Magnetic Splitting and Identification of Spectral Lines in Ap Stars

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Abstract. We present a high-resolution atlas of the red spectrum of the Ap star HD 94660, to be used as a reference for future studies of Ap stars in that spectral region. The lines of this star are observationally resolved into their magnetically split components. We take advantage of this to perform their identification.

1. Introduction

Identification of spectral lines in magnetic Ap and Bp stars is an intricate task. Indeed, elemental abundances in the outer layers of these stars are highly non-solar, with in particular huge enhancements (by up to 5 dex) of "exotic" chemical species, like rare earths. The observed abundance patterns can be very different from star to star, with no or little obvious relation to their other characteristics (temperature, surface gravity, rotation, magnetic field,...). Furthermore, the distribution of the elements over the stellar surfaces is often inhomogeneous, sometimes extremely so.

While the UV and optical spectral regions have been the object of a number of line identification studies, the red spectrum of Ap stars still remains poorly known. This situation mainly finds its origin in historical reasons, the poor quality of photographic plates as red-sensitive detectors being a major factor, which still partly accounts for the relative scariness of laboratory data on red atomic spectra. But advantage can now be taken of the generalization of the use of CCDs in astrophysics to gain a deeper insight into the physical properties of Ap stars through the study of the red portion of their spectra. This approach can be expected to be particularly beneficial for the diagnosis of the magnetic fields, as the Zeeman effect increases quadratically with wavelength. On the other hand, some or most of the main diagnostic lines that can be used to derive the abundances of several chemical species lie in the red spectral region. In Ap stars, in this range are found not only lines of "classical" elements like C, N, O, or Li, but also many of the strongest lines of doubly ionized rare earths — the dominating ionization stage (Cowley 1984) — as well as important diagnostic lines of other species of interest, like Ga (Lanz et al. 1993).

One of the main difficulties in such studies of Ap stars based on the red part of their spectra is that one must first carry out the line identification. At
present, this has to be done from scratch, starting from laboratory line lists. This step would be greatly simplified if one could use as a starting point an already existing line identification list for a typical Ap star of similar type. Here we present a preliminary report on a project aimed at providing such a reference.

2. An atlas of HD 94660

In order to perform reliable line identifications in the red spectral region, we applied an original approach. Namely, we took advantage of the fact that a number of Ap stars rotate sufficiently slowly and have a strong enough magnetic field so that their lines are observed resolved into magnetically split components. The number, relative strengths and wavelength shifts of those components differ from line to line (or, in other words, different lines generally have different Zeeman patterns). This can be used to confirm the identifications, by checking the consistency of the observed splitting with the pattern that the transition is expected to have for the assumed identification.

Using this approach, we are preparing an atlas of identifications for the red spectrum of HD 94660. HD 94660 is an A0p EuCrSi star, whose lines are magnetically resolved. We have been studying its magnetic field for more than 6 years. During that period, the mean modulus of this field has varied between 6.1 and 6.4 kG. The latter value appears to be the field maximum; it was observed in 1991. However, we have not observed a complete cycle of variation yet, so that the rotation period of HD 94660 is still unknown, but it must exceed 6 years. The peculiarity of HD 94660 is not extreme: the vast majority of the lines seen in its spectrum (at least, in the red) are also observed in most other Ap stars of similar temperature that we know of. These properties, together with the fact that the maximum rate of occurrence of the Ap phenomenon is around spectral types A0–B9, make HD 94660 a particularly well-suited target for the production of a first red reference atlas of an Ap star.

Our observations also revealed that HD 94660 is a spectroscopic binary. Careful inspection of our data however failed to reveal any hint of a secondary spectrum.

For the production of the atlas, we recorded spectra at a resolving power of 10^5 with the long camera of the European Southern Observatory Coudé Echelle Spectrograph (CES) fed by the 1.4 m Coudé Auxiliary Telescope (CAT). These observations were performed in March 1990 and March 1991. 80 frames were recorded at various central wavelengths. They cover the spectral range 5550–6868 Å (except for a gap between 6276 Å and 6328 Å, where a large number of atmospheric O_2 lines preclude most astrophysical studies). A number of redder domains of particular interest (e.g., containing C, N, O lines) were also recorded. Some regions were observed both in 1990 and in 1991. The spectral variations of HD 94660 over the year elapsed between the two runs, if any, were at most marginal.

A preliminary line identification has been carried out through the "classical" approach. That is, laboratory line lists were scanned to find possible identifications. Other lines belonging to the same multiplet and/or supermultiplet as the tentatively identified transition were then sought in the observed spectra, and their relative intensities were compared to those of laboratory lines. If reason-
Figure 1. Portion of the spectrum of HD 94660, with the corresponding Zeeman patterns and line identifications (see text for more details).

able consistency was achieved, the identifications made in that way were kept for the next step: the comparison of the observed magnetic splitting with the expected Zeeman pattern.

