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NAHUAL: a near-infrared high-resolution spectrograph for the GTC optimized for studies of ultracool dwarfs

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Abstract. We present the status of an ongoing study for a high-resolution near-infrared echelle spectrograph for the 10.4-m GTC (Gran Telescopio de Canarias) which will soon start operating at the Observatorio del Roque de los Muchachos on the island of La Palma. The main science driver of this instrument, which we have baptized NAHUAL, is to carry out a high precision radial velocity survey of exoplanets around ultracool dwarfs. NAHUAL is being especially designed to achieve the highest possible accuracy for radial velocity measurements. The goal is to reach an accuracy of a few m/s. It is thus required that the instrument is cross-dispersed and that it covers simultaneously a wide wavelength range. Absorption cells will be placed in front of the slit which will allow a simultaneous self-reference similar to an iodine-cell in the optical regime. It is planned to place the instrument at one of the Nasmyth platform of the GTC behind the Adaptive Optics system. Our current design reaches a maximum spectral resolution of $\lambda/\Delta\lambda$=50,000 with a slit width of 0.175 arcsec, and gives nearly complete spectral coverage from 900 to 2400 nm.

Key words: very low mass stars, brown dwarfs, instrumentation, spectroscopy

1. Introduction

The 10.4-meter GTC (Gran Telescopio de Canarias) is expected to start scientific operations by 2007. Three first-light instruments are well under development, ELMER and OSIRIS (optical imaging and low-resolution spectroscopy; García Vargas et al. 2004, and Cepa et al. 2003, respectively), and Canari-Cam (a mid-infrared imager, Telesco et al. 2003). A second-generation instrument, EMIR (a near-infrared (NIR) imager and multi-object spectrograph) is also under construction (Garzón et al. 2003). Another second-generation GTC instrument will be FRIDA (a near-infrared imager and low-resolution spectrograph for the adaptive optics focus).

In this paper we present the status of an ongoing study for GTC's near-infrared high-resolution spectrograph (NAHUAL). This instrument will cover the niche of near-infrared high-resolution spectroscopy for the GTC community. Few other large telescopes will have similar instruments. CRIRES at the VLT will have similar spectral resolution than NAHUAL, but it is not cross-dispersed, and hence the free spectral range will be much smaller (Moorwood et al. 2003). Gemini South currently offers Phoenix, a visiting near-infrared high-resolution spectrograph, but it is also not cross-dispersed.

In the last decade the most successful method to discover exoplanets has been high-precision radial velocity (RV) surveys of hundreds of stars. This situation may change with the advent of the Corot and Kepler satellites, which will survey thousands of stars for transits. These satellites are likely to yield hundreds of candidate exoplanets that will need follow-up radial velocity observations with ground-based large-aperture telescopes (e.g., Bordé, Rouan & Léger 2003). NAHUAL will offer the possibility of carrying out some of those follow-up observations. Moreover, the main exoplanet search methods use only the optical wavelength window.

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NAHUAL will allow for a high-precision exoplanet RV survey at near-infrared wavelengths. This is the main design driver of NAHUAL. The instrument will be optimized to search for planets around M, L and T dwarfs, which typically have $R-J$ colors larger than 4. These cool stars and brown dwarfs (BDs) constitute the majority of the nearest stars. By looking at lower mass primaries, NAHUAL will allow to detect exoplanets that are typically nearer and have lower masses than those currently known. In this paper we describe the ongoing study of NAHUAL, which is now entering its second year.

2. Key science driver: Exoplanets around cool stars and brown dwarfs

Precise RV-measurements of stars have led to the discovery of more than 100 extrasolar planets. A statistical analysis of the radial velocity survey results by Lineweaver & Grether (2003) shows that the frequency of planets with masses $m\,sin\,i \geq 0.3\,M_{Jup}$ orbiting old G to K-stars at distances of ≤ 5 AU is about 9%. In a few cases (Charbonneau et al. 2000; Alonso et al. 2004; Bouchy et al. 2004; Torres et al. 2004), eclipses have been observed which confirm that these objects **are** planets. Additionally, in the case of Gl 876, the planetary masses of the companions are confirmed by astrometric observations (Benedict et al. 2002).

The frequency of massive planets of 9% (distance $\leq\ 5$ AU) is quite similar to the fraction of binaries, which is 13%, and 8.1% for G and M-stars, respectively (distance ≤ 3 AU; Mazeh et al. 1992; Fischer & Marcy 1992). However, the distribution of exo-planet masses is not a continuation of the distribution of binary stars. Inbetween the stars and planets, there is a brown dwarf (BD) desert. The frequency of BDs orbiting normal stars at a distance of ≤ 3 AU is only $0.5 \pm 0.2\%$ (Marcy et al. 2003).

