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Photonic Spectrograph for new Technology Telescope (PSTT)

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Abstract. We outline a high stability precision infrared spectrograph intended for the New Technology Telescope at ESO's La Silla Observatory. This spectrograph known as PSTT (Photonic Spectrograph for new Technology Telescope) is intended to incorporate a number of new technologies that have recently become available, e.g., reformatting photonic lanterns, broadband laser combs and $4k^2$ infrared arrays. Elements such as OH suppression and an integrated photonic spectrograph should also be considered. The intention is to deliver a high resolution infrared spectrograph that can deliver sub-m/s radial velocity precision to the ESO community. This will enable the opportunity to discover and characterise Earth-mass planets around nearby objects as well as follow-up on results from transit surveys from the ground and space.

Key words. Stars, Brown Dwarfs, Planets, Abundances, Atmospheres, Infrared

1. Introduction

Exoplanetary science (the search for and study of planets orbiting other stars) has grown over the last two decades as the agenda-setting science item linking dynamically to other areas of science and driving international research agendas. In addition it now rivals cosmology as one of the astronomical fields of most interest to the general public.

A glance at the exoplanet statistics can tell one that our Doppler follow-up capabilities lag far behind the abilities of transit searches to uncover objects suitable for follow-up. Kepler's astounding discoveries will not make precision Doppler work from the ground obsolete for two reasons (1) Kepler's discovery space is limited by ground-based capability to follow-up on its results – this frustration is likely to continue to increase with K2 and NGTS (as a large number of new faint objects show tantalizing signals to follow-up) though of course this is just the beginning of the oversupply problems of transiting objects for follow-up promised by TESS and PLATO. Furthermore it is necessary to complement Kepler's statistical studies of faint and distant stars with detailed studies of nearby and bright stars from the ground. Such work is required to target the plentiful terrestrial-mass planets orbiting nearby stars. In the end these targets have the highest value because they will presumably be the sites that a future generation of robotic science missions may attempt.

A primary focus for exoplanetary science over the next decade will be probing the formation mechanisms and observed frequencies of terrestrial-mass planets. The Kepler satellite is revolutionising the field, having demonstrated the ability to detect Earth-sized planets orbiting faint and distant stars in the Kepler search field – by the time its analysis is finished it will have significantly improved our understanding of their statistics. The focus for ground-based work will be identifying equivalent terrestrial-mass planets orbiting bright, nearby stars for which critical detailed follow-up observations will be possible – in short, undertaking the goal of seeking "nearby habitable planets". Recent results from the HARPS facility have pointed the way for this work over the next decade, while at the same time demonstrating the clear need for a stabilised Doppler facility to make these key observations.

PSTT has been created in response to a call from ESO for new ideas for the NTT. It is some years since a clear community desire was expressed for a high resolution stable infrared capable instrument suitable for use in a variety of science cases, e.g. Kaufl (2005). In part this led to the rapid development of the CRIRES and GIANO spectrographs. At a similar time the consolidation of UK resources into ESO killed Gemini and UKIRT plans for high resolution spectrographs, but similar ideas were at the fore elsewhere and CARMENES and SPIROU were born. All of these represent exciting new projects and each represents a huge leap beyond the capability offered by the retiring generation of CSHELL (IRTF), CGS4 (UKIRT), PHOENIX (Gemini) and complementarity with the more flexible workhorse coverage offered by the likes of CRIRES (UT1), IRCS (Subaru) and NIRSPEC (Keck). While there are a number of Northern instruments under construction the infrared capable spectrographs provided by European groups are significant: (1) CRIRES and GIANO deliver high resolution and work to specification, (2) CARMENES will offer complementary red and infrared capability, (3) SPIROU will include K-band and spectropolarimetry. The upgrade of CRIRES to include cross-dispersion is an excellent development to serve a wide wavelength range, however, its throughput and design may not offer an obvious stepping stone to a similar E-ELT instrument.

