NAHUAL: A cool spectrograph for planets of ultra-cool objects

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Abstract. We present the status of an ongoing study to built a high resolution near infrared Echelle spectrograph (NAHUAL) for the 10.4-m-Gran Telescopio Canarias (GTC) which will be especially optimised for planet searches by means of high precision radial velocity measurements. We show that infrared radial velocity programs are particularly suitable to search for planets very low mass stars and brown dwarfs, as well as active stars. The goal of NAHUAL is to reach an accuracy of the radial velocity measurement of a few $ms^{-1}$, which would allow the detection of planets with a few earth-masses orbiting low-mass stars and brown dwarfs. It is planed that NAHUAL covers simultaneously the full wavelength range in the J, H, and K-band, and will also serve as a general purpose high resolution near infrared spectrograph of the GTC. The planed instrument will have a resolution of $\lambda/\Delta\lambda = 50,000$ with a 0.175 arcsec slit, and an AO-system. An absorption cell will serve as a simultaneous wavelength reference.

1. Introduction

In this contribution, we will present a study for a high-resolution spectrograph which is especially designed for high precision radial velocity
(RV) measurements at near infrared (IR) wavelength. The instrument is called NAHUAL \textsuperscript{1} for Near-infrAred High-resolUtion spectrogrAph for pLanet hunting, and will be operated at the 10.4-m-GTC telescope (Gran Telescopio Canarias). The GTC will see first light in 2006. NAHUAL will also serve as a high-resolution spectrograph IR spectrograph for general use (Martín et al. 2005). In the second section of this contribution, we will discuss the benefits if RV-planet search programs are being carried out at IR-wavelength, and in the third and fourth section, we will discuss the requirements and present the conceptional design of the instrument.

2. The benefits of high-resolution NIR spectroscopy for exoplanet research

2.1 Planets of brown dwarfs and very low-mass stars

Most of the efforts for detecting extra-solar planets have hitherow been concentrated on main sequence F,G,K stars. These surveys show that while a large fraction of the stars are binaries and many have massive planets, there is a lack of close-in brown dwarf (BD) companions. This result has often been used as an argument that there are two distinct formation tracks: one leading to planets, and the other to stellar companions. In the standard model massive planets form by core accretion: In the first step a solid core of about 0.01 to 0.03 $M_{Jupiter}$ forms, which subsequently accretes gas from the disk in order to form a massive planet. The core accretion scenario is supported by the fact that stars with an overabundance of heavy elements also have a higher frequency of massive planets (Santos, Israeliian, & Mayor, 2004). The discovery of HD 149026 b, which has 0.21 $M_{Jupiter}$ core composed of elements heavier than helium also supports the core accretion scenario (Sato et al. 2005).

What would be expected, if we go to stars of lower mass? According to Laughlin, Bodenheimer, & Adams (2004), stars of lower masses had also disk of lower masses and thus should also have planets of lower masses. This idea is in good agreement with the observations, as Butler et al. (2005) estimate that the fraction of Jupiter-mass planets of M-stars is at least a factor of 5 smaller than of FGK-stars. However, up to now it is not yet clear whether this is solely a result of the lower masses of the proto-planetary disks, or at least partly due to evaporation due to the strong UV radiation of young M-stars.

\textsuperscript{1}A NAHUAL is also a kind of shaman in Mexican mythology that is a person in daytime but a hunter at night time.
What would we expect, if we go to even lower masses, planets of brown dwarfs (BDs) and very low mass stars (VLMSs)? For BDs the evaporation due to the strong UV radiation is certainly irrelevant. If planets can only form by core accretion, one would expect to find only planets of very low mass (\(\sim 0.01\ M_{\text{Jupiter}}\) or a few \(M_{\text{earth}}\)) in this case. Likewise, one may argue that BDs resemble Jupiter and we might expect to see only Io or Ganymede-type objects. Again this implies that BDs should have planets of only a few \(M_{\text{earth}}\) (Desidera 1999). However, even such planets could be detected with an accuracy of RV-measurements of 5 to 10 ms\(^{-1}\) (Fig.1). On the other hand, one may argue that BDs and VLMSs should have massive planets, simply because there are many BD-BD binaries and the mass-ratio between a BD and a massive planet is only \(\sim 1:10\). Since for field objects there is no break in the initial mass function at 13 \(M_{\text{Jupiter}}\), such “BD-planet binaries” could be possible. Of course, the best evidence for the existence of such objects is 2MASSW J1207334-393254 (Chauvin et al. 2005). If BDs
have massive planets, we would thus expect that there is no correlation with metalicity, as these planets would not have been formed by core-accretion.

