we find evidence for a significant 42 day signal after subtraction of longer period magnetic cycles, rising doubt on the planetary hypothesis for this period. Although our statistical model (including activity indicators) strongly suggests that the 42 day signal is Doppler in origin, we conclude that the residual effects of stellar rotation are too difficult to fully model and remove from this dataset. Given the number of instruments involved, sampling density, observational baseline, and independent confirmation of magnetic cycles and rotational period for this star, this study serves as a 'Gold Standard' test case for future works that aim to detect small planets orbiting 'Sun-like' stars using RV measurements, particularly the cases where moderate correlations between the RVs and activity indicators are found to be present.

René Doyon Université de Montréal - iREx
The Near-Infrared Planet Searcher (NIRPS)

João Faria Institute of Astrophysics and Space Sciences, U. Porto
Searching for planets around metal-poor stars

Stellar metallicity and planet formation are intimately linked. While giant planets are known to be more common around metal-rich stars, planet formation theories predict that low-mass planets should orbit stars with a wide range of metallicities. The existence of a planet-metallicity relation for the low-mass planets is not yet fully confirmed or quantified observationally. To address this problem, we have been using HARPS radial-velocity observations to study a sample of metal-poor stars. Our goal is to detect low-mass planets, with masses close to that of the Earth and Neptune, and to estimate their frequency around low-metallicity stars. I will present the latest results of this decade-long search, and explain some of the difficulties that both stellar activity and instrumental noise pose for planet detection.

Tobias Feger Macquarie University
The RHEA spectrograph

We present RHEA, a compact and cost-effective echelle spectrograph that can be produced in quantities of order 10 to 100 or more units as budgets allow. The instrument is fed by a single-mode fiber with the aim of eliminating modal noise and to achieve high spectral resolution. Particular attention is paid to designing cost-effective solutions for ensuring high radial velocity precision in the potentially hostile environments of small telescope facilities. We present the current status of development and first observations with a 0.4 m telescope at the Macquarie University Observatory. The obtained on-sky data showed promise in terms of sensitivity (detecting the 5-minute oscillation in solar spectra) and the ability to detect Jupiter-like radial velocity variations in the stellar signal of a V=1.64 magnitude star.

Fabo Feng University of Hertfordshire

Agatha: disentangling periodic signals from correlated noise in a periodogram framework

Radial velocity is one of the most promising methods for the detection of Earth analogs. However, the sub-meter radial velocity variation caused by Earth-like planets is comparable with noise correlated in time and wavelength. To disentangle Keplerian signals from correlated noise, we develop a framework of periodograms based on likelihood marginalization and optimization. This framework is further implemented to produce an online application, called "Agatha". We compare Agatha with other periodograms for the detection of Keplerian signals in synthetic radial velocity data produced for the Radial Velocity Challenge as well as in radial velocity datasets of several Sun-like stars. We find that Agatha outperforms other periodograms in terms of removing correlated noise and assessing the significances of signals with more robust metrics. Moreover, it can be used to select the optimal noise model and to test the consistency of signals in time. Agatha is intended to be flexible enough to be applied to time series analyses in other astronomical and scientific disciplines. Agatha is available at http://www.agatha.herts.ac.uk.

BJ Fulton Caltech

APF-50: A Robotic Search for Earth's Nearest Neighbors

Our high-cadence Doppler survey of nearby, Sun-like stars to search for close-in, low-mass planets is nearing completion. We leverage the advantages of the robotic Automated Planet Finder (APF) telescope to search for planets orbiting a small sample of stars with greater sensitivity to low-mass planets than was previously possible with classically-scheduled instruments. The APF-50 survey builds on the Eta-Earth Survey at Keck Observatory, but with improved Doppler precision due to the high observing cadence and a larger number of measurements. I'll discuss RadVel, our open-source toolkit for modeling radial velocity observations, which has been used to provide accurate and precise mass estimates for all planets detected in our survey. I will provide an update on the occurrence rates and mass function of small planets in our local neighborhood and discuss the implications of these results in the context of our recent discovery of a gap in the radius distribution of small planets discovered by Kepler.

Jian Ge University of Florida

The High Precision Dharma Planet Survey around Bright Nearby Stars and Lessons Learned

The Dharma Planet Survey (DPS), being operated on Mt. Lemmon, aims to monitor ∼150 bright FGKM stars (V<9.5) during 2016-2020 using the TOU optical very high resolution spectrograph (R∼100,000, 380-900nm) at the dedicated 50-inch fully automatic Telescope. The main objectives are to systematically search for and characterize low-mass planets, including habitable ones, around these stars and accurately measure their occurrence rates. The DPS will also conduct high precision spectroscopic follow-up of ∼30 small-radius planet candidates around bright TESS G, K, and M dwarfs in 2019-2020 to search for their RV signals and confirm and characterize these low-mass planets from the TESS wide field transit survey. Operated in high vacuum (<0.01mTorr) with precisely controlled temperature (∼1 mK), TOU has delivered ∼ 0.5 m/s (RMS) long-term instrument stability, which is a factor of two times more stable than any of existing Doppler instruments to our best knowledge. DPS aims at reaching better than 0.4 m/s Doppler measurement precision for bright survey targets in 2017. Early DPS science results including low-mass planet candidates, technical advances and lessons learned will be presented.

Sujit Ghosh NC State University

Semi-parametric Statistical Methods to Extract Signals with Heteroscadstic Errors

Majority of the statistical methods that are used to extract signals from observations measured with errors are based on the assumption that errors are distributed from a distribution with fixed (but unknown) variances. In recent years, several Bayesian Hierarchical Models (BHM) have been developed to alleviate homoscadastic errors assumption but such models are often based on strong parametric assumptions (e.g., Gaussian distributions). This work presents a flexible semi-parametric model that extends the BHM to allow for multiplicative errors and also non-Gaussian distributions for the measured signals. Customized computational algorithms will also be presented which provides much faster estimation as compared to using standalone software based algorithms.

Emily Gilbert UChicago

The MAROON-X Solar Telescope

MAROON-X is a fiber-fed, red-optical, high-precision radial-velocity spectrograph that will be installed on the Gemini North Telescope on Mauna Kea, Hawaii. MAROON-X is designed to deliver 1 m/s on-sky radial velocity precision for mid and late M dwarfs as dim as V = 16. The primary science goal of MAROON-X is the confirmation and mass measurement of low-mass planet candidates identified in the habitable zone of nearby M dwarfs by ground- and space-based transit surveys such as TESS. These planets will be prime targets for future atmospheric studies with JWST.

Before MAROON-X becomes available at Gemini North in early 2019, we aim to thoroughly characterize the instrument. We have started a campaign of intensive lab measurements to assess instrumental stability and develop a complete data reduction and analysis pipeline. In order to test the analysis pipeline on real data before the deployment at the telescope, we are feeding solar light into the spectrograph to calculate radial velocities for the integrated solar disk. Here we describe the construction and installation process of a fully automated solar telescope for MAROON-X.

Nathan Hara Observatoire de Paris

Radial Velocity and Compressed Sensing

The search for periodic signals is key in the analysis of radial velocity data to identify planetary candidates. This search is often performed with a Lomb-Scargle periodogram or variants that search for one frequency at a time. The problem with such methods is that the frequency giving the best fit might be spurious. Indeed, the energy of the signal at this frequency might come from the contribution of other sources of signal added coherently. We present a tool based on Compressed Sensing theory that allows to search for several frequency at a time and to limit the occurrence of such situations. This one can be used like a periodogram and has the same aspect but with fewer peaks due to aliasing. We discuss the strengths and limits of such an approach and show examples of applications.

Melissa Hobson Laboratoire d'Astrophysique de Marseille
INTEGRATION AND VALIDATION TESTS OF THE SPIROU SPECTROPOLARIMETER
The search for exoplanets around M-dwarfs using radial velocities derived from near-infrared (nIR) spectra is a rapidly-growing field. In this work, I will discuss the integration and validation tests of SPIRou, a nIR spectropolarimeter and high-precision RV instrument, designed for the detection of exoplanets around low-mass stars and for the detection of magnetic fields of young stellar objects. SPIRou is currently under integration tests in Toulouse, and will be mounted on the 3.6m Canada-France-Hawaii telescope, with a first light foreseen for the end of 2017.
Some results of the integration and validation tests carried out so far are presented, with particular focus on the calibration unit, with the selection and calibration of the hollow-cathode and white source lamps and Fabry-Perot etalon. I will also discuss the development of the data reduction system (DRS) to locate and extract the spectral orders, and perform the wavelength calibration.

Bradford Holden University of California Observatories
COMPARING THE NOISE BEHAVIOR OF THE LEVY SPECTROGRAPH AND THE PLANET FINDING SPECTROGRAPH
Discovering and characterizing planets around nearby stars requires precise and accurate measurements of stellar velocities. We compare the noise properties of two spectrometers, the Levy on the APF with the Planet Finding Spectrometer on Magellan that have very similar designs. Both use an iodine cell, have thermal but no pressure control, use only slit apertures, and sit at the Nasmyth platform of the telescopes. We find that the PFS has consistently better noise performance, by at least 0.7 m/s, even at a similar signal to noise, on the same star. Directly comparing simultaneous observations of the same object. Given the similarities in the spectrometer, the natural source of noise improvement must come from the tip/tilt image stabilization in the Magellan telescopes. Comparing the guider image quality from the APF to the resulting spectra, we find that there is roughly an additional 1" in FWHM of image motion that comes from atmospheric speckles.

Howard Isaacson University of California, Berkeley
KECK/HIRES AND PRECISE RVS OF KOIS
The Keck Telescope has traditionally supported NASA space missions with ground based follow-up. The HIRES spectrometer has been used since the launch of Kepler to collect planet-mass measurements on small planets between one and four Earth-radii found by both Kepler and K2.

James Jenkins Universidad de Chile

The EMPEROR Project: A new signal detection tool to detect small Doppler signals in precision RV data

In this talk I will introduce the first results using our new Exoplanet Mcmc Parallel tEmpering Radial velOcity fitteR (EMPEROR) code. EMPEROR is available to the community and explores the parameter space using an affine invariant Markov Chain Monte Carlo method. Correlated noise models are employed in the samplings, and EMPEROR makes use of parallel tempering to ensure the parameter space is well explored. Bayesian model comparisons are used to automatically determine the statistically significant number of Doppler signals in the data. I will highlight the flexibility of the code and show the benchmark results that were applied to the RV Challenge data that were developed for the last of the EPRV conference series meetings. Finally, I will also discuss new results from some 'gold standard' data sets from HARPS, PFS, CHIRON, and Keck, including the nearby naked eye star HD26965.

Erik Johnson Institut für Astrophysik Göttingen

Measuring the Hα Central Absorption Feature in CARMENES stars

Hα has been the principle activity indicator for M stars for several decades. However the formation processes and altitude of this feature in the M star atmosphere is not well understood. In order to probe this issue further we have measured the central absorption feature of Hα. Preliminary results show that the wings, minimum point and pseudo equivalent width measurement are all useful diagnostics. It is hoped further investigation of this feature will reveal useful constraints on models of M star atmospheres and assist in the reduction of stellar activity induced radial velocity jitter.

David Jones SAMSI / Duke

textscJointly modeling radial velocity and stellar activity time series

Radial velocity signals are often corrupted by stellar activity making it difficult to detect low mass planets and planets orbiting more active stars. A principled approach to recovering planet radial velocity signals in the presence of stellar activity was proposed by Rajpaul et al. (2015) and involves the use of dependent Gaussian processes to jointly model the corrupted radial velocity signal and multiple proxies for stellar activity. We build on this work in two ways: (i) we propose using dimension reduction techniques to construct more informative stellar activity proxies; (ii) we extend the Rajpaul et al. (2015) model to a larger class of models and use a model comparison procedure to select the best model for the particular stellar activity proxies at hand. Our framework enables us to compare the performance of various proxies and models in terms of the resulting statistical power for planet detection.