Any radial velocity instrument needs to find a home where it can access enough telescope nights and thus objects and epochs to do ground-breaking radial velocity work. A useful touchstone here is UVES on the highly oversubscribed VLT-UT2. Although it has potentially long been the best radial velocity instrument (e.g., Butler et al. 2004) UVES has only managed to support one relatively modest radial velocity survey (e.g., Kurster et al., 2003). The NTT on the other hand is a natural choice for a number of reasons: (1) infrared optimised telescope, (2) high-speed slew and acquisition, (3) La Silla location is excellent for minimising the impact of telluric lines - a function of site altitude and precipitable water vapour, (4) a Southern site is preferred to be complementary with ESO's other high resolution precision spectrographs such as HARPS and ESPRESSO, (5) significantly more Southern targets due to our location "above" the galactic mid-plane (e.g., Yanny & Gardner 2013).

Table 1. illustrates a representative large M dwarf survey based on a very conservative J=12, S/N=150 in 1 hour. It assumes fraction of sky observable = 0.66, an ad hoc parameter which represents the fraction of stars useable for an RV survey (no selection on activity or v sin i), min-max integration per object = 60-4800.0 sec, observing efficiency = 90.0%, fixed overhead/star/epoch = 60.0 sec, av. no. of epochs = 30 (objects with RV signals will be observed more / those without less), max no. of targets per LF bin = 200.0, hours of observing per night = 11.0, survey duration = 5.0 yr based on 194 nights per yr.

Sp Type	Mass	No. of stars
M2.5V	0.3	200
M3.0V	0.24	200
M4.0V	0.19	200
M5.0V	0.15	200
M6.0V	0.12	114
M6.5V	0.1	37
M8.0V	0.09	14
M9.0V	0.08	5
Total		970

2. PSTT science

The primary purpose for PSTT would be a precision radial velocity spectrograph and it is envisaged that programmes associated with this capability would effectively compete for most of the available telescope time. On the other hand as a highly efficient spectrograph it can be expected to be able to make a contribution across a wide range of other science. In particular, a queue scheduled, fast slew telescope such as the NTT should prove crucial in the unpredictable follow-up of GRBs, SNe and Solar System objects.

2.1. An M dwarf survey

An infrared RV survey with PSTT should survey stars that span a mass range of at least a factor of 5, from <0.08–0.4 $M_{\odot}$. This is complementary to the mass range currently being surveyed by optical RV programs (~0.3–1.5 $M_{\odot}$) and illustrates the significant parameter space to be explored. Four major scientific areas can be addressed by a PSTT survey: (1) predictions for planet formation as a function of mass, (2) incidence of terrestrial planets in their habitable zones, (3) the identification of the closest planet host stars for direct imaging and (4) characterisation of candidates from transit surveys.

While it is expected that the frequency of Neptune mass, close-orbiting, planets peaks for 0.4 $M_{\odot}$ stars, the mass distribution peak is expected at 10 $M_{\rm Earth}$ for 0.2 $M_{\odot}$ stars, with a tail extending down to a few $M_{\rm Earth}$. In fact the early-M Kepler planetary candidates now confirm that Earth-mass to Neptune-mass planets, many of which are in < 0.1 AU orbits, are 2.5–4x more numerous around M stars than earlier spectral types (Borucki et al., 2011) (and in greater numbers than transiting Jupiter size planets orbiting earlier spectral types). Moreover, using HARPS, Bonfils et al. 2013 have determined Eta Earth, the frequency of HZ planets orbiting early-M dwarfs to be 0.36. From the Kepler sample (Kopparapu et al. 2013) has estimated M dwarf planet frequencies = 0.36–0.61 in the 0.5–2 $R_{\rm Earth}$ regime, and 0.90+/-0:04 when this is extended to 4 $_{\rm Earth}$ (Dressing & Charbonneau, 2013). Low amplitude signals in the HARPS early-M dwarf sample that indicate 10–100 day RV signals are abundant, with $\eta_{\rm Earth}$= 0.33–1.0 (Tuomi et al. 2014). By extrapolation, we expect late-M dwarf planets in orbits up to a few 10s of days, continuing the trend with semi-major axis distribution found by Currie (2008).

