A&A 403, 645–651 (2003)
DOI: 10.1051/0004-6361:20030376
© ESO 2003

Astronomy & Astrophysics

Discovery of a 14.5 kG magnetic field in the NGC 2516 star HD 66318*

S. Bagnulo[1], J. D. Landstreet[2], G. Lo Curto[1], T. Szeifert[1], and G. A. Wade[3]

[1] European Southern Observatory, Casilla 19001, Santiago 19, Chile
e-mail: glocurto@eso.org;tszeifer@eso.org
[2] Department of Physics and Astronomy, University of Western Ontario, London, Ontario, Canada N6A 3K7
e-mail: jlandstr@astro.uwo.ca
[3] Department of Physics, Royal Military College of Canada, PO Box 17000, Station "Forces", Kingston, Ontario, Canada, K7K 7B4
e-mail: Gregg.Wade@rmc.ca

Received 13 January 2003 / Accepted 12 March 2003

Abstract. We have been searching for magnetic Ap stars in open clusters, in order to clarify the time evolution of magnetic fields in middle main sequence stars from the ZAMS to the TAMS. We have discovered that the star HD 66318 in the open cluster NGC 2516 has an extraordinarily large magnetic field: the measured mean longitudinal component $B_l \approx 4.5$ kG, and the mean field modulus $B_s \approx 14.5$ kG. This star thus has one of the largest fields so far discovered in a non-degenerate star, and the largest field known in a current Ap star cluster member.
We estimate that HD 66318 has completed about 16 ± 5% of its main sequence life. It thus appears to contradict the hypothesis of Hubrig et al. that magnetic fields are only found in stars that have completed at least 30% of their main sequence lifetimes.
There is no indication that the spectrum or brightness of the star is variable, and the spectral lines are very sharp. The star probably has a very long rotation period (years).
We have modelled some parts of the observed spectrum, assuming that the chemical composition is uniform both horizontally and vertically, and using a simple multipolar expansion for the field structure; although our model does not reproduce exactly the observed spectrum, it is clear that the atmospheric chemical composition of the star is very peculiar, with Ti, Cr and Fe overabundant by between 1.5 and 2.5 dex. Both La II and III are apparently about 4 dex overabundant. In contrast, evidence for the presence of other rare earths is difficult to find in the spectrum. It appears that Ce III, Pr III, Nd II and III, and Eu II are detected with inferred overabundances ranging between 1.5 and 5 dex, but for most of these elements, the abundance of the non-detected ionization state is significantly lower than that inferred for the detected state. HD 66318 thus seems to exhibit strong discrepancies between abundances deduced for different ionization states of rare earths, a phenomenon so far found only in somewhat cooler stars.
Even within one ionization state it has not been found possible to fit most observed lines with a single value of abundance. For example, when we fit medium strength lines of Fe II, the calculated strong lines of this ion are deeper than observed, and the calculated weak lines are less deep than observed. This situation is probably due to strong vertical abundance stratification of most of the elements studied.
Finally, HD 66318 also shows a new form of core-wing anomaly in Hα in which the observed line profile falls *below* the computed one in the core. These characteristics clearly suggest that the atmospheric structure of HD 66318 is not closely similar to that of a normal main sequence A star of similar parameters.

Key words. stars: chemically peculiar – stars: magnetic fields – stars: individual: HD 66318 – Galaxy: open clusters and association: individual: NGC 2516

1. Introduction

The time evolution of the global magnetic fields found in a few percent of main sequence Ap and Bp stars is far from clear. Theoretically, the observed fields are expected to evolve under the combined influences of ohmic dissipation (probably on a time scale longer than the main sequence lifetime of the parent stars) and as a result of both changes in stellar structure and internal circulation currents ("meridional circulation"). However, because most main sequence stars have rather poorly known ages, there is little observational evidence that may be used to constrain or test theoretical predictions. The observational evidence that exists is rather confusing. From classification

Send offprint requests to: S. Bagnulo, e-mail: sbagnulo@eso.org
* This paper is based on data obtained at the European Southern Observatory VLT during observing runs 68.D-0403 and DDT-269.D-05022.

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20030376

studies of clusters, Abt (1979) has argued that the chemical peculiarities that distinguish middle main sequence magnetic stars appear only after a threshold of time has passed; he finds no Ap SrCr younger than about 10^8 yr. Thompson et al. (1987) tried to study the evolution of fields by comparing the distribution of fields of magnetic Ap stars thought to be members of the Sco-Cen association to the distribution in magnetic Ap stars in the field; however, the membership of A stars in this association was sufficiently uncertain to make the results of that study rather inconclusive.

More recently, two studies based on Hipparcos parallaxes have come to contradictory conclusions. Gomez et al. (1998) looked at the distribution in the Hertzsprung-Russell diagram of all the spectroscopically classified SrCrEu, SiCr, and Si type Ap stars, classifications which are excellent predictors of the presence of magnetic fields, and found that these magnetic stars are distributed approximately uniformly across the main sequence band from the ZAMS to the TAMS. In contrast, when Hubrig et al. (2000) examined the (highly selected) sample of magnetic stars that have small enough values of $v \sin i$ that the mean field modulus or surface field B_s can be measured, they found that none of the stars in this sample appeared close to the ZAMS. Neither of these studies clearly indicated how field strengths evolve across the main sequence, but Hubrig et al. suggested the hypothesis that magnetic fields do not appear in middle main sequence stars until about 30% of their main sequence lifetime has been completed.