Adrian Kaminski Landessternwarte, Zentrum für Astronomie der Universität Heidelberg

CARMENES - Design of an Earth-like Planets Hunting Instrument

The CARMENES instrument is installed at the 3.5 meter telescope at the Calar Alto Observatory in Spain and is in operation since January 2016. Its design is tailored to the search for extrasolar planets around M dwarfs. CARMENES consists of two independent but si-

multaneously fiber-fed high-resolution échelle spectrographs. Together both channels cover the wavelength range from 520 to 1710 nm. Thereby CARMENES is the first instrument on sky that is dedicated to and optimized for precise radial velocity measurements at the level of a few meters per second across the visual and the near-IR wavelength range.
Except for the camera and detector systems, the two channels are identical in their design. Both spectrographs are being operated in vacuum. The visual channel is operated at room temperature, whereas the near-infrared instrument is cooled down to around 140 K. The calibration strategy involves spectra from hollow-cathode lamps and Fabry-Perot etalons, which together provide an absolute reference, as well as instrumental drift monitoring. Calibration light can be fed into a secondary fiber simultaneous to the science observations.
Here we describe the optical design of the instrument in detail. The entire light path from the telescope to the detectors includes the Front-End at the Cassegrain focus, which provides the mechanical interface to the telescope and a fiber-link to the calibration unit, the FN-system, the image slicer, the collimator, the échelle grating, the grism cross-disperser, and the camera system. Results from the characterization of the system are also presented, demonstrating the instrument's capability of achieving high precision radial velocity measurements.

Molly Kosiarek UC Santa Cruz

New Mass Measurements of K2-3 and GJ3470 from Radial Velocity

We report masses and densities for two planetary systems, K2-3 and GJ3470, derived from Keck HIRES radial velocity measurements. Both systems orbit bright, nearby M dwarf stars. K2-3 hosts three super-Earth planets between 1.5 - 2 Earth Radii at orbital periods between 10 and 45 days. GJ3470 hosts one 4 Earth Radii planet at an orbital period of 3.3 days. These planets are high-priority targets for atmospheric transmission spectroscopy with JWST and HST in order to characterize their atmospheric compositions.

Thomas Loredo Cornell University

Demographics and detection

Exoplanet scientists use hierarchical Bayesian (HB) models to distill information about the demographics of exoplanet systems from characterizations of detected planets. The goal is to pool together information from imperfect measurements of individual systems to learn population properties, accounting for sources of uncertainty such as measurement errors and selection effects. But there is an important feedback loop in the discovery chain leading from observations of individual systems to inference of population properties. Population properties, including occurrence rates and distributions of characteristics of planets and host stars, bear on the problem of detection of planets in individual systems. HB methods can implement this kind of feedback. I will discuss the role of HB demographics in exoplanet detection, including proper calculation of false-alarm probabilities for candidate detections, and emerging work on using the demographics of stellar activity to quantify detection uncertainty in the extreme-precision radial velocity regime, where jitter from stellar activity must be accounted for.

Jacob Luhn Pennsylvania State University

RVs with K2: Jitter, New Planets, and Transit Probabilities for Subgiants

Recently, Bastien et al. (2014) have shown that short timescale photometric variations from high-precision Kepler light curves, coined "flicker", can be linked to radial velocity (RV) noise, or "jitter", in chromospherically inactive stars. We extend the relation between flicker and jitter to stars with flicker measurements from K2 campaigns, more than doubling the original sample size. The initial Kepler sample included 12 stars with surface gravities 3 < log(g) < 4.5, effective temperatures 4900 < Teff< 5900, and chromospheric activity -5.3 < log(R'HK) < -5.0. Our sample includes over 50 stars across a slightly wider range of surface gravities (2.5 < log(g) < 5), effective temperatures (4700 < Teff < 6100), and much larger range of chromospheric activity (-5.4 < log(R'HK) < -4.1). The wider range of stellar parameters will allow for predictions of stellar jitter for stars with high-precision light curves from K2 or TESS. We also present the discovery of several RV planets around subgiant hosts. Finally, we present transit times, durations, and probabilities for a large sample (40+) of subgiants with radial velocity observations that host planets as a resource for future TESS observations. We report 6 planets with transit probability greater than ∼10%.

Bo Ma University of Florida

Pipeline Development for the Dharma Planet RV Survey

TOU is a extremely high resolution optical spectrograph, which is designed to detect small mass exoplanets in the Dharma Planet Survey using radial velocity technique. We describe the data reduction pipeline for TOU spectrograph and its performance on RV stable stars and planet host stars. We have analyzed all the possible rv measurement error sources related to our instrument and demonstrate that with a carefully controlled instrument environment, sub-m s-1 RV precision is achievable. We will share all the important lessons we learned from our own pipeline development with the community, and discuss possible way to achieve 0.1m/s RV precision.

Luca Malavolta Università di Padova

Keplerian versus dynamical modelling of radial velocities: does the difference matter?

"State-of-the-art research on high-precision radial velocities (RVs) has focused mostly on the technological challenges to build ultra-stable spectrographs, and the extraction of weak signals in the presence of stellar noise. Little to no attention has been dedicated to the modelling of center-of-mass motion in multi-planet systems. RV analysis commonly assumes that planets move on purely Keplerian orbits, neglecting any interactions between them. We know however that such interactions do exist and in many cases are not negligible, as demonstrated by the observation of Transit Timing Variations. Compact planetary systems around low-mass cool dwarfs are the most affected by planetary interactions, and since these systems are also the main targets of present and future RV follow-up of planets in the habitability zone, it is of extreme importance to assess whether or not the Keplerian assumption still holds. Here I'll show how neglecting such interactions can lead to systematic differences between Keplerian RVs and RVs from dynamical integrations obtained with the same orbital parameters and their epoch T0 as starting point. The analysis comprises three planetary systems with super-Earths in the habitability zone of their host star, namely Proxima Cen, TRAPPIST-1 and LHS 1140 (assuming the presence of an undetected companion for single-planet systems.). Most of the time the average difference between Keplerian and dynamical RVs is well over the 10 cm/s precision goal for the next-generation RV survey, with the amplitude of this difference increasing with the distance from the starting epoch (i.e. the time span of the integration). In the case of TRAPPIST-1 this difference could be already detectable by the actual generation of velocimeter, having an amplitude of 1 m/s after just one year from the starting epoch. I will conclude remarking the importance of reliable and accurate RVs for the dynamical fit of the data. "

Richard McCracken Heriot-Watt University

New technologies for astrocombs

We present recent advances in astrocomb technology for precision calibration of astronomical spectrographs. We detail first results from a compact high-resolution Fourier-transform spectrometer for comb-line identification; we discuss progress in high-repetition-rate solid state lasers which will remove the need for Fabry-Pérot filter cavities; and we describe recent work towards achieving full spectral coverage from 0.4–2.4 μm from a single comb source for deployment on the ELT.

Nate McCrady University of Montana

The MINERVA survey of nearby stars with 1 m/s RV precision

MINERVA is a robotic observatory with four 0.7-meter telescopes at Mt. Hopkins, Arizona, dedicated to precise photometry and radial velocity observations of bright, nearby stars for the discovery and characterization of small exoplanets. We present radial velocity results from the first year of spectroscopic operations at Whipple Observatory, demonstrating m/s precision over month-long timescales. These results demonstrate that MINERVA is capable of achieving its primary science goal of finding super-Earths around the nearest, brightest stars.

Dinko Milakovic ESO

Radial velocities and fundamental physics

Our understanding of the Universe relies on two (very successful) physical theories: the Standard Model and General Relativity. However, the evidence for dark matter and dark energy suggests either the existence of unknown particles or the need for a more fundamental theory. Extensions of the current paradigm include higher dimensional theories, additional scalar fields, the 'Chameleon' mechanism, and others. Many of these models allow (or even require) the laws of physics to vary in space, time, or with local density of matter.

New instruments designed for extremely high precision and accuracy in radial velocities, such as VLT/ESPRESSO (to be commissioned this year) and ELT/HIRES (expected in late 2020s), will allow these models to be tested in a cosmological context. The Laser Frequency Comb (LFC) will be of crucial importance for this task.

In this talk, I will present the results of a study comparing the accuracies of two LFC systems installed on HARPS during a campaign in 2015. Furthermore, I will discuss the importance of the LFC for accurate wavelength calibration and its role in two cosmological tests of fundamental physics: looking for variations of fundamental constants and measuring the expansion history of the Universe.

David Montes UCM, Universidad Complutense de Madrid

Quantifying the chromospheric activity of M dwarfs from visible and near-infrared CARMENES spectra

CARMENES is a brand-new, ultra-stable, double-channel spectrograph at the Spanish-German 3.5m Calar Alto telescope for radial-velocity surveys of M dwarfs with the aim of detecting Earth-mass planets orbiting in the habitable zones of their host stars. The CARMENES survey, which began in January 2016 and will last for at least three years, aims to observe approximately 300 M stars, spread over the complete M spectral range. In this contribution we use the visible and near-infrared CARMENES spectra taken until now to analyse in detail the temporal variability of the chromospheric activity level and quantify the effect of the stellar jitter in the radial velocity determinations. In addition to the well known optical chromospheric activity indicators as the Na I D1, D2 HeI D3, H alpha and Ca II IRT lines we also investigate the behavior of some others as the HeI 10830 AA, P gamma and P beta lines that are included in the near-infrared spectral range covered by CARMENES. The chromospheric contribution in these lines has been determined using the spectral subtraction technique, that is by subtraction of a synthesized stellar spectrum constructed using artificially rotationally broadened, radial-velocity shifted, and weighted spectrum of an inactive star chosen to match the spectral type and luminosity class of the active star under consideration.

Annelies Mortier University of St Andrews

Stacking periodograms: tracking the significance of a periodic signal

Distinguishing between a signal induced by stellar activity or a planet is the main challenge in radial velocity searches for low-mass exoplanets these days. Even when the presence of a transiting planet and hence its period are known, stellar activity can be the main barrier in nailing down the correct amplitude of the radial velocity signal. Several tools are being used to help understand which signals come from stellar activity in the data. We present a new tool, using the Bayesian general Lomb-Scargle periodogram, that can be used for the purpose of identifying periodicities caused by stellar activity, based on the principle that stellar activity signals are variable and incoherent. This tool can also be used to track the SNR of the detection over time.

Claire Moutou CFHT

The SPIRou instrument

SPIRou is a near-infrared spectropolarimeter and high-precision radial-velocity spectrograph soon to be installed at the 3.60m Canada-France-Hawaii Telescope. Its spectral range expands from 0.98 to 2.35 microns at a resolving power of 75,000. SPIRou design is optimized to provide high-precision radial velocities of stars, especially low-mass stars and young stars. SPIRou will be kept in a highly stabilized environment in the coude room of CFHT where the spectrograph is fed by a fiber. At the telescope, the Cassegrain unit is equipped with a polarimeter which allows to measure the polarization of stars -and hence, the magnetic field at their surface. The simultaneous monitoring of stellar polarization and radial velocity is an advantage for correcting for stellar activity, in the search for planetary signals. After a phase of optical alignments, SPIRou is currently under performance testing; it is foreseen to the shipped to Maunakea Observatory at the end of 2017 for on-sky testing and start of operations. A large survey is proposed to the CFHT community, focussing on exoplanet search and characterization, stellar magnetism and star/planet formation. In this talk, I will present the instrument design and requirements, science objectives, then I'll give the status of the performance tests, and list the lessons learned so far.

Patrick Newman George Mason University

Simulating Radial Velocity Precursor Surveys for Target Yield Optimization in Future Exoplanet Direct Imaging Missions

Future direct imaging missions such as WFIRST, HabEx, and LUVOIR aim to catalog and characterize Earth-analogs around nearby stars. With the scope and expense of these missions, the exoplanet yield is strongly dependent on the frequency of Earth-like planets, and the a priori knowledge of which stars specifically host suitable planetary systems. Ground-based radial velocity surveys can potentially perform the pre-selection of targets and observation times at a fraction of the cost of a blind direct imaging survey. We present the first phases of simulations of such a survey. We consider multiple telescopes, including their locations, weather conditions, observation time limitations, and instrument sensitivities. Multiple target selection optimization algorithms are considered. From this, we generate realistic measurement frequencies, qualities, and RV precision. We will next inject and recover the masses and orbital parameters of real and simulated planets, estimating the effectiveness and optimizing the yield of a precursor radial velocity survey.

