ATMOSPHERIC MODELS OF FLARE STARS:
THE QUIESCENT STATE OF AD LEO

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ABSTRACT

We compute a semi-empirical atmospheric model for the dMe star AD Leo, which constitutes the first model computed to match the continuum observations, as well as a wide set of chromospheric spectral lines. We find good agreement between the computed and observed spectral features, with the exception of the Ca II K line.

Subject headings: Stars: atmospheres; Stars: chromosphere; Stars: late-type; Stars: Flare
1. Introduction

Dwarf M stars are divided into two subclasses according to whether the Balmer lines are in emission or not. This fact distinguishes the emission dMe stars from the non-emission dM stars. The presence, in both types, of many atomic lines and molecular bandheads in absorption, proves the existence of a cool photosphere. Emission lines are instead signatures of a chromosphere with a considerable temperature rise. The difference between the spectra of dM and dMe stars could be similar to that between quiet and active regions on the Sun. The possible heating mechanism of the chromosphere is supposed to be more efficient in correspondence to a concentration of the magnetic field, as in solar faculae. The presence on dMe stars of strong magnetic fields, with an area coverage greater than 70 % (Saar 1990), supports the idea that most of the stellar surface is covered by facular network and that the contribution to the emitted spectrum comes essentially from these bright regions.

Atmospheric models for a grid of dM stars were computed by Mould (1976), from the deep photosphere to approximately the temperature minimum. The temperature minimum region and the chromosphere are instead poorly modeled. Cram & Mullan (1979) computed very schematic chromospheric models using only Balmer-line data as chromospheric diagnostics; Giampapa et al. (1982) computed single component homogeneous models that are consistent with high resolution profiles of the Ca II K line for some representative dMe and dM stars. Their models have microturbulent velocities between 1 and 2 km s$^{-1}$.

To study the atmospheric properties of a dMe star we chose AD Leo (Gl 388), which is one of the flare stars most extensively observed both in the quiescent and in the flaring states. It is a single red dwarf star, on the main sequence, with an effective temperature of 3500 K (Pettersen 1980), and a spectral type M3.5e (Kunkel 1975). Vogt et al. (1983) measured a projected rotational velocity $v \sin(i)$ of 5 km s$^{-1}$ from an absorption line profile (Ba II λ6141 Å) at high resolution, and suggested that such a rapid rotation is the necessary condition for the existence of photometric modulation by starspots and active regions (the BY Draconis syndrome). This possibility was confirmed by Spiesman & Hawley (1986), who measured a photometric period $P = 2^{d}.7 \pm .05$.

High resolution spectral observations of the quiescent state show chromospheric emission lines that range from a weak emission core in the center of the Na I D (5891, 5896 Å) and the Ca II IR lines (8498, 8542, 8668 Å) to a strong emission in the He I D$_3$, Mg II h and k, Ca II H and K and H I Balmer lines (Giampapa et al. 1978, Pettersen & Coleman 1981, Worden et al. 1981, Doyle 1987). Sundland et al. (1988) found that the Balmer lines are the most important components to the chromospheric radiation loss.

AD Leo is an active flare star: on the average one outburst is detected every 1 - 1.5 hours. Long term changes have been analyzed for the period between 1972 - 1988 (Pettersen et al. 1984, 1986, 1990) and only marginal variations in the flare activity have been found.

Hawley & Fisher (1992) computed a theoretical model of the quiescent atmosphere of AD Leo from the corona to the photosphere. The structure of the corona and the transition region is computed for a loop of length $L = 10^{10}$ cm and an apex coronal temperature of $3 \times 10^6$ K, in hydrostatic and energetic equilibrium. The photosphere is taken from the grid of models by Mould (1976). The chromosphere is simply an interpolation joining the transition region and the photosphere. They consider this atmospheric model only as a schematic one, chosen to test a certain heating model of the flare atmosphere and not to fit the observed spectral features of the star.

In this paper we present an atmospheric model of AD Leo, computed to fit several spectral features. In §2 we present our model, and discuss the fit to the observations. In §3 we compute the radiative losses to be balanced by the chromospheric heating. Finally, in §4 we discuss the results.
2. The atmospheric model

We compute a semi-empirical model of the photosphere and chromosphere of AD Leo. For semi-empirical we mean that the model was computed to match a certain number of spectral features as well as possible. For a given model, we compute the continuum fluxes, the profiles for the Balmer, Na D, Mg b, and Ca II K and λ8499 Å lines, and the total fluxes in the Lyα and the Mg II h and k lines, which are compared with the observations. The atmospheric model is then iteratively modified to improve the match.