In contrast to the planets of the solar system, the eccentricity of exoplanets usually is high. There seems to be little, if any, difference between the eccentricity distribution of exoplanets and binary stars. Another surprise was that there are massive planets at very small distances from the host stars. Last, but not least, studies of the metallicity of the host stars showed that the frequency of planets is higher for very metal rich stars (Gonzalez & Laws 2000; Santos, Israelian & Mayor 2001; Ecuvillon et al. 2004).

The new discoveries have inspired a large number of theoretical efforts aimed at explaining the observational properties. Planet formation models appear divided in basically two different fronts: Giant planets may form either by a gravitational instability of the disk, or by core accretion of planetesimals until a 10 M_{Earth} planet is formed and has enough gravitational pull to accrete gas from the nebula (see Wuchterl, Guillot & Lissauer 2000 for a review). The strange properties of the known exoplanets have been interpreted as evidence that planets form in both ways (Santos, Israelian & Mayor 2004).

However, all these results are based on studies of old, solar-like F-K stars, which all have about one solar masss. Few radial velocity surveys for planets of M-stars have been carried out (Marcy et al. 1998; Delfosse et al. 1998; Butler et al. 2004) but only 3 exoplanets have been detected so far. Remarkably, one of them is the lowest mass exoplanet found to date, with a minimum mass of only 0.067 Jupiter masses (21 earth masses). These surveys of M-stars are limited to small samples because they use optical spectrographs, and they are hampered by the high activity levels of many targets.

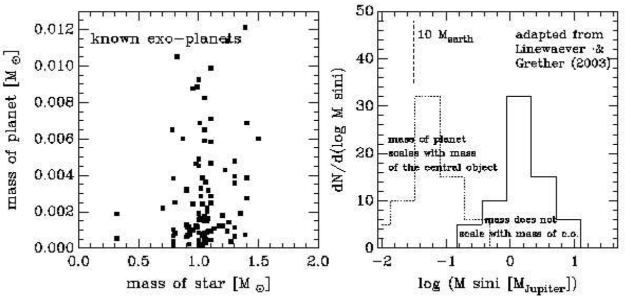

Fig. 1. Left panel: Distribution of the masses of currently known exoplanets versus the masses of the host stars. The currently available data clearly does not allow to draw any conclusion on the relation between the masses, because the current search programs are strongly biased towards solar mass stars (Schneider 2004). Right panel: There are two possibilities: The mass-distribution of the planets may, or may not scale with the mass of the central object. The figure is adapted from the observed mass-distribution of planets for solar-like stars (Lineweaver & Grether 2003). The decrease for small masses is an observational bias, and it is expected that the true mass-distribution continues to rise towards smaller masses.

There are several advantages of going to the near-infrared. One is to observe not only many M-stars, but also VLM stars ($M\ \leq\ 0.2 M_{\odot}$) and BDs. Another important advantage is that the effect of starspots on the RV-accuracy is expected to diminish by about a factor of 10 from optical to NIR wavelengths. Among the key questions that could be addressed by a RV-survey for exoplanets around VLMSs and BDs we underline the following:

- Is the frequency vs. separation distribution for solar-mass stars, VLMSs and BDs the same, or are they different?
- Does the mass of the planets of VLMSs and BDs simply scale with the mass of the central object and/or the mass of the disc? (see Figure 1)
- Do we find the same eccentricity distribution as in solar-mass stars?
- Do we find the same dependence with the metallicity as in solar-mass stars?

Surveys of visual companions of BDs already have identified a number of BD-BD binaries (Bouy et al. 2003; Close et al. 2003; Martín et al. 2003) and one planet around a BD (Chauvin et al. 2005). The first dynamical masses of BDs have been obtained from orbital monitoring of some of these binaries (Bouy et al. 2004; Zapatero Osorio et al. 2004). Additionally, a spectroscopic BD-BD binary in the Pleiades has also been found (Basri & Martín 1999). This binary consists of two BDs with masses of 0.06 to 0.07 $M_{\odot}$ and an orbital period of 5.8 days. By searching for close BD-BD companions, one might hope to find a eclipsing binaries which will then allow the determination of the accurate masses and radii.