For the latter, the Zeeman pattern of the transition assumed to be responsible for the observed line was plotted opposite that line, and it was visually checked whether the splitting seen in the stellar spectrum corresponds to that pattern. The wavelength shifts of the individual components within the pattern have been computed for a uniform field strength of 6.4 kG. The relative strengths of the $\pi$ and $\sigma$ components correspond to an angle between the magnetic field and the line of sight of 55°. Of course, depending on the actual field geometry, the relative component intensities that are observed cannot be fully consistent with the relative strengths estimated in that way. But they should not depart too much either, as real observed lines result from the integration over the visible stellar hemisphere of the flux emerging from the stellar surface. At different points of the star’s surface, the angle between the local magnetic vector and the line of sight is different. The observed line thus corresponds to an average of different angles between the magnetic field and the line of sight, of which the adopted angle value of 55° can be regarded as reasonably representative.

The method is illustrated in Figures 1 and 2. They show portions of the spectrum of HD 94660, together with the line identifications and the corresponding Zeeman patterns. The latter are represented in the conventional way, that is, each component appears as a bar whose length is proportional to the relative
strength of the component within the pattern, with the $\pi$ components above the horizontal (wavelength) axis, and the $\sigma$ components below it. Note that the component strengths should only be compared within a given pattern, not between patterns corresponding to different transitions. One clearly sees in these figures how lines having different patterns are split in a different way under the effect of the magnetic field. (Note that both figures show the overlap between two ranges observed in different exposures. This gives an idea of the achieved signal-to-noise ratio.)

The regions shown in the figures are good illustrations of some of the main chemical species seen in the red spectrum of HD 94660. Note the correspondence between the magnetic splitting of the observed lines and the Zeeman patterns of the transitions to which they are attributed. It is particularly revealing, in that respect, to consider the Fe II lines: compare the doublet at 6149.2 Å, the quasi-quadruplet at 6147.7 Å, and the two quasi-triplets of different type at 5839.0 Å and 5842.3 Å. The Cr II lines appearing in the two illustrated regions are also good examples of the power of the method.

It may be mentioned here that for Fe II and Cr II, as well as for other iron-period elements, we used as the main source for our identification work Kurucz’s line list (1989, private communication), rather than laboratory line lists. One advantage of Kurucz’s list is that it includes all the lines predicted from the known energy levels. In this way, for instance, Kurucz’s list of lines for Cr II is more complete than any laboratory line list; it should include, in
particular, all the important high-excitation transitions (Johansson 1994, private communication). As a matter of fact, one remarkable result of this identification work is that a large number of transitions issued from a high-excitation lower level (i.e., in the range 80 000–90 000 cm\(^{-1}\)) are found both for Fe II and for Cr II.

Among the most conspicuous lines in the studied wavelength range are those of the third spectra of several rare earths. That Pr III is responsible for several of the strongest lines of the red spectrum of many Ap stars had already been firmly established by Mathys & Cowley (1992). In HD 94660, a number of strong lines in the red spectral region are probably due to Nd III and to Tb III. For Nd III, the observed splitting of the lines matches well their expected Zeeman pattern. But the correspondence between Zeeman pattern and line profiles for Tb III is much less good, as can be seen in Figure 2 for the line \(\lambda 5847.2\). We attribute this to the fact that the shapes of the Tb III lines observed in HD 94660 are dominated by their hyperfine structure, and not by the magnetic splitting.

3. The need for more laboratory data

Even though it is globally successful, the identification work described here cannot be entirely completed: we are unable to identify a significant number of lines, some of them among the strongest ones in the observed range. A few examples are seen in Figures 1 and 2: e.g., there is a strong blend (indicated by an arrow) on the blue side of the line Fe II \(\lambda 5842.3\), due to an unidentified transition which is not strongly sensitive to the magnetic field. As the lines of doubly ionized rare earths turn out to be among the strongest in the observed spectral range, and as laboratory studies of the red region of the third spectrum of several rare earths are still lacking, we tend to suspect that a significant fraction of the lines that we cannot identify may be lines of doubly ionized rare earths for which laboratory data are still missing.

