The Atmospheres of Chemically Peculiar Stars: A Laboratory for Atomic Physics

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Abstract. A brief review on the chemically peculiar (CP) stars of the upper main sequence is presented. I show that CP star studies not only need a large quantity of high quality atomic data, but also that these stars serve as a laboratory for checking the accuracy of the atomic data. Examples concerned with accurate wavelengths and isotopic shifts for heavy elements, magnetically split lines and Landé factors, and autoionization features are discussed. In particular, the new Si\(^+\) photoionization cross sections provided by the Opacity Project (OP) bring a dramatic improvement for the interpretation of the far ultraviolet spectrum of Ap Si stars. Finally, I present a few suggestions for desirable progress beyond the OP project from the point of view of a stellar spectroscopist.

1. CP Stars: What Are They?

Stars are called chemically peculiar as soon as their surface chemical composition differs from the “standard” composition, the composition of the solar photosphere. There are many types of chemically peculiar stars, in almost any range of effective temperatures from Wolf-Rayet stars to carbon and S-type stars, and in all evolutionary stages. This reflects of course a wide variety of causes, e. g., different original composition (Population II metal-poor stars), stripped stellar cores (Wolf-Rayet stars), accretion of nuclear-processed material from an evolved companion (Barium stars), or gravitational settling and radiative levitation (e. g., white dwarfs). A panorama of these stellar chemical peculiarities has been presented during the recent IAU Symposium 145 (Michaud & Tutukov 1991). In this paper, I will focus on the chemically peculiar stars of the upper main sequence, the CP stars. I will discuss how recent progress in atomic physics helps to improve their study and, conversely, what we could learn from them for atomic physics.

The CP stars are B- to F-type stars, encompassing the classical Am and Ap stars. They are main sequence objects, and chemical peculiarities appear to be present during the entire main sequence stage. Preliminary Hipparcos results show that the CP stars fill the whole main sequence band in the H-R (Hertzsprung-Russell) diagram (Gómez 1994). This means that the build up of the chemical anomalies should be efficient, probably rapidly attaining an equilibrium when the stars arrive on the main sequence. Up to now, no
convincing evidence has been found that the chemical anomalies change during the main sequence lifetime of the stars. Strictly speaking, there are as many peculiarities as individual stars when they are studied in detail. However, the CP stars can be classified in few groups according to their main spectral peculiarities (see e.g., Preston 1974, Wolff 1983) which appear to be related primarily to two main parameters, the effective temperature and the magnetic field.

The CP stars have been grouped according to the most obvious line strength anomalies seen in classification spectrograms. The designations given in Table 1 reflect the elements for which significant abundance anomalies are found. Some other chemical elements also exhibit large abundance anomalies (up to several orders of magnitude), which might be not so conspicuous in the blue spectral range at low resolution. Let me mention two examples. Weak neutral helium lines are typical in the spectrum of hot CP stars; helium is also predicted to be underabundant in the atmosphere of cooler CP stars (T\text{eff} < 10,000 K), but it is difficult to observe directly, and it is therefore not a characteristic anomaly in the spectra of cool CP stars. The second example relates to the strong lines from the first ions of several rare earths in the blue spectrum, which are characteristic features of the spectrum of Ap SrCrEu stars. Rare earths are also overabundant in Am stars and probably in hotter CP stars. In the last case, such abundance anomalies have been explored to a much lesser extent, because the dominant ion becomes the second ion whose strongest lines are in the ultraviolet and in the red regions. Identifications in the ultraviolet are hampered by numerous lines of iron peak elements. The red spectrum is still little explored, but recently, for example, Mathys & Cowley (1992) identified strong Pr III lines between 5700 Å and 6700 Å, which markedly contrast with the absence or weakness of Pr II lines in the blue spectrum. Abundances in CP star photospheres have been recently reviewed by Takada-Hidai (1991), Dworetsky (1993), and Cowley (1993).