The confusing observational situation concerning magnetic field evolution on the main sequence has led us to begin a project to survey the fields in magnetic stars in star clusters of known ages. Global-scale magnetic fields in stars are detected by two different methods. In most cases, in stars in which rotational Doppler broadening of spectral lines is larger than typical Zeeman splitting, the field is detected through observation of its longitudinal component averaged over the surface, B_l, which is measured by observation of net circular polarization in the wings of spectral lines due to the Zeeman effect. In the small fraction of magnetic A and B stars which have fields in excess of about 3 kG and $v \sin i$ of less than a few km s^{-1}, the mean field modulus (the "surface field") B_s may be measured from the flux spectrum via the directly observable Zeeman splitting. Since B_l is detectable in almost all magnetic Ap stars while B_s can only be measured for a small fraction, our cluster survey is based on measurements of B_l. (For a detailed discussion of measurement of fields in magnetic Ap stars, see e.g. Landstreet 2001.)

In order to access A stars in a sufficiently large number of open clusters, each having at most only a few potential magnetic Ap stars, a survey of perhaps 20 or more clusters is required. This in turn implies that the survey must have a limiting magnitude of at least $V \sim 10$. Thus this project requires the use of telescopes of 4-m class or larger. At present, the only polarization analyzers capable of measuring B_l on large telescopes are the FORS1 low-dispersion multi-object spectrograph on one of the European Southern Observatory's 8-m Very Large Telescopes (VLT), and the analyzer available on the 6-m telescope at the Special Astrophysical Observatory. We have shown that the FORS1 in polarimetric mode is capable of being used effectively as a Balmer line Zeeman analyzer (Bagnulo et al. 2002), and have begun a survey using this polarimeter.

One of the first results of this survey was the detection of an extremely large field in the star HD 66318 = NGC 2516-24 in the cluster NGC 2516. The field detected in this star is sufficiently large that we are reporting this discovery before our survey is finished. The properties of HD 66318 and its very large field are the subject of this paper. In the next section we summarize what is already known about this star. Section 3 describes our magnetic and spectral observations, and modelling of these data are discussed in Sect. 4. The significance of these data is considered in the final section.

2. HD 66318

As a relatively bright, nearby open cluster, NGC 2516 has been extensively observed. Its age is estimated by Sung et al. (2002) to be $\log t = 8.2 \pm 0.1$ yr. *UBV* photometry of many of the brighter stars in the cluster field was obtained by Cox (1955) and Eggen (1972). A much more extensive photometric study, also in Johnson *UBV*, was carried out by Dachs & Kabus (1989), which also includes very useful finding charts and many literature references. The position of the $V = 9.7$ star HD 66318 in Hertzsprung-Russell diagrams constructed with this photometry are completely consistent with the star being a member of the cluster. However, no radial velocity measurement of this star was available to further test its membership in NGC 2516.

HD 66318 was classified by Hartoog (1976) as an A0p SrCrEu star, a spectral classification almost always associated with the presence of a detectable magnetic field. It was found by Maitzen & Hensberge (1981) that the Δa photometric index of HD 66318 is very large, indicating that this star is extremely peculiar. North (1987) observed HD 66318 repeatedly to search for evidence of photometric variability due to rotation, but found it to be constant within his errors.

Using the available *uvbyβ* photometry, the calibration of Stępień (1994) leads to an effective temperature (after dereddening) of 9020 K, while Geneva photometry with the calibration of Hauck & North (1993) gives an effective temperature of 9370 K. We adopt $T_e = 9200 \pm 200$ K. Next, we place the star on the isochrone for a cluster of age of 1.6×10^8 yr, using the Geneva stellar evolution tracks for $Z = 0.02$ (Schaller et al. 1992). This leads to a determination of the mass of HD 66318 as $2.1 \pm 0.1\ M_\odot$, and $\log g = 4.25$. Based on the Schaller et al. tracks, HD 66318 is 16 ± 5% of the way from the ZAMS to the TAMS, where the uncertainty includes both that due to the error in the cluster age and that due to uncertainty in the effective temperature of HD 66318. This result contradicts the hypothesis of Hubrig et al. (2000) that magnetic fields only appear in Ap stars after about 30% of the main sequence lifetime has elapsed.

