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# High precision radial velocities in the near-infrared domain: Status and prospects

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**Abstract.** The extension of the highly successful Doppler technique into the near-infrared (0.9–2.5 $\mu$m) is highly desirable as it would open the possibility for searches for extra-solar planets around young stars, very low-mass stars and brown dwarfs. Here we review the current status of this technique and discuss future prospects with particular emphasis on challenging problems for the next decade.

## 1. BACKGROUND

In less than two decades, more than 700 exoplanets, brown dwarfs (BDs) and planetary mass objects (3-13 Jupiter mass free floating objects) have been identified. In addition, we have witnessed a revolution in the field of debris disks studies with the completion of extended surveys that have identified about 300 stars that harbor debris dust, shedding light into the frequency of planetesimal formation (the building blocks of planets) and the characterization of extra-solar planetesimal belts. Although a very interesting picture of this rich "zoology" is emerging, several important questions remain to be answered, such as for example: What is the diversity of planetary systems, including long period planets (beyond the reach of radial velocity (RV) and transit surveys) and exotic systems? What is their dynamical evolution? What are the properties of exoplanets (orbits, masses and atmospheric properties)? What are the frequencies and properties of planetesimal belts and what are the implications for the frequency of terrestrial planet formation, for the habitability of the planetary system and for water delivery into the terrestrial planet region? How common are Earth-like planets?

These, and other related questions, are of critical importance from an astrobiological point of view because they can help us place the evolution of the Solar System and the establishment of basic habitability conditions on at least one of its planets, the Earth, into perspective. Studies of extrasolar planets have revealed an astonishing diversity of masses, semi-major axes and eccentricities, from the short period "hot Jupiters", to planets in very elongated orbits, to planetary systems with multiple Jupiter-mass planets, to the super Earth mass planets with orbital periods of a few days [1, 2]. According to a recent report from the ExoPlanet Task Force (ExoPTF), organized jointly by the National Science Foundation and NASA (http://www.nsf.gov/mps/ast/exoptf.jsp), planet studies in the next decade must address three compelling questions: (1) What are the characteristics of Earth-mass/Earth-size planets in the habitable zone around nearby, bright stars? (2) What is the architecture of planetary systems? And (3), how do planets and planetary systems form? ExoPTF recommends that the near-term highest priority be given to improving RV precision and providing more telescope time to intensify RV studies with the goal of detecting (several) Earth mass planets around bright stars.

Very recently, a new population of low-mass planets in the Uranus to sub-Neptune mass range (5-21 Earth masses) with orbital periods of a few days, called super Earth mass planets, has been detected by the RV surveys [3], whose precision has improved from 3–10 m/s before ∼2003 to ∼1 m/s afterwards. So far a total of ∼20 such planets have been announced among ∼200 bright stars searched for super Earth mass planets, mostly using state-of-the-art high-resolution cross-dispersed echelle optical spectrographs, such as HARPS at the ESO 3.6-m telescope and HIRES at the 10-m W. M. Keck observatory. These discoveries usually require ∼30–100 observations with around 1 m/s precision, since their velocity amplitudes are extremely small (a few m/s).

Although the sample of super Earths is still scarce, the observed properties show different trends with respect to the known giant planets. Unlike the giant planets, whose frequency scales as the square of the host-star metallicity [4], the super Earth frequency seems to weakly depend on the host-star metallicity. Also, the 3-day orbital period pile up observed for giant planets [5] does not appear to be present for super Earths. These early results indicate that they may belong to a new planet population whose formation and evolution may be very different from that of the giant planets. For instance, they may be formed without accumulating a substantial amount of gaseous material, unlike the gas giant planets. In other words, they may be terrestrial rocky planets. Their lower masses may make them less capable of opening up gaps in protoplanetary disks, so they may have undergone a very different migration history than the gas giants, and some may have been formed in-situ.

Most ($>80\%$) of the nearby stars and brown dwarfs are significantly cooler and less massive than the Sun. They have spectral types M, L and T, corresponding to effective temperatures in their photospheres ranging from 3800 to 600 K ("ultra-cool dwarfs"). They are very faint at optical wavelengths because the bulk of their luminosity is emitted in the infrared. Current strategies to search for exoplanets are focused on the optical wavelength domain, but it is very inefficient to observe ultra-cool dwarfs in the optical. As a consequence, exoplanet searches around ultra-cool dwarfs are limited to a small number of targets due to the large amount of telescope time needed to observe them.

A new generation of high-resolution near-infrared spectrographs capable of extending accurate Doppler measurements from the optical into the near-infrared (NIR) domain is currently under study [6–8]. To detect rocky planets in the habitable region around M dwarfs, the required RV precision is about 1 m/s, whereas it will take a precision of 10 cm/s to reach a similar science goal around G-type stars (Figure 1) since the gravitational pull of such planets is smaller around solar-type stars.

