White Papers for High-Resolution Optical Spectroscopy @ Gemini

Cool dwarfs: new insights on chemical evolution, young stars and planets

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Despite being the most abundant stellar component of our Galaxy cool dwarfs have been so far neglected for many studies. This is mainly due to two reasons: 1) their spectra is more complex and therefore are harder to analyse; 2) they are intrinsically faint requiring thus large telescopes. Below we describe the importance of a high resolution spectrograph on Gemini to study M and late K dwarfs and the potential results that could be obtained with such an instrument.

1. Chemical abundances: metallicities and planets

Although the chemical composition is a key quantity to understand the formation and evolution of stars and planets, M dwarfs remain largely unexplored for chemical abundance work due to both their faintness and the complexity of their spectra. Valenti et al. *(1998, ApJ, 498, 851)* pioneered the use of spectral synthesis of TiO and atomic lines in high resolution abundance analyses of M dwarfs. Bean et al. *(2006a, ApJ 652, 1604)* tested Valenti et al. technique employing five visual binary pairs, where the primary is a solar-type star and the secondary is an early M dwarf, and found that Valenti et al. severely underestimated the iron abundance by about 0.6 dex (a factor of 4). Bean et al. (2006a) technique lowered the discrepancy between binary pairs to only 0.1 dex, but if systematic errors on the T_{eff} scale of their primaries are corrected then the iron abundances in their M dwarfs would be a worrisome 0.2 dex lower than in their primaries. This test has been performed only for five early M dwarfs with [Fe/H] = -0.1 ± 0.1 dex, so it still remains to be seen whether metal-poor and metal-rich M dwarfs can be studied using the same technique. Furthermore, the spectroscopic temperature they derive for their coolest M dwarfs seem to off by as much as 300 K when compared with temperatures expected from spectral types, thus further observations are required to settle this issue.

Bean et al. *(2006b, ApJ, 653, L65)* applied their technique to M dwarfs with planets and found them to be about a factor of two more metal-poor than the Sun. This is quite puzzling because most planet hosting stars are metal rich. Interestingly, when photometric metallicity calibrations (Bonfils et al. *2005, A&A, 442, 635)* are applied to the same planet-hosting M dwarfs, systematically higher metallicities are found, with the difference being as high as a factor of two for the star GJ 436. A recent study by Johnson & Apps *(2009, ApJ, 699, 1906)* found that even the photometric calibration of Bonfils and collaborators systematically underestimates the metallicities of M dwarfs by a factor of 2. So, overall the metallicity of M dwarfs is uncertain by about a factor of 10, depending on which scale is adopted. Although planet-hosting M dwarfs extend the baseline in mass available to study planet formation, their metallicity scale is far from being well-established, so reliable metallicities must be obtained to disentangle the mass and metallicity effects on planet formation (e.g. Johnson et al. *2007, ApJ; 670, 833)*.

A new feature that could be employed by Gemini users to obtain iron measurements is iron hydride (e.g. Schiavon et al. *1997, ApJ, 484, 499*) using the FeH Wing-Ford band located in a relatively clean region at 988nm (Fig. 1), thus being ideal for metallicity determinations in M dwarfs. Although the region around 1000 nm still remain largely unexplored, current CCDs have reasonable QE at these wavelengths, making studies around this region feasible. Also, it makes more sense to study M dwarfs at this region, where there are brighter, than in the optical. This work can be undertaken with R > 40,000 and covering 980-1000 nm.

The large collecting area @ Gemini would allow to undertake an ambitious plan to calibrate the metallicity scale of M dwarfs for -1.5 < [Fe/H] < +0.5. The same spectra could be used to test the temperature scale of cool dwarfs. Once the metallicity scale has been tested, it will become routine to find reliable metallicities for M dwarfs, including M dwarfs with planets. M dwarfs are becoming more and more important in exoplanet research, as, due to their low luminosity, the so-called habitable zone is located quite near the star where orbital periods are short and radial velocity signals of terrestrial planets are high enough to be detected (Fig. 2). Yet, due to the current large uncertainty in the stellar parameters of M dwarfs, the properties of habitable planets around M dwarfs would be very uncertain, unless a serious effort is done to characterize M dwarfs. Once a large sample of M dwarfs with planets has been characterized, we should be able to separate the metallicity effects from the mass effects on planet formation (Johnson et al. *2010, arXiv:1005.3084).*