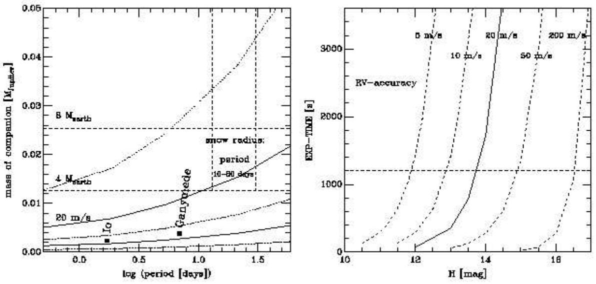

Fig. 2. Left panel: NAHUAL sensitivity to planets around a BD with mass 40 M_{Jup}. The curved lines show the RV-amplitude ($\times\, sin\, i$) of 2, 5, 10, 20, 50 m/s (the 5 and 20 m/s are full lines). Also shown are the positions for the "scaled" Io and Ganymede. Right panel: The accuracy of RV measurements that are foreseen with NAHUAL. The curved lines shows the exposure-times need for an accuracy of 5, 10, 20, 50, and 200 m/s (again 20 m/s shown as full line). With an exposure time of 20 minutes, it would thus be possible to detect planets of 4 to 8 M_{Earth} if the brown dwarf is brighter than 12.5 mag in H.

Young BDs have accretion disks when they are young, and thus might also form planets (Barrado y Navascu´es & Mart´ı n 2003; Klein et al. 2003; Mohanty, Jayawardhana & Basri 2004). If the disk of BDs are just scaled down versions of disks of young stars, we may speculate that the resulting planets are just scaled down versions of the planets of stars. In this case, 10% of the BDs should have planets with the mass of a few M_{Earth}. Since also the snow-radius of the disk scales with the mass of the central object, such planets would be located at a distance of $\leq\ 0.1$ AU from the BD (Stevenson & Lunine 1988). Another view is that the planetary systems of BDs could be scaled up version of the Jovian moon-system. In contrast to our planetary system, where most of the angular momentum is in Jupiter, and not in the sun, in the case of the Jovian moon-system most of the angular momentum is in Jupiter, and not in its moons. If the planetary systems of BDs resemble the Jovian moon-system, we would again expect planets of a few M_{Earth} but at much closer distance from the central object. The third possibility, of course is that the distribution of companions is continuum, so that BDs also have planets of M_{Jup}. In any case, we expect that possible planets have periods of 40 days or less, which implies that they have to be searched for by means of RV-monitoring.

A survey for planets of VLMSs and BDs would be of key-importance for understanding the formation of stars and planets. Fig. 1 (left) shows that if the planets of BDs are scaled-down versions of exo-planets of solar like stars, or scaled up versions of Jovian moons, an accuracy of $\sim$ 10 m/s will allow to detect them. Figure 2 (right) shows that an accuracy of 20 m/s can be achieved with NAHUAL for objects with an H-magnitude of about 13 in an hour. There are more than 300 known VLMSs and BDs in the solar neighborhood and in nearby open clusters and associations for which such studies can be carried out. Certainly, NAHUAL will revolutionize this field of research.

3. Summary of NAHUAL top level requirements

This is a summary of the top level requirements for NAHUAL in order to achieve the main scientific goal outlined above.

- Large spectral coverage. Our current optical design covers from 0.9 to 2.4 microns in one shot with some gaps in the red edge. This requirement calls for a cross-disperser and a large format NIR detector. The detector is likely to be a 2048 x 2048 HAWAII-2 PACE HgCdTe, similar the one used in EMIR.
- High throughput, hence the need to install it at the GTC. We estimate that the combination of NAHUAL and GTC will allow to search for planets around nearby VLM stars and brown dwarfs using modest exposure times (Figure 2).
- Sufficient spectral resolution to resolve spectral lines. Our design reaches $\lambda/\Delta\lambda =$ 50,000 in AO mode with a 0.175 arcsec slit width. We are considering to implement an image slicer to observe point sources without the AO system.
- Stable environment. This requirement calls for a temperature controlled enclosure in one of the Nasmyth foci of the GTC.
- Self calibration for high-precision RV-measurements. Absorption cells for the near-infrared are being developed and calibrated in the laboratory by us and by other teams. A simultaneous fiber-fed emission spectrum from a lamp may also be implemented.
- High spatial resolution to allow using a narrow slit for high spectral resolution. It is currently envisaged that NAHUAL will sit in an optical bench behind the GTC AO facility, but it could also work without the AO system.