GIANO for the Telescopio Nazionale Galileo in La Palma is the most advanced project [7]. It is a cross-dispersed echelle spectrograph providing a spectral resolution up to 46.000 and a very high spectral stability to measure RV with an accuracy of few m/s (better than 10 m/s). A reference spectrograph with very-high accuracy in the visible range is HARPS at the ESO 3.6-m telescope in La Silla, having a measured short-term stability of 0.2 m/s during one night, and a long-term stability of ∼1 m/s, these values being the present limit of standard technologies. Despite of the fact that HARPS only has one highly specialized observing mode, it is one of the most demanded instruments at ESO.

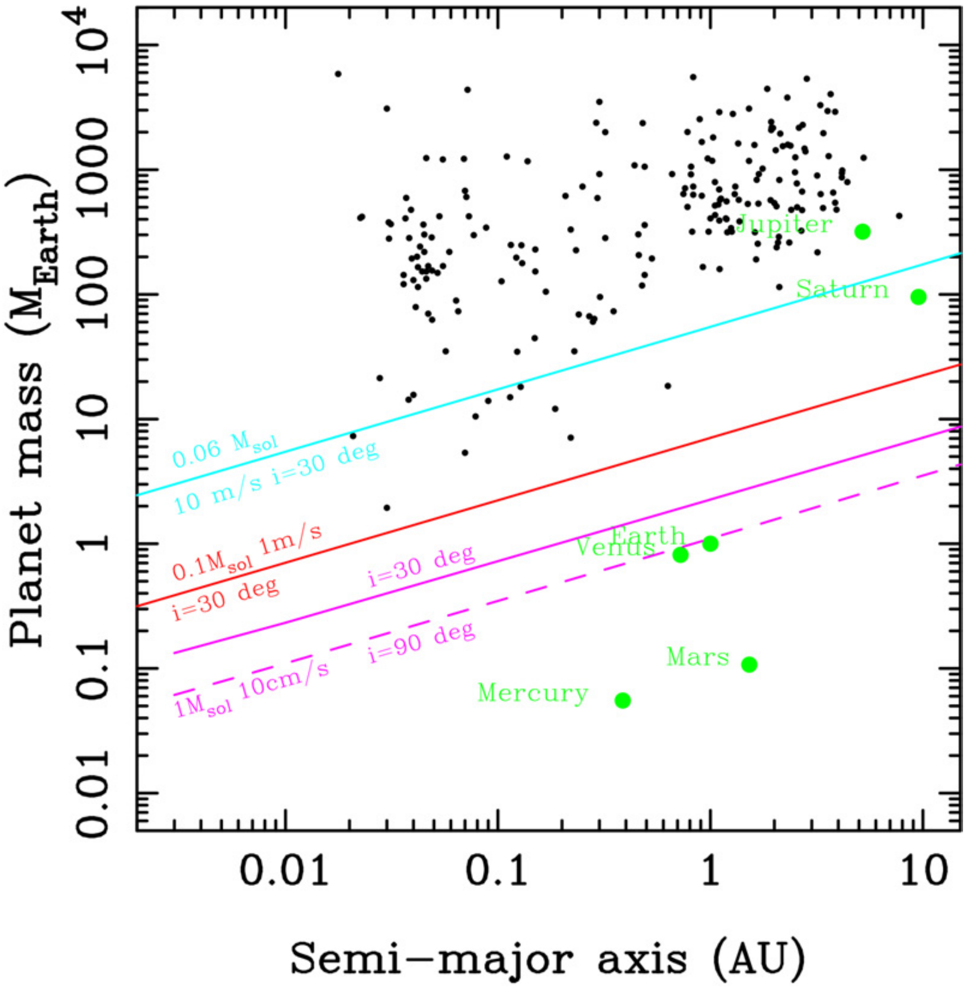


**Figure 1.** Discovery space for rocky planets (inclined lines) compared with the known exoplanets (tiny dots). The RV precisions needed for habitable rocky planet detection around solar-type and very low-mass stars, and around brown dwarfs are indicated with magenta, red and blue lines, respectively.