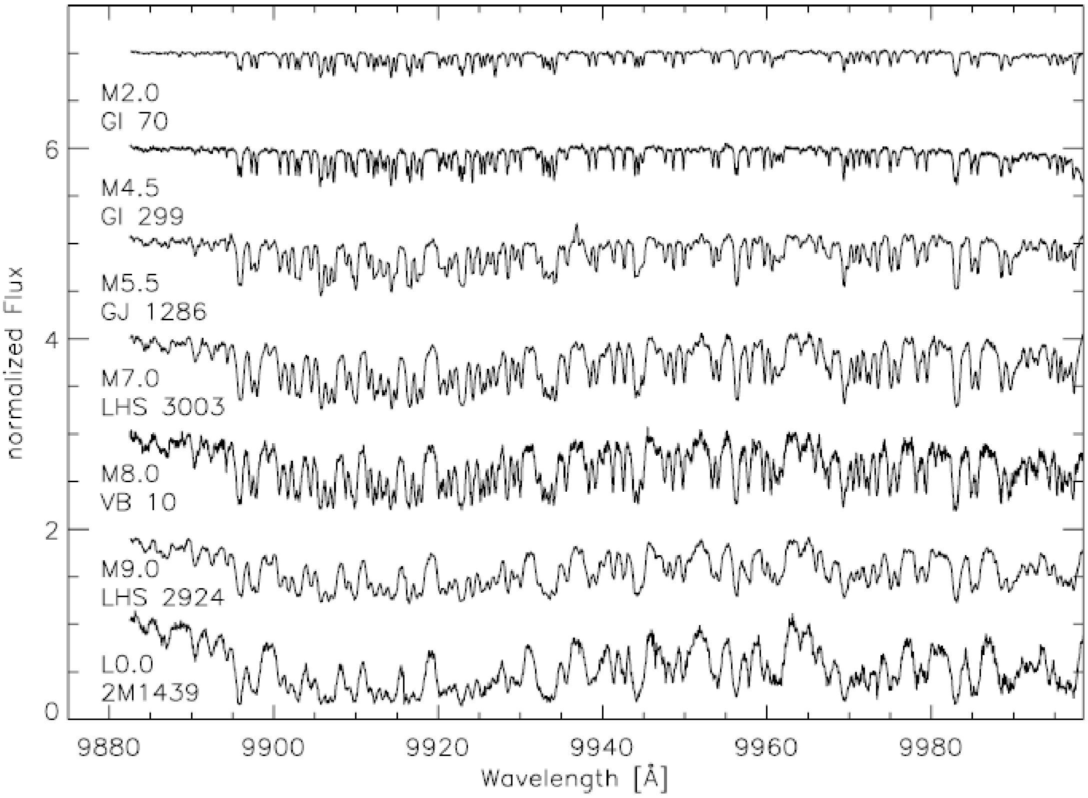

Fig. 1. Observed FeH Wing-Ford band head in dwarfs of spectral type M2-L0 (Reiners & Basri 2006, ApJ, 644, 497). This region could be used to obtain reliable metallicities in M dwarfs because it is much cleaner than the optical. Thus, coverage of the 980-1000nm region is essential for establishing a firm metallicity scale for M dwarfs.

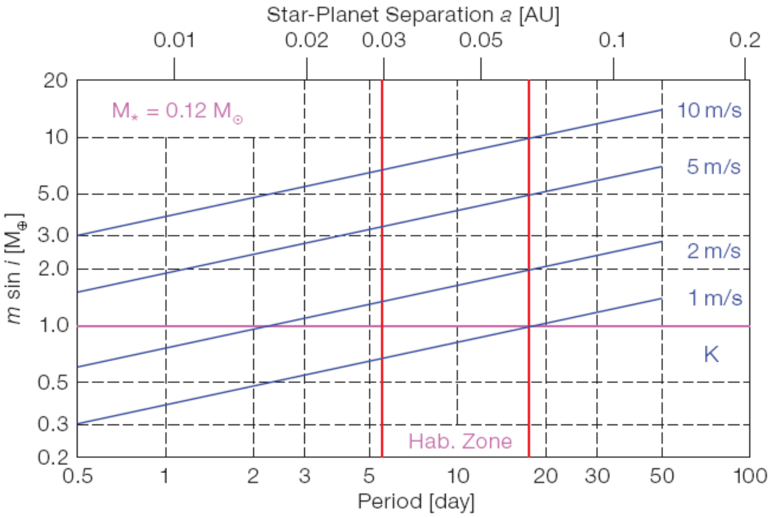

Fig. 2. Minimum planet masses m sin i for radial velocity signals with different semi-amplitudes K as a function of orbital period or star-planet separation **a** *(scale at top). This example is for a star with 0.12 MA , e.g. Proxima Centauri. The habitable zone is located between the solid vertical lines. High resolution spectroscopy at Gemini can characterize the fundamental properties of the host stars of habitable worlds. Taken from Kürsten et al. 2006, The Messenger, 123, 21.*