In this paper we use the observations published by Pettersen & Hawley (1987), which have a 3.5 Å resolution. Although for some lines there are observations with better resolution, we consider that it is important to take a consistent set of observations, made at the same time and calibrated uniformly.

The calculations were done using the computer code Pandora, kindly provided by Dr. E. Avrett (see Avrett & Loeser 1992 for an explanation of the program’s features). Given a temperature vs. height distribution, the hydrogen density at each height is computed assuming hydrostatic equilibrium (HSE). The set of statistical equilibrium equations, coupled with the radiative transfer equation, is then solved to compute the electron density and the emergent spectrum. These calculations are done self-consistently for H, He I, Mg I, Na I, Fe I, Si I, Ca I and Al I (solar abundances are assumed).

We used a microturbulent velocity between 1 and 2 km s\(^{-1}\), both in the HSE equation and for the line-profile calculations. Although this is a rather arbitrary choice, the values are similar to the ones given by Giampapa et al. (1982).

Observations of magnetically sensitive infrared lines by Saar & Linsky (1985), give a value for the filling factor (relation of the facular area to the total area of the star) of 0.73 ± 0.06. Given the high value of the filling factor, we follow the standard assumption found in the literature, and neglect the contribution of the non-facular area to the total brightness of the star. Thus, we assume that a one component plane-parallel model is a good approximation to the mean state of the stellar atmosphere.

The model that represents the best fit to the chosen set of observations is shown in Fig. 1, together with the region of formation of the lines used in the modeling. For reference, we also show in Fig. 1 the model obtained by Hawley & Fisher (1992). The atmospheric parameters are listed in Table 1. The columns given represent the column mass in g cm\(^{-2}\), the electron temperature in K, the microturbulent velocity in km s\(^{-1}\); the continuum optical depth at 5000 Å; the hydrogen, proton, and electron density in particles per cm\(^3\); and the height (in km) above the level where \(\tau_{5000\text{ Å}} = 1\).
In Fig. 2 we compare the observed continuum spectrum (smoothed to 5 Å) with the results obtained for this model. The error of these observations has been estimated at around 10% (Hawley, private communication).

A very important factor to take into account when modeling a cool star like AD Leo, is the inclusion in the opacity calculations of the line blanketing due to the numerous weak atomic lines, and to the molecular...
species present in the atmosphere, in particular TiO and CaOH (Mould 1976). In this work we included the $5.8 \times 10^6$ atomic and molecular lines computed by Kurucz (1991a). It should be pointed out that these calculations do not include any triatomic molecules, that are thought to be important for this type of stars. The heads of the most important molecular bands observed in AD Leo are indicated in Fig. 2.

In Fig. 2, the dotted line represents the results obtained for this atmospheric model, but without considering line blanketing. It is clear that the inclusion of this opacity source (dashed line in Fig. 2) is of great importance to match the observed spectrum. It should be pointed out that line blanketing affects not only the computed continuum spectrum, but also the equilibrium of the different atomic species and hence the computed model. As it is seen in Fig. 2, although the general behaviour of the observed spectrum is reproduced, and many observed spectral features are matched, there are still some molecular bands clearly absent from our calculations, notably CaOH and H$_2$O. It can also be noted that the opacity due to TiO seems to be overestimated. Kurucz (1991b) cautions against the use of his opacity calculations to compute the atmospheres of M stars. However, based on the present results, we believe Kurucz’s compilation is quite good even for this case.

In Table 2 we list the observed flux values obtained with the Johnson UBVR filters and with IR filters, together with the fluxes computed from our model (integrated with the corresponding filter profile, see Schaffers and Voigt 1982; for the IR filters, we used a square filter profile). As it can be seen, the general agreement is good.

Note the large differences for the visible filters between the integrated fluxes with and without line blanketing. This implies that models based on a fit to the filter values, computed without taking into account these opacities, can be strongly in error.

