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MINERVA: SMALL PLANETS FROM SMALL TELESCOPES

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ABSTRACT

The *Kepler* mission has shown that small planets are extremely common. It is likely that nearly every star in the sky hosts at least one rocky planet. We just need to look hard enough – but this requires vast amounts of telescope time. MINERVA (MINiature Exoplanet Radial Velocity Array) is a dedicated exoplanet observatory with the primary goal of discovering rocky, Earth-like planets orbiting in the habitable zone of bright, nearby stars. The MINERVA team is a collaboration among UNSW Australia, Harvard-Smithsonian Center for Astrophysics, Penn State University, University of Montana, and the California Institute of Technology. The four-telescope MINERVA array will be sited at the F.L. Whipple Observatory on Mt Hopkins in Arizona, USA. Full science operations will begin in mid-2015 with all four telescopes and a stabilised spectrograph capable of high-precision Doppler velocity measurements. We will observe ∼100 of the nearest, brightest, Sun-like stars every night for at least five years. Detailed simulations of the target list and survey strategy lead us to expect 15±4 new low-mass planets.

Key words: telescopes – methods: observational – techniques: radial velocity – techniques: photometric – stars: planetary systems

1. INTRODUCTION

Twenty years after the first extrasolar planets were discovered, we now find ourselves in the midst of an explosion of new discoveries which are transforming the way we think about our Universe. We not only know of ∼1000 confirmed exoplanets and nearly 4000 candidate planets from NASA's *Kepler* mission[1], we are also able to observe their atmospheres, densities (and hence bulk compositions), system architectures, and statistical distributions (e.g. masses, orbital periods, orbital eccentricities). The vast majority of our understanding of planetary system properties has been achieved by the two primary detection techniques: the radial-velocity (Doppler) method, and the transit method. The radial-velocity method detects the small changes in a host star's velocity caused by the gravitational pull of an orbiting planet. The transit method takes advantage of fortuitous geometry, whereby an extrasolar planet is seen to pass in front of its host star, causing a small drop in the light received from that star.

Results emerging from the *Kepler* spacecraft (Borucki et al., 2010) and high-precision radial-velocity surveys indicate that small planets are vastly more common than large planets. Howard et al. (2012) and Fressin et al. (2013) demonstrated from the *Kepler* transiting

[1] http://exoplanets.org

planet candidates that about 25% of Sun-like stars host Earth-size planets in short periods (less than 50 days). The radial-velocity results are in agreement with this conclusion: that low-mass planets, despite being more difficult to detect, are much more prevalent (Howard et al., 2010; Wittenmyer et al., 2011). More recently, Petigura et al. (2013) and Foreman-Mackey et al. (2014) estimate the frequency of Earth-like planets in Earth-like orbits to be between 2–6%.

However, there is a significant observational bottleneck which severely limits our ability to detect and characterise the treasure trove of terrestrial planets which we now know to be ubiquitous. The more then 4000 *Kepler* transiting planet candidates are an extremely valuable resource for building the statistics of planetary system architecture, but a complete characterisation can only be achieved with the radial-velocity method. Only with a radial-velocity orbit can a planet's mass and orbital eccentricity be measured (though for the special cases of multiple-transiting systems, timing variations can be used to infer dynamical masses, e.g. Steffen et al., 2012, Lithwick, Xie, & Wu, 2012). Radial-velocity programs are usually subject to the exigencies of scheduling on shared large telescopes, such that they typically are allocated time in a single block each month, during the bright lunation. This strategy simply will not work for the lowest-mass planets, because planets with orbital periods of 1-2 months and small radial-velocity signals can be easily missed. Dense phase coverage also provides an increase in the precision with which a signal can be detected, scaling as the square root of the number of observations. There is a desperate need for a dedicated observational facility which can achieve the cadence and phase coverage necessary to densely sample a candidate planet's full orbit.

MINERVA (MINiature Exoplanet Radial-Velocity Array), an observatory purpose-built and dedicated wholly to the task of searching for these planets, is the way forward. This strategy – observing every star, every night – has been proven to enhance the detectability of low-mass planets. The "Rocky Planet Search" campaigns conducted by the Anglo-Australian Planet Search, in which a small sample of stars was observed for 48 continuous nights, have dramatically increased sensitivity to short-period planets (O'Toole et al., 2009a; Wittenmyer et al., 2010), resulting in the detection of five low-mass planets (O'Toole et al., 2009b; Vogt et al., 2010; Tinney et al., 2011). Results from other high-precision radial-velocity surveys have shown that some apparently "stable" stars actually host one or more very low-mass planets (Pepe et al., 2011). These planets had escaped detection until a sufficiently large number of extremely high-quality observations were obtained. Combined with the emerging statistics on low-mass planet occurrence from *Kepler*, it is entirely possible that nearly *every* star that is observed intensively enough may be found to host planets.