Belinda Nicholson University of Southern Queensland

Mapping the surface of young stars and searching for their exoplanets

Pre-main sequence, non-accreting stars can provide power insights into the behaviour of the young sun, and the chance to find young, newly-formed planets. However, their extreme activity presents challenges for detecting exoplanets. Using the technique of Doppler Imaging (DI) on high-resolution spectropolarimetric data, we map stars' surface brightness inhomogeneities, and use this information to characterise the activity-related jitter in radial velocity (RV) measurements, and then remove it to explore any underlying RV signals due to the presence of young exoplanets. We present the results of DI and RV analysis for two young (2-10Myrs), Solar-mass, non-accreting weak-line T Tauri stars as part of the Magnetic Topologies of Young Stars and the Survival of close-in giant Exoplanets (MaTYSSE) program.

Louise Nielsen Observatory of Geneva

Exploring the power of Fabry-Perot calibration with the spectrographs SOPHIE and CORALIE

"The SOPHIE echelle spectrograph at the 1.93 m Haute-Provence Observatory (OHP) is commonly used for radial velocity follow-up of planet-candidates identified through photometric transit-surveys including ground- and space-based projects such as SuperWASP, HAT, Kepler and CoRoT. SOPHIE operates in two modes; High Resolution (HR, R$\sim$75,000)

and High Efficiency (HE, R∼40,000) which trades lower resolution for 1 magnitude higher throughput.
The recently installed Fabry-Perot calibration unit at OHP enables radial velocity precision of 3 m/s on mV=11 targets observed in HE mode with simultaneous Fabry-Perot. The SOPHIE HE-mode will be a crucial tool in the TESS follow-up activities on the northern hemisphere, as the HR mode will only be able to observe the brightest few tens of candidates. In the southern hemisphere the spectrograph CORALIE at the Swiss 1.2 m telescope Euler, which has made use of simultaneous Fabry-Perot spectra since June 2015, will play a similar role.
We will discuss the latest results from the SOPHIE Fabry-Perot tests and demonstrate the improved performance of the spectrograph. An estimate of the expected number of TESS-candidates which can be observed with SOPHIE and CORALIE, based on the new calibration schemes, will be presented as well."

Bo Ning North Carolina State University

Nonparametric Prediction and the Exoplanet Mass-Radius Relationship

Statistical estimation of the joint distribution of exoplanet masses and radii plays a fundamental role in understanding the physical and chemical composition of exoplanets. The majority of recent works in this active area of astronomy are based on an assumed parametric power-law regression model for masses as a function of radii. However, there are some arbitrary choices made in the parametric model, including how to choose a proper distribution to describe the intrinsic scatter of masses; how to choose the functional radius dependence of that distribution's variance; and even whether to assume a power-law function or not. In this paper, we present a nonparametric model to estimate the underlying joint distribution of masses and radii for exoplanets. The model is flexible enough to allow us to drop the assumptions made in the parametric model. We applied our model to the dataset used in Wolfgang, Rogers and Ford (2016), derived the conditional distribution of masses given radii from the joint mass, radius distribution, and found that a power-law is a valid assumption for the planets with radius less than 4 R Earth. We also found the variance of the conditional distribution is not a constant. Furthermore, we applied our model to a larger dataset which consists of all the Kepler observations in the NASA Exoplanet Archive. Finally, we created a tool for astronomers to predict planet mass given its radius.

Masashi Omiya National Astronomical Observatory of Japan

InfraRed Doppler instrument for the Subaru telescope (IRD)

We are planning a new planet search project for detecting Earth-like planets around low-mass M dwarf stars using the InfraRed Doppler (IRD) instrument for the Subaru telescope. The project aims detecting Earth-like planets in the habitable zone and understanding configurations of planetary systems (including Earth-mass to Jupiter-mass planets) around low-mass stars by the infrared Doppler method. A large strategic survey with IRD/Subaru is necessary for collecting statistically significant number of Earth-like planets and achieving our scientific goals. The IRD instrument consists of a stable Infrared high dispersion echelle-spectrograph and a laser-frequency comb as a precise wavelength calibrator covering the wavelength range of 0.97-1.75 micron. The instrument was installed on the Subaru telescope in this spring and we will have a first light in this summer. In our presentation, we report the current status of the IRD instrument, a plan of the planet search and goals of our project.

Joel Ong Yale University

Characterising Effects of Pixel-positioning Error for Extreme Precision Wavelength Calibration with a Laser Frequency Comb

Photolithographic CCD fabrication results in per-pixel positioning errors of around 1-3% of a pixel width, previously estimated to induce mean radial velocity (RV) estimation errors of order 1 cm/s. We examine the effect of such errors as result from wavelength calibration performed by a simulated laser frequency comb. Making some strong assumptions about how this error is propagated to the radial velocity solution, we find that the mean error in wavelength estimation resulting from pixel positioning nonuniformity has a standard deviation of about 25 cm/s, per echelle order. We find this to be the case for both randomly distributed and periodic fixed-pattern pixel-positioning errors. It is clear that with the next generation of radial-velocity spectrographs, aiming for velocimetric precision of order 10 cm/s, leaving these errors unaccounted for would consume a nontrivial fraction of the error budget.

Francesco Pepe University of Geneva, Department of Astronomy

ESPRESSO@VLT Lessons 'learned'

ESPRESSO is a high-resolution, high-fidelity spectrograph for ESO's Very Large Telescope and the first 'incoherent' instrument able of working with the equivalent of a 16-m optical telescope. The scientific drivers for ESPRESSO are the search for and characterization of rocky exoplanets in the habitable zone of their parent stars and the determination of the possible variability of physical constants. These drivers set extreme performance requirements to the instrument. ESPRESSO has been tested in laboratory and will be commissioned by the end of 2017 in Paranal, Chile. In addition to the scientific goals and the instrument design, we shall present a summary of the laboratory test results as well as some lessons learned from this 7-years long and challenging project.

Ryan Petersburg Yale University

Maximizing Scrambling Gain and Mitigating Modal Noise for Fiber-fed Spectrographs

Optical fiber modal noise and imperfect scrambling are critically limiting factors for signal-to-noise in visible and near-infrared high precision spectroscopy and may induce radial velocity errors that hinder the discovery of low mass planets. Next-generation radial velocity spectrographs, such as the Extreme Precision Spectrograph (EXPRES), require precisely engineered and carefully characterized optical techniques to mitigate these issues and achieve less than 10 cm/s uncertainty. This is especially important as the community moves to more highly coherent light sources, such as laser frequency combs, for wavelength calibration. Using a double scrambler and non-circular fibers, the EXPRES fiber architecture is designed to provide a scrambling gain greater than 5,000 corresponding to radial velocity errors less than 3 cm/s. Also, select EXPRES fibers will be mechanically agitated using high amplitude coupled harmonic motion to optimally reduce modal noise with high throughput efficiency. Motivation for these design decisions and the subsequent characterization results are presented in anticipation of EXPRES commissioning by late 2017.

Peter Plavchan George Mason University

Precise Radial Velocities with CSHELL and iSHELL

Dr. Rafael Probst Menlo Systems GmbH

Recent developments in the field of astronomical frequency combs

More precise spectrograph calibration is essential for making the radial-velocity method sensitive enough to find Earth-like exoplanets around Sun-like stars. Laser frequency combs (LFCs) as next-generation calibration sources promise to provide the necessary boost in precision. They generate a regular pattern of sharp emission lines, whose optical frequencies are referenced to an atomic clock. A recent campaign at the HARPS spectrograph characterized the relative performance of two LFCs demonstrating cm/s stability. As the technology has matured, the LFC at HARPS is being qualified for routine astronomical use. As a consequence of this development, a rapidly growing number of spectrographs are presently being equipped with LFCs. With our latest technical development efforts, we are trying to extend the wavelength coverage of astronomical LFCs both on the blue side and on the infrared side of the spectrum. Our goal is to make wavelength ranges from 380 nm to 2.4 μm available in the near future.

Monica Rainer INAF - Brera Astronomical Observatory

GIARPS at TNG

Since 2012, thanks to the installation of the high resolution echelle spectrograph in the optical range HARPS-N, the Italian telescope TNG (La Palma) became one of the key facilities for the the study of the extrasolar planets. In 2015 TNG also offered GIANO to the scientific community, providing a near-infrared (NIR) cross-dispersed echelle spectroscopy at a resolution of 50,000. The synergy between these two instruments is particularly appealing for a wide range of science cases, especially for the search of exoplanets around young and active stars and the characterisation of their atmosphere. Through ""WOW"" (the funding scheme of the Italian Ministry of the Education, University and Research promoting the research of the Italian community working in the planetary field), the Italian National Institute for Astrophysics (INAF) proposed the simultaneous use of these spectrographs with the aim to achieve high-resolution spectroscopy in a wide wavelength range (0.383 - 2.45 μm) obtained in a single exposure, giving rise to the project called GIARPS (GIANO-B & HARPS-N). In this talk I will present the project and the activities required to obtain such an instrument configuration as well as the results of the Commissioning runs. Because of its characteristics GIARPS can be considered the first and unique worldwide instrument providing not only high resolution in a large wavelength band, but also a high precision radial velocity measurement both in the visible and in the NIR arm, since in the next future GIANO-B will be equipped with gas absorption cells.

Ansgar Reiners Institut für Astrophysik Göttingen

CARMENES - high-precision RVs at long wavelengths

The CARMENES survey is monitoring 300 M-dwarfs at continuous wavelength coverage between 550 and 1750nm. The instrument consists of two arms; CARMENES-VIS (550-1000nm) and CARMENES-NIR (1000-1750nm). Both arms are stabilized high-resolution spectrographs designed for m/s-precision. After more than 18 months of operation, we have collected more than 6500 spectra from each arm allowing us to draw significant conclusions about high-precision RV spectroscopy at long wavelengths. In this overview talk, I will provide main conclusions from our experience with precision velocimetry at NIR wavelengths including calibration, stability, spectroscopic features, and RV information content.

Paul Robertson Penn State & **Christian Schwab**

An introduction to NEID, the publicly-accessible ultra high precision RV spectrometer

We present a brief description of the design, capabilities, and science goals of NEID, an extremely precise radial velocity spectrometer that will be accessible to the entire community on the 3.5m WIYN telescope at Kitt Peak National Observatory. We highlight the state-of-the-art thermomechanical stability and optical design that will facilitate single measurement precision better than 50 cm/s for bright stars. NEID will be a workhorse exoplanet spectrometer for the TESS age, serving projects to both discover and characterize nearby exoplanets.

Arpita Roy California Institute of Technology

THE DELETERIOUS EFFECTS OF SCATTERED SUNLIGHT CONTAMINATION IN EXTREME PRECISION RADIAL VELOCITY MEASUREMENTS

Solar contamination, due to moonlight and atmospheric scattering, can cause systematic errors in high precision radial velocity (RV) measurements. The addition of low-level spectral contamination at variable velocity offsets introduces systematic noise when measuring velocities using classical mask-based cross-correlation techniques. The magnitude of this effect depends on median site sky brightness, target-moon separation, lunar phase, ecliptic latitude, zenith angle, and phase of the solar cycle. Here we present simulations estimating the scale of RV measurement error induced by uncorrected scattered sun-light contamination. We also explore potential correction techniques that could reliably reduce this source of error below the ~10 cm/s level. In our simulations, we focus on estimating the expected Doppler error for the NEID instrument, though these calculations are readily adaptable to other instruments at different observatories.

Suri Rukdee Pontificia Universidad Católica de Chile

Exoplanet hunters in Chile: FIDEOS and TARdYS

The Center of Astro-engineering UC-AIUC is developing high resolution spectrographs to measure radial velocity. In two projects, we target low-mass cool stars which potentially host the habitable planets, and hot Jupiters around G-stars. Our goal is to build low-budget instruments for planet detection and transit follow up with precision better than 10 m/s. Targeting low-mass cool stars, TARdYS works in near infrared Y band with R~60,000. It is under construction and will be installed at the TAO 6.5-meter optical-infrared telescope. Targeting hot Jupiters, FIDEOS works in 420-800 nm range with R~45,000. It has recently been installed at ESO 1 m telescope in La Silla. Our spectrographs employ dual-fibers to carry out wavelength calibration simultaneously, and image-slicers to reach a higher resolution. We use ThAr lamp, U lamp and Iodine Cell as calibrators. Recent first-light observation with FIDEOS demonstrates 8 m/s RV precision on a single measurement. We will present current results of our exoplanet hunters, instrumentation challenges and ongoing development.

