The Chemistry and Magnetism of Young and Old Intermediate-mass Stars Observed with CRIRES

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In contrast to the case for the late-type stars, our knowledge of atomic transitions in intermediate-mass chemically peculiar stars and in Herbig Ae/Be stars is still quite poor. This is especially true in the infrared region of the spectrum. The recent availability of ESO's high-resolution spectrograph CRIRES now offers the opportunity to study numerous spectral features in the near-infrared spectra of these types of stars. Example observations are presented and the chemistry and magnetic field properties are discussed. During these studies a CO ring was detected around the Herbig Ae star HD 101412.

Upper main sequence stars with rich ultraviolet and optical spectra

Stars on the upper main sequence have a wide variety of chemical abundances. They are often unrelated to the processes that contributed to the bulk composition of the Sun or the population of stars with masses less than about 1.5 $M_{\odot}$. The compositions of the lower-mass stars are due to nuclear processes acting throughout the history of the Galaxy, to form chemical elements other than hydrogen and helium. Spectra of upper main sequence chemically peculiar (CP) stars reveal compositions generally thought to be confined to the surface regions, and not to the bulk of the stars. The majority of one sub-group of the CP stars, Ap/Bp stars, exhibit magnetic fields that belong to the stars as a whole and not just to star spots. Neither the origin of these magnetic fields nor the surface chemistry of this sub-group is thoroughly understood.

For the Sun or solar-type stars, there are good road maps for the near-infrared (NIR) region of the spectrum covered by the CRIRES spectrograph (c.f. Ryde et al., 2010). The same cannot however be said for A- and B-type stars, and in particular for CP stars. We know from the optical and ultraviolet (UV) spectra of CP stars that they are replete with transitions from exotic elements, as well as with high excitation transitions from overabundant elements.

Owing to the extreme richness of their UV and optical spectra, the upper main sequence CP stars have been intensively studied at the highest possible spectral resolution over the last few decades. These stars present a natural laboratory to study the element enrichment of stellar atmospheres due to the operation of various competing physical effects (such as, for example, microscopic diffusion of trace atomic species) in the presence of strong magnetic fields. Due to their generally slow rotation, it is also possible to study the isotopic and hyperfine structure of certain elements and their interaction with the magnetic field.

While many of the CP abundance patterns may be explained by separation processes in the stars themselves, there is a class of CP stars where this does not seem to be the case. These stars are named after their prototype, λ Bootis. The class represents only about 2 % of the population of A and B stars, to be compared with CP stars which may be as many as 30 % of all A and B stars. For the λ Boo stars, the chemical separation processes may have taken place outside of the stars themselves – possibly in circumstellar or even interstellar material.

The progenitors of CP stars

What might these CP stars have looked like when they were very young? Recently, considerable effort has been given to investigations of young, pre-main sequence stars known as Herbig Ae/Be stars. These stars are considered as progenitors of main sequence stars of intermediate mass. The Herbigs, as they are called, are often associated with gaseous and dusty regions of our Galaxy, where star formation is known to occur. The letter e appended to their class denotes emission. The lowest Balmer lines, Hα and Hβ, typically have emission stronger than the stellar continuum (see the example in Figure 1), while higher Balmer lines may show emission in their absorption cores.

If some fraction of Herbig Ae/Be stars are the progenitors of CP stars, we might expect them to have measurable mag-

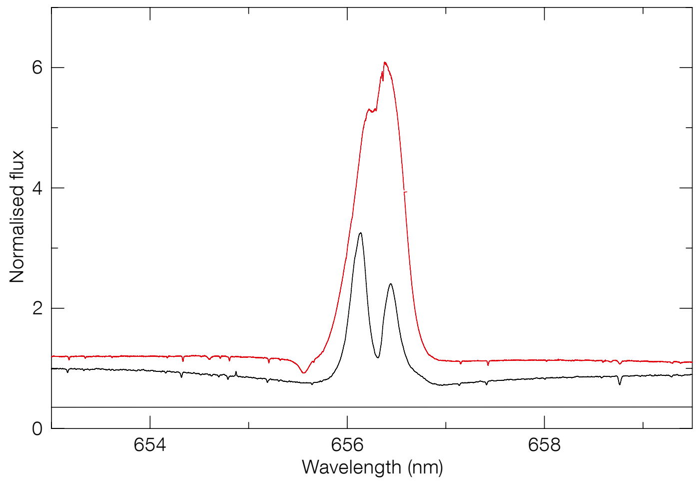


Figure 1. Example Hα emission line profiles in the two magnetic Herbig Ae stars HD 101412 (lower spectrum) and HD 190073 (upper spectrum) are shown.