Table 2 Observed and computed fluxes at earth (erg cm$^{-2}$ s$^{-1}$) for different spectral features. For the optical continuum filters, the first value was computed considering line blanketing, and the second one without considering it.

| filter | ref | obs     | computed |
|--------|-----|---------|----------|
| U      | 1   | 6.5E$^{-14}$ | 4.2E$^{-14}$ | 6.2E$^{-13}$ |
| B      | 1   | 2.9E$^{-13}$  | 2.7E$^{-13}$  | 7.2E$^{-13}$  |
| V      | 1   | 6.6E$^{-13}$  | 7.1E$^{-13}$  | 1.4E$^{-12}$  |
| R      | 1   | 1.5E$^{-12}$  | 1.1E$^{-12}$  | 2.0E$^{-12}$  |
| 12µm   | 2   | 7.1E$^{-24}$  | 8.8E$^{-24}$  |           |
| 25µm   | 2   | 2.4E$^{-24}$  | 1.6E$^{-24}$  |           |
| Ly$_{\alpha}$ | 3   | 1.0E$^{-12}$  |           | 2.9E$^{-12}$  |
| Mg II h+k | 3   | 2.5E$^{-12}$  | 1.1E$^{-12}$  | 1.4E$^{-12}$  |
| Ca II K | 3   | 1.2E$^{-12}$  |           | 2.5E$^{-13}$  |
| H$_{\alpha}$ | 3   | 4.4E$^{-12}$  |           | 5.9E$^{-12}$  |
| H$_{\beta}$ | 3   | 2.4E$^{-12}$  |           | 2.1E$^{-12}$  |
| H$_{\gamma}$ | 3   | 1.2E$^{-12}$  |           | 1.0E$^{-12}$  |
| H$_{\delta}$ | 3   | 8.7E$^{-13}$  |           | 6.3E$^{-13}$  |

1 Pettersen (1976)
2 Mathioudakis and Doyle (1991)
3 Hawley (1989)

Finally, we would like to point out that the good agreement between the observed and computed spectra implies that the photospheric part of our model can be considered quite reliable.

2.2) The Balmer lines

Figure 3 compares the computed profiles for the first Balmer lines with the observations (H$_{\epsilon}$ is not shown, because it appears blended with Ca II H). Since the observations have a spectral resolution of 3.5 Å, we have smeared our computed profiles with a gaussian profile of 3.5 Å FWHM. When comparing the profiles, we plot the computed profile with a dashed line, and the smeared one with a full line. In Figure 4 we show the source function and the Planck function for H$_{\alpha}$ and H$_{\gamma}$, together with those for the Na D$_{1}$ and the Ca
II K lines. We also indicate in this figure the depth of formation at line center for two different values of $\mu = \cos \theta$. The computed and observed line fluxes are listed in Table 2.

Some observations with better spectral resolution are available for H$_{\alpha}$ (Giampapa et al. 1978; Worden et al. 1981; Pettersen & Coleman 1981). We will attempt a comparison of our calculations with these profiles, even if they were taken in different conditions than the ones modeled here. Giampapa et al. (1978) and Worden et al. (1981), with spectral resolutions of the order of 0.25 Å, measured a contrast ($I_{\text{peak}} / I_{\text{continuum}}$) of 2.05 and 6.57 respectively. Our computed contrast, after convolution with the appropriate instrumental profile, is 5.77. Pettersen & Coleman (1981) measured a contrast of 3.1, with a spectral resolution of 0.45 Å. Our computed contrast (after convolution) is 4.9.

In our calculations we find for H$_{\alpha}$ a FWHM of 1.4 Å, which is in good agreement with the observed values of 1.4, 1.35, and 1.29 Å (Giampapa et al. 1978; Pettersen & Coleman 1981; Worden et al. 1981, respectively). The separation between the computed emission peaks is 1. Å, while the observed one is 0.6 Å (Pettersen & Coleman 1981).

It should be noted that the self reversal of H$_{\alpha}$ that can be seen in the computed profile before convolution with the instrumental response (Figure 3, dotted line), can also be seen in two of the quoted papers. After convolution with the instrumental profile appropriate to each observation we find a self reversal of the order of 1.6, which is larger than observed.

The observed differences may be ascribed to different levels of chromospheric activity of the star. The present model, which has been computed to match a given set of observations, yields an H$_{\alpha}$ profile comparable with other observations within a factor of two, and may be considered a good starting point to represent an average atmosphere of AD Leo.