Andreas Seifahrt The University of Chicago

MAROON-X - A NEW HIGH PRECISION RADIAL VELOCITY SPECTROGRAPH FOR THE 8M GEMINI TELESCOPE

"MAROON-X is a fiber-fed, red-optical, high-precision radial-velocity spectrograph currently under construction at the University of Chicago. MAROON-X is optimized to find and characterize rocky planets around nearby M dwarfs with an intrinsic per measurement noise floor below 1 m/s. The instrument is based on a commercial echelle spectrograph customized for high stability and throughput. A microlens array based pupil slicer and double scrambler, as well as a rubidium-referenced etalon comb calibrator will turn this spectrograph into a high-precision radial-velocity machine. Originally designed for one of the 6.5m Magellan Telescopes in Chile, it will instead be brought to Gemini in 2019 to increase its reach and allow access by a larger user community. "

David Sliski University of Pennsylvania

MINERVA-RED: A TELESCOPE DEDICATED TO THE DISCOVERY OF PLANETS ORBITING THE NEAREST LOW-MASS STARS

Discoveries of the Earth-sized exoplanets orbiting Proxima Centauri and Trappist 1 lend further evidence that terrestrial planets may be numerous around low mass stars. Since low-mass stars are intrinsically faint at optical wavelengths, obtaining m/s Doppler resolution to detect their planetary companions remains a challenge for instruments designed for sun-like stars. To study these “redder” stars, new spectrometers must be developed. We describe a novel, high-cadence approach aimed at detecting and characterizing planets orbiting the closest low-mass stars to the Sun. MINERVA-Red is an echelle spectrograph optimized between 800 nm and 900 nm, where M-dwarfs are brightest. The spectrograph will be temperature controlled at 30C +/- 5mk and in a vacuum chamber which maintains a pressure below 0.01 mbar while using a Fabry-Perot etalon and U/Ne lamp for wavelength calibration. The spectrometer will operate with a robotic, 0.7-meter telescope at Mt. Hopkins, Arizona. We expect first light in 2017.

Gudmundur Stefansson Penn State University

BREAKING THE MILLI-KELVIN SPECTROGRAPH STABILITY BARRIER

Insufficient instrument thermo-mechanical stability is one of the many fundamental roadblocks in achieving 10 cm/s Doppler radial velocity precision—the precision needed to detect Earth-twins orbiting solar-type stars. Highly temperature and pressure stabilized spectrographs allow us to better calibrate out instrumental drifts, thereby helping in distinguishing instrumental noise from astrophysical and planetary signals. In this talk, we discuss the design and stability performance of the Environmental Control System (ECS) approach for the Habitable-zone Planet Finder (HPF), the next generation near-infrared fiber-fed (NIR) spectrograph for the 10m Hobby-Eberly Telescope, and NEID, the new NASA/NSF NN-EXPLORE fiber-fed optical spectrograph for the 3.5 m WIYN telescope. For HPF, this ECS has demonstrated 0.6mK RMS temperature stability over 15 days, at the 180K operating temperature of HPF. For NEID, this system is even more stable, demonstrating better than 0.2mK stability over 30 days on the NEID optical bench. Both systems have maintained high-quality vacuum ($< -10^7$ Torr) over months. In this talk, we will discuss the versatility of this control scheme, allowing it to be applied as a blueprint to stabilize future NIR and optical high-precision Doppler instruments over a wide temperature range from $\sim$77 K to elevated room temperatures. Valuable lessons learned in designing, building and testing these systems will be discussed.

David Stenning SAMSI/Duke University

A Manifold Learning Approach for Modeling Apparent Doppler Shifts Induced by Stellar Activity

Stellar activity corrupts the radial velocity signal of low-mass exoplanets orbiting active stars. Davis et al. (2017) recently proposed a method for reducing the dimensionality of a time series of stellar spectra and constructing proxies of stellar activity using principal component analysis (PCA), which assumes that the data can be well-represented by projecting it into a linear subspace formed by a few orthogonal basis vectors. This assumption is difficult to verify in practice as the data is very high-dimensional (i.e. $\sim$250,000 wavelengths per spectrum). On the other hand, manifold learning techniques such as diffusion maps are capable of finding low-dimensional nonlinear structures, but produce results that are difficult to interpret. We build on Davis et al. (2017) to develop physically motivated PCA- and diffusion-map-based proxies of stellar activity. The first coordinate of the low-dimensional reconstruction is forced to be the apparent Doppler shift, after which the algorithms are allowed to find remaining linear (PCA) or nonlinear (diffusion map) structure that can be captured by a few additional coordinates. Initial results are promising in terms of the statistical power for planet detection, and the inclusion of the physically-motivated component allows for direct interpretation of the detected Doppler-shift signal.

Julian Stuermer University of Chicago

Rubidium-traced white-light etalon calibrator for radial velocity measurements at the cm/s level

We report on the construction and testing of a vacuum-gap Fabry–Pérot etalon calibrator for high precision radial velocity spectrographs. Our etalon is traced against a rubidium frequency standard to provide a cost effective, yet ultra precise wavelength reference. We describe here a turn-key system working at 500 to 900 nm, ready to be installed at any current and next-generation radial velocity spectrograph that requires calibration over a wide spectral bandpass. Where appropriate, we have used off-the-shelf, commercial components with demonstrated long-term performance to accelerate the development timescale of this instrument. Our system combines for the first time the advantages of passively stabilized etalons for optical and near-infrared wavelengths with the laser-locking technique demonstrated for single-mode fiber etalons. We realize uncertainties in the position of one etalon line at the 10cm/s level in individual measurements taken at 4 Hz. When binning the data over 10 s, we are able to trace the etalon line with a precision of better than 3cm/s. We present data obtained during a week of continuous operation where we detect (and correct for) the predicted, but previously unobserved shrinking of the etalon Zerodur spacer corresponding to a shift of 13cm/s per day.

Andrew Szentgyorgyi Harvard-Smithsonian CfA

G-CLEF: A PRV Instrument for the ELT Era

The GMT-Consortium Large Earth Finder (G-CLEF) will be an optical band echelle spectrograph for the Giant Magellan Telescope (GMT). G-CLEF is vacuum-enclosed and fiber-fed, enabling precision radial velocity (PRV) measurements. The G-CLEF design incorporates many novel technical innovations. G-CLEF will be the first PRV spectrograph to have a composite optical bench to exploit that material's extremely low coefficient of thermal expansion.This design feature, combined with a extremely precise thermal control system, should make G-CLEF an instrument with standard-setting wavelength-scale stability. We describe these and other technical innovations that we have prototyped during the G-CLEF critical design phase, as well as a powerful analytical formalism to predict the performance of the G-CLEF. We conclude with a instrument design/build status update.

Marcelo Tala Pinto Landessternwarte, ZAH

CARMENES - Design of an Earth-like Planets Hunting Instrument

The CARMENES instrument is installed at the 3.5 meter telescope at the Calar Alto Observatory in Spain and is in operation since January 2016. Its design is tailored to the search for extrasolar planets around M dwarfs. CARMENES consists of two independent but simultaneously fiber-fed high-resolution échelle spectrographs. Together both channels cover the wavelength range from 520 to 1710 nm. Thereby CARMENES is the first instrument on sky that is dedicated to and optimized for precise radial velocity measurements at the level of a few meters per second across the visual and the near-IR wavelength range.
Except for the camera and detector systems, the two channels are identical in their design. Both spectrographs are being operated in vacuum. The visual channel is operated at room temperature, whereas the near-infrared instrument is cooled down to around 140 K. The calibration strategy involves spectra from hollow-cathode lamps and Fabry-Perot etalons, which together provide an absolute reference, as well as instrumental drifts monitoring. Calibration light can be fed into a secondary fiber simultaneous to the science observations.
Here we describe the optical design of the instrument in detail. The entire light path from the telescope to the detectors include the Front-End at the Cassegrain focus, which provides mechanical interface to the telescope and a fiber-link to the calibration unit, the FN-system, the image slicer, the collimator, the échelle grating, the grism cross-disperser, and the camera system. Results from the characterization of the system are also presented, demonstrating the instrument's capability of achieving high precision radial velocity measurements.

Ryan Terrien NIST/Carleton College

Laser frequency combs for extremely precise radial velocities

Laser frequency comb systems provide the stable, dense, and uniform grid of calibration lines required for extremely precise radial velocity measurements. These systems provide not only a cm/s-level simultaneous calibration precision, but also an invaluable resource for understanding and mitigating other sources of systematic radial velocity measurement uncertainty. I will contrast different approaches for the generation of frequency combs, and the use of these combs for extremely precise radial velocities. Several frequency comb systems have been demonstrated in the field, including recent deployments for long-term use, and I will highlight recent results from some of these systems. I will also discuss new systems under development, including a near-infrared electro-optic frequency comb being developed at NIST, and the outlook for frequency comb systems in the context of the rapidly expanding community of high-precision radial velocity spectrographs.

Johanna Teske Carnegie Observatories/DTM

Halpha as a Diagnostic of Solar-type Stellar Atmospheres

The detection of exoplanets via radial velocity (RV) has become increasingly dependent on a deep understanding of the behavior of stellar atmospheres. Periodic variations due to stellar activity, rotation, pulsation, etc., can be and have been confused with signals of orbiting planets, but are also diagnostic of fundamental properties of stars, like age or interior structure. Studying such variation diagnostics across a wide sample of stars is thus important to tease out different dependencies to aid in the detection of (especially small) planets. I will present a study of the stellar activity as reckoned from the Halpha Balmer line of hydrogen at 6563A in $\sim$43,000 HIRES spectra of $\sim$1500 FGKM stars being monitored for planets, many for over ten years. The motivation to use an additional activity index, besides Ca H&K, comes from the low flux of M dwarf stars in the Ca H&K wavelength region; these stars are the most promising candidates for habitable planets. However, I will show that the variation in Halpha flux is also diagnostic of higher mass star properties, proving its utility across a wide SpT space for both RV planet detection and stellar atmosphere characterization.
Note that I have given two "status update" talks on this topic at other conferences, but that by EPRVIII I plan to have a more comprehensive picture, including statistically characterizing the relationship between Halpha and Ca H&K median values and trends over time in individual systems.

Sam Thompson University of Cambridge

The Terra Hunting Experiment with HARPS3

We present an overview of the Terra Hunting Experiment planned for HARPS3 on the 2.5m Isaac Newton Telescope. The Terra Hunting Experiment is scheduled from end-2019 and will be conducted over 10 years. Our aims are to detect, via radial velocity measurements, Earth-mass planets in Earth-like orbits around our nearest and brightest solar-like stars. The Terra Hunting Experiment will be conducted using HARPS3 in a robotic operation; HARPS3, like its predecessors HARPS and HARPS-N, is a stable, high-resolution spectrograph. In addition we will implement improved detector characterisation via pixel to pixel mapping and temperature control via a new design continuous flow cryostat. Our observation strategy is in the collection of long, dense time-series with the aim of measuring each target once per night. Our best candidates for the Terra Hunting Experiment will have $\sim$1500 RV measurements collected over the course of 10 years; we present some initial simulation results demonstrating the potential of our sampling strategy.

Chris Tinney UNSW Sydney

The Veloce Rosso Doppler Spectrograph for the Anglo-Australian Telescope

The Veloce Rosso spectrograph and the VeloceCal astrocomb will go into operation at the AAT early in 2018, opening up a new area of exoplanet detection for Australia. Delivering a capability to obtain sub-m/s Doppler velocity precision at wavelengths between 600 and 900nm, it will use multiple design innovations to target multiple science cases critical for exoplanetary science. Innovations include a focal plane segmenting IFU; butt-joined octagonal-to-round fibre cables for image scrambling; simultaneous calibration with a single-mode injected laser-comb; and a "just stabilised enough" environmental control design strategy to control costs. Its science goals include the follow-up of new potentially habitable exoplanets discovered by the NASA TESS satellite (just like everyone else at this meeting); utilising variability measures from TESS to identify the best transiting systems to target for long-term studies of their system architectures (i.e. finding the subsequent planets that don't transit); and carrying out a new generation of exoplanetary surveys on "the most stable-of-all" host stars.