At infrared wavelengths, surveys targeted at searching for low mass planets associated with low mass stars (70% of the solar neighbourhood population) can be achieved with realistic timescales. CRIRES and UVES (Bean et al., 2010; Barnes et al. 2014) have reported around 5 m/s (binned for CRIRES) on Proxima Cen which is highly promising. The RV "noise" for M dwarfs (which may show uniformly spotted photospheres) is estimated to be 2x smaller in the J-band than the V-band (Barnes et al., 2011), with magnitudes 0.5 - 2.0 m/s based on solar activity levels, indicating that a m/s precision can be achieved assuming solar activity levels. Rotation and activity are important factors that must be taken into account when observing late-M stars. There is a clear correlation between rotation and activity, with active stars showing the largest RMS (Barnes et al., 2014). The effects of starspots on line profiles can be reduced with line-cleaning methods (e.g., Moulds et al. 2013), enabling low-mass planet detections with as few as 20 epochs.

In order to gauge the practicality of conducting a high-precision RV survey in the infrared we construct a notional survey. The input population of ultra-cool dwarfs in the solar neighbourhood is based on the Nstars project (e.g., Reid et al. 2008) and the observed IR colours and magnitudes of M and L dwarfs. Our analysis based on the Bouchy et al. (2001) formulation indicates that, for our theoretical models, a S/N of 300 is required to reach a velocity precision of ∼ 1 m/s. As an independent check we have an RV code to extract radial velocities from synthetic spectra and obtained very similar results. On the other hand, the limited real data of late type M dwarfs that we have acquired from CRIRES, HIRES, PHOENIX, NIRSPEC and CGS4 suggest that S/N of 125 or less will suffice to reach 1 m/s (noting considerable sensitivity to spectral type and metallicity). In comparison the HARPS time exposure calculator assumes a S/N=110 for a slow rotating G2V. There are large variations seen for different spectral types and metallicity. For simulation purposes a value of S/N=150 is adopted. As part of this testing process we also investigated the effect of telluric emission and absorption. Even for extreme cases where telluric features are given motions of 100m/s, radial velocity information may be recovered. Our simulations are based on 4mm of water and ignoring 30 km/s around telluric features deeper than 2% (we have not attempted correction, e.g., Cotton et al., 2014). They indicate that most of the Y, about a quarter of J and half of the H band of the PSTT wavelength region is available.

As expected for a survey spanning a factor of 100 in absolute infrared magnitude, it is easy to observe many of early-/mid-M types at relatively little cost in telescope time. The required amount of observing time for these bright targets is largely driven by the fixed overhead, not by the integration time, and hence there is a strong premium on minimising the observing overheads (e.g. target acquisition).

The key to the characterisation of the most interesting exoplanets is a combination of low RMS error and a large number of epochs. The observational data gathered to date and simulations both stress the importance of large numbers of epochs for reliable orbital fitting. For example, Cumming et al. finds that only at 50+ epochs do detection amplitudes become comparable to RMS precision. It can be seen that the most interesting (and famous) exoplanets have indeed required a lot of epochs to define their orbital characteristics.

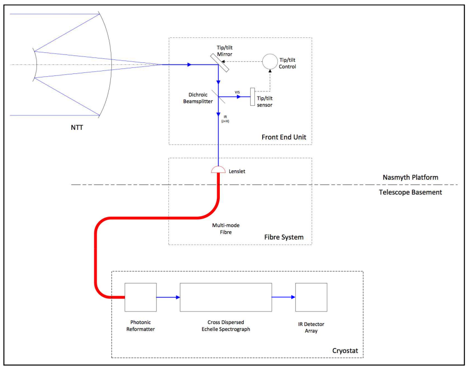

Fig. 1. The calibration system allows light from a calibration source to be simultaneously detected along with the light from the target star. The source is a highly stable broad band laser frequency comb which provides an simultaneous wavelength reference during observations.