We are privileged to be in the first generation of humans to *know* that many of the points of light dusting our nighttime sky are host to orbiting worlds, some of which may be like our Earth. With that privilege comes the mighty task of our time, to stand on the shoulders of those who probed the heavens before us, to unlock the secrets of the diversity of worlds. This great unveiling starts with the nearest and brightest stars – it starts with MINERVA.

2. MINERVA OVERVIEW

A complete description of the MINERVA design and commissioning is given in Swift et al. (2015), and we here summarise a few salient points therein. The MINERVA design is centred on the fact that the cost of small commercially-produced high-quality amateur telescopes scales as the aperture diameter D, whereas for custom professional telescopes the cost scales as D^2. By using four 0.7m telescopes, we achieve the collecting area of a 1.4m telescope, but at $\sim 1/4$ the cost of a single custom-built 1.4m. The major components of MINERVA are "off the shelf" commercially available instruments. This approach mitigates risk, reduces costs, and accelerates the timeline to science operations. The PlaneWave CDK700 Telescope (Figure 1) is a 0.7m, alt-azimuth mounted telescope system (Hedrick et al., 2010)[2]. The CDK700 has dual Nasmyth port outputs at f/6.5, with an image scale of 22 microns per arcsecond. The telescope pointing is controlled by two direct drive motors with high-speed encoders, resulting in a pointing accuracy of 10 arcseconds RMS, a pointing precision of 2 arcseconds, and a tracking accuracy of 1 arcsecond over a three-minute period. Additionally, the focuser is also motor-controlled and can be remotely adjusted, useful for defocusing the telescope when doing photometric work. Cooling fans and temperature sensors are used to equilibrate the primary mirror, and the control software is built to automatically correct for wind gusts and other perturbations, increasing overall system stability. The four CDK700s will reside in two "Aqawan" enclosures developed by Las Cumbres Observatory Global Telescope (Brown et al., 2013).

The light from each telescope will be fed into an optical fibre using a custom focal plane unit (Bottom et al., 2014). These four fibres will then form a pseudo-slit at the entrance of a high resolution ($R \approx 80,000$) echelle spectrograph. Four distinct traces will be imaged on a $2\,\mathrm{k}\times2\,\mathrm{k}$ detector covering a spectral range from 500 to 630 nm over 26 echelle orders. Two additional calibration fibres bracket the science fibres and provide stable wavelength calibration by use of a Thorium-Argon lamp. The spectrograph will be housed in a purpose-built class 100,000 clean room, with the critical components inside a vacuum chamber and thermally stabilised to $\pm0.01^{\circ}$C. The spectrograph point-spread function will be calibrated using an iodine absorption cell in the light path, a well-established technique (Marcy & Butler, 1992; Butler et al., 1996; Valenti et al., 1995). Our target single-measurement Doppler velocity precision is $0.8\,\mathrm{m\,s^{-1}}$.

The MINERVA array is sited at the Fred Lawrence

[2] http://planewave.com

Figure 1. MINERVA commissioning site on the Caltech campus showing the open Aqawan and telescopes 1 and 2 inside.

Whipple Observatory (FLWO) on Mount Hopkins, Arizona, at $(\phi, \lambda) = 31^\circ\ 40'\ 49.4''$ N, $110^\circ\ 52'\ 44.6''$ W at an elevation of 7816 feet (2382.3m). From weather records (Bakos et al., 2002; Irwin et al., 2009; Gibson et al., 2012), we anticipate ∼271 nights per year with at least 6.5 usable hours and median seeing of $1.2''$.

3. MINERVA SCIENCE PROGRAMMES

The modular design of MINERVA enables us to pursue both spectroscopy and photometry simultaneously. Each telescope is equipped with a wide field photometric camera on one of the two Nasmyth ports. For example, one telescope can "break formation" and switch to photometric mode on a different target while the others remain on a spectroscopic target. This innovative flexibility facilitates two complementary science programmes aimed at the detection and characterisation of planets.