3. Observations

The initial detection of a large magnetic field in HD 66318 was made using the FORS1 multi-object spectrograph in polarimetric mode. Grism 600R was used, allowing us to obtain

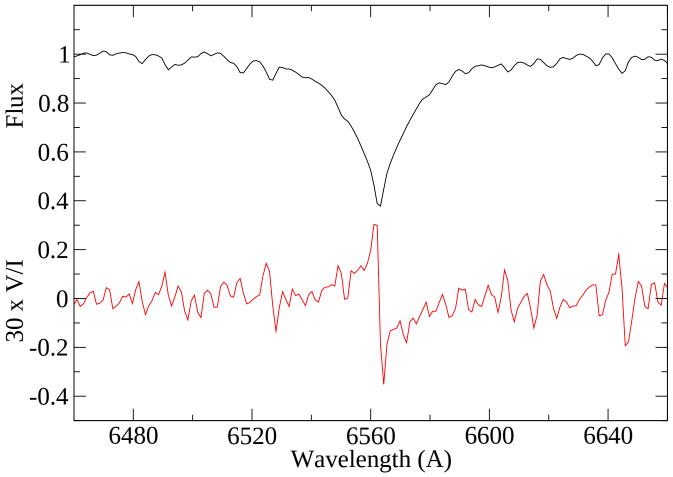

Fig. 1. FORS1 polarized spectrum of HD 66318: I centred on Hα (upper curve) and V/I (lower curve; V/I is multiplied by 30 relative to the scale shown on the y-axis). Note the large Zeeman signature in the V/I profile of Hα line, and smaller signatures in most of the metal lines of the flux spectrum.

circularly analyzed spectra of up to 9 objects simultaneously, a capability that we exploit heavily for observations of open clusters. The spectra have a resolving power of about 2500 and cover a window about 2000 Å long. The position of the spectral window in wavelength varies from one object to another according to the position of the star in the slit plane, but a typical observed window is 5300–7400 Å. The window always includes Hα at 6563 Å. For each object, a spectrum is obtained in both I (flux) and V/I (circular polarization). The longitudinal field is measured via the circular polarization of opposite signs induced in the two wings of Hα by the Zeeman effect when the stellar field has a mean line-of-sight component B_l that is significantly different from zero. The use of FORS1 as a Balmer-line Zeeman analyzer has been tested with the known magnetic star HD 94660 (Bagnulo et al. 2002); it is found that longitudinal fields can be detected with a standard error of about 100–200 G, provided enough photons can be obtained. It has also been shown that non-magnetic stars do not produce spurious detections.

HD 66318 was in one of eight fields observed in NGC 2516. The exceptionally large amplitude of B_l in this star was immediately apparent when the data were reduced. Using the relationship between polarization and slope of the line wing expected for the Zeeman effect, as described by Bagnulo et al. (2002), we deduce a value of $B_l = 4565 \pm 140$ G, at a mid-exposure date of 2452310.715 (2002 February 05 05:10 UT). This is a *very large field*; only a handful of other magnetic Ap stars (e.g. HD 32633, HD 65339 = 53 Cam, and HD 214441 = Babcock's star) are known to show such large values of B_l. At the same time, it was noted that the Hα line (in I) is unusually strong and broad even for an A star. The I and V/I spectra of HD 66318 are shown in Fig. 1.

Because the longitudinal field of HD 66318 was so exceptionally large, we followed up the field detection by obtaining a spectrum of the star using the Coudé Echelle Spectrograph (CES) of the 3.6-m ESO telescope at La Silla. This spectrum, a composite of four exposures totaling 1.5 hours and centred on JD 2 452 364.615 (2002 March 31 02:45 UT), covers the spectral window from 6133 to 6166 Å with a resolving power of about 210 000 and has a signal-to-noise ratio of a little more than 100. Most of this spectrum is shown in Fig. 2. This spectrum immediately revealed that HD 66318 has very sharp lines, and hence a very low value of $v \sin i$ (at most a few km s^{-1}), and that almost every line in the spectrum is strongly and obviously split into several components by the Zeeman effect. The field deduced from the splitting in this spectrum (see below) is about 14.5 kG. Again this places HD 66318 among the magnetic Ap stars with the largest values of the surface field B_s; as a comparison, note that only five of the 42 stars with measured values of B_s listed by Mathys et al. (1997, Table 2) sometimes exhibit values of the mean field modulus as large as that of HD 66318.

Because of the great interest of a star with such a large field, we applied for Director's Discretionary Time to obtain two spectra of HD 66318 at two different times using the Ultraviolet Echelle Spectrograph (UVES) on the ESO VLT. These spectra allow us to explore almost the full wavelength range from 3100 Å to 1.04 μm at a resolving power of about 80 000, and provide some constraints on variability of the spectrum and/or surface field of the star. These spectra were obtained on JD 2 452 413.48 (2002 May 18 23:16 UT) and JD 2 452 424.49 (2002 May 29 23:44 UT). Each spectrum was obtained (as usual for full spectral coverage) in two exposures each requiring an integration time of 450 s (May 18) or 600 s (May 29). Both spectra have a SNR at 5000 Å of about 100.