2.2. Other science

The stringent instrument requirements for precision radial velocities are also useful for many other areas, e.g., chemical composition & physics of Solar System planetary atmospheres, measurements of exoplanetary atmospheric composition, brown dwarf spectroscopy for Doppler imaging and to define models, low-mass spectroscopic binaries, distribution of vsini in young clusters, use of atomic lines (e.g., [FeII], CI, H2) to probe geometry in hot protostellar discs, stellar magnetic fields using Zeeman splitting, use of FeII lines to measure extinction, excitation, electron density across emitting regions in jets and shocks, followup of bright GRBs and SNs to measure gas and metallicities at high redshifts, asteroseismology for red stars, non-zero fine structure constant tests. In addition there are a number of other cases for high resolution infrared echelles, and we refer to the ESO publication "High resolution Infrared Spectroscopy in Astronomy" (2005, Käufl et al.), which describes a wide variety of studies of the chemistry, structure, winds and climatology of planetary atmospheres; comets; stellar abundances, pulsations, magnetic fields, disks, in-flows, out-flows, and the chemistry and kinematics of the interstellar medium.

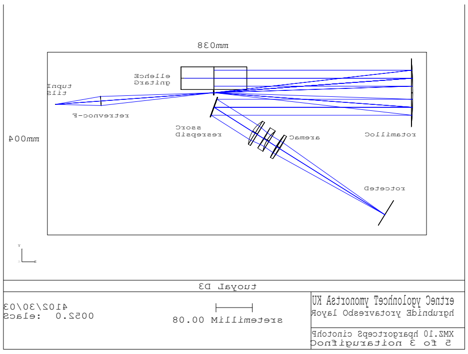

Fig. 2. Spectral format on detector: twenty-seven orders (from 34 to 61) cover the spectral range from 1.0-1.8μm. The spectral orders are shown in red (the length of each order represents the free spectral range); the footprint of the Hawaii-4RG detector is shown in light blue.

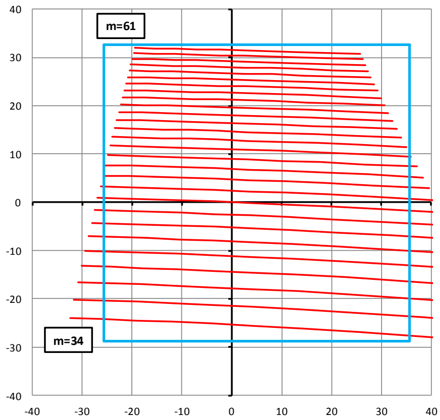

Fig. 3. Spectrograph Optical Layout. For R=70000, 2.5 pixel sampling on a Hawaii 4RG detector (pixel size 15μm) and an R4 echelle grating this gives a required collimator focal length of 175mm and a camera focal length of 325mm. The output beams from the reformatter are single mode Gaussian beams of width 9μm. This gives a far field divergence angle (at 1.8μm) of 7.3degrees or equivalent to an F/4 beam. The beam diameter at the grating is then 43.7mm and the camera f-ratio is F/7.4. The cross disperser is a first order grating of 175 lines/mm. This is shown as a ruled reflective grating; a transmissive VPH grating would be a viable alternative, subject to a detailed trade study of efficiency vs. wavelength coverage.

3. New generation instrument

Our goal is to provide a new-generation of high throughput spectrograph using appropriate key new developments which might include: (1) a photonic lantern, (2) an ultrabroad band laser comb, (3) OH suppression, (4) an integrated photonic spectrograph, and (5) large format infrared arrays (e.g., Hawaii 4RG). There is a strong heritage of precision radial velocity spectrographs iterating their design in order that sub-m/s velocities can now be achieved by several spectrographs. Of these, the HARPS spectrograph is particularly known for its precision and quality of design, making it the current benchmark instrument. While there is much discussion in the literature as to the precision floor that may be reached for stars there are a number of areas of the HARPS design which can be significantly improved on. PSTT is envisaged to solve limitations of the current HARPS design – namely modal fibre noise, precision limitation of ThAr calibration, low efficiency and large size.

3.1. Photonic lanterns

Bland-Hawthorn et al. (2011) dramatically showed that optical fibre guided-wave transitions can be used to efficiently reformat a multimode telescope PSF into a diffraction-limited (in one axis) pseudo-slit and fused with non-periodic Bragg gratings can suppress OH lines. While grating technology remains very expensive, the reformatting ability of photon lanterns is already robust technology.