### 2.3) The Na I lines

Figure 5 shows the observed and computed profiles for the Na I D lines and for the infrared lines at λ8183 Å and λ8195 Å. The source and Planck function for the D$_1$ line are shown in Fig. 4.

It can be seen that, while the agreement in the infrared lines is quite good, the difference between computed and observed profiles for the D lines is larger. It should be noted, however, that the D lines lie over two molecular bands, of TiO and H$_2$O.

The D lines were also observed, at better spectral resolution, by Giampapa et al. (1978), Worden et al. (1981) and Pettersen & Coleman (1981). In all these cases a central emission peak, unresolved in the Pettersen & Hawley observations, has been seen. In our computed spectrum, besides a central emission, we find a self-reversal that cannot be resolved at the resolution of neither set of observations.

### 2.4) The Mg b lines

The formation of the Mg I b lines have been successfully applied to solar flare atmospheric models (see Maus et al. 1988, 1990; Metcalf et al. 1990). For this reason, it seemed natural to choose them as one of the features to be reproduced by our model. However, in the spectrum of cool stars the b lines lie over the head of a molecular TiO band (at 5167 Å), and thus observations at low resolution do not provide reliable information on their intensity. In any case, a comparison between the observed and computed spectra is shown in Fig. 6. Unfortunately, no better resolution observations of these lines are available.

### 2.5) The Ca lines

A line sometimes used for spectral classification is the Ca I λ4227 Å. It seems to be the broadest line in the quiet spectrum of AD Leo, with a FWHM of 13 Å (see Fig. 7). However, in the flare spectra at these wavelengths three emission features are visible (dotted lines in Fig. 7), one corresponding to the central wavelength of the Ca line, and the other two in the supposed wings.

The more obvious explanation is the presence of other strong metallic lines, some of which turn into emission during the flare. If this is the case, other metallic lines are blended with Ca I λ4227 Å in such a way that, at the present spectral resolution, we cannot separate the different contributions in the quiet spectrum. For this reason, we did not use this line to construct our model.

Figure 8 shows a comparison between the computed and observed spectra for the Ca II K and the infrared line at λ8498 Å (we also computed the lines at λ8542 and 8668 Å which are not shown here). The source...
and Planck functions for the K line can be found in Fig. 4, and its computed and observed line fluxes are compared in Table 2. It can be seen that, even if the agreement for the IR line is acceptable, the computed intensity for the K line is only a fourth of what is observed. Since the Ca II K line and H $\gamma$ have the same height of formation, we used the relation $I(H \gamma)/I(Ca \ II \ K)$ as a parameter to test our models. For the final model, the computed value of this intensity ratio is 3.3 times larger than the observed one, and in the different models we tried the relation between the computed and observed ratio varied from 3 to 7. There is no way to diminish this relation without destroying the agreement for the other lines.

For this reason, we believe that the problem is not in the atmospheric model, but in the way the lines are treated. For example, it is worth noting that, in the present calculations, collisions with hydrogen atoms were not taken into account in the statistical equilibrium equation, except for the hydrogen lines. However, in a cool star like AD Leo, these collisions can be of importance, bringing the solution closer to local thermodynamic equilibrium, which for the Ca II K line would mean a higher computed intensity. To quantify this effect, we made a calculation including (for Ca II) collisions with hydrogen assuming a hydrogenic rate (Kanakys 1985). The computed central intensity did in fact increase, but only by a 50%. However, the approximation we used was quite crude, and we believe the difference with the observations can be due to the effect of collisions with hydrogen atoms.

Another factor that should be considered when computing the Ca II H and K lines is that these lines are affected by partial redistribution (PRD). Even if this effect is important mainly in the line wings, differences in the PRD parameters adopted do alter the core intensity. For the K line, changing the PRD parameters can change the central intensity by as much as 20%. The profiles shown here are the larger ones we could obtain, which correspond to a broad complete redistribution core (for details on how PRD is treated, see Mauas, Avrett, & Loeser 1989).