Comparing these two UVES spectra with each other and with the CES spectrum, we come to the following conclusions. (1) There has been no detectable change between the three spectra, obtained over a period of about two months. (2) The UVES spectra clearly have slightly lower resolution than the CES spectrum, which means that the $v \sin i$ broadening by rotation must be essentially negligible ($v \sin i \leq 3$ km s^{-1}). Thus it appears probable that HD 66318 is a star with a rotation period of at least one or two years. (Alternatively, it could be a star whose rotation axis is pointed directly at us, but this is an improbable configuration.) (3) The measured radial velocity on the UVES spectra, corrected for terrestrial motion, is about 25 km s^{-1}. This value is consistent with the range of radial velocities of cluster members (about 21–26 km s^{-1}) as determined by Gonzalez & Lapasset (2000). It thus appears reasonably certain that HD 66318 is a member of NGC 2516.

4. Modelling

The spectra we have obtained have been modelled using one of the versions of the spectrum synthesis programme ZEEMAN.F, which has been described by Landstreet (1988) and Landstreet et al. (1989), and more recently compared with other synthesis programmes of similar capabilities by Wade et al. (2001). This code predicts the spectrum in various spectral windows, in LTE, for a specified model atmosphere, magnetic field configuration, and abundance model. It solves the full set of four radiative transfer equations for the four Stokes components required to treat the transfer of radiation in a stellar atmosphere permeated by a magnetic field. It is capable of searching for a

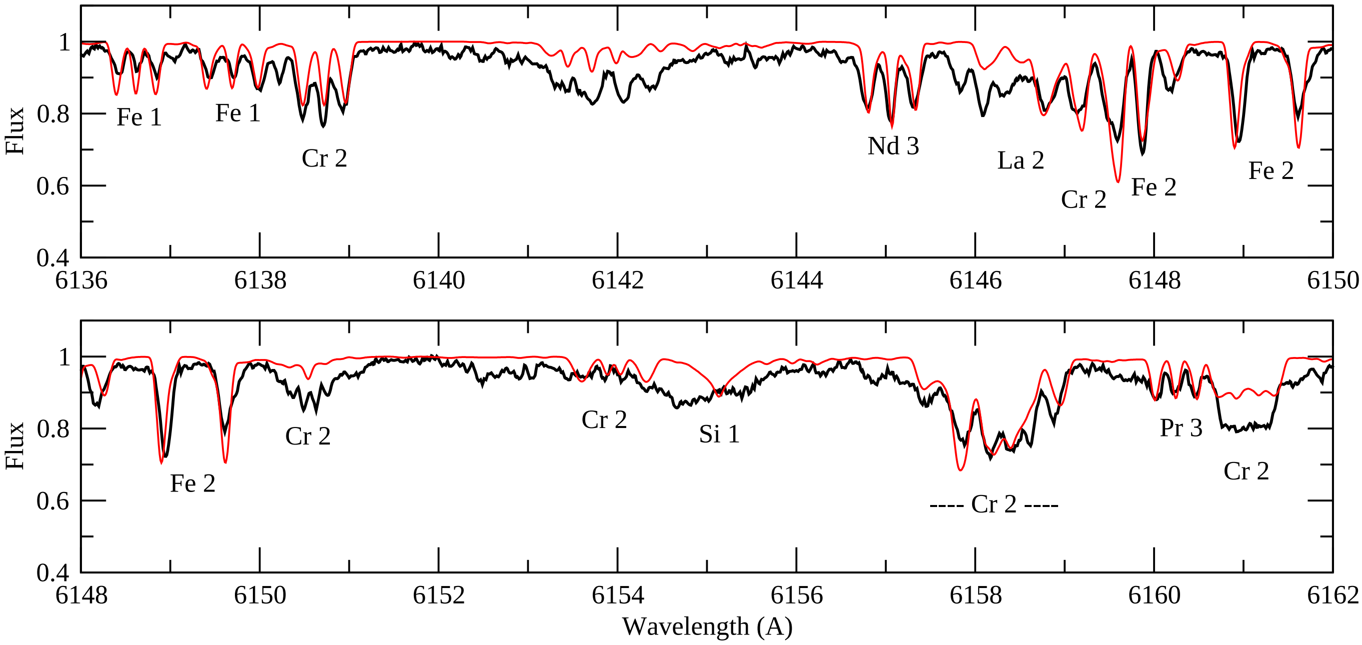

Fig. 2. Most of the first high-resolution spectrum of HD 66318, obtained with the CES (heavy line). Virtually every spectral line is split into easily recognizable Zeeman patterns. The ion responsible for each of the stronger lines is indicated below the line. The figure also shows the spectrum calculated from an approximate model of the magnetic field and abundances of this star as described in Sect. 3; however, several of the abundances reported in Table 1 have been modified to fit this spectrum better. (As discussed in the text, inconsistencies between abundances derived from lines in various spectral regions, and from lines of different strengths, are probably due to substantial vertical variations in abundances through the atmosphere of the star.)

limited set of parameters (e.g. the abundances on a set of several rings axisymmetric about the magnetic axis, or parameters of a simple field expansion in linear multipoles).