3.2. Ultrabroad band laser combs

Turnkey laser combs will be delivered this year to HARPS and HARPS-N. While these devices should deliver a step change in calibration they will cover only a relatively narrow wavelength range rather than the full wavelength region available. The current technology involved uses filtering to reduce the number of modes to a useful number, this approach introduces sidebands some of which are expected to be problematic. A new approach is the use of so-called OPOs (optical parametric oscillators) together with Ti:sapphire lasers; these can provide a 1.4–1.8 μm laser comb with lines spaced by 10 GHz and so require no filtering. The next step envisaged for these devices will be to include frequency mixing in order to produce tunability from blue to mid-infrared wavelengths and thus comfortably covering the 1-2 μm regime. Such devices are currently under development as optical bench experiments and so not portable or commercially available. However, active locking of Ti:sapphire laser OPO comb devices with several control loops has been achieved and they can already run for hours.

3.3. Outline design

We base this on top level requirements of Y, J, H band coverage, spectral resolving power R>70,000 and sampling>2.5 pixels. Light from the telescope is fed into a front end unit mounted on the Nasmyth platform. Visible light from the target star (R and I bands) is split off onto a tip/tilt sensor via a dichroic beamsplitter while Y, J, H light passes though into the fibre system. The tip/tilt sensor is used to control a tip/tilt mirror which stabilises the target image on the input to the fibre system. A set of beam combining optics is used to allow simultaneous detection of light from the target star and light from a calibration system.

The beam enters a multi-mode fibre via a lenslet which matches the numerical aperture of the telescope beam with that of the multimode fibre. The number of modes supported by the fibre will be chosen to at least match the number of modes in the telescope PSF. The fibre carries light to a spectrograph located in the telescope basement. The multimode fibre is coupled to a photonic reformatter, which converts the multi-mode beam from the fibre into a linear array of single mode outputs. This reformatter takes the form of either a single integrated-optic chip (of the form demonstrated in Harris et al. 2014), or a hybrid fibre-integrated optic device based (e.g.,Thomson et al, 2012 and Birks et al., 2012). Once the photonic reformatting has been performed, the linear array of modes form the diffraction limited entrance slit for a spectrograph.

The spectrograph is a crossed dispersed echelle spectrograph using the white pupil design used in HARPS and other similar highly stable radial velocity spectrographic instruments. The detector system uses a single Hawaii 4RG IR detector array. The spectrograph is cryogenically cooled and is located in the telescope basement to ensure optimal stability. The main function of the calibration system is to allow light from a calibration source to be simultaneously detected along with the light from the target star. This calibration source is a highly stable broad band laser frequency comb (e.g., Sun et al., 2007) which provides an accurate simultaneous wavelength reference during observations. The calibration system also includes other sources which allow offline calibrations to be performed (e.g. flat fields, daytime wavelength calibrations etc.)

The number of modes in the telescope PSF is given by: $M \sim (\pi \chi \mathrm{D}/4\lambda)^2$, where M = number of modes, χ = the seeing angle as defined by the full width half maximum of the PSF, D = the telescope aperture diameter and λ = the wavelength. Assuming a tip/tilt corrected FWHM of 0.5 arcsec then with a telescope diameter of 3.6m and a wavelength of 1μm the number of modes is approximately 46.

The single mode width produced by the reformatter is approximately 9mm. Using a 2xN output arrangement from the reformatter and allowing for a calibration reference these can be arranged into an effective spectrograph slit size of 20 x 250mm. As detailed above other output arrangements of the modes are possible though for this layout dimensions of the major optical components are: Echelle grating 190 x 50mm, Collimator mirror -150mm diameter, Cross disperser -50mm diameter, Camera lenses - 60mm diameter.

4. Conclusions

M dwarfs are rather too faint in the optical though an infrared photonic spectrograph should provide a route to the precise and efficient measurement of their radial velocities. PSTT is designed to provide stable high resolution infrared spectroscopy to the ESO community. PSTT can provide a simple workhorse instrument capable of field changing discoveries and serve as a pathfinder for future high resolution spectrometers. The intended targets for PSTT will have excellent astrometry reported by Gaia.

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