René Tronsgaard SONG / Aarhus University (Denmark)

Re-writing the iodine code in Python

We present a Python-based framework capable of reducing iodine cell spectra to RVs. It is designed with flexibility in mind, featuring fully pluggable algorithms and models for fitting the spectrum and combining the chunks into the final timeseries. When released, the code will be public and freely available for the community to use, expand, and build upon. The software is currently being tested within the SONG network with good performance and consistent results.

The aim of this work is not to replace, but to supplement the existing IDL code, developed over the past two decades. The new framework is simpler to set up for new instruments, there are no IDL license fees, and it is straightforward to experiment with new fitting algorithms, custom chunk sizes, or different models.

Gautam Vasisht JPL - Caltech

PARVI: a diffraction limited high resolution RV spectrograph

PARVI is a single mode high resolution spectrograph for the Hale Telescope at Palomar, a reincarnation of the high contrast imager Project 1640. It works together with the extreme AO system Palm 3000 and a electro-optic modulation comb to provide R$\sim$100,000 near IR spectra in the J and H bands. Given that it adopts a lot from P1640, we are working on this affordable new facility instrument for, planning a relatively fast turnaround to first observations.

Sharon Xuesong Wang Carnegie DTM

Mitigating Spectral Contamination for PRVs

Spectral contamination, such as the telluric absorption and the moonlight, often causes additional uncertainty and bias when measuring precise radial velocities (PRVs) from the stellar spectra. This talk will review the impacts of spectral contamination on PRVs, especially on the telluric absorption. The talk will cover previous works on data analysis or observing strategies for mitigating spectral contamination, the effectiveness of these methods, and what needs to be done to control the damage of spectral contamination to below 10 cm/s.

Sharon Xuesong Wang Carnegie DTM

RVxK2: Simultaneous PRV Program with Kepler/K2 Campaign 16

Introducing the RVxK2 program: Using Keck/HIRES, APF, IRTF/iSHELL, we will perform simultaneous PRV observations with Kepler/K2 Campaign 16, from Dec 7 2017 through Feb 26 2018. K2 will provide short cadence photometric data on five carefully selected stars, including the brightest M dwarf in C16 field, a solar analog, and three bright G/K subgiants. K2 will also provide long cadence data on the next three brightest K or M dwarfs in the C16 field. Our campaign includes several precise RV instruments around the globe, including Keck/HIRES, APF, IRTF/iSHELL, SONG, MINERVA, PARAS, representing the first organized, extensive, simultaneous RV campaign with space photometry. Our primary science goal is to characterize and understand stellar jitter and stellar activity. This RV+K2 campaign will provide the community with an unprecedented dataset of RV spectra and precise photometry to study stellar jitter on a broad range of time scales, from minutes to 80 days. We will gather the first ever RV+photometry dataset aiming at characterizing stellar granulation, the most poorly understood term among all astrophysical sources of stellar jitter. This project will also enable the first asteroseismic studies with simultaneous precise RVs and photometry, while searching for planets in the brightest nearby G to M dwarfs in the field.

Darren Williams Penn State Behrend

Searching for Planetary Moons in the Spectra of Rotating Stars

Exoplanets that happen to transit their stars will produce a drop in integrated light as well as a measurable Doppler shift of monochromatic light from asymmetric masking of different regions of a rotating star. The Doppler signal is the familiar Rossiter-McLaughlin (RM) effect, and is a function of system geometry in addition to planet size. Here we examine changes to the RM signal resulting from exoplanetary satellites. We show that sizeable moons, exceeding the mass of Mars, are detectable in both integrated and monochromatic light, assuming a Doppler precision $<$ 1m/sec is possible with future instruments.

Rob Wittenmyer University of Southern Queensland

Toward true Solar system analogs: the role of less-precise RVs in the EPRV era

Radial velocity searches for exoplanets have undergone a revolution in recent years: now precisions of 1 m/s or better are being demonstrated by many instruments, and new purpose-built spectrographs hold the promise of bringing Earth-mass planets into the realm of secure detectability. In the ""race to the bottom,"" it is critical not to overlook the impact of long-running planet search programs that continue to hold the advantage of time. We highlight the continuing impact of the 18-year Anglo-Australian Planet Search: the characterisation of long-period giant planets, and the insights into the occurrence rate of Jupiter and Saturn analogs. To fully understand the origins of planetary systems and the fundamental question of how common (or rare) the architecture of the Solar system is in the Galaxy, we must continue these ""legacy"" surveys to probe ever-larger orbital separations. We describe the ongoing value of 2-4 m/s velocities for understanding the outer regions of planetary systems.

Angie Wolfgang Penn State

Population Inference from RVs: How Do Observers' Choices Affect Our Understanding of Exoplanet Compositions?

Over the last few years, EPRV resources have increasingly shifted toward follow-up of previously detected transiting planets. As a result, our understanding of the so-called "mass-radius relation" has dramatically improved for the smallest planets, with corresponding insights into the range of compositions possessed by Earth- to Neptune-sized planets. As we begin to prepare for TESS, whose goal is to provide 50 more points on the mass-radius diagram, it is prudent to assess how we could maximize the scientific return of these future observations.

Using the Automated Planet Finder's TESS follow-up simulator developed by Jennifer Burt and Brad Holden, I will present how the mass-radius relation we infer from RV measurements is affected by different observational choices. These choices include a night-by-night decision of which planets to observe under variable weather conditions given different prioritization schemes for the RV signal's phase coverage, as well as an over-arching strategic decision to target a few planets or to survey a larger sample. The aim is to start a conversation about how we could work together as a community to leverage our combined observational resources for improved understanding of the planet population, while respecting individual teams' scientific priorities and goals.

Duncan Wright University of New South Wales

Precision velocities, activity and spectral variability in M Dwarfs

Understanding the causes of activity-induced Doppler velocity variation is paramount to improving low-mass planet hunting success. I will show new work using archival HARPS data of bright M Dwarf stars investigating the time-variability of spectral lines throughout the spectrum of many M Dwarfs. Significant variation is observed in ionised and neutral metal lines throughout the spectrum of many M stars. The variation is completely different to that observed for the many molecular features in the spectrum which contribute the bulk of the Doppler velocity information. The variability of the neutral and ionised metal lines is retrievable for many precision velocity surveys and may be a better tracer of activity to be used instead or alongside current activity tracers, or alternatively it may provide information on regions to be avoided when determining the Doppler velocity for the star.

Jhon Yana Galarza Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas

A new sample for hunting planets around solar twins

The first generation of ∼100 solar twins was discovered using the Hipparcos catalog. Thenceforth, the number of applications of these objects have increased considerably. For example, they were used for testing stellar interiors and evolution models, investigating the chemical evolution of the Galactic disk, studying the rotational evolution of the Sun and discovering new planets, including a Jupiter twin around a solar twin.

With the first data release of TGAS (Tycho-Gaia), we found 468 solar twins candidates through constraints on color (using the Tycho and 2MASS catalogs), absolute magnitude (employing Gaia parallaxes) and reddening corrections (using different reddening maps). We intend to observe this sample and determine its precise stellar parameters in order to identify new solar twins for different applications, from studying the exoplanet-chemical composition connection, to discovering new planets. This extended sample will allow us to better assess how common is our Solar System."

Mathias Zechmeister Institut für Astrophysik Göttingen

SERVAL - THE SPECTRUM RADIAL VELOCITY ANALYSER

The CARMENES survey is a high-precision radial velocity (RV) program that aims to detect Earth-like planets orbiting low-mass stars. We develop least-squares fitting algorithms to derive the RVs and additional spectral diagnostics. The RVs are measured using high signal-to-noise templates created by coadding all available spectra of each star. Using the RVs measured in the echelle orders, we define the chromatic index as the RV gradient as a function of wavelength. Additionally, we compute a differential line width by correlating the fit residuals with the second derivative of the template to track variations in the stellar line width. Using HARPS data our SERVAL code achieves a RV precision at the level of 1 m/s. Applying the chromatic index to CARMENES data of the active star YZ CMi we identify apparent RV induced stellar activity. The differential line width is found to be an alternative indicator to the commonly used full-width half-maximum. We find that at the red-optical wavelengths (700–900 nm) obtained by visual channel of CARMENES, the chromatic index is an excellent tool to investigate stellar active regions, and to identify and perhaps even correct for activity-induced RV variations.

4 Conference Participants

Fabienne Bastien	Pennsylvania State University
Thomas Beatty	Pennsylvania State University
Eric Bechter	University of Notre Dame
Andrew Bechter	University of Notre Dame
Chas Beichman	IPAC/NExScI
Sagi Ben-Ami	Harvard-Smithsonian Center for Astrophysics
Serena Benatti	INAF - Astronomical Observatory of Padova
Chad Bender	University of Arizona
Ryan Blackman	Yale University
Cullen Blake	University of Pennsylvania
Isabelle Boisse	LAM
Jennifer Burt	MIT
Robert Butler	Carnegie/DTM
Caleb Cañas	The Pennsylvania State University
Rich Capps	NASA/JPL
Heather Cegla	University of Geneva
Abhijit Chakraboty	Physical Research Laboratory
Ryan Cloutier	University of Toronto
Bill Cochran	McDonald Observatory, University of Texas
Matthew Cornachione	University of Utah
David Coutts	Macquarie University
Jeff Crane	Carnegie Observatories
Johnathan Crass	University of Notre Dame
Lisa Crause	South African Astronomical Observatory
Justin Crepp	Notre Dame
Ian Crossfield	MIT
Bekki Dawson	The Pennsylvania State University
Rodrigo Díaz	IAFE (CoNICET/Bueons Aires University)
Matías Díaz	Universidad de Chile
René Doyon	Université de Montréal
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Jian Ge	University of Florida
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Emily Gilbert	UChicago
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Nathan Hara	Observatoire de Paris
Matthias He	The Pennsylvania State University
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Brad Holden	University of California Observatories
Andrew Howard	Caltech
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James Jenkins	Universidad de Chile
Erik Johnson	Institut für Astrophysik Göttingen
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Adrian Kaminski	Landessternwarte, Zentrum für Astronomie der Universität Heidelberg
Shubham Kanodia	PSU
Kyle Kaplan	The University of Arizona
Chip Kobulnicky	University of Wyoming
Peter Kornik	New England Optical Systems, Inc.
Molly Kosiarek	UC Santa Cruz
David Latham	Harvard-Smithsonian Center for Astrophysics
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Tom Laredo	Cornell University
Jacob Luhn	Pennsylvania State University
Bo Ma	University of Florida
Mariah MacDonald	Penn State
Suvrath Mahadevan	Penn State
Luca Malavolta	Università di Padova
Richard McCracken	Heriot-Watt University
Nate McCrady	University of Montana
Dinko Milakovic	ESO
Andy Monson	Penn State
David Montes	UCM, Universidad Complutense de Madrid
Annelies Mortier	University of St. Andrews
Claire Moutou	CFHT
James Neff	National Science Foundation
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Bo Ning	North Carolina State University
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Joel Ong	Yale University
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Suri Rukdee	Pontificia Universidad Católica de Chile
David Ruppert	Cornell University
Brian Sands	Notre Dame
Andreas Seifahrt	The University of Chicago
Steinn Sigurdsson	Pennsylvania State University
David Sliski	University of Pennsylvania
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Ryan Terrien	NIST/Carleton College
Johanna Teske	Carnegie Observatories/DTM
Sam Thompson	University of Cambridge
Chris Tinney	UNSW Sydney
René Tronsgaard	SONG / Aarhus University
Noah Techow	Penn State
Joseph Tufts	Semiconductor Technology Associates, Inc.
Gautam Vasisht	JPL-Caltech
Sharon Xuesong Wang	Carnegie DTM
Austin Ware	Pennsylvania State University
Darren Williams	Penn State Behrend
Rob Wittenmyer	University of Southern Queensland
Angie Wolfgang	Penn State
Alex Wolszczan	Penn State
Jason Wright	Penn State
Duncan Wright	University of New South Wales
Jhon Yana Galarza	Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas
Mathias Zechmeister	Institut für Astrophysik Göttingen

5 Code of Conduct

The Third Workshop on Extremely Precise Radial Velocities (EPRV III) has a zero tolerance policy for harassment of any kind. All attendees have the right to a space free of all forms of discrimination, harassment and retaliation. Harassment on the basis of any characteristic, protected or otherwise, is a form of misconduct, and violators of this policy will be subject to disciplinary action, as outlined below.