In general, we know that magnetic Ap stars may have significantly non-dipolar field structure, and abundance distributions that are quite non-uniform, both horizontally and vertically. However, in the present case, the complete lack of any spectrum variability (probably because HD 66318 rotates so slowly, or possibly because we see it pole on) implies that we have available essentially only one view of the star under consideration. Furthermore, due to the small value of $v \sin i$ we have no Doppler resolution in stellar longitude. Thus we do not have enough information (such as observations of the star from different directions as it rotates) to develop a well-constrained global surface model. Hence we will only look for relatively simple models of the field structure and abundances. We attempt to match the observed spectrum in various spectral windows assuming uniform abundances both horizontally and vertically in the atmosphere.

The magnetic field is taken to be a superposition of a coaxial dipole, quadrupole, and octupole components, with the relative strengths chosen to give a reasonably good match to the observed line splitting and to the value of the longitudinal field observed with FORS1. (We assume from the lack of photometric or spectrum variability that B_l has probably remained nearly constant over the time interval between the FORS1 observation and the UVES observations.) From a single observation of Stokes I (even supplemented with V/I), it is impossible to recover the two-dimensional structure of the magnetic field. Thus the modelling we have carried out basically only allows us to indicate the approximate strength of the overall magnetic field, and to estimate the global abundances of a number of elements (primarily iron peak and a few rare earth elements). The field adopted in the modelling described below is a superposition of a dipole of polar field strength 22 kG, a linear quadrupole of polar field −7 kG, and a linear octupole of polar field −7 kG, viewed at an inclination angle of 55° from the magnetic pole; this field reproduces reasonably well both the observed line profiles in the I spectra and the observed value of B_l.

A plausible fit to the CES spectrum is shown in Fig. 2, and to a very small portion of the observed UVES spectrum in Fig. 3. Notice that almost all the features in the observed spectrum (which are primarily lines of Ti, Cr, Fe and La) correspond to features in the computed spectrum; it appears that the line list, obtained from the Vienna Atomic Line Database (Kupka et al. 1999) is largely complete for this star. Furthermore, both the general line strengths and the Zeeman patterns are fairly well reproduced by the synthetic spectrum. However, there are also systematic discrepancies: weak lines of Fe II, Cr II, and of Ti II tend to be too weak in the computed spectrum, while strong lines of Fe II, Cr II and Ti II, and weaker lines of Cr I and Fe I tend to be too strong in the computed spectrum. It has been shown by Bagnulo et al. (2001) and Ryabchikova et al. (2002) that this effect is a clear symptom of vertical stratification of these ions, and is probably due to a substantially lower abundance of Fe, Cr and Ti high in the atmosphere compared to the abundances near $\tau \approx 1$. This effect is not included in the present model.