Table 1. Types of CP stars (from Landstreet 1992)

<table>
<thead>
<tr>
<th>Range of T\text{eff}</th>
<th>Magnetic stars</th>
<th>Nonmagnetic stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000 - 10,000 K</td>
<td>Ap SrCrEu</td>
<td>Am, λ Boo</td>
</tr>
<tr>
<td>9000 - 14,000 K</td>
<td>Ap Si</td>
<td>Ap HgMn</td>
</tr>
<tr>
<td>13,000 - 18,000 K</td>
<td>He-weak Si, SrTi</td>
<td>He-weak PGa</td>
</tr>
<tr>
<td>18,000 - 22,000 K</td>
<td>He-strong</td>
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As indicated in Table 1, the CP stars are divided into two sequences depending on the presence or the absence of a magnetic field. This means that it is common to detect a strong magnetic field in many stars whose spectral peculiarities are listed in the second column, while attempts to do so for the "nonmagnetic" stars have been generally unsuccessful. Magnetic CP stars have strong fields with a mean magnetic field modulus of several kilogauss, up to 34 kG for HD 215441, the CP star with the strongest known field. The component
of the field along the line of sight has generally a non-vanishing average over the visible stellar hemisphere which varies while the star rotates. Therefore, this implies that the magnetic field is organized on a large scale. Magnetic geometries have often been modeled by low order multipoles, but it seems that the geometry might be more complicated in some stars (Mathys 1993). The so-called nonmagnetic stars do not have such strong, organized magnetic fields, though they might possibly possess fields with a more complicated geometry like that of the Am star o Peg (Mathys & Lanz 1990). The origin of the magnetic field is not a completely settled question, but a fossil origin is now favored (Moss 1994). A comprehensive review of stellar magnetic fields is that by Landstreet (1992).

There is now a fair consensus that the primary physical mechanism for the origin of the chemical anomalies in CP stars is radiative diffusion, as originally proposed by Michaud (1970). In a stable chemically heterogeneous stellar atmosphere, there is competition between gravitational settling and radiative levitation of heavy elements, relative to the hydrogen gas. Depending on the radiation field and the absorption cross sections of the ions, some elements like helium are not supported in the photosphere, while other elements may accumulate in certain limited layers. If the accumulation occurs in the line-forming region, the spectrum will shown anomalously strong lines of these elements. A parameter-free model allows us to explain several general observational features (at least for nonmagnetic stars), although few problems remain (see e. g., Michaud 1986).

The detailed properties of the CP stars have been discussed in several reviews, which have been presented during a recent IAU colloquium dedicated to these peculiar stars (see Dworetsky et al. 1993).

2. Topic in CP Star Research: Astrophysics

In the 1960’s, the CP stars were very fashionable objects. It was the period when the nucleosynthetic origin of the elements was worked out. Then it was important to understand the origin of the large overabundances of heavy elements in CP stars. As it turned out later, the CP phenomenon is linked to radiative processes in stellar atmospheres and envelopes, and not to nuclear processes. The interest towards these stars has then somewhat faded. Yet, the CP stars present many interesting problems of stellar physics. I will discuss briefly some of them, based on my own interests and biases.

On the main sequence, A-type stars are located at a juncture between the hot and the cool stars. They do not show strong stellar winds like OB stars, and they do not possess a convection zone like cool stars. Yet, we find a whole zoo of chemical peculiarities. This should tell us that we see some additional process(es) at work, which are absent or masked in hotter or cooler stars. Indeed, no chemical accumulations can be build up in these hotter or cooler stars by radiative diffusion. In presence of a wind, even with a mass loss rate as weak as $\dot{M} = 10^{-12}$ $M_\odot$ yr, no chemical separation is possible (see e. g., Babel
1992). Similarly, convection (and overshooting) ensures the chemical homogeneity of cooler stars. Interestingly, chemical separation processes might be at work in all A-type stars, since virtually all A stars seem to be chemically peculiar to some degree (Cowley 1991). Some well known examples are Sirius, whose abundance pattern resembles the pattern in Am stars, and Vega with metallic underabundances like the λ Bootis stars. In some way, this suggests that A-type and CP stars form a distinct category on the main sequence. But, we may also take an opposite view, and see how CP stars relate to phenomena occurring in hot and cool stars, especially as magnetic CP stars are concerned. The He-strong stars, as well as some He-weak stars, show spectroscopic evidence of winds. The regions of outflow are expected to be restricted to the magnetic polar regions. Helium is levitated around the magnetic equator where it cannot flow out, explaining the observed helium abundance (Shore 1987). Linsky et al. (1992) have, moreover, reported that they found nonthermal radio emission for the different classes of magnetic CP stars with the exception of the Ap SrCrEu stars. However, this emission appears to differ from hot star wind sources. Additionally, a few X-ray sources have been found from the ROSAT All Sky Survey (Drake et al. 1994). Both the radio and the X-ray emissions arise from the stellar magnetosphere, but there is no simple one-to-one correspondence between the radio and the X-ray sources. The two CP stars detected in both energy domains nevertheless suggest similitudes with the most active late-type stars. Linsky (1993) has conjectured that the magnetic CP stars could be some kind of hot analogs of the active cool stars.