It is important to bear in mind that harassment is in the eye of the victim. Participants asked to stop any harassing behavior are expected to comply immediately.

What is harassment?

Harassment is defined as epithets, slurs or negative stereotyping; threatening, intimidating or hostile acts; denigrating jokes and display or circulation of written or graphic material that denigrates or shows hostility or aversion toward an individual or group. It includes any unwelcome contact or discussion of a sexual nature, unwelcome sexual advances, requests for sexual favors, verbal or physical harassment of a sexual nature, and obscene or sexist remarks. Harassment can be targeted at one particular characteristic, or can be intersectional in tone. Women of color, for example, can experience racialized sexual harassment that targets the intersection of their identities.

For more information on sexual harassment and how it can manifest in astronomy, see the Fed Up With Sexual Harassment series on the Women in Astronomy blog. The fifth in the series specifically deals with harassment at the intersection of gender and race:
http://womeninastronomy.blogspot.com/2014/05/fed-up-with-sexual-harassment-defining.html
http://womeninastronomy.blogspot.com/2014/05/fed-up-with-sexual-harassment-survival.html
http://womeninastronomy.blogspot.com/2014/05/fed-up-with-sexual-harassment-serial.html
http://womeninastronomy.blogspot.com/2014/05/fed-up-with-sexual-harassment-power-to.html
http://womeninastronomy.blogspot.com/2014/05/fed-up-with-sexual-harassment-guest.html

Often these incidents can take the form of "microaggressions," which are one of the most pervasive and damaging forms of harassment. Microaggressions are the everyday verbal, nonverbal, and environmental slights, snubs, or insults, whether intentional or unintentional, which communicate hostile, derogatory, or negative messages to target individuals based upon their marginalized group membership. For example, commenting on a woman's appearance rather than her work is a microaggression; telling someone of colour that they "speak such good English" is another example. Exclusion from a group can be a common nonverbal form of microaggression. Often, microaggressions can be couched in the form of a "compliment," (e.g. "you're too attractive to be a scientist") which causes additional stress to the target when trying to decide how to respond. Targets of microaggressions must spend time decoding the insult ("This person just implied that I don't belong in science"), wondering whether it was intentional ("Did this person mean it in the way I took it? Should that affect my response?"), and deciding whether to speak up and risk being branded as "oversensitive" by the perpetrator or others in the group ("All s/he did was pay you a compliment! Why are you overreacting?") or ignore the comment and feel like they should have said something ("Why didn't I stand up for myself? Does s/he now think that's an OK thing to say to me?"). Over time, these comments can take a great toll on mental and emotional health, and the target's feeling of belonging in science and academia.

Recognizing Harassment

If you are feeling uncomfortable in a situation, or if you notice an interaction between others that makes you uncomfortable, trust your gut, even if you can't explain exactly what triggered your response. An excellent guest post on John Johnson's blog (http://mahalonottrash.blogspot.com/2013/12/closing-time-at-astronomy-nightclub.html) described the "alarm bells" that we all have that tell us that something isn't right, even if we can't identify exactly what. Trust these instincts! Research shows that we are often subconsciously picking up on warning signs that we have not consciously registered.

If you notice an interaction between other people that causes you concern, be prepared to intervene. This can be as simple as joining their conversation, or inviting them to join yours. Again, the guest blog post linked above has some good suggestions for ways to intervene without potential risks to a junior colleague's career. If you do not feel comfortable taking direct action, please contact a member of the EPRV III organizing staff for assistance, even if you are unsure of the situation.

Procedure for reporting harassment

If you wish to report harassment, suspect that someone else is being harassed, or have any other concerns, please contact a member of the EPRV III local organizing committee immediately. No one will be faulted for making a report in good faith about suspected harassment. The committee's response to witnessed or experienced harassment will be to report the conduct to Penn State as per the University's anti-harassment policy (see below) and, based on discussion and agreement with the person being harassed, take action accordingly. This can range from requesting that no administrative processes be initiated, to informal resolution such as a letter of reprimand, to formal resolution including disciplinary action and police involvement. Penn State's policy for following up reports involving visitors to the University ("third parties") is outlined here: http://www.psu.edu/dept/aaoffice/resolution.htm.

You may also directly and anonymously report harassing behavior to Penn State at http://universityethics.psu.edu/penn-state-hotline.

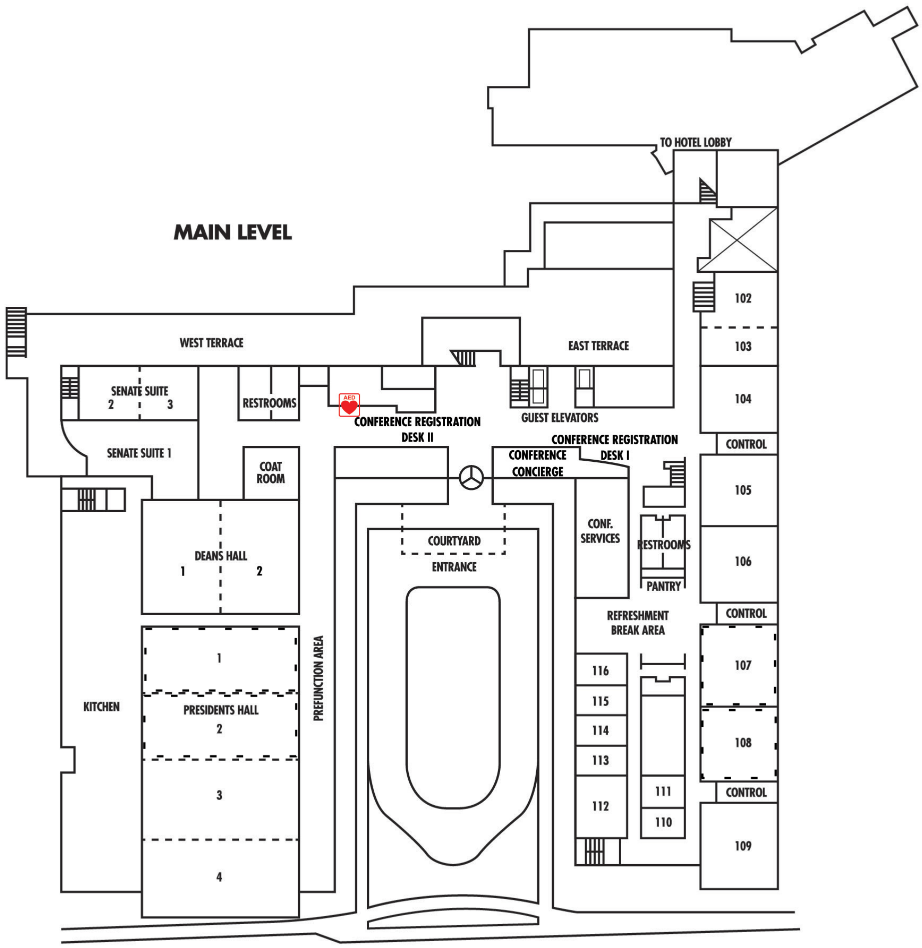
Penn State's anti-harassment policy states:

"The University is committed to equal access to programs, facilities, admission and employment for all persons. It is the policy of the University to maintain an environment free of harassment and free of discrimination against any person because of age, race, color, ancestry, national origin, religion, creed, service in the uniformed services (as defined in state and federal law), veteran status, sex, sexual orientation, marital or family status, pregnancy, pregnancy-related conditions, physical or mental disability, gender, perceived gender, gender identity, genetic information or political ideas. Discriminatory conduct and harassment, as well as sexual misconduct and relationship violence, violates the dignity of individuals, impedes the realization of the University's educational mission, and will not be tolerated. Gender-based and sexual harassment, including sexual violence, are forms of gender discrimination in that they deny or limit an individual's ability to participate in or benefit from University programs or activities."

The full policy may be found here: https://guru.psu.edu/policies/ad85.html. The EPRV III meeting and its participants are covered under this policy, as it includes all interactions between visitors to the Penn State campus. Any violations of Penn State's anti-harassment policy are required to be, and therefore will be, reported to Penn State. Once the actions required for compliance with this policy have been taken, the LOC will endeavor to advocate for and support the person being harassed, to any reasonable extent that they are requested to do so.

If you have any questions or concerns regarding this policy, please contact the EPRV III Local Organizing Committee at eprv.loc@gmail.com.