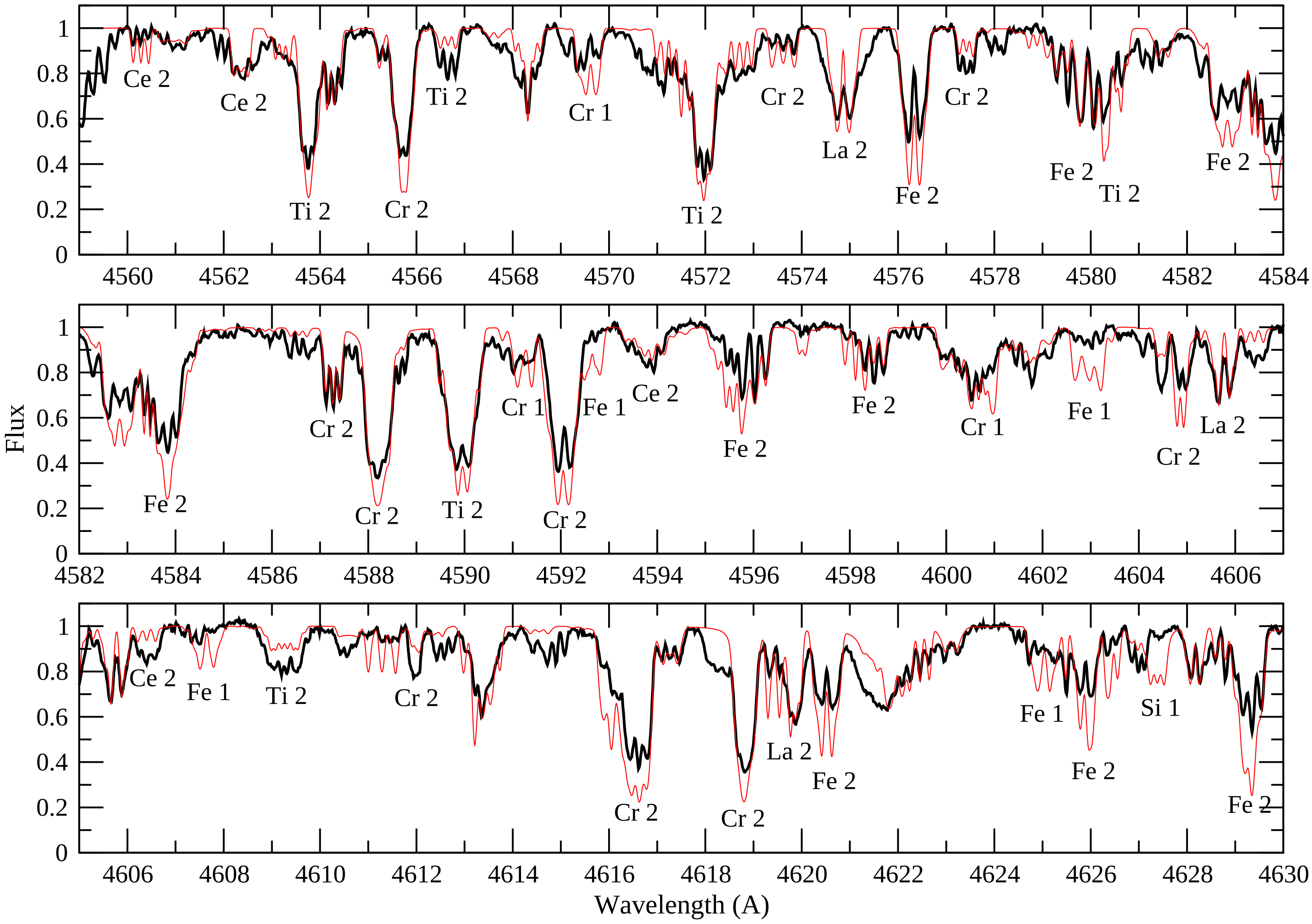

Fig. 3. Comparison of the spectral region between 4560 and 4620 Å in HD 66318 as observed in the first of our UVES spectra (thick lines) and as synthesized for our rough model using abundances from Table 1 (thin lines). The main contributing ions for a number of absorption features are indicated on the figure; the spectrum is dominated by lines of Ti, Cr, Fe and La. Note that the model systematically predicts weak lines that are weaker than observed, and strong lines that are stronger, except for weak lines of neutrals, which are formed high in the atmosphere and are mostly computed to be stronger than observed.

The fit we obtain allows us to estimate the mean field modulus to be about 14.5 ± 0.5 kG. The best fit mean field modulus varies slightly from line to line, which provides us with our uncertainty estimate.

The atmospheric abundance table (abundance of element *A* with respect to H), as deduced from the spectral regions fit in our experiments, is given in Table 1. The table includes information on which lines or regions were used for the abundance determination, as abundances determined in regions of strongly different continuous opacity or from lines formed at different altitudes may differ by one dex or more. It is clear that even though the abundances listed here are uncertain, at least by factors of order three, the atmospheric abundances found in HD 66318 are very peculiar, consistent with the large Δa index.

Among the light elements, we have good abundance determinations only for O, Mg and Si. O is underabundant compared to solar by more than one dex, as is often found in magnetic Ap stars. Mg appears to be slightly underabundant compared to the Sun. Si is enhanced by at least one dex, but weaker lines (and especially Si I lines, see Fig. 3) are certainly discordant with the abundance deduced from the very strong lines we have used.

The iron peak elements are all near solar (Ca and Mn are slightly below) or considerably enhanced; Fe, Ti and Cr are all between 1.4 and 2.5 dex overabundant with respect to solar values. All three elements also show strong evidence of stratification: when the abundance of any of these elements is reduced enough to bring the calculated line cores of the strongest lines up to the observed cores (see Fig. 3), all the calculated weaker lines are far too weak. This is a definite symptom of vertical stratification (cf. Bagnulo et al. 2001; Ryabchikova et al. 2002); the effect is present because the abundance of each of these elements starts from a highly overabundant state near $\tau = 1$ but drops strongly with altitude. Since this effect is not incorporated in the present model, when abundances are determined using lines that are formed deep in the atmosphere, the calculated profiles of strong lines (whose cores are formed high in the atmosphere), and of lines of neutrals (also formed high in atmosphere where the temperature is low), have cores that are deeper than are actually observed because the line-to-continuum opacity ratio high in the atmosphere is overestimated.

One unblended Cr II line, at 3935 Å, is a magnetic null line, and is therefore totally unbroadened by the magnetic field.

Table 1. Abundances derived from synthetic spectrum.

Element	$\log\left(\frac{n_A}{n_H}\right)$	$\log\left(\frac{n_A}{n_H}\right)_\odot$	Remarks
O	–4.6	–3.17	7770 Å triplet
Mg	–4.95	–4.42	4481 Å
Si	–2.8	–4.45	5979, 6347, 6371 Å
Ca	–6.4	–5.64	3933 Å
Ti	–5.15	–6.98	4500–4700 Å
Cr	–3.8	–6.33	4500–4700 Å
Mn	–6.85	–6.61	3440–3500 Å
Fe	–3.05	–4.50	4500–4700 Å
La II	–6.85	–10.83	4500–4700 Å
La III	–6.0:	–10.83	3171, 3517 Å
Ce II	≤–7.5	–10.42	3400–3540 Å
Ce III	–5.5:	–10.42	3400–3540 Å
Pr II	≤–8.3:	–11.29	6166 Å
Pr III	–8.3	–11.29	6160 Å
Nd II	–9.0:	–10.50	4061 Å
Nd III	–7.0:	–10.50	6145 Å
Sm II	≤–9.0 :	–10.99	3920–3950 Å
Eu II	–8.4:	–11.49	6645 Å
Eu III	≤–9.0:	–11.49	6666 Å
Gd II	≤–9.0 :	–10.78	4030–4070 Å

The value of $v \sin i$ derived from this line is 3 km s^{-1} or less, consistent with our previous conclusions about $v \sin i$.