Up to now, only two programs to search for planets by means of RV-measurements have been carried out. Joergens (2005) monitored 7 young BDs in the Chameleon cluster, and found one companion candidate. Additionally, she found that the RV-variations caused by activity decreased with the mass of the object. Guenther & Wuchterl (2003) monitored the 26 VLMSs and BDs, and found apart from three binaries one object which showed significant RV-variations: LP944-20. Unfortunately, it is not yet clear, whether these are caused by surface features, or by an orbiting planet.

A search program for planets of VLMSs and BDs with NAHUAL will thus show, whether BDs and VLMSs have planets or not, and if so whether these planets formed by core-accretion or not.

2.2 Calibrating evolutionary tracks and the atmospheres of BDs

The lack of knowledge of the true masses of VLMSs and BDs at young age is a severe problem for this field of research. A dedicated search program for eclipsing BD-BD, or BD-planet binaries should solve the problem. Eclipsing systems could best be found with NAHUAL in a survey in which many BDs are observed but each BD is observed only three times.

NAHUAL will also allow to study the atmospheres of low-mass objects in detail, because it is possible to obtain spectra covering simultaneously J, H, and K-band at a resolution of $\lambda/\Delta \lambda = 50,000$. Such observation would allow to determine $T_{eff}$, log(g) and the abundances, for example.

Young BDs show clear signs of accretion. The presently available optical data seems to indicate that $\dot{M} \sim M_\ast^2$ (Mohanty, Jayawardhana, & Basri 2005). Because the disk mass $M_d \sim M_\ast$, one would deduce that VLMSs and BDs should take much longer than solar-like stars to form. Since the flux of the Bracket $\gamma$ line is well correlated with the accretion rate, observations with NAHUAL will shed more light on to this question.

2.3 Planets of active stars

One problem of the RV-technique is that not only orbiting planets but also stellar spots, plage regions, changes of the granulation pattern, and oscillations can also lead to RV-variations. However, the only effect that causes RV-variations that does not depend on wavelength is an orbiting object. Thus, be carrying out RV-measurements at optical and
IR wavelength, it is possible to distinguish between orbiting planets and other effects.

In interesting question is, whether the RV-scatter caused by stellar activity becomes larger, or smaller when going from optical to IR wavelength. Paulson et al. (2002) used their precise RV-data of the Hyades stars in order to investigate the cause of the RV-scatter. They find that the scatter is mainly caused by spots. Plage regions are less important. This result is confirmed by RV-monitoring of the very active star EK Dra (König et al. 2005). The main effect is that the 90 to 95% light deficit of a spot causes a hump in the profile of a spectral line which moves across it with the rotation of the star. We modelled this effect and find that it is reduced by a factor of 10 at IR wavelength, because the difference in brightness between a spot and the photosphere is smaller in the IR.

3. Scientific requirements

In order to achieve the highest possible accuracy for the RV-measurements, the top requirements are:

- Large spectral coverage: This requirement calls for a cross-dispersed Echelle spectrograph and a 2048x2048 HAWAII-2 PACE HgCdTe detector. NAHUAL will cover the whole region from 0.9 to 2.4 µm, with only some small gaps in the K-band.

- High signal-to-noise ratio: This requirement implies a high throughput and a big telescope, the GTC. Additionally, the instrument will be cooled to 70 K.