Penn Stater Conference Center Floor Plan: Floor 1

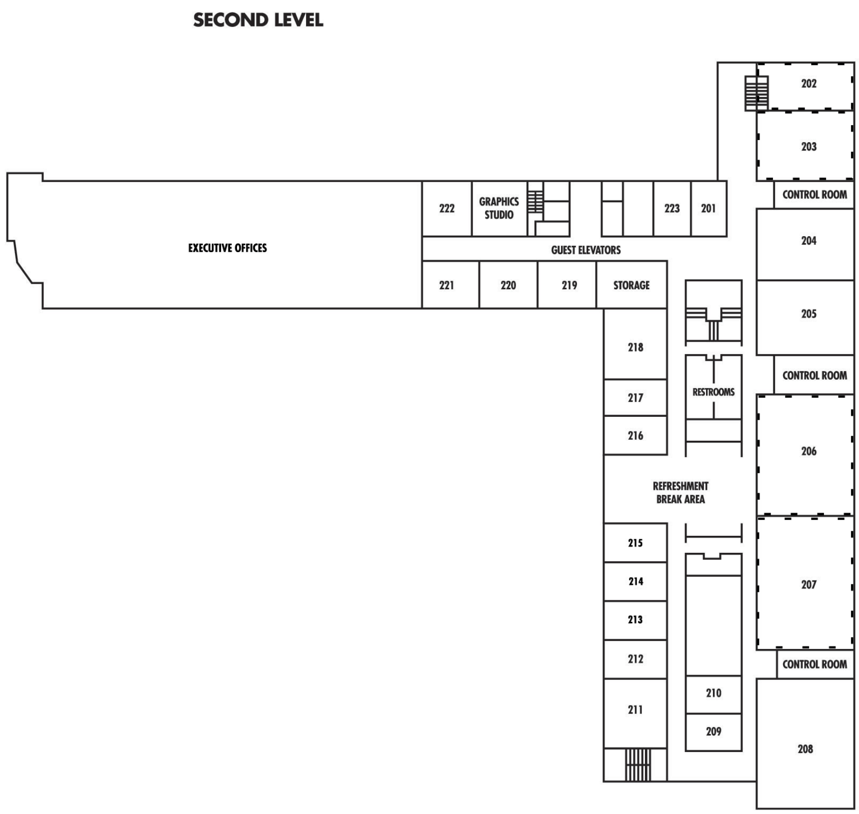


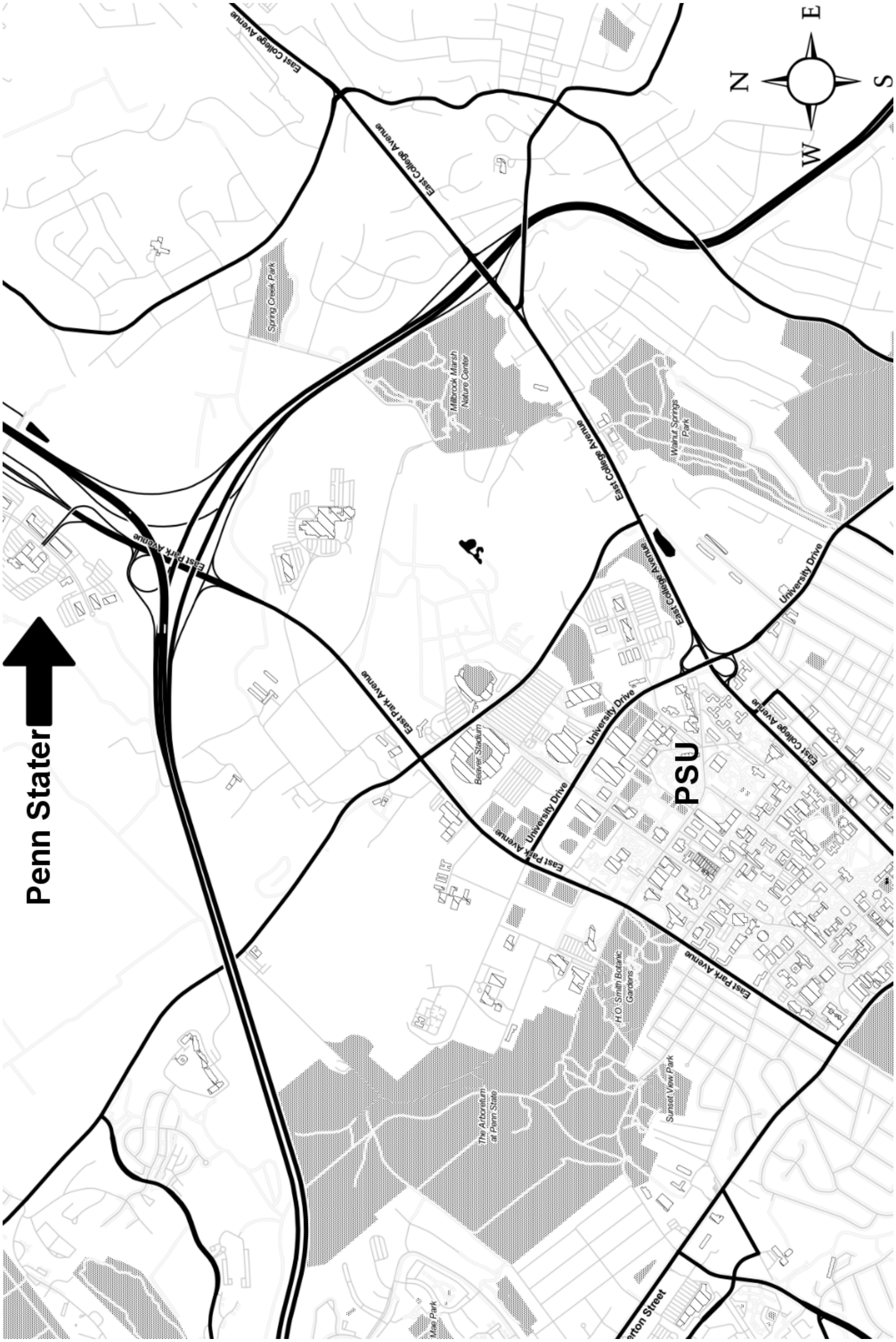
Plenary Sessions: Presidents Hall 1

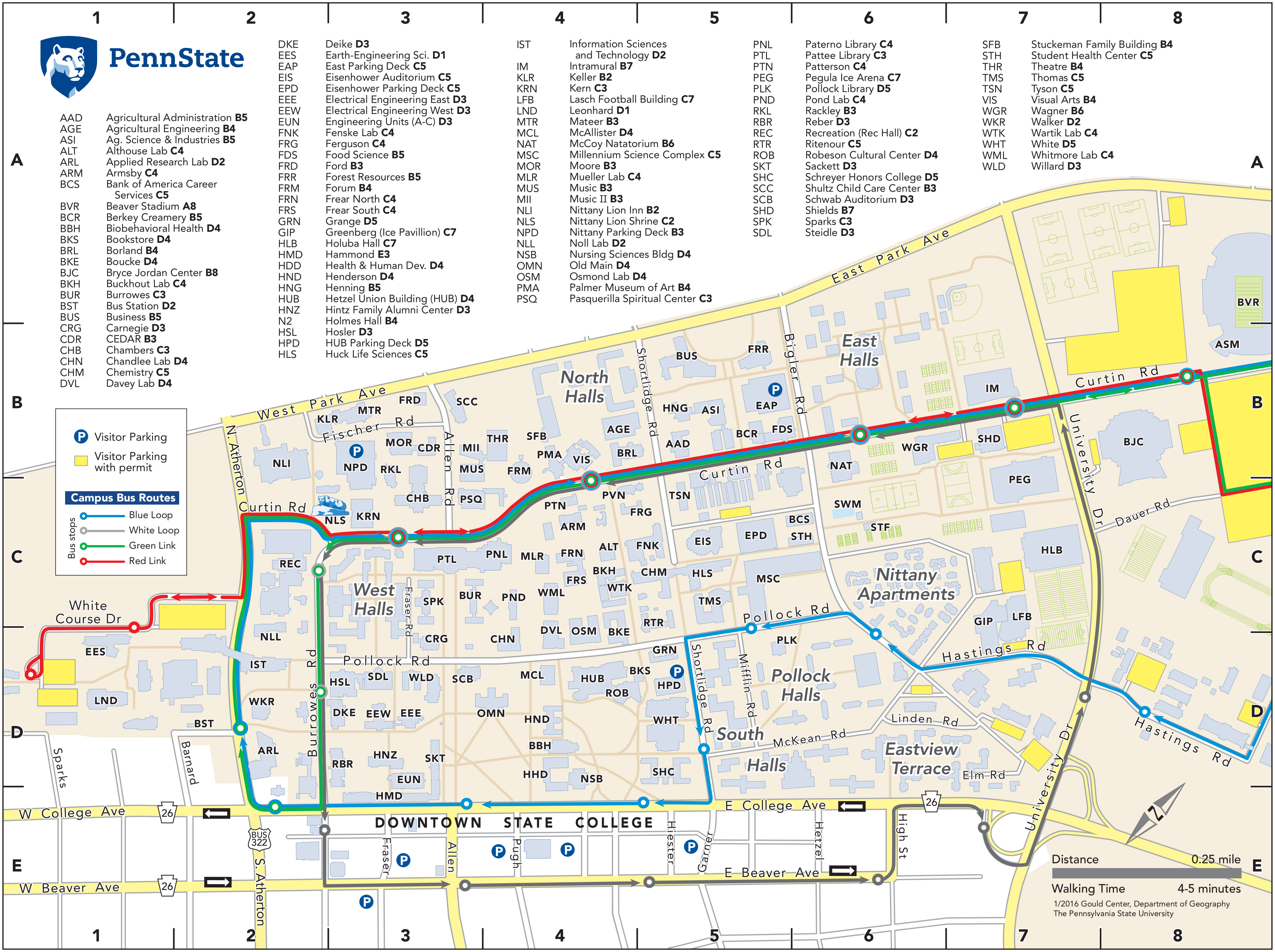
Posters: Presidents Hall 2

Breakout rooms: 107, 108, 202, 203, 206, 207

Penn Stater Conference Center Floor Plan: Floor 2

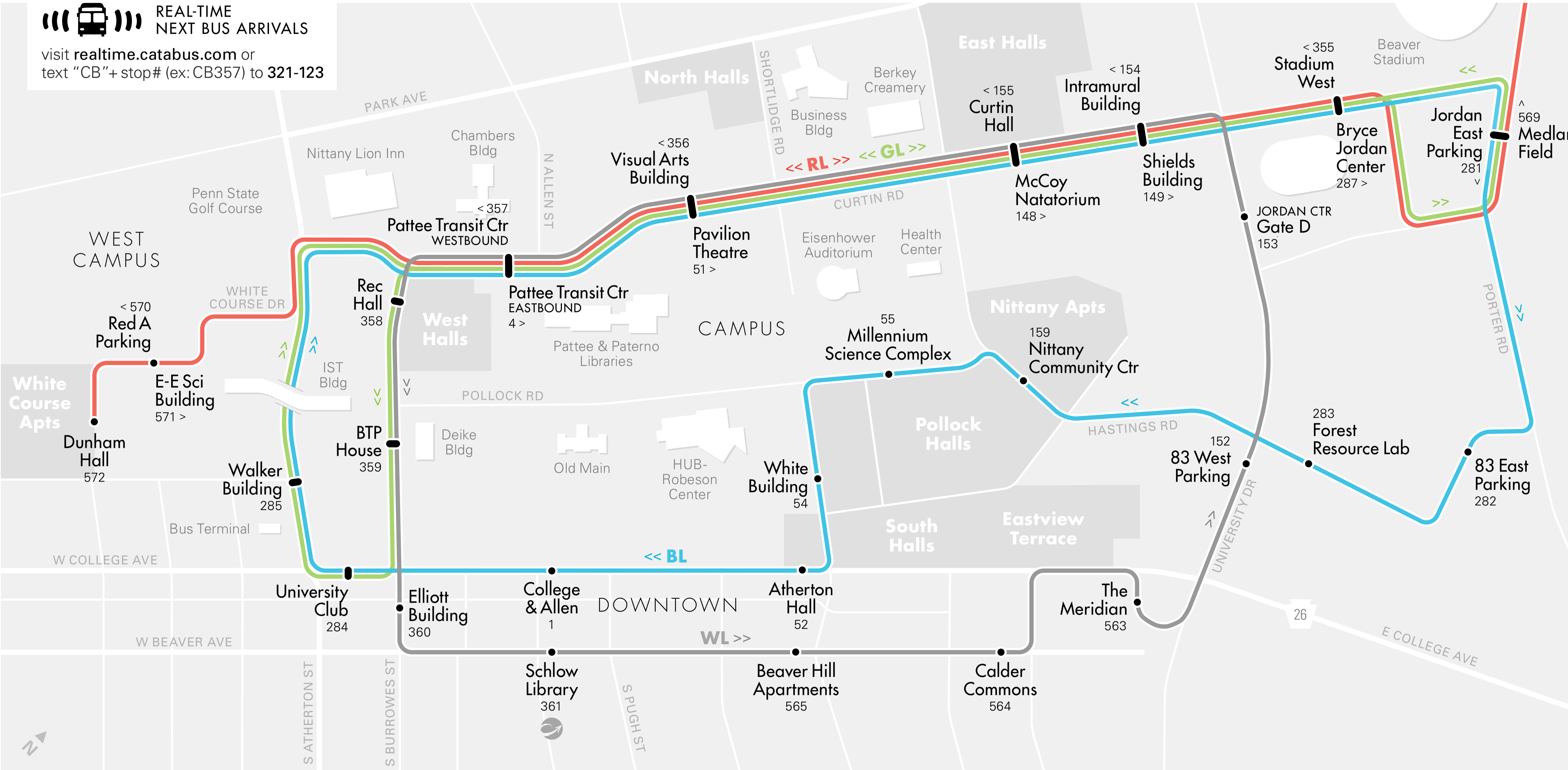



Penn Stater
PSU
East College Avenue
East Park Avenue
University Drive
Spring Creek Park
Millbrook Marsh Nature Center
Walnut Springs Park
Beaver Stadium
H.O. Smith Botanic Gardens
The Arboretum at Penn State
Sunset View Park
N
E
S
W