In nondegenerate stars, magnetic fields are found only in CP stars and in solar-type stars. The origin and the structure of the field differ drastically between the two groups of stars. Structurally complex fields are created by a dynamo effect in the convective zone of cool stars. The magnetic fields in CP stars are on the other hand much simpler, having in the first approximation a large scale, dipolar geometry. Our knowledge of the exact field geometry remains, however, quite limited. For most magnetic CP stars, this geometry has been derived only from the changes of the longitudinal component of the field due to the rotation of the star and the inclination of the magnetic axis relative to the rotation axis (the oblique rotator model). Yet, more data can be obtained for CP stars with very low apparent rotational velocities. In this case, the different individual components of the Zeeman pattern of spectral lines can be observed, and the mean modulus of the field can be directly measured. Up to a few years ago, only about 10 such stars were known, and four have been studied throughout their rotation cycle. In a new program, we have discovered about 30 more stars showing magnetically split lines, and we are observing them repeatedly to derive magnetic geometries (Mathys & Lanz 1992, Mathys et al. 1993). A knowledge of the detailed field geometry will give precious insights for understanding the origin of the field and, if the field is indeed fossil, additional inputs for star formation.

Many magnetic CP stars exhibit periodic line profile variations, which have been interpreted as implying a heterogeneous distribution of the chemical elements over the stellar surface. From high resolution spectra which sample the rotation cycle well, detailed maps have been obtained. These maps reveal
over/under- abundant bands and caps, corresponding roughly to the magnetic equator and poles, respectively (see e. g., Hatzes 1991). Part of the line profile variations may also come from changes in the local profiles that depend on the local magnetic field. Landstreet (1988) has, therefore, introduced a method to model consistently the magnetic field and the abundance distribution. These structures over the stellar surface can also be understood in the framework of radiative diffusion. Horizontal or vertical field lines will indeed prevent or allow, respectively, the diffusion of ions. The ions also follow oblique field lines. Detailed modeling of a few stars can thus show how well radiative diffusion is able to predict the "observed" maps (Babel & Michaud 1991, Babel 1992), which would be the ultimate test for radiative diffusion as the explaining mechanism of the CP phenomenon. Moreover, this might provide additional insights concerning the hydrodynamic state of these stellar atmospheres, such as the presence of very weak winds (Babel 1992).

In summary, the CP stars are not just oddities or curiosities. They are quite relevant to our understanding of stellar atmospheres, particle transport, stellar magnetism, and star formation.

3. Topics in CP Star Research: Atomic Physics

Astronomers have extensive needs for atomic data. They use them to feed sophisticated computer codes to calculate synthetic spectra of astronomical objects. Comparing the predictions to observations and varying the input model parameters, detailed physical properties of distant astronomical objects are finally derived. For the physicists, who provide the atomic data, it often remains unclear, however, how the new atomic data improve the astrophysical modeling. It is true that astronomical objects are complex. CP stars do not depart from this rule. However, I would like to show with few examples how the quality of some atomic data can be assessed when studying CP stars. In this respect, CP stars can be truly a laboratory for atomic physics despite all remaining shortcomings of the underlying structural models.

Leckrone et al. (1993) presented superb quality spectra of the B9.5p HgMn star χ Lup obtained in the echelle mode with the Goddard High Resolution Spectrograph (GHR S) of the Hubble Space Telescope. They achieved signal-to-noise ratios up to 100 with a resolving power λ/Δλ ≈ 85,000. Thanks to the quality of the spectra, they were able to firmly identify Ru II lines for the first time. However, the published wavelengths for these lines (Shenstone & Meggers 1958) are larger by about 0.016 Å than the measured wavelengths on the GHR S spectrum. Subsequent new FTS measurements at Lund showed that the published wavelengths were in error, and confirmed the GHR S wavelengths at the 1 to 2 mÅ level. This first example demonstrates how high resolution stellar spectra can assess laboratory wavelengths. It also shows the need for very accurate wavelengths. With additional iron peak lines, Leckrone et al. showed that the accuracy of the wavelength scale of the GHR S is of the order of 2 to 3 mÅ. Such an accuracy allowed them to study in detail the mercury isotopic abundance anomaly in χ Lup, since the isotopic
Fig. 1. High resolution spectrum of the A0p EuCrSi star HD 94660, showing magnetically split lines. Identifications and predicted Zeeman patterns are indicated at the bottom.