## 2. STATE OF THE ART

Infrared RV monitoring has been carried out for intrinsically red objects such as pre-main sequence stars, red giants, very low-mass stars and brown dwarfs. For example, [9] used VLT/CRIRES to monitor TW Hya for 6 nights and reported an rms dispersion of 35 m/s, which did not confirm the presence of a short-period giant planet around this young star. CRIRES has also been used to follow a red giant for 5 hours with a RV accuracy of 20 m/s [10] and some nearby late-M dwarfs during 6 months with an accuracy of 5 m/s [11]. IRTF/CSHELL has been used to obtain RV measurements for a sample of young stars and reached a precision of 100 m/s [12]. Gemini-South/PHOENIX was utilized during 5 nights to monitor a sample of L dwarfs and obtain rms dispersion of 300 m/s [13]. Using Keck/NIRSPEC, [14] obtained a dispersion of 110 m/s for the dM8 vB10 over 1 hour, and a dispersion of 360 m/s for the bdM9.5 LP944-20 over 6 nights. The same instrumental setup was used by [15] to infer an rms dispersion of 500 m/s for a T4.5 dwarf over several days; and by the same team [16] to report a dispersion of 300 m/s for vB10 over seven years. The latter paper hinted at RV variability in VB10 in accordance with astrometric observations that indicated the presence of a giant planet around this star [17], and make use of PHOENIX models (see del Burgo et al. in these proceedings) that have provided good fits to T dwarf NIRSPEC spectra [18].

All of the aforementioned previous work has made use of spectrographs that are not stabilized and do not have specific tools for high-precision RV calibrations. It has been demostrated by those authors that calibrations using telluric absorption lines and/or ThAr emission arcs can provide an accuracy down to 20 m/s and perhaps even 10 m/s. To improve this level of precision, the use of gas cells has been proposed [6, 19] and it is starting to be implemented [8, 11]. However, there are many issues involved in the future development of a new generation of high-precision near-infrared spectrographs that can yield accurate RV measurements that are comparable to the state-of-the-art in the optical. In the next section we will mention of some those issues and in the rest of the paper we will deal with the two main wavelength calibration options.

## 3. AN OPTIMIZED NEAR-IR SPECTROGRAPH FOR PRECISION RV

In September 2008, the fifth NAHUAL (http://www.ucm.es/info/Astrof/nahual/index.html) science meeting was held in the dream Island of Fuerteventura, and the following optimal spectrograph for accurate NIR RV work was defined:

- High stabilization in pressure and temperature. No moving parts. The main problem with this requirement is to stabilize the spectrograph when operating at cryogenic temperatures.
- High quality detector with cosmetics, read-out noise and dark current comparable with CCDs.
- Accurate and simultaneous wavelength calibration. It is not clear yet what method should be used. In the optical regime, two different wavelength reference systems are used: ThAr and an absorption cell. More recently the laser-comb method [20] has been investigated in the laboratory but it has not been fully implemented yet for RV surveys. Moreover, it has been proven to work only in a narrow wavelength range.
- High enough spectral resolution to resolve the spectral lines; simulations indicated that a resolving power of at least 60,000 would be adequate for late-M dwarfs, and broad spectral coverage to maximize the amount of Doppler information in each spectrum.
- Homogeneous illumination of the spectrograph entrance. With HARPS image scrambling is used for this purpose. The image scrambler contains one optical system to transform the light at the exit of the optical fibre into parallel light, and another system that the re-injects the light into a second fibre. At the exit of the second fibre there is another optical system that changes the f-ratio to the one of the spectrograph.

## 4. DISCUSSION ON WAVELENGTH CALIBRATION METHODS

The main difference between the two main currently used wavelength calibration modes is that the spectral lines of the gas absorption cell are superimposed onto the spectrum of the star, whereas in the ThAr-method there are two beams: one containing the spectrum of the star, the other the calibration lamp. The ThAr-method works only if the internal variation of the shift between the two spectra is smaller than the desired accuracy of the RV-measurements. The mechanical requirements and the optical design of both systems are thus quite different.

In all cases the RV-accuracy that can be reached in the IR also depends on the quality of the IR detectors and the optical design of the spectrograph. Experiments showed that a regular pattern on detector (like even-odd effect) has strong effects on accuracy. The optical design has to be made in such a way that the "astrometric distortions" can be calibrated with as high as possible a number of references lines.

In order to minimise the shift of the two spectra in the case of the ThAr-method, the light of the star and the light of the calibration lamp are fed into the spectrograph via fibres. In order to avoid that

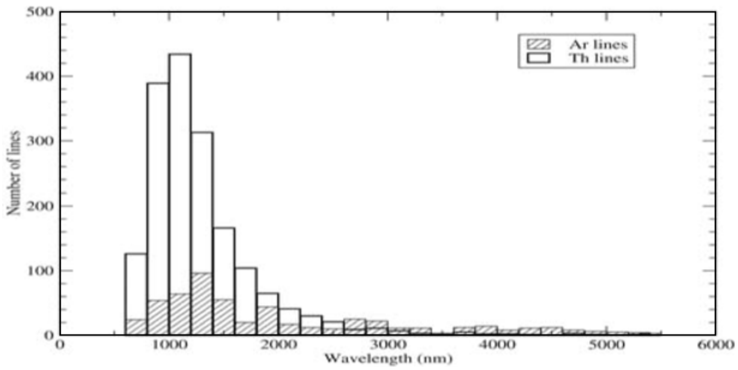


**Figure 2.** Number of ThAr lines as a function of wavelegth [21].

tracking errors of the telescope induce shifts of the spectra, instruments like HARPS use double image scramblers in addition to fibres. We will discuss these devices in more detail below.