netic fields and some indication of chemical peculiarities. Additionally, the progenitors of λ Boo-type peculiar stars might show some characteristic signature in their circumstellar material. Recent spectropolarimetric observations of a few Herbig Ae/Be stars have indicated that magnetic fields are important ingredients of the intermediate-mass star formation process. As an example, the sharp-lined young Herbig Ae star HD 101412 with a strong surface magnetic field of the order of a few kiloGauss (kG) has, over the past few years, become one of the most studied targets among the Herbig Ae/Be stars using optical and polarimetric spectra (Hubrig et al., 2011).

Chemistry and magnetism in the near-infrared

The recent availability of ESO's high-resolution CRyogenic Infra-Red Echelle Spectrograph (CRIRES) installed at the Antu telescope on Cerro Paranal now offers the opportunity to acquire much better knowledge of spectral features in intermediate-mass stars in the near-infrared (NIR) range (specifically 950–5200 nm). In recent months we have carried out, in a few wavelength regions, the first line identification work for the two strongly magnetic Ap stars with resolved Zeeman split lines, γ Equ and HD 154708, the magnetic Herbig Ae/Be star HD 101412, and one of the fastest rotating Herbig Be stars, 51 Oph (Hubrig et al., 2012). The CRIRES observations covered the spectral regions around the hydrogen recombination line Paγ at 1094 nm, the He I line at 1083 nm, the region of the most magnetically sensitive Fe I lines at infrared wavelengths at 1565 nm and the CO band head at 2300 nm.

The stellar lines were identified using the method of spectrum synthesis. For each star, we computed an ATLAS9 model with fundamental parameters taken from previous studies carried out by various authors. The models were used to compute synthetic spectra with the SYNTHE code (Kurucz, 1993). We adopted the atomic line lists taken from Kurucz's website[1], but we substituted the log gf values with those from the NIST database, whenever they were available. In addition, in some cases, we replaced the Kurucz log gf values for Si I by those from Meléndez & Barbuy (1999). We added a few lines of Ce III with wavelengths and log gf values computed by Biémont (private communication), and a Dy II line at 1083.594 nm taken from the VALD database (e.g., Heiter et al., 2008). The line-broadening parameters are those computed by Kurucz; they are available for most of the identified lines, except for the Sr II, Ce III, and Dy II lines, where they were computed using classical approximations.

Results of the wavelength survey of all targets, apart from the very fast rotating star 51 Oph, with $v \sin i$ = 256 km/s, may be seen on F. Castelli's web page[2]. The strongest lines are due to hydrogen and helium. Also strongly seen are C I, N I, Mg I, Si I, and Fe I. The only exotic spectral lines identified so far were due to doubly ionised cerium, Ce III (1584.8 nm and probably 1571.6 nm) in the Ap stars γ Equ and HD 154708, and singly ionised dysprosium, Dy II (1083.6 nm) in HD 154708. Apart from Ce III and Dy II, the only other lines identified from elements beyond the iron peak were due to Sr II, which were observed in all targets.

The line identification in strongly magnetic Ap stars with resolved Zeeman split lines can be strengthened by comparing the observed and expected magnetic splitting patterns. In stars with strong fields, both the central line position and the whole line profile shape, as determined by the number and relative strengths of the Zeeman π and σ components, can serve as a consistency check in the cases where line identification is doubtful. When an external magnetic field is applied, spectral lines can split into several differently polarised π and σ components of slightly different wavelengths, depending on the direction of the observer. In a longitudinal magnetic field, the π components vanish and the σ components on opposite sides of the non-magnetic line wavelength have opposite circular polarisation. Synthetic line profiles for a few magnetically sensitive lines were calculated using the software SYNTHMAG developed by Piskunov (1999). An example of our synthesis using this code assuming a surface magnetic field of 4.0 kG, $v \sin i$ = 0 km/s, and an iron abundance −4.4 dex is presented for the magnetically sensitive Fe I line at λ 15648.5 nm (Landé factor g = 2.97) in the spectrum of γ Equ in Figure 2.