The abundances of the rare earths reported in Table 1 are derived using lines of either singly or doubly ionized species, depending on what lines are detected. The only rare earth for which we have a really secure abundance is La, for which a large number of reasonably strong lines of La II are found throughout the spectrum. This element appears to be substantially more abundant than any of the other rare earths (except possibly Ce III). La II appears to be overabundant in much of the atmosphere by about four dex. Two strong lines of La III appear to be present at 3171 and 3517 Å; the calculated lines for both these features are somewhat too weak when the abundance of La II derived from the blue lines (Table 1) is used. The abundance of La III required to fit the UV lines is reported separately in Table 1. This is one apparent example in this star of the discrepancy between second and third spectra that is often found in cooler Ap stars (e.g. Ryabchikova et al. 2002).

Ce II appears to have a number of weak lines in the ultraviolet and blue spectral regions (see Fig. 3), but none of these is so strong as to be completely unambiguous. Our abundance for this ion may be regarded as an upper limit. However, several lines of Ce III appear to be present in the UV and require an abundance of Ce at least about two dex larger than for Ce II. Abundances of Pr and Nd are each based on a single weak line of the third spectrum in the red (see Fig. 2); other expected lines are mostly apparently blended. No line of Pr II has been securely identified, and the abundance upper limit for this ion is about the value required to fit the single line of Pr III. In contrast, one line of Nd II appears to set the abundance of this ion about two dex lower than that of Nd III. The abundance of Eu is based on a single line of Eu II that seems to be present at 6645 Å, and one line of Eu III that may be present at 6666 Å; the two abundances differ significantly (by about 0.5 dex), but here it is the singly ionized species that has the higher abundance, not the doubly ionized one. For Sm and Gd we have only upper limits based on the absence of expected strong lines. Thus we find that several rare earths are overabundant in the atmosphere of HD 66318 by substantial factors, but that the overabundance factor varies considerably from one ion to another, being much higher for La and Ce than for the other rare earths. We find evidence for overabundance of third ions relative to that of second ions for La, Ce, and Nd, and the opposite behaviour for Eu; this behaviour has not been previously found in magnetic Ap stars as hot as HD 66318.

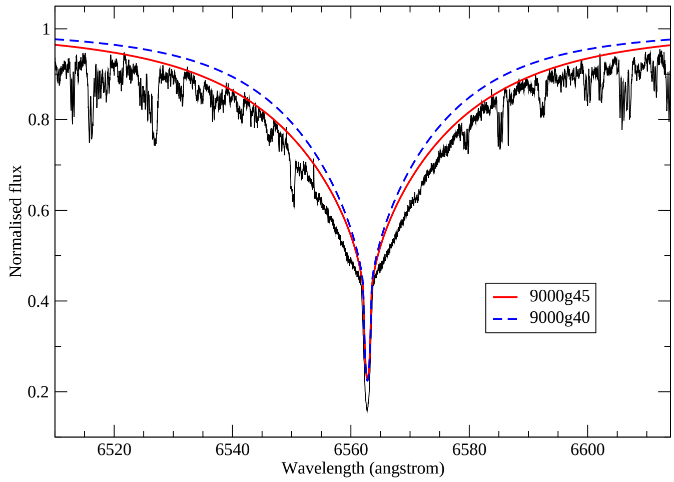

Fig. 4. Comparison of the observed profile of Hα with Atlas model lines for 9000 K and $\log g$ = 4.0 (dashed line) and 4.5 (solid line). Note that the $\log g$ = 4.5 model fits the far wings well, but is considerably too narrow in the inner wings.

One other remarkable feature of HD 66318 is found by examining its Balmer lines. These have a very distinctive shape, different from the lines calculated using standard broadening theory and conventional atmosphere models. This is reminiscent of the core-wing anomaly discovered by Cowley et al. (2001) for cool Ap stars (stars with $T_e \leq 8000$ K, thus rather cooler stars than HD 66318). In the core-wing anomaly discussed by Cowley et al., the core of the Hα line in the affected cool Ap star is shallower and narrower than the core of a normal A star of similar temperature, and also shallower and narrower relative to the core of a theoretical Hα profile calculated with a conventional model. A tentative explanation of this phenomenon in terms of a high-temperature region in the atmosphere of a cool Ap star has been proposed by Kochukhov et al. (2002).

In HD 66318 the core-wing anomaly that is observed is somewhat different. Here (see Fig. 4) the model line profile that fits the wings of Hα satisfactorily (for T_e = 9000 K and $\log g$ = 4.5) is *shallower* than the observed profile, rather than too deep as in the normal core-wing anomaly. This anomaly certainly suggests that the structure of the atmosphere of this star is not very precisely described by the normal Atlas models that we use for spectrum synthesis. This appears to represent the discovery of a new aspect of the core-wing anomaly, both in extending the phenomenon to substantially higher effective temperature, and in fact that the anomaly is rather different from what has been found previously.