PennState
AAD Agricultural Administration B5
AGE Agricultural Engineering B4
ASI Ag. Science & Industries B5
ALT Althouse Lab C4
ARL Applied Research Lab D2
ARM Armsby C4
BCS Bank of America Career Services C5
BVR Beaver Stadium A8
BCR Berkey Creamery B5
BBH Biobehavioral Health D4
BKS Bookstore D4
BRL Borland B4
BKE Boucke D4
BJC Bryce Jordan Center B8
BKH Buckhout Lab C4
BUR Burrowes C3
BST Bus Station D2
BUS Business B5
CRG Carnegie D3
CDR CEDAR B3
CHB Chambers C3
CHN Chandlee Lab D4
CHM Chemistry C5
DVL Davey Lab D4
DKE Deike D3
EES Earth-Engineering Sci. D1
EAP East Parking Deck C5
EIS Eisenhower Auditorium C5
EPD Eisenhower Parking Deck C5
EEE Electrical Engineering East D3
EEW Electrical Engineering West D3
EUN Engineering Units (A-C) D3
FNK Fenske Lab C4
FRG Ferguson C4
FDS Food Science B5
FRD Ford B3
FRR Forest Resources B5
FRM Forum B4
FRN Frear North C4
FRS Frear South C4
GRN Grange D5
GIP Greenberg (Ice Pavillion) C7
HLB Holuba Hall C7
HMD Hammond E3
HDD Health & Human Dev. D4
HND Henderson D4
HNG Henning B5
HUB Hetzel Union Building (HUB) D4
HNZ Hintz Family Alumni Center D3
N2 Holmes Hall B4
HSL Hosler D3
HPD HUB Parking Deck D5
HLS Huck Life Sciences C5
IST Information Sciences and Technology D2
IM Intramural B7
KLR Keller B2
KRN Kern C3
LFB Lasch Football Building C7
LND Leonhard D1
MTR Mateer B3
MCL McAllister D4
NAT McCoy Natatorium B6
MSC Millennium Science Complex C5
MOR Moore B3
MLR Mueller Lab C4
MUS Music B3
MII Music II B3
NLI Nittany Lion Inn B2
NLS Nittany Lion Shrine C2
NPD Nittany Parking Deck B3
NLL Noll Lab D2
NSB Nursing Sciences Bldg D4
OMN Old Main D4
OSM Osmond Lab D4
PMA Palmer Museum of Art B4
PSQ Pasquerilla Spiritual Center C3
PNL Paterno Library C4
PTL Pattee Library C3
PTN Patterson C4
PEG Pegula Ice Arena C7
PLK Pollock Library D5
PND Pond Lab C4
RKL Rackley B3
RBR Reber D3
REC Recreation (Rec Hall) C2
RTR Ritenour C5
ROB Robeson Cultural Center D4
SKT Sackett D3
SHC Schreyer Honors College D5
SCC Shultz Child Care Center B3
SCB Schwab Auditorium D3
SHD Shields B7
SPK Sparks C3
SDL Steidle D3
SFB Stuckeman Family Building B4
STH Student Health Center C5
THR Theatre B4
TMS Thomas C5
TSN Tyson C5
VIS Visual Arts B4
WGR Wagner B6
WKR Walker D2
WTK Wartik Lab C4
WHT White D5
WML Whitmore Lab C4
WLD Willard D3
Visitor Parking
Visitor Parking with permit
Campus Bus Routes
Bus stops
Blue Loop
White Loop
Green Link
Red Link
East Park Ave
West Park Ave
Curtin Rd
University Dr
Dauer Rd
Hastings Rd
Bigler Rd
Shortlidge Rd
Allen Rd
Fischer Rd
N. Atherton
White Course Dr
Pollock Rd
Burrowes Rd
Fraser Rd
Mifflin Rd
McKean Rd
Linden Rd
Elm Rd
W College Ave
E College Ave
W Beaver Ave
E Beaver Ave
High St
S. Atherton
Sparks
Barnard
Fraser
Allen
Pugh
Hiester
Garner
Hetzel
North Halls
East Halls
West Halls
Nittany Apartments
Pollock Halls
South Halls
Eastview Terrace
DOWNTOWN STATE COLLEGE
Distance 0.25 mile
Walking Time 4-5 minutes
1/2016 Gould Center, Department of Geography
The Pennsylvania State University

REAL-TIME NEXT BUS ARRIVALS

visit **realtime.catabus.com** or text "CB"+ stop# (ex: CB357) to **321-123**



Full Service Hours & Frequencies

MONDAY–FRIDAY

				Thu, Fri nights
BL	4:45a (20 MIN)	7:30a (6-8 MIN); 8:00p (11 MIN)	12:10a	2:10a (11 MIN)
WL	7:30a (7-10 MIN)		12:10a	3:40a (5-10 MIN)
GL	7:30a (12 MIN)		3:30p	
RL	4:55a		11:55p	

SATURDAY & SUNDAY

				Sat night
BL	9:00a (22 MIN)	3:00p (11 MIN*)	12:10a	2:10a (11 MIN)
WL	9:00a (20 MIN)	3:00p (7-10 MIN*)	12:10a	3:40a (5-10 MIN)
RL	8:45a (Sun: 12:05p)		(Sun: 9:15p) 11:45p	

Reduced Service Hours & Frequencies

MONDAY–FRIDAY

BL	4:45a (20 MIN)	7:30a (8-12 MIN); 6:00p (22 MIN)	9:40p
RL	4:55a		6:25p

SATURDAY

RL	8:45a	5:55p

(thick line)	every 5–12 minutes
(thin line)	every 20–22 minutes
(dashed line)	*see schedule (over)*
7:30a	first/last bus departs Jordan East (BL), Schlow Library (WL) or Dunham Hall (RL)
7:30a	service begins/ends or frequency changes

*20-22 MIN Sunday after 10p

Calendar 2016–17

Fall Semester (8/20–12/17)
Full Service *except:*
- **9/5** Sunday (Full) Service
- **11/19–11/23** Reduced Svc
- **11/24** No Service
- **11/25** Reduced Service

Winter Break (12/18–1/6)
Reduced Service *except:*
- **12/25, 1/1** No Service
- **12/26–12/30** Saturday (Reduced) Service

Spring Semester (1/7–5/7)
Full Service *except:*
- **3/5–3/12** Reduced Service

Summer Sessions (5/8–8/18)
Reduced Service *except:*
- **5/29, 7/4** No Service

RED LINK Schedule

MON–FRI Full Service

	1	2	3	4	5	6	7	1
4a	–	–	–	–	–	45	53	55
	55	59	06	10	–	13	21	24
5a	24	28	35	39	–	42	50	53
	58	02	09	13	–	16	24	27
6a	27	31	38	42	–	45	53	56
	–	–	–	–	–	59	07	14
	45*	49	56	00	08	16	24	31
7a	02	06	13	17	25	33	41	48
	19	23	30	34	42	50	58	05
	36	40	47	51	59	07	15	22
	53	57	04	08	16	24	32	39
8a	10	14	21	25	33	41	49	56
	27	31	38	42	50	58	06	13
	44	48	55	59	07	15	23	30
9a	01	05	12	16	24	32	40	47
	18	22	29	33	41	49	57	04
	35	39	46	50	58	06	14	21
	52	56	03	07	15	23	31	38
10a	09	13	20	24	32	40	48	55
	26	30	37	41	49	57	05	12
	43	47	54	58	06	14	22	29
11a	00	04	11	15	23	31	39	46
	17	21	28	32	40	48	56	03
	34	38	45	49	57	05	13	20
	51	55	02	06	14	22	30	37
12p	08	12	19	23	31	39	47	54
	25	29	36	40	48	56	04	11
	42	46	53	57	05	13	21	28
	59	03	10	14	22	30	38	45
1p	16	20	27	31	39	47	55	02
	33	37	44	48	56	04	12	19
	50	54	01	05	13	21	29	36
2p	07	11	18	22	30	38	46	53
	24	28	35	39	47	55	03	10
	41	45	52	56	04	12	20	27
	58	02	09	13	21	29	37	44
3p	15	19	26	30	38	46	54	01
	32	36	43	47	55	03	11	18
	49	53	00	04	12	20	28	35
4p	06	10	17	21	29	37	45	52
	23	27	34	38	46	54	02	09
	40	44	51	55	03	11	19	26
	57	01	08	12	20	28	36	43
5p	14	18	25	29	37	45	53	00
	31	35	42	46	54	02	10	17
	48	52	59	03	11	19	27	31
6p	13	17	22	26	34	42	50	54
	36	40	45	49	57	05	13	17
	59	03	08	12	20	28	36	40
7p	22	26	31	35	43	51	59	03
	45	49	54	58	06	14	22	26
8p	08	12	17	21	29	37	45	49
	31	35	40	44	52	00	08	12
	54	58	03	07	15	23	31	35
9p	17	21	26	30	38	46	54	58
	40	44	49	53	00	08	16	20
10p	25	29	34	38	45	53	01	05
11p	10	14	19	23	30	38	46	50
	55	59	04	08	15	23	31	35

MON–FRI Reduced Service

	1	2	3	4	5	6	7	1
4a	–	–	–	–	–	45	53	55
	55	59	06	10	–	13	21	24
5a	24	28	35	39	–	42	50	53
	58	02	09	13	–	16	24	27
6a	27	31	38	42	–	45	53	56
	45*	49	56	00	07	15	23	30
7a	10	14	21	25	32	40	48	55
	35	39	46	50	57	05	13	20
8a	00	04	11	15	22	30	38	45
	25	29	36	40	47	55	03	10
	50	54	01	05	12	20	28	35
9a	15	19	26	30	37	45	53	00
	40	44	51	55	02	10	18	25
10a	05	09	16	20	27	35	43	50
	30	34	41	45	52	00	08	15
	55	59	06	10	17	25	33	40
11a	20	24	31	35	42	50	58	05
	45	49	56	00	07	15	23	30
12p	10	14	21	25	32	40	48	55
	35	39	46	50	57	06	14	21
1p	00	04	11	15	22	30	38	45
	26	30	37	41	48	56	04	11
	50	54	01	05	12	20	28	35
2p	16	20	27	31	38	46	54	01
	40	44	51	55	02	10	18	25
3p	06	10	17	21	28	36	44	51
	30	34	41	45	52	00	08	15
	56	00	07	11	18	26	34	41
4p	20	24	31	35	42	50	58	05
	46	50	57	01	08	16	24	31
5p	10	14	21	25	32	40	48	55
	36	40	47	51	58	06	14	21
6p	00	04	11	15	22	30	38	45
	26	30	37	41	48	56	04	11

SAT/SUN

	1	2	3	4	5	6	7	1	FULL SERVICE	REDUCED SERVICE
8a	45	49	56	00	07	15	23	30	SAT	SAT
9a	35	39	46	50	57	05	13	20	SAT	SAT
10a	25	29	36	40	47	55	03	10	SAT	SAT
11a	15	19	26	30	37	45	53	00	SAT	SAT
12p	05	09	16	20	27	35	43	50	SAT & SUN	SAT
	55	59	06	10	17	25	33	40	SAT & SUN	SAT
1p	45	49	56	00	07	15	23	30	SAT & SUN	SAT
2p	35	39	46	50	57	05	13	20	SAT & SUN	SAT
3p	25	29	36	40	47	55	03	10	SAT & SUN	SAT
4p	15	19	26	30	37	45	53	00	SAT & SUN	SAT
5p	05	09	16	20	27	35	43	50	SAT & SUN	SAT
	55	59	06	10	17	25	33	40	SAT & SUN	SAT
6p	45	49	56	00	07	15	23	30	SAT & SUN	
7p	35	39	46	50	57	05	13	20	SAT & SUN	
8p	25	29	36	40	47	55	03	10	SAT & SUN	
9p	15	19	26	30	37	45	53	00	SAT & SUN	
10p	05	09	16	20	27	35	43	50	SAT	
	55	59	06	10	17	25	33	40	SAT	
11p	45	49	56	00	07	15	23	30	SAT	

Even hour times (i.e. 2p, 4p) in **BOLD** / Odd hour times (i.e. 1p, 3p) in RED

*First bus to Innovation Park; earlier trips end at Mt Nittany Medical Ctr

CATABUS

CAMPUS SERVICE

FREE

Frequent Fare-Free Downtown / Campus Circulator LOOP and Cross-Campus LINK Service
Effective August 20, 2016

BL BLUE LOOP	Clockwise around Campus and Downtown via College Ave	↻
WL WHITE LOOP	Counter-Clockwise around Campus and Downtown via Beaver Ave	↺
RL RED LINK	West Campus to/from Medical Center and Innovation Park via Curtin Rd	⇆
GL GREEN LINK	Campus to/from Commuter Parking Lots via Curtin Rd	⇆

PennState

Fare-free service on campus is made possible by a partnership between CATA and the Pennsylvania State University through Penn State Transportation Services.

CENTRE AREA TRANSPORTATION AUTHORITY

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realtime.catabus.com