The second observed Ap star, HD 154708, with a magnetic field modulus of 25 kG, possesses one of the strongest magnetic fields detected among the Ap stars (Hubrig et al., 2005). Stars with magnetic field strengths that exceed 20 kG are rare and only a very few such strongly magnetic stars have been detected so far. Nearly 30 % of the spectral lines remain unidentified in our study, both due to unavailability of atomic data and to the complex structure of the profiles, which sometimes are the blend of the central component of a line with the split component of a nearby line. In Figure 3 we present the magnetically-split lines belonging to Mg I 1081.11 nm, and

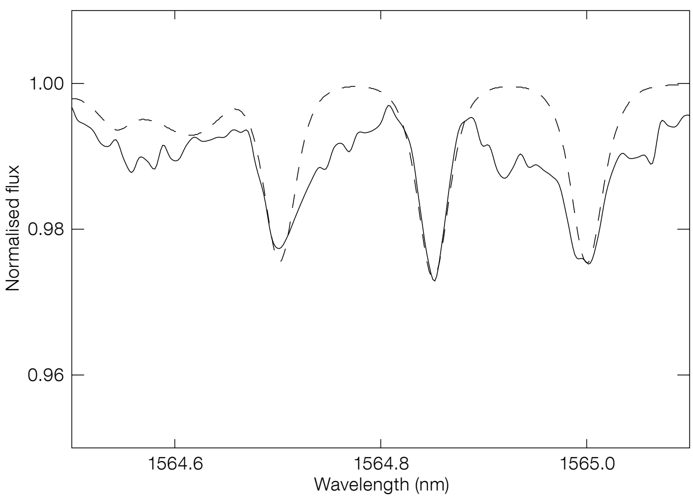
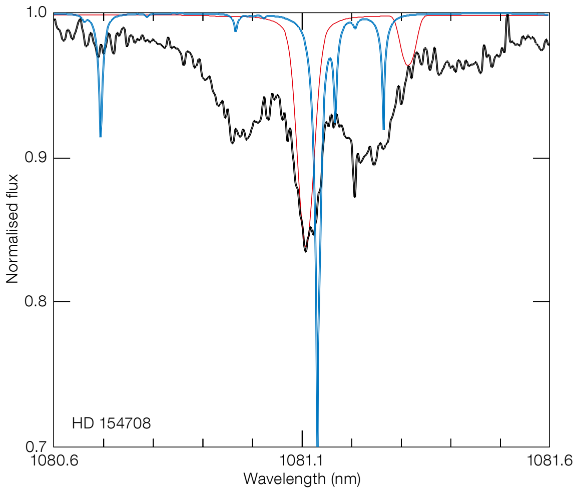


Figure 2. The synthetic line profile (dashed line) calculated for Fe I 15648.5 nm with a value of the Landé factor of g = 2.97 compared to the CRIRES spectrum (full line) of γ Equ.



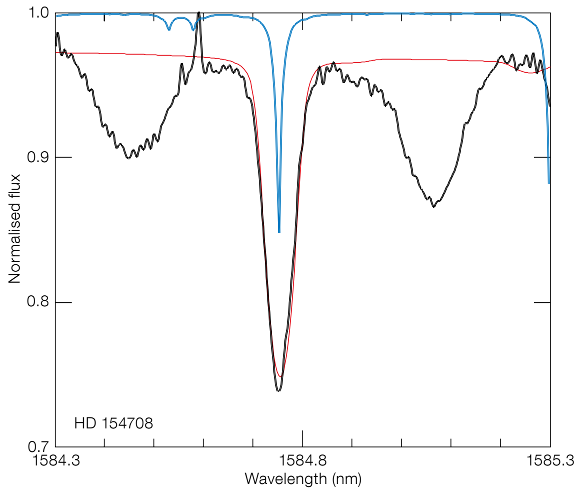


Figure 3. Magnetically split lines belonging to Mg I 1081.11 nm and Ce III 1584.76 nm in the CRIRES spectrum of the Ap star HD 154708 are shown. The blue lines indicate the contribution of the telluric absorptions. The red lines indicate the synthetic spectrum. Only the central components of the magnetically split lines have been fitted in the line identification process.