Shifts between $^{198}$Hg and $^{204}$Hg are of the order of 0.02 Å for Hg II $\lambda$1942 and Hg III $\lambda$1738. The observed wavelength of the Hg II $\lambda$1942 line corresponds to better than 1 mÅ with the wavelength of the $^{204}$Hg transition. They deduced that nearly all the mercury ions are $^{204}$Hg, while $^{204}$Hg represents just 7% of the mercury in the solar system. Moreover the line shape cannot be reproduced with a solar isotopic mix. The Hg III $\lambda$1738 lines confirm these results.

Earlier I mentioned that there are some magnetic stars with very slow rotation and strong magnetic fields. The spectral lines are sharp enough to exhibit the Zeeman splitting in this case. As an example, a portion of the red spectrum of HD 94660 is displayed in Figure 1. Generally, line identifications are made on the basis of wavelength coincidences. To benefit from the Zeeman splitting, Mathys & Lanz (1994) have proposed to use the Zeeman pattern as an additional criterion to make identifications more secure. Four lines have been identified in the wavelength interval shown in Figure 1, but so far the other features remain unidentified. For each identified line, all the components of the Zeeman pattern are displayed. A magnetic field of 6.2 kG, as measured by Mathys & Lanz (1992), and an equal total strength for the $\sigma$- and the $\pi$-components are assumed. Two lines have normal Zeeman triplets with significantly different Landé factors and splittings, while the two other lines
have patterns with many components. These two patterns have quite different line strength distributions, one of them being quite close to a triplet. The correspondence of the Zeeman patterns with the observed stellar line profiles is quite good, both for the Zeeman component relative strengths and wavelengths. Three lines are indeed triplets in the stellar spectrum, while the Cr II \( \lambda 5743.895 \) line has a triangular shape with a width agreeing with its complicated Zeeman pattern. The Fe II \( \lambda 5746.575 \) has a blue \( \sigma \)-component which is too strong. This is clearly due to a blend by the redder component of a close unidentified line. This second example shows an additional tool for line identification in stellar spectra. Moreover, this also shows that we can use stellar spectra to assess Landé factors, which is especially important when intermediate coupling is suspected.

4. Autoionization Features in Stellar Spectra

Very broad absorption features characterize the ultraviolet (\( \lambda 1400, 1570, 1780 \)) and the visible (\( \lambda 4200, 5200, 6300 \)) spectra of magnetic CP stars. These features can be most efficiently used as detection criteria for CP stars. In particular, broadband photometry peculiarity indices based on the \( \lambda 1400 \) and the \( \lambda 5200 \) features have been devised to detect CP stars (Hauck 1974, Maitzen 1976, Jamar et al. 1978). These features have defied firm identification for a long time. I shall discuss in this section how the new photoionization cross sections give an answer, at least for the UV features, and conversely how we can use these features to check the recent atomic calculations.

The strongest UV feature, \( \lambda 1400 \), was discussed in detail by Jamar et al. (1978), who listed several reasons to attribute this feature to Si II autoionization lines. In particular, the \( \lambda 1400 \) feature is prominent in Si-rich stars. However, they could not reproduce the feature due to the very incomplete laboratory data available. This prompted a new \textit{ab initio} calculation of the Si\(^+\) electronic structure to obtain autoionization widths and radiative transition probabilities for Si II autoionization lines (Artru et al. 1981a). Artru et al. (1981b) then showed that Si II autoionization lines are indeed a major opacity source below 1500 \( \text{Å} \) in Si-rich stars. The strongest and broadest lines were predicted yet at \( \lambda 944 \) and 1221. Numerous narrower lines are present around \( \lambda 1400 \). A synthetic spectrum calculation degraded to a low resolution comparable to TD-1 observations predicts a broad absorption feature that resembles the observed feature if a high silicon overabundance (100 times the solar abundance) is assumed. This feature is a result of the cumulative effect of all these relatively sharp autoionization lines. Using their new atomic calculation, Artru et al. (1981b) concluded on the other hand that the flux depressions in the visible spectrum cannot be attributed to Si II autoionization lines.