A second disadvantage is that in principle two fibres are required: one for the starlight, a second for the ThAr lamp. Thus, the orders have to be sufficiently well separated, which requires a large dispersion of the cross-disperser, and the format of the detector has to be wide enough.

A third important issue is the number of spectra lines per wavelength interval. RV-measurements are essentially determinations of the position of lines on the detector. This means that it is possible to measure the "astrometric" distortion on the detector with sufficient accuracy if the number of lines available is sufficiently high. The figure below shows the number of spectral lines per wavelength interval (taken from [21]). This atlas lists about 1500 ThAr-lines in the near-infrared domain. This number sets a strong constrain on the optical design. It is required to calibrate the distortions to an accuracy that the wavelength calibration has an error of the order of 1 m/s or less.

A fourth issue are aging effects of the ThAr-lamps. It is well known that the relative intensities of the ThAr-lines change with time. In the case of blended lines, this results in wavelength shifts. It is thus required to calibrate the lamp that is being used against some wavelength reference that is known to be constant. In the case of HARPS several lamps are used that are calibrated against each other. The key point is that the Argon lines are less variable than the Thorium lines.

Another issue is the cross-talk between the fibres. In the case of HARPS, the stability is so good that the simultaneous wavelength calibration is actually not used during the night; ThAr-spectra are only taken at the beginning and at the end of the night. In this way the problem of the cross-talk of the fibres is avoided. In the infrared the cross-talk is certainly smaller.

Summary of pros and cons of the ThAr-method:

- Con: Needs at least two fibres (star and calibration, separately).
- Con: Possible need of image scramblers.
- Con: Age effect of lamps.
- Con: Need of very high stability because calibration and star-light are in different fibres.
- Con: Sufficient number of lines is required in the wavelength range of operation.
- Pro: 1 m/s, even 0.3 m/s, stability demonstrated with HARPS.

For the ThAr-method, we require an optical system that efficiently works in the Y, J, and H, bands. Estimating the efficiency of the scramblers is very difficult. In the case of the optical spectrograph SOFIE, there are two modes: one with scrambler, one without. The difference in efficiency between these modes is a factor $2.40 \pm 0.02$. Since both modes have a 3 arcsec entrance aperture, we may estimate the efficiency of the scrambler 42%. A similar figure is also estimated for HARPS. However, in order to obtain a better estimate of the efficiency of an image-scrambler in the IR, a test model is required. More details can be found in [22].

For the absorption cell method, in the optical regime, an iodine cell is used. Iodine produces a very dense grid of lines in the wavelength regime between 500 and about 620 nm. For higher temperatures of the cell, the lines extend further into the red but even with a cell temperature of 200 K, the lines only extend up to about 900 nm. The RV shift is obtained by modelling the observed spectrum of the star together with the superimposed forest of absorption lines. Very high-resolution spectra of the iodine cell and of the star are convolved with the PSF of the spectrograph. The latter determined iteratively during the process. The RV of the star and the instrumental shift are free parameters of the model that are determined when the observed spectrum is modelled. In the optical regime, the very high-resolution spectrum of the star is usually obtained by de-convolving a spectrum of that star taken without the cell. Because the instrumental shift is obtained in the same beam as the starlight, the constraints on mechanical stability are much lower. Since the iodine cells are unsuitable in the infrared, it is required to use a different gas. Laboratory developments of gas cells by our team are presented elsewhere in these Proceedings (see Valdivielso et al.).

Summary of pros and cons of the absorption cell method:

- Pro: Only one fibre needed.
- Pro: No strict need for image scramblers, although they might be helpful.
- Pro: Possibly no aging effect.
- Pro: No need of very high mechanical stability.
- Con: Gases, which produce a dense grid of lines, are needed.
- Con: Superposition of lines makes it difficult to use the spectrum for other purposes than RV.
- Con: Throughput loss because of cell continuum absorption.

To summarize, our current understanding of this problem indicates that the ThAr method could work in the Y and J-bands, while the cell absorption method could be preferable in the H and K-bands because of the insufficient density of ThAr lines at those longer wavelengths. These studies are of interest not only for NAHUAL but also for other similar projects, such as CARMENES [23].

Hence, it would be very informative to set up a testbed for comparison of different calibration methods in the laboratory under identical conditions. Simulations of the RV precision indicate that for late-M and L dwarfs (24) there is significant Doppler information in all the near-infrared bands, and thus calibration methods for all of them should be pursued because all the Doppler information adds up, and the effects of surface inhomogeneities can be disentangled better if simultaneious observations at widely separated wavelengths are compared.

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