Ce III 1584.76 nm showing a rather similar split Zeeman structure.

In the absence of a magnetic field, the line at 1081.11 nm results from the superposition of five transitions of Mg I, of which the one at 1081.1053 nm is the strongest. The individual transitions correspond to different combinations of the lower and upper *J* quantum numbers. Within both the lower and the upper term, the levels of different *J* are separated from each other by less than 0.1 cm^{-1}. Thus, in the strong external magnetic field of HD 154708, which is much stronger than the atom's internal magnetic field, the electron coupling is disturbed and both terms are subject to the full Paschen–Back effect. The interesting feature of the split line profiles in the spectra of HD 154708 is that the Zeeman σ components are broad, in particular considerably broader than the π components. This indicates that the spread of the field strengths over the visible stellar hemisphere is rather large, probably significantly larger than it would be for a centred dipole.

The huge rotational line broadening of the B9 Herbig star 51 Oph with $v \sin i$ = 256 km/s prevented the reliable identification of spectral lines apart from the Mg I line at 1081.1 nm, the He I 1083.0 nm line, and the Paγ line. The spectra of the Herbig Ae star, HD 101412, have fewer lines, which accords with its abundance pattern that resembles that of the λ Boo stars. Our previous study of the abundances of the Herbig Ae star HD 101412 using UVES and HARPS spectra indicated that it may reflect a mild λ Boo, or Vega-like abundance mechanism, where the refractory elements are depleted while the most volatile elements are nearly normal (Cowley et al., 2010). The majority of the lines identified in the CRIRES spectrum belong to the elements Mg and Si, followed by a few lines belonging to N, C, Fe and Sr. Iron is underabundant, while the carbon abundance is solar; nitrogen may actually be slightly overabundant.

Detection of a narrow, inner CO ring around the magnetic Herbig Ae star HD 101412

A further surprise was found in the longest wavelength regions studied, which include the vibrational and rotational transitions of the CO molecule. The CRIRES spectra revealed a ring of gas in orbit around the magnetic Herbig Ae star HD 101412 (Cowley et al., 2012). Individual emission lines in the first overtone band of CO are presented in Figure 4. The M-shaped profiles arise because of Doppler shifts from the ring of emitting gas which is in Keplerian rotation about the star.

In HD 101412 CO-emitting gas is driven, or perhaps was evaporated, from a massive disc feeding material to the central star. Observations at high spectral resolution are capable of discerning the location and radial extent of the emitting gas. In Figure 5 we present the region of the CO band head. Because of convergence to the head, vertical sides of the profiles approach one another, coincide, and eventually cross.

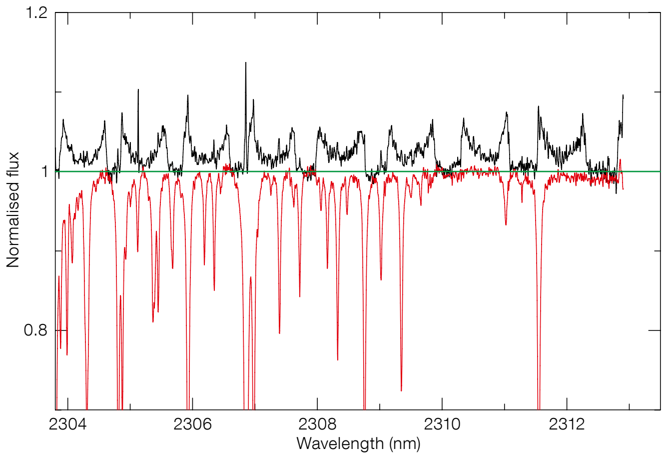


Figure 4. The black spectrum shows CO emission lines R(20) (right) to R(27) (left) in HD 101412 after removal of telluric lines using the standard (red) star HR 4537.