2.6) Ly$\alpha$ and the Mg II h and k lines

Hawley (1989) gives an integrated flux for the Ly$\alpha$ line of $1 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Our computed values are too large, and even adjusting the PRD parameters we can only obtain a value of $2.9 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. It should be noted that, while the computed profiles for Ly$\alpha$ are larger than the observations, the inverse is true in the case of the Ca II K line. Thus, the agreement in the Ca II K line is best with a very broad complete redistribution core (as is the case for the Mg II lines, see below), which increases the total flux in the line, while for Ly$\alpha$ a large amount of PRD is needed.

Hawley (1989) gives a total observed line flux for the Mg II h and k lines of $2.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. We can reproduce this value, adjusting the PRD parameters, as can be seen in Table 2. High resolution IUE observations of these lines were published by Ambruster et al. (1989). They give a total flux in agreement with Hawley (1989), an average flux of the h line of $1.13 \pm 0.11$ erg cm$^{-2}$ s$^{-1}$ and a flux of the k line (not averaged for saturation problems) of $1.4$ erg cm$^{-2}$ s$^{-1}$ which are in very good agreement with our computed values. However, our computed profiles have a central intensity twice as large as the observed ones, and half the FWHM. It is worth noting that in the present calculations we did not include any macroturbulence, which can correct part of this difference (see e.g. Lites & Skumanich 1982).

2.7) Discussion

Some conclusions can be drawn from comparison of our model with the one by Hawley & Fisher (1992, HF). The first one is that the photospheric part of both models are quite similar. In fact, the photosphere of the model by HF was taken from the work by Mould (1976), who constructed a grid of photospheric models for M dwarfs. As the main opacity source in the continuum is given by the different molecular species, and in both works these opacities are treated in LTE, this agreement is not surprising. However, we should point out that Mould’s work included the opacity due to H$_2$O, while we did not include any triatomic molecules. On the other hand, the chromospheres of both models are very different. Regarding this difference, we should note that HF simply interpolated between their computed, theoretical, transition region and Mould’s photosphere. In our case, the chromosphere was computed to match a set of observations.

As indicated in Fig. 1, there is a lack of spectral features originating in the temperature minimum and the low chromosphere, which could serve as reliable diagnostics of the structure of this region. On the other
hand, the source function of the chromospheric lines depends strongly on the structure of the $T_{\text{min}}$ (see Fig. 4), and therefore these lines give some indication on this region. In fact, we needed a broad $T_{\text{min}}$ to avoid a strong emission in the Mg b and Na D lines, which is not observed. However, it would be very helpful for future chromospheric modeling if some lines formed at the $T_{\text{min}}$ were available. These lines are weaker and narrower than the chromospheric ones, thus a much better spectral resolution is needed.

We can also see in Fig. 1 that HF’s transition region is placed at a lower column mass than ours. This is a consequence of their theoretical approach, starting from a specific physical model for the corona that determines the structure of the transition region. The position of the transition region strongly influence the computed Ly$\alpha$ flux, which in their case is stronger than the observed one by a factor of 10.

3. The radiative losses

To estimate the energetic balance in the photosphere and chromosphere of the star, it is important to know the radiative losses due to the different species. Here we compute the radiative cooling rate $\Phi$ (ergs cm$^{-3}$ s$^{-1}$), i.e. the net amount of energy radiated at a given depth by the atmosphere, which is given by

$$\Phi = 4\pi \int \kappa_\nu (S_\nu - J_\nu) \, d\nu .$$

In this study we computed the contributions due to H$^{-}$, H, He I, Mg I and II, Ca I and II, Fe I, Si I, Na I, Al I and CO. The overall results and the most important individual contributions are presented in Fig. 9. A positive value implies a net loss of energy (cooling), and a negative value represents a net energy absorption (heating).

It can be seen that in the region around the temperature minimum, H$^{-}$ is a net heating agent. At this height, in fact, there is a missing cooling agent, a fact that was already noted for the Sun (e.g. Mauas et al. 1990). However, it should be pointed out that in this region CO is a strong coolant, and that the addition of the other molecules present in this star should bring the model closer to radiative balance.

The energy radiated above the temperature minimum gives an estimate of the amount of chromospheric heating required to sustain this model. It can be seen that there are two peaks, one in the mid-chromosphere and the other in the transition region. A similar effect can be seen in the Sun (see Vernazza et al. 1981).