However, later on, Artru (1986) showed that the \( \lambda 1400 \) feature could be attributed to a single autoionization transition, \( 3s^23d \; ^2D - 3s3p \; (^1P) \; 3d \; ^2F_0 \). This transition was erroneously predicted at \( \lambda 1221 \) by Artru et al. (1981a). Based on a new empirical determination of the energy of the \( 3s3p \; (^1P) \; 3d \; ^2F_0 \) and \( ^2D_0 \)
Fig. 2. Photoionization cross section from the excited level 3d $^2D^*$ of Si$^+$. The top and the bottom panels show how synthetic spectra change when this cross section only is added to the opacity. Different silicon abundances (dotted lines: no opacity from Si$^+$; silicon abundance is 1, 10, and 100 times solar for dashed, full thick, and full thin lines, respectively) have been assumed.

terms, Artru (1986) has suggested that the $^2F^0$ term is also predicted about 10,000 cm$^{-1}$ too high. With a corrected energy, the wavelength of the 3d $^2D - 3d^1\ ^2F^0$ transition is shifted to about 1400 Å. Including this transition at $\lambda$1400 in spectrum synthesis calculations, Artru & Lanz (1987) have been able to match high resolution far-UV spectra of several Si-rich stars recorded by IUE quite well.

New R-matrix photoionization calculations have appeared recently. Detailed photoionization cross sections have been calculated for many Si$^+$ levels by Mendoza et al. (1994) in the framework of the Opacity Project (OP, Seaton et al. 1992). Additional improvements have been introduced in the
target description by M. Le Dourneuf, to insure the best possible accuracy and to prove the ability of the theoretical method to provide the shapes of resonances. The improved calculation yields a better prediction of the energy level. As far as the cross section shapes are concerned, the results are quite close. As an example, the photoionization cross section from level 3d $^2D$ is displayed in the middle panel of Figure 2. These new \textit{ab initio} calculations predict now indeed a strong, broad autoionization resonance at $\lambda 1400$ from the 3d $^2D$ level. There is also an additional strong resonance at about $\lambda 1280$, as well as some narrower resonances. The top and bottom panels of Figure 2 show the effect of this single cross section on predicted stellar spectra. We have considered two effective temperatures and several silicon abundances, which are representative of the parameters of Ap Si stars. The only other opacity sources included in these spectra are the bound-free absorptions by atomic hydrogen and carbon. The effect of these broad resonances are quite small for normal, solar composition stars, and are probably unobservable with the many absorption lines of iron peak elements in this region. However, the Si II resonances have a dramatic effect in Si-rich stars.

How well can we match now a real stellar spectrum? To illustrate this point, we have chosen a typical bright Ap Si star, HD 34452, well observed with IUE. Stellar parameters for this star have been taken from Artru & Lanz (1987); in particular, the silicon abundance has been fixed by fitting the Si II $\lambda 1526$ and $\lambda 1533$ resonance lines. LTE is assumed. Figure 3 displays our results. The top two panels show the dramatic effect of the additional opacity due to the photoionization of Si$^+$. There are two features to emphasize specifically: first, besides the $\lambda 1400$ feature, there is a second broad absorption that is predicted at about $\lambda 1570$ Å; second, the flux below $\lambda 1310$ is almost completely absorbed. This is in part due to several resonances, but there is additionally a photoionization edge of Si$^+$ at about $\lambda 1310$ corresponding to the ionization to the ground state of Si$^{2+}$ from the 3p$^2$ $^2D$ level, which is possible only through configuration interactions (3p$^2$ and 3d). Artru & Lanz (1987) have predicted that this edge should be important and observable on the basis of Ap Si spectra. The bottom panel of Figure 3 finally shows a comparison with the IUE high resolution spectrum of HD 34452, degraded to a resolution of 1.5 Å. The overall agreement is very good. The $\lambda 1570$ feature can be assigned unambiguously to the Si II 3p$^2$ $^2D$ - 4s$^2$ $^2P^o$ transition; this broad feature was attributed by previous authors to an accumulation of Fe III lines. It must also be emphasized that the silicon abundance has not been adjusted to improve the match with the observations. Note moreover that the adopted silicon abundance (25 times the solar abundance) is now within the typical over-abundance range for Ap Si stars. The previous interpretation by Artru et al. (1981b) required a larger abundance (100 times solar) to predict a significant $\lambda 1400$ feature. However, one can still notice some slight discrepancies: missing opacity around $\lambda 1330$, $\lambda 1660$, and a resonance predicted too strong at $\lambda 1570$. A detailed account of this study is in preparation (Lanz et al. 1995).
Fig. 3. Model spectra of the Ap Si star HD 34452. The adopted parameters are $T_{\text{eff}} = 13650$ K, $\log g = 3.9$. The silicon and iron peak elements abundances are 25 and 10 times solar, respectively. The two top panels compare theoretical spectra with (thick lines), and without (thin lines) the opacity due to the photoionization from the six lowest excited levels of Si$^+$. Atomic lines have been added in the synthetic spectra displayed in the middle panel. The bottom panel shows a comparison between the IUE spectrum of HD 34452 (SWP 3156, thin line) and a theoretical spectrum (thick line) including Si$^+$ photoionization and a “complete” line list. Flux units are ergs/cm$^2$/s/$\mu$m, and a distance factor has been empirically determined for the theoretical spectrum.