5. Discussion and conclusions

HD 66318 emerges from our study as a highly peculiar magnetic Ap star. It appears on the basis of lack of photometric or spectroscopic variability, as well as on the basis of very sharp spectral lines, to be a star with a very long rotation period, probably of the order of a year or more. Our radial velocity measurements support that view that HD 66318 is a *bona fide* member of the open cluster NGC 2516. The star has one of the largest fields known among magnetic Ap stars, and the largest field known in a current member of an open cluster.

From the effective temperature (9200 K) derived on the basis of available photometry, we can place the star on the isochrone of NGC 2516. Using the evolution tracks of Schaller et al. (1992), we find that HD 66318 has completed only about 16 ± 5% of its main sequence lifetime. This result contradicts the hypothesis of Hubrig et al. (2000) that magnetic fields are found only in stars that have completed at least 30% of their main sequence lifetimes.

HD 66318 has a very peculiar surface chemistry, dominated by large overabundances of Si, the even-*Z* iron peak elements Ti, Cr and Fe, and the rare earth La. The abundances of these dominant ions show excesses relative to the solar abundance table of up to four dex. A similar abundance of Ce III – but not of Ce II – is found. It is remarkable that the overabundances of La and Ce III are larger than those of the several other rare earth elements (Nd, Pr, Eu) whose presence is deduced – with reservations – from very weak spectral lines, and that other rare earths are not detectable at all even in the extensive spectral material at our disposal.

Furthermore, HD 66318 shows strong evidence, from discrepancies found when we try to fit simultaneously weak and strong spectral lines of a given ion, for non-uniform vertical distribution of several elements, including all those with large overabundances. Probably for the same reason, the two detected La III lines lead to a deduced La abundance still larger than the very high value deduced from the La II lines. The star also exhibits a new kind of core-wing anomaly in Hα, in which the observed line core falls *below* that of a standard line calculation, in a stars well above the temperature range in which core-wing anomalies were previously known to exist.

Even among magnetic Ap stars, HD 66318 is a remarkable star.

Acknowledgements. This work was supported in part by the Natural Sciences and Engineering Council of Canada. We gratefully acknowledge important resources provided by the Vienna Atomic Line Database, operated by the Institut für Astronomie of the University of Vienna; by the SIMBAD astronomical database, operated by the CDS, Strasbourg, France; and by NASA's Astrophysics Data System.

References

Abt, H. A. 1979, ApJ, 230, 485
Bagnulo, S., Wade, G., Donati, J.-F., et al. 2001, A&A, 369, 889
Bagnulo, S., Szeifert, T., Wade, G. A., Landstreet, J. D., & Mathys, G. 2002, A&A, 389, 191
Cox, A. N. 1955, ApJ, 121, 628
Cowley, C. R., Hubrig, S., Ryabchikova, T., et al. 2001, A&A, 367, 939
Dachs, J., & Kabus, H. 1989, A&AS, 78, 25
Eggen, O. J. 1972, ApJ, 173, 63
Gomez, A. E., Luri, X., Grenier, S., et al. 1998, A&A, 336, 953
Gonzalez, J. F., & Lapasset, E. 2000, AJ, 119, 2296
Hartoog, M. R. 1976, ApJ, 205, 897
Hauck, B., & North, P. 1993, A&A, 269, 403
Hubrig, S., North, P., & Mathys, G. 2000, ApJ, 539, 352
Kochukhov, O., Bagnulo, S., & Barklem, P. S. 2002, ApJ, 578, L75
Kupka, F., Piskunov, N. E., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
Landstreet, J. D. 1988, ApJ, 326, 967
Landstreet, J. D., Barker, P. K., Bohlender, D. A., & Jewison, M. S. 1989, ApJ, 344, 876
Landstreet, J. D. 2001, in Magnetic Fields Across the Hertzsprung-Russell Diagram, ed. G. Mathys, S. K. Solanki, & D. T. Wickramasinghe (San Francisco: Astronomical Society of the Pacific), 277
Mathys, G., Hubrig, S., Landstreet, J. D., Lanz, T., & Manfroid, J. 1997, A&AS, 123, 353
Maitzen, H. M., & Hensberge, H. 1981, A&A, 96, 141
North, P. 1987, A&AS, 69, 371
Ryabchikova, T., Piskunov, N., Kochukhov, O., et al. 2002, A&A, 384, 545
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Stępień, K. 1994, in Chemically peculiar and magnetic stars, ed. J. Zverko, & J. Žižňovský (Tatranska Lomnica: Slovak Academy of Sciences), 8
Sung, H., Bessell, M. S., Lee, B.-W., & Lee, S.-G. 2002, ApJ, 123, 290
Thompson, I. B., Brown, D. N., & Landstreet, J. D. 1987, ApJS, 64, 219
Wade, G. A., Bagnulo, S., Kochukhov, O., et al. 2001, A&A, 374, 265