2. Chemical evolution of the Galaxy using isotope ratios

Our understanding of the evolution of the Galaxy is built in part on the interpretation of abundance ratios measured in stars of different metallicity. Elemental abundance ratios in large samples of disk stars (e.g., Edvardsson et al. *1993 A&A 275 101*) and halo stars (e.g., Ryan et al. *1996 ApJ 471 254*) have provided insight into the cycle of star formation, evolution and death that has controlled the composition of gas in the Galaxy. Complementary theoretical endeavours predict the evolution of the abundances of all elements from carbon through zinc. While elemental abundances are easier to measure than isotopic ratios, the latter are more important because nuclear reactions actually produce or destroy specific isotopes. Thus *isotopes provide direct insight into nucleosynthesis, stellar interior mixing, stellar evolution and in general into the chemical evolution of the Galaxy.* Comparing the observed and predicted evolution of isotopic abundances will test Galactic chemical evolution models in a way that is just not possible with elemental abundances.

2.1 Magnesium Hydride (MgH). Mg is one of the rare elements for which stellar isotope ratios can be measured from MgH molecular lines (Fig. 3). Three stable isotopes exist: ^{24}Mg, ^{25}Mg, and ^{26}Mg. The alpha-nucleus ^{24}Mg is synthesized during carbon and neon burning by massive stars which return fresh Mg to interstellar gas via a supernova explosion. Production of the rarer neutron-rich isotopes ^{25}Mg and ^{26}Mg also occurs in massive stars (via helium burning). Additionally, intermediate-mass (3-8 M Sun) asymptotic giant branch (AGB) stars are predicted to synthesize these Mg isotopes in their helium-burning shell (Karakas & Lattanzio *2003*). Therefore, measurement of the Mg isotope ratios in stars covering a range in metallicity: *(a)* offer the most stringent test of the contributions of stellar nucleosynthesis to Galactic chemical evolution and *(b)* serve to highlight the onset of the heaviest (and shortest lived) AGB stars to Galactic chemical evolution and thereby provide a measure of the formation timescale of the halo (Meléndez & Cohen *2007*).

For sufficiently cool stars, the strength of the MgH molecular lines does not strongly depend on metallicity (Cottrell 1978 *ApJ, 223, 544*). A decrease in the metal abundance will weaken the atomic lines whilst the MgH lines remain strong. This characteristic of MgH (and molecular hydride species in general) ensures that Mg isotope ratios can be measured in cool stars (M and late K) covering at least 3 orders of magnitude in metallicity. The isotopic splitting, due to the change in reduced mass, for ^{24}MgH and ^{26}MgH is only 0.2 A (the lines are never fully resolved due to line broadening). Mg isotope ratios can only be measured by comparing synthetic spectra and observed spectra (for example, see Fig. 3). The spectral requirements are R > 60,000 and S/N > 150 (per resolution element) for the MgH lines near 514 nm.

Within the limited samples at low metallicity, [Fe/H] < -2, there is no hint of an excess of the neutron-rich isotopes. This is in contrast to what is seen at higher metallicity, [Fe/H] > -2. More data at lowest metallicity are urgently needed to constrain the yields from massive stars and to probe the onset of the contribution of the heaviest and shortest lived AGB stars to the halo and therefore the formation timescale for the halo. A high-resolution optical spectrograph would enable additional measurements of Mg isotope ratios thereby engaging both observational and theoretical astronomers within, and beyond, the Gemini community.