4. Progress report on absorption cell laboratory experiments

As part of the NAHUAL study, we have started a laboratory experiment aimed at providing a reference spectrum in the near-infrared using a gas mixture in an absortion cell. The gases are mixed in a controlled vacuum chamber and the spectra are measured with a Cary spectrophotometer available at the IAC optical laboratory.

In Figure 3 we show an example of a laboratory spectrum obtained with a mixture of four gases with the following concentrations: N2O (30%), H2C2 (27%), He (25%), and CH4 (18%). Such spectrum contains a number of absorption bands over a wide spectral range, which can be used for calibration purposes. We have tested that this gas mixture is stable over a time scale of months under the atmospheric conditions of the IAC laboratory.

5. Progress report on optical design

Our optical engineers (Uwe Laux in Tautenburg and Ernesto S´anchez Blanco in IAC) are working on the conceptual optical design of NAHUAL. Our current design is based on

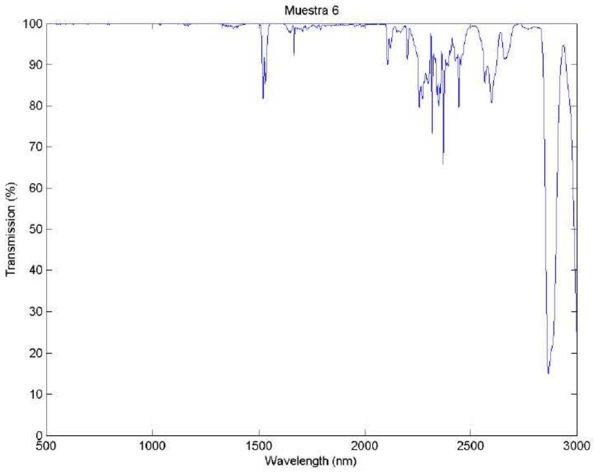

Fig. 3. Laboratory spectrum of a gas cell with a combination of four gases (acetylene, nitrogen oxyde, methane and helium). The spectral resolution is 2 nm and the wavelength range 500-3000 nm.

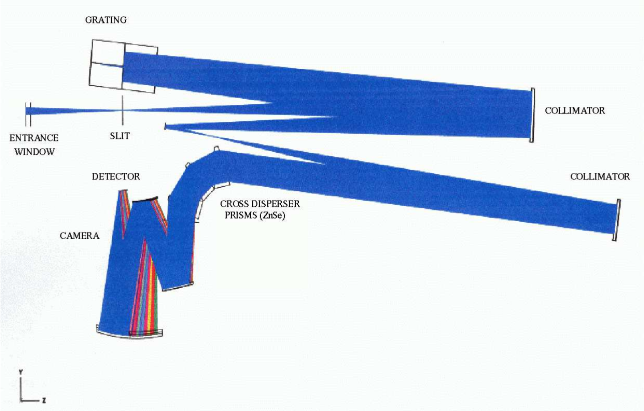

Fig. 4. Conceptual optical design for NAHUAL. The resolving power is 50,000 for a slit width of 0.175 arcsec, and a nearly complete spectral coverage from 900 to 2400 nm.

the GIANO concept (http://www.bo.astro.it/giano/) modified for the GTC (focal ratio F17) and optimized to minimize vignetting effects. It can cover in one shot the wavelength range from 900 to 2400 nm (although with some gaps at the red edge) with a spectral resolution of 50,000 for a slit width of 0.175 arcsec, which is well suited for the expected diffraction limit of the GTC. In Figure 4 we show the optical layout of this concept. The main optical components are labelled, namely, a slit wheel, a collimator, an echelle grating, a collimator, a cross disperser, a camera and a detector.

6. Summary and schedule

We have presented the concept of NAHUAL, a high resolution near-infrared echelle spectrograph for the GTC. The main scientific driver of this instrument is to carry out a high-precision radial velocity search for exoplanets around very low-mass stars and brown dwarfs. Our current understanding of brown dwarfs indicates that they form like stars and are likely to harbor planets.

We have shown the status of two lines of work related to NAHUAL: a) the development of calibration gas cells in the near-infrared, b) a conceptual optical design.

Our current schedule is to continue with conceptual optical design studies and calibration gas cell development into 2006. In early 2006, we expect to submit a proposal to the Spanish PNAA to obtain most of the funding for the instrument, which is currently estimated to cost around 2.5 million euros. Detailed opto-mechanical design should take place in 2007 and 2008. Fabrication of components is planned to start in 2008 and integration should take place at IAC in 2009. We aim at having first light in the GTC late in 2009 or early in 2010. The commissioning of the instrument is foreseen for 2010.

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