3.1. High-cadence Radial-velocity Observations

The primary mission of MINERVA is to obtain high-precision radial velocities of nearby, bright stars. The stabilised high-resolution spectrograph will allow us to obtain radial velocities with precisions of $<1\,\mathrm{m\,s^{-1}}$. This will permit the detection of planets down to ∼3 Earth masses with orbital periods shorter than 200 days (for a 0.8 solar-mass host star). We will perform nightly observations of ∼100 nearby bright stars to search for these terrestrial-mass planets. This extremely high cadence is a totally new observational regime, and these are exactly the types of planets which are now known to be ubiquitous (Fressin et al., 2013). The MINERVA target list is drawn from the NASA/UC $\eta_\oplus$ sample comprising 164 nearby, chromospherically inactive stars currently monitored by Keck/HIRES for orbiting exoplanets (Howard et al., 2009). A key advantage of bright host stars is that follow-up observations are considerably more tractable, making these planetary systems much more scientifically valuable than those found around faint stars. Examples of such follow-up investigations include studies of planetary spin-orbit alignment, atmospheric characterisation, and the search for transits or additional planets in the system. Extensive simulations of the MINERVA target list, accounting for stellar radial-velocity jitter, operational overheads, and weather are detailed in McCrady & Nava (2014) and Swift et al. (2015). Those simulations estimate a yield of 15±4 new planets after three years of observations. Of these, 1.0 ± 0.8 are expected to transit their host star. Currently there are 16 radial-velocity detected planets with declinations $\delta > -20^\circ$, periods less than 30 days, $M \sin i < 50\,\mathrm{M}_\oplus$ and $V < 10$. With an additional ∼ 10 from MINERVA, the total transit yield is expected to exceed unity.

3.2. Transit Photometry

The secondary science programme is to use the MINERVA photometers to search the transit windows of low-mass, radial-velocity detected planets. Terrestrial-mass planets, when they orbit nearby, bright stars, are extremely scientifically valuable as their proximity facilitates a multitude of follow-up studies. Hence, even the discovery of a single low-mass transiting planet around a bright star would be a high-impact result. The gas giant planets transiting bright stars have been a boon to our understanding of the interior structures of such planets. The next generation of nearby transiting planet discoveries will have masses and radii comparable to or less than Neptune – MINERVA is well-positioned to lead the way in these new discoveries. Low-mass exoplanets such as 55 Cancri e (Winn et al., 2011) and GJ 1214b (Charbonneau et al., 2009), which transit bright stars, have already provided many exciting follow-up opportunities with the *Hubble* and *Spitzer* space telescopes, and point the way for future detections and studies of other sub-Neptunian systems in the Solar neighbourhood. This secondary science aim is a natural extension of the first, as each Doppler detection provides an opportunity to detect transits if the geometric configuration is favourable. The orbital solution provided by highly precise MINERVA radial velocities will give an estimate of the timing of the transit window to guide follow-up photometric observations with the MINERVA photometers. The advantage of the multi-telescope array is that both science programmes can be pursued robotically from the same site, whenever opportunities present themselves.

4. PROJECT STATUS AND FUTURE DIRECTIONS

All four MINERVA telescopes are complete and their performance has been validated. Pending validation of the second Aqawan enclosure, the telescopes and Aqawans will be relocated to FLWO in 2014 November. The class 100,000 clean room that will house the spectrograph is currently under construction. The upgrades to the spectrograph including a fully operational vacuum chamber are now complete and it is undergoing tests in the lab awaiting the completion of the spectrograph room at Mt. Hopkins. The delivery of the spectrograph is expected by the end of winter 2015, and we expect to be performing fully automated, robotic control of the array and spectrograph by the summer of

2015. The primary survey will follow.

In the longer term, the next logical extension of the MINERVA project is a similar facility in the Southern hemisphere. With an abundance of transiting planet candidates to come from the Kepler K2 ecliptic mission (Howell et al., 2014) and the *Transiting Exoplanet Survey Satellite* (TESS: Ricker et al. 2015), there is a treasure trove of planets which will require follow-up characterisation. Unlike the *Kepler* prime mission, the K2 and TESS fields will also be accessible from the Southern hemisphere. As both missions will favour bright ($V < 12$) stars, the coming decade will offer major scientific opportunities for those who are ready. We are now seeking partners and making preliminary plans for a MINERVA-South, sited in Australia or Chile, to be operational by 2018 to capitalise on the TESS southern candidates.

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