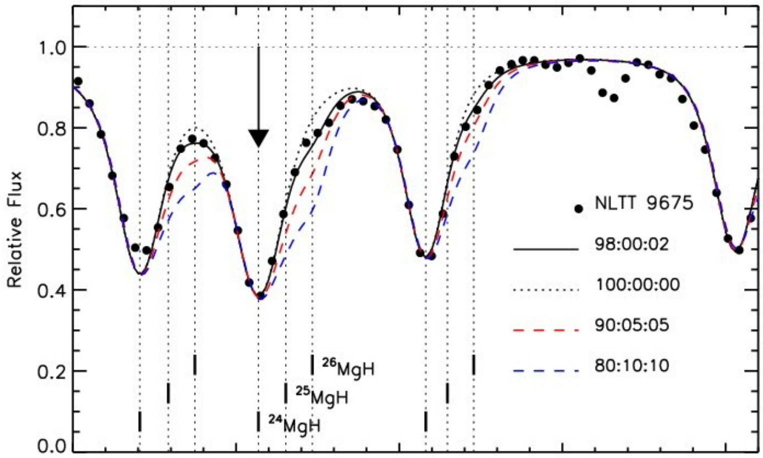

Fig. 3. Example showing the determination of Mg isotope ratios in a cool metal-poor dwarf. The star was observed with the Magellan Clay 6.5m telescope @ R = 65,000. From Yong et al. (unpublished).

2.3 Titanium Oxyde (TiO). In a recent work, Chavez & Lambert *(2009, ApJ, 699, 1906)* have shown that it is feasible to obtain Ti isotopic abundances from the TiO molecule in M dwarfs. Previous works on Ti isotopes in cool giants date back to three decades ago (Lambert & Luck 1977, ApJ, 211, 443; Clegg et al. 1979, ApJ, 234, 188). Until recently the chemical evolution of the Ti isotopes was a theoretical exercise, but now for the first time models can be constrained with observational data (Fig. 4). Surprisingly, most observations do not match the theoretical expectations: while the observations suggest a plateau (around the solar values) for all isotopic ratios, the models predict an increase of up to a factor of 4 in the isotopic ratios from [Fe/H] = -1 to [Fe/H] = 0. The disagreement with the predicted ^{47}Ti/^{48}Ti ratios is particularly worrisome, as the models are off by about a factor of 8. Independent determinations of Ti isotopic ratios must be performed in order to see if the fault is with the observations or with the predicted supernova yields. Since ^{47}Ti is being severely underproduced, an important nucleosynthesis source may be missing in supernova models, probably not only of Type Ia supernovae, but also of Type II supernovae since ^{47}Ti is being underproduced even at low metallicities.

The sample studied by Chavez & Lambert *(2009)* is relatively bright (V = 8-11), but with Gemini we should be able to observe fainter M dwarfs of the Galactic halo, allowing to test models in the early Galaxy. Coverage of the 700nm region and R > 60,000 are needed for this work.

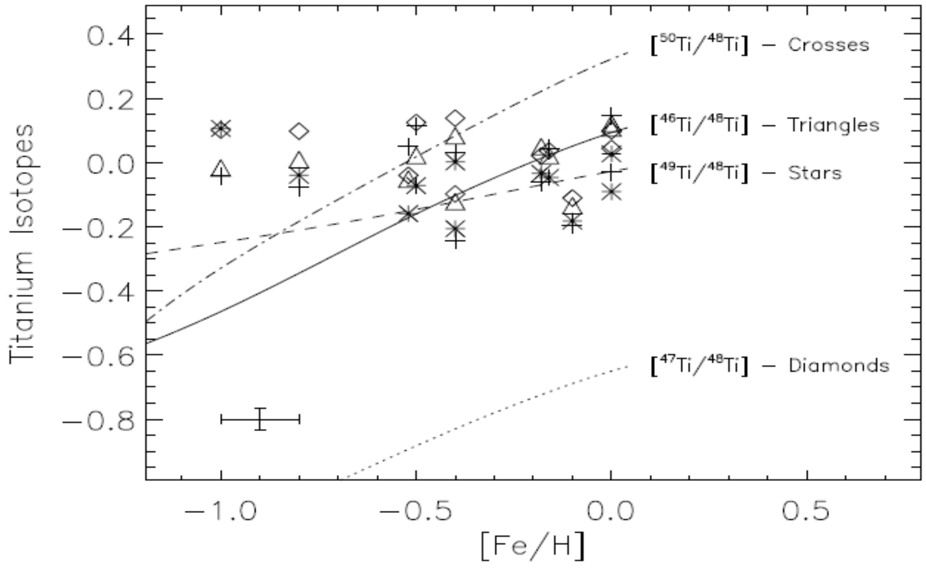

Fig. 4. The lines show the evolution of titanium isotope ratios in the solar neighbourhood using the dual-infall models of Hughes et al. (2008). The 11 local disk & halo stars observed by Chavez & Lambert (2009) are labelled. Representative errors are shown in the lower left corner. Figure from Hughes et al. (2008, MNRAS, 390, 1710).