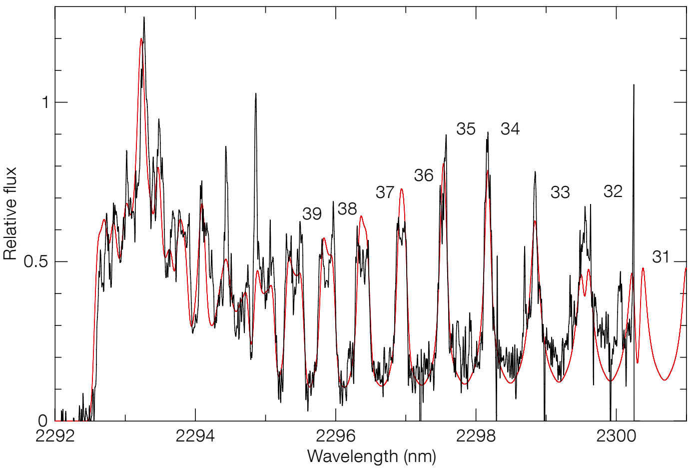


Figure 5. First overtone band head with partially cosmetic fit is shown for HD 101412. We subtracted one, and scaled the remainder vertically to fit the observations. R-branch labels are written above the M-shaped profiles. The overall distribution of intensities is somewhat better fit by assuming T = 2500 K rather than 2000 or 3000 K.

The CRIRES observations restrict the gas to a sharply defined ring, about one astronomical unit from the central star. The radial extent of the ring is less than a third of the distance of the ring from the star. The toroidal, or doughnut-shaped, structure poses immediate questions: How permanent is the structure? What forces might act to preserve it for times comparable to the stellar formation time itself? Is it maintained by magnetic structures? Is it held in place by orbiting planets, as with the shepherd satellites of planetary rings? Why do turbulent motions not tear the ring apart?

From a study of the relative intensities of the CO emission lines, it is possible to measure a temperature of some 2500 K (see Figure 5). This is much hotter than a planet would be at this distance. How is the gas heated, and how is the temperature maintained? The CO can be only one constituent of the gas ring. A variety of other molecules, atoms, and ions must also be present. Future observations can identify and study these species to unfold the mystery of the CO ring around HD 101412.

References

Cowley, C. R. et al. 2010, A&A, 523, A65
Cowley, C. R. et al. 2012, A&A, 537, L6
Heiter, U. et al. 2008, J. of Physics Conf. Ser., 130, 012011
Hubrig, S. et al. 2005, A&A, 440, L37
Hubrig, S. et al. 2012, A&A, in press, arXiv:1204.0652
Hubrig, S. et al. 2011, A&A, 525, L4
Kurucz, R. L. 1993, SYNTHE Spectrum Synthesis Programs and Line Data. Kurucz CD-ROM No. 18. Cambridge, Mass.: Smithsonian Astrophysical Observatory
Meléndez, J. & Barbuy, B. 1999, ApJS, 124, 527
Piskunov, N. E. 1999, in ASSL, Vol. 243, *Solar polarization*, eds. Nagendra, K. N. & Stenflo, J. O., (Dordrecht: Kluwer Academic Publishers), 515
Ryde, N. et al. 2010, A&A, 509, 20

Links

[1] R. Kurucz's website: http://kurucz.harvard.edu/
[2] F. Castelli's web page: http://wwwuser.oat.ts.astro.it/castelli/stars.html

This image of the Galactic field including the star cluster NGC 6604 combines 2.2-metre MPG/ESO telescope and Wide Field Imager U, B, V, R and $H\alpha$ exposures. NGC 6604 is the cluster to the upper left of the image and is part of the Serpens OB2 association. The many OB stars in NGC 6604 are part of a larger star formation region powering the H II region Sharpless 54 and an outflow chimney perpendicular to the Galactic Plane. See Release eso1218 for more details.