- A resolution that is high enough to resolve the spectral lines: Given the $v \sin i$-values of VLMSs and BDs, this implies a resolution of $\lambda/\Delta\lambda \geq 50,000$.

- An absorption cell for the wavelength-self reference.

- AO-system to allow for a narrow slit, and for stabilising the star on the slit.

- Stable environment: The instrument will be placed at the Nasmyth platform, evacuated, and temperature stabilised. Kjelsen et al. (2005) has demonstrated that an amazing accuracy of 0.44 m s$^{-1}$ can be achieved with UVES, which is also placed at the Nasmyth platform, and also uses an absorption cell as a wavelength self-reference.
4. Conceptual design of NAHUAL

The resolution of the spectrograph per arcsec is given by

\[ R_\varphi = \frac{2(d/D)\tan\alpha}{\tan B} \]

where \( R \) is the resolution, \( \varphi \) the slit width on the sky, \( d \) the diameter at the collimated beam, \( D \) the telescope diameter and \( \alpha_B \) is the blaze angle. The first thing to discuss is whether a grating with \( \tan\alpha_B = 4 \), or 2 should be used. While a \( \tan\alpha_B = 4 \)-grating gives a higher resolution, it requires a spectrograph camera of very short focal length with a large field of view. Unfortunately, we studied several possibilities but all of them suffer from vignetting at the edge of the field. This essentially is because a three mirror system has to be used. We thus have to choose a \( \tan\alpha_B = 2 \)-grating. We also studied instrument concepts with collimated beam diameters of 200 and 100 mm but finally decided for the smaller beam diameter in order to keep the instrument manageable (Fig. 2). Forseen is a gold coated grating of 23.2 gr mm\(^{-1}\) with \( \alpha_B = 63^\circ \).

These parameters already fix the slit-width to 0.175 arcsec for a resolution of \( R=50000 \). NAHUAL will thus be work with an AO-system. A natural seeing mode with an image-slicer is also being studied. By placing a flat mirror in front of the Echelle grating NAHUAL will also allow to take spectra with \( R \sim 300 \), using only the three ZnSe prisms of the cross-disperser. Because the AO-system will not change the f-ratio of the GTC, the focal length of the two collimators are fixed to 1700 mm. Given the pixel size of the 2048x2048 HAWAII-2 PACE detector, we designed a three-mirror camera of 420 mm focal length, which has no vignetting even at the edge of the 40x40 mm field of view. It is interesting to note that for designing the instrument we used the GIANO (http://www.bo.astro.it/giano/) concept as a starting point but then finally came up with a design that is closer to HARPS. In the conceptual design NAHUAL is 2.5 m long and 1.2 m wide.

5. The absorption cell laboratory

In order to achieve a high accuracy of the RV-measurements an absorption cell has to be placed in front of the spectrograph. Such a cell imposes a large number of dark lines on to the spectrum of the object which are recored simultaneously with the observations (self-reference spectrograph). While an \( I_2 \)-cell is commonly used in the optical regime, the best choice of gases for an infrared cell still has to be found. As part of the NAHUAL study, we have started a laboratory experiment to try out various gas mixtures. The gases are mixed in a controlled vacuum chamber and the spectra are measured with a spectrophotometer which
is available in the IAC optical laboratory. Promising is a mixture of $N_2O$ (30%), $H_2C_2$ (27%), He (25%), and $CH_4$ (18%).

6. Schedule and Conclusions

We have outlined the potential of NAHUAL for surveys of planets of VLMSSs and BDs. We would like to give one example for the power of NAHUAL at the end. With UVES and the VLT it is possible to achieve an RV-accuracy of 500 $ms^{-1}$ with an exposure time of 20 minutes for the BD LP944-20. With NAHUAL it will be possible to achieve 5 $ms^{-1}$ with an exposure time of only 5 minutes. Thus, we hope that NAHUAL will open up an entirely new window for planet research. The plan is to finish the design study of NAHUAL in 2006, and by 2010 to have the first light.

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Figure 2.: The figure shows the conceptual optical design of NAHUAL.