3. Young stars: magnetospheric accretion, physical properties and chemical abundances

T Tauri stars are young, optically visible, low-mass stars contracting toward the main sequence. The so-called classical T Tauri stars still experience accretion from a circumstellar disk, where planets can be formed. One of the greatest challenges in star formation is to understand the accretion process from the disk to the star. Accretion has a significant impact in the initial evolution of low mass stars, regulating their fundamental properties (mass and angular momentum), and some of their most surprising characteristics (excess emission compared to stars of the same age that do not accrete anymore and mass loss through collimated jets). The discovery of almost 500 extra-solar planets in the last years has made the evolution of circumstellar accretion disks a major discussion topic also in planet formation. The characterization of the accretion process in young stellar systems and of their disks is therefore a major step to establish plausible scenarios of star and planet formation.

With high resolution spectroscopy it is possible to characterize the structure of the accretion flux and its dynamical evolution in various timescales. The stellar magnetic field is the key element in the star-disk interaction (see Bouvier et al. *2007a, Protostars and Planets V, 479*). They are typically kilogauss magnetic fields (Donati et al. *2007, MNRAS, 380, 1297; 2008, MNRAS, 386, 1234*) that destroy the inner disk region at distances of a few stellar radii and channel disk material to the star along field lines. The magnetic accretion process leads to the truncation of the inner disk, to the formation of magnetic accretion columns and to the appearance of accretion shocks at the stellar surface, where the accreting material in free-fall is rapidly decelerated. These various components (inner disk structure, accretion shocks and columns) are not directly observable due to the distances to the stars, but they generate spectral features that can be analysed to understand the accretion flux structure and also its dynamics. One of the best studied cases is the young star AA Tau that was the target of several observational campaigns over the last decade (Bouvier et al. *1999 A&A 349, 619; 2003, A&A 409, 169; 2007b, A&A 463, 1017*). High resolution spectroscopy with high signal to noise is necessary to distinguish line emission and absorption components that are formed in different regions of the young star-disk system (stellar photosphere, accretion columns, disk, winds and jets). Only then can we make the analysis of the dynamics of the circumstellar material and the star-disk interaction in young stellar systems.

Recently we showed with photometric observations made with the CoRoT satellite of the young open cluster NGC 2264 that several classical T Tauri stars present the same photometric behaviour as AA Tau and would therefore deserve a more detailed spectroscopic study (Alencar et al. *2010, A&A, in press, arXiv:1005.4384*). However, NGC 2264 is at about 760 pc and the M stars in the cluster are too faint to be observed with high signal to noise and high resolution spectroscopy from even a medium-sized telescope (3 to 4 m). This is an example of work that can only be done with high-resolution spectrographs in 8 to 10 m telescopes.

In a collaboration between Brazilian astronomers from Univ. São Paulo (Jane Gregorio-Hetem) and UFMG (Silvia Alencar) we are interested in analysing high-resolution spectra and light curves and evaluating accretion episodes of T Tauri stars. Disk models to fit the spectral energy distribution of AK Sco, for example, indicate that dynamical effects due to tidal interaction of the binary system are responsible for pushing the inner disk radius outwards. High resolution optical spectra are of great interest for our group in order to evaluate spectral variability T Tauri Star and eclipses of circumstellar material, related to inhomogeneities in protostellar disks.

Finally, we are interested in the physical properties and chemical abundances of low-mass young stars (T Tauri). Gregorio-Hetem & Hetem (2002, MNRAS, 336, 197) and Hetem & Gregorio-Hetem (2007, MNRAS, 382, 1707) use a model that fits the spectral energy distribution to reproduce their observed infrared excess and to evaluate the individual contribution of the circumstellar components (dust disk and/or envelope) to the total emitted flux, in order to classify T Tauri stars in different evolutionary stages of pre-MS. In the work by Rojas, Gregorio-Hetem and Hetem (2008, MNRAS, 387, 1335) we determined abundances and metallicities, based on spectral synthesis, of young stars that are candidates to present debris disks. The extension of this work to faint cool stars requires an echelle spectrograph on a large telescope.

4. Technical requirements

A spectral coverage from 500nm to 1000nm will cover our science requirements. The spectral resolution required for our programs are R >= 60 000, but some of them (sections 1 and 3) could be developed even at R = 30 000. Yet, note that the determination of isotope ratios (section 2) can not be performed for a resolution R < 60, 000.