The original approach outlined above, in which we seek a confirmation of tentative line identifications through a comparison of the observed magnetic splitting of spectral lines with their expected Zeeman pattern requires, of course, the knowledge of the latter, thus of the Landé factors of the levels between which the transitions occur. However, for many levels, there are no published laboratory measurements of Landé factors. In such cases, those factors can be computed through simple formulae from the quantum numbers characterizing the atomic level of interest. But this is satisfactory only provided that the level belongs to a pure coupling scheme (e.g., \(LS\)-coupling). Real levels often depart from this ideal situation. Then the Landé factors computed under the pure coupling assumption can dramatically differ from the actual ones (see e.g. Mathys 1989). This stresses the need for more experimental values of Landé factors. Alternatively, detailed quantum mechanical calculations of the atomic structure may provide useful theoretical values. As an illustration of this, the Landé factors computed by Kurucz (1989, private communication) for the iron-period elements were shown to be much better than those determined through pure coupling formulae (Mathys 1990b). Accordingly, they were used in the present study to calculate the Zeeman patterns of the lines of Cr II and of Fe II for which no laboratory data were available.
On the other hand, there are a number of other physical processes that affect the spectral line shapes, which are still very incompletely studied. We have already mentioned above the hyperfine structure of the Tb III lines. Hyperfine structure is a very significant effect for many rare earth lines, as well as for a number of other elements that are sometimes very overabundant in Ap stars, like Mn. Not only is there a great need for more studies of the hyperfine structure alone, but even more, its combination with a magnetic field, which may lead to a quite intricate situation in which transitions are split into a large number of components forming very complex patterns, is very poorly known.

Another intricate issue which needs to be studied is the combination of the Zeeman and Stark effects, especially for the lines for which the latter is large. This is particularly relevant for Si II lines. An example is seen in Figure 2, where the contribution of the Stark effect to the profile of the line Si II $\lambda 5846.1$ is apparent through the fact that the Zeeman split components of this line are significantly broader than those of other lines.

Finally, it may be noted that in some cases, the magnetic splitting of the levels is not small with respect to the fine structure of the spectroscopic term to which they belong. Lines involving such levels are no longer formed in a regime of pure Zeeman effect, but rather they undergo partial Paschen-Back effect. Their magnetic splitting is no longer perfectly described by "standard" Zeeman patterns; in particular, it looses the property of symmetry about the line centre. The best documented example of this effect in Ap stars is the pair of Fe II lines $\lambda 6147.7$ and $\lambda 6149.2$ (Mathys 1990a), seen in Figure 1. Again, the study of such cases in stars is severely hampered by the lack of relevant laboratory data.

It should be stressed that the laboratory data mentioned above would be needed not only for the identification work described in this paper, but even more critically for the physical study of the magnetic fields of the Ap stars and of their other atmospheric characteristics.

4. Conclusion

We have shown how a unique property of Ap stars, their large-scale organized magnetic field, can be exploited for the identification of their spectral lines. Admittedly, the approach that we apply can only be used for a restricted number of stars, those which rotate slowly enough and which have a sufficiently strong magnetic field so that their lines are observationally resolved into magnetically split components. The number of such stars known now reaches 40, mainly as a result of a systematic programme that we have undertaken a few years ago (Mathys et al., in preparation). Stars in this sample range in spectral type from F2 to B8. It will be most useful to undertake a line identification project for the red spectrum of a few of them, to complement the atlas of HD 94660 presented here with similar references for stars of other temperatures.

Discussion

*Martin:* Which line list do you use for the identification of Nd III?
Mathys: The laboratory spectra of both Nd III and Tb III have hardly been studied, and our identifications rely on unpublished laboratory line lists kindly made available to us by C.R. Cowley. The list for Nd III contains only the wavelengths and the intensities of the transitions. It is likely contaminated by a number of lines not pertaining to Nd III (in particular, lines of Nd II). Accordingly, we only considered those lines whose wavelength corresponds to a transition between well established levels of Nd III (that is, levels appearing in the NBS compilation: Martin et al. 1978). All the strongest Nd III lines from this laboratory list responding to this criterion are found in the spectrum of HD 94660. Furthermore, their observed splitting corresponds well to their expected Zeeman pattern, so that their identification can be regarded as very probably correct.

In the Tb III laboratory list, the levels between which the transitions occur are identified. In the spectrum of HD 94660, we find lines at the wavelengths of all the strongest laboratory lines of this ion in the considered wavelength range, with relative intensities consistent with those from the laboratory. Thus the identification also appears rather secure, even though, as mentioned, the observed line profiles do not match well the expected Zeeman patterns, probably as a result of the large hyperfine structure.

Griffin: The spectra which you have shown look impressive, and I would like to ask whether the same technique and instrumentation can be used to obtain the blue and near UV regions too.

Mathys: In principle, the same instrumentation could be used. But the efficiency of the CCDs presently used with the CES at ESO decreases sharply at shorter wavelength, so that observations bluer than about 4 000 Å would be very difficult in practice.

References

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