What may be concluded from this example? A first point can be drawn for stellar atmosphere models. The opacity of Si$^+$ photoionization is a main contributor to explain the overall shape of the far UV spectrum of HD 34452. This is the spectral region where the maximum of the flux is emitted. A correct description of the opacity in this region is critical to compute accurately the temperature structure of the atmosphere. While certainly essential for CP stars, the effect of additional photoionization opacities ought to be assessed
also for normal stars. Kurucz (1992) accomplished a major task by including the opacity of $10^7$ to $10^8$ spectral lines in his model atmospheres, but only very limited data on photoionization opacities are included due to their paucity. Thanks to the OP, this is no longer the case. It is worthwhile to include updated photoionization opacities in model atmospheres.

The second point concerns the assessment of the accuracy of the new atomic calculations. Many comparisons between different sources and laboratory measurements are generally available for gf-values (see e. g., Allard et al. 1990). Similarly, the final product, Rosseland mean opacities, obtained by the OPAL and the OP groups completely independently have also been compared (Seaton 1992), yielding a quite satisfactory agreement. However, an assessment of individual photoionization cross sections themselves is more difficult. There are only very few available laboratory data, and they concern mostly photoionization from the ground state of neutral atoms. Our stellar study, however, shows that sophisticated, modern ab initio atomic calculations provide now reasonably accurate cross sections. While wavelengths could be still incorrect by few Ångströms, the general shape is good, and the improvement relative to older calculations is obvious. The excellent agreement between the observed and the predicted spectra supports the reliability of the new cross sections. This provides a strong indication of the good quality which may be expected from the new extensive atomic databases, though accuracy may vary from ion to ion. In spite of probable shortcomings of stellar atmosphere modeling (e. g., we assumed a homogeneous atmosphere, and no magnetic field) and that the "source" is a mix of different chemical species, this study shows that the atmospheres of Si-rich CP stars can be used as a laboratory to check the new atomic data. This is mainly due to the silicon features becoming prominent in the spectrum with a large silicon abundance. Modeling the atmospheres of CP stars is somewhat more difficult, but their large chemical overabundances can be turned to a definite advantage for this purpose. Other types of chemically peculiar stars could be used in a similar way.

5. Spectroscopic Needs

The purpose of the extensive atomic calculations made during the recent years by the OP and the OPAL groups was to provide new Rosseland mean opacity tables for stellar interior studies. This is the reason why these calculations have been focussed on radiative data for the cosmically most abundant species. Detailed opacities are also needed to interpret spectra within the LTE approximation. They require both quality oscillator strengths and photoionization cross sections. As an illustration, I have just shown how these new atomic data improve, or even are necessary for, the interpretation of the far-UV spectrum of Si-rich stars. The availability of TOPBASE, the OP database (e. g., Mendoza 1992), and of the Kurucz (1991) line list is, therefore, of tremendous importance for spectroscopic analyses. Let me, however, illustrate briefly a few areas where progress can help to improve the spectroscopic work, especially for CP stars.
For mass production, OP has chosen to provide data without fine structure. We obviously need it to match spectroscopic observations at a sufficient resolution. This is not difficult, as long as LS-coupling is a good approximation. However, some neutral spectra are significantly better described with intermediate coupling (see e.g., Wiese & Deters 1993). Second, TOPBASE, as opposed to Kurucz data, is a database with \textit{ab initio} theoretical data. Thus the energies have not be fitted to observed ones, producing problematic wavelength shifts for bound-bound transitions, as well as for sharp autoionization resonances. Incorporating observed energies in the database would be an immense help. A third point concerns the spectral resolution of the photoionization cross sections. The resolution has been optimized to represent the resonances well without increasing the space and computing time requirements out-of-proportion. Unfortunately, many sharp resonances are undersampled in the OP data when such resonances are studied in high-resolution spectra. Finally, the cross section for a given level incorporates all possible channels. This is satisfactory to compute opacities, but it is problematic for NLTE calculations. In this case, the rate equations should be solved, and we should know the individual transition rates between any two levels. It is not really obvious or possible to separate the contributions to the different channels from a given lower level (e.g., normal photoionization and autoionization). Moreover, NLTE models require collisional data in a similar extent.