H$^{-}$ is the main cooling agent in the low and mid-chromosphere, while the hydrogen bound-bound and bound-free transitions are important in the high chromosphere and in the transition region. We show in Fig. 10 a detailed analysis of the cooling rates in this region of the atmosphere. It can be seen that from 7000 to 15000K the main contribution to the hydrogen cooling rate comes more or less equally from H$\alpha$, the remaining Balmer lines, and the Lyman and Balmer continua. Above 15000K the cooling is almost exclusively due to Ly$\alpha$.

Another interesting feature is the fact that around 12000K the contribution of the Mg II lines becomes important, with a cooling comparable to that of H$\alpha$. In fact, the difference between the hydrogen rate and the total in Fig. 10 is due to Mg II.

It should be pointed out that in this paper we were not able to match the observed flux in the Ca II K line, which may become an important component. However, as this flux is maximum in the region were the hydrogen emission takes place, we do not believe a more accurate value for this flux would change the global values presented here.

Conversely, our computed flux for Ly$\alpha$ is about 3 times larger than the observations. This fact should be kept in mind when considering the rates above 15000K, where Ly$\alpha$ is the main cooling agent.
4. Conclusions

We present a semi-empirical atmospheric model for the dMe star AD Leo. This constitutes the first model computed to match a wide set of observations, from the continuum emission to a set of several chromospheric lines. The agreement found between the observed and computed spectral features is generally good.

In particular, the continuum calculations presented here match quite well the observations when line blanketing is included. On the other hand, we show that the calculations done neglecting line blanketing grossly overestimates the continuum emission. This indicates that models based on continuum observations computed without properly including line blanketing should be taken with caution.

The main disagreement between the observations and the computed profiles reside in the Ca II K line. In fact, while the calculations for H\(\alpha\) and Ly\(\alpha\) overestimate the observations, the computed intensity for Ca II K is almost a factor of 4 smaller than observed, and we were not able to get a better agreement for Ca II K without completely destroying the agreement for the other lines. A similar problem was found by Giampapa et al. (1982), who concluded that it is not possible with a homogeneous model to fit both the Ca and the Mg II h and k lines. Similarly, Hawley & Fisher (1992) had problems matching the Ca and Mg II fluxes.

This suggests that the problem may be due not to our chromospheric model, but to an incorrect treatment of the atomic parameters of Ca II, in particular to the not inclusion of collisions with hydrogen.

Finally, we would like to point out that there are some uncertainties in the atmospheric model, mainly due to the fact that no reliable diagnostics of the T\(_{\text{min}}\) region is available. To find an indicator of the temperature in this region, observations with better spectral resolution are needed.

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Figure captions

Figure 1 Temperature distribution for our atmospheric model. Also shown are the heights of formation of the lines used in the modeling. The dashed line represents the model by Hawley & Fisher (1992).

Figure 2 Comparison of the observations (full line) in the continuum with the results computed for our model, with (dashed line) and without (dotted line) considering line blanketing. Also indicated are the heads of the most important molecular bands.

Figure 3 Comparison of the observations (crosses) in the Balmer lines and the results computed for our model. Here and in the next figures, the dashed line shows the computed profile with “infinite” spectral resolution, and the full line shows the calculations smeared to the same resolution than the observations.

Figure 4 Planck function ($B_\nu$, full line) and source function ($S_\nu$, dashed line) for different lines. The depth of formation (peak of the contribution function) of the line center is also shown. The values at disk center are indicated above the $S_\nu$ curve, and those at $\mu = 0.6$ are indicated below it.

Figure 5 Comparison of the observations in the Na D and infrared lines and the results computed for our model. See fig. 3.

Figure 6 Comparison of the observations in the Mg b lines and the results computed for our model. See Fig. 3.

Figure 7 Comparison of the observations in the Ca I $\lambda4227$ Å in the quiet spectrum (solid line) and the flare spectrum at two different times (dotted line).

Figure 8 Comparison of the observations in the Ca II K and infrared line and the results computed for our model. See Fig. 3.

Figure 9 Total net radiative cooling rate for our model (full line), and the most important contributions to it.

Figure 10 Detail of the hydrogen cooling rates. The difference between the total rate (heavy line) and the hydrogen rate (full line), is due to Mg II. Bal refers to the Balmer lines from H$_{\beta}$ to H$_{\delta}$, and continua are the Lyman and Balmer continua.