Recent efforts have been centered on light and iron-peak elements, since they are the most abundant and therefore are the main opacity sources. The peculiar nature of CP stars requires, however, often additional data for heavier elements, like the Sr-Y-Zr group, the lanthanides, or the Pt-Au-Hg group. Data are often quite old and of limited quality and quantity. The data are moreover scattered in the literature and, contrary to light elements, there is still no way to extract them from a computerized database. It is not my intention to make a long list of needs for heavier elements, but I instead want to indicate to atomic physicists that improvements in the present state of atomic data for heavier elements are badly needed. Abundances of heavier elements in different astrophysical objects are indeed a key to our understanding of nucleosynthetic processes in stars and of the chemical evolution of galaxies.

6. Conclusions

I have shown several examples of how a stellar object can be used as a laboratory to assess atomic data. Chemically peculiar stars with large overabundances of selected species in their photosphere have the advantage that the spectral features from these species are prominent in their spectra, facilitating their study. In particular, I have discussed the importance of broad Si II autoionization resonances to explain the far ultraviolet spectra of Ap Si stars. The new photoionization cross sections from the Opacity Project provide the ability to reproduce the far UV spectrum of Ap Si stars. This good agreement is a strong indication that these cross sections are reliable. This conclusion is particularly important in view of the larger opacities obtained by the OP and the OPAL groups compared to earlier calculations. These larger
opacities improve the agreement of observation and theory in many aspects of stellar astrophysics. An assessment of these opacities is therefore essential. The laboratory data to check the atomic calculations are, however, very limited, and, therefore, this type of stellar study provides a welcome additional check.

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Discussion

Underhill: The attention paid to overly strong or overly weak lines in comparison to LTE predictions would better be paid to taking account of non-simple physics (for example, as in Si II with dielectronic recombination
through autoionizing levels - known since the 1930's) than emphasizing abundance differences. Throughout the outer layers of the envelope and of the atmosphere full account must be taken in models of the complexities of the physics of the atomic spectra before saying that the stars are chemically peculiar.

Lanz: It is indeed what I have shown. Detailed cross sections with autoionization resonances are a must to interpret the ultraviolet spectrum of Si-rich stars. However, silicon overabundances in the photosphere of ApSi stars are still required. I think that these overabundances are well established now in these stellar photospheres. As far as departures from LTE are concerned, Si II is the dominant ion stage and strong departures are not expected. Notice that Si II resonance lines as well as autoionization features are well matched assuming the same silicon abundance.

Adelman: Kurucz's new enhanced metallicity model atmospheres in the effective temperature range of the CP stars show features similar to those of the λ5200 features. They appear to be due at least in part to differential line blanketing. The λ4200 and λ6200 features are not fit by the models' flux predictions. Some stars have stronger λ5200 features than those predicted by the ten times solar metallicity model atmospheres. (Details will appear in a paper to be published in Astronomy & Astrophysics in early 1995.)

Lanz: As far as Si II autoionization lines are concerned, they explain the UV broad features in the spectrum of CP stars. However, we have not found any convincing identifications for the visual features. Differential blanketing seems indeed attractive for the λ5200 feature.

Linsky: I would like to comment on the false logic that since the chemically peculiar A- and B- type stars do not have convective zones, they should not show phenomena seen in the late-type stars. Stephen Drake and I have now detected nonthermal radio emission from about 30 of these stars and X-ray emission from 4 single chemically peculiar stars in the ROSAT all-sky survey. So, some or many have both hot and nonthermal electrons in their coronae.