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Stellar evolution of the hypergiants HR 8752 and ρ Cassiopeiae on human timescales

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Abstract. In this article we report first observations of the hypergiants HR 8752 and ρ Cas in the near ultraviolet and communicate for the first time the finding of spectroscopically recorded large changes of the effective temperature of the cool hypergiant HR 8752 which cannot be ascribed to the regular variability of a supergiant atmosphere. High-resolution near-ultraviolet spectra of the yellow hypergiants HR 8752 and ρ Cassiopeiae indicate high effective temperatures placing both stars near the low-$T_{\rm eff}$ border of the "yellow evolutionary void". At present, the temperature of HR 8752 is higher than ever. For this star we found $T_{\rm eff}$=7900±200 K, whereas ρ Cassiopeiae has $T_{\rm eff}$=7300±200 K. This finding is based on a unique combination of high-resolution optical spectra which span a period of about 30 years. Thus, HR 8752 turned to be the first cool supergiant that showed the effects of stellar evolution from a study of its 30 years old spectroscopic history. Both, HR 8752 and ρ Cassiopeiae have developed strong stellar winds with $V_\infty \simeq 120$ km s^{-1} and $V_\infty \simeq 100$ km s^{-1}, respectively. Over the past decades two yellow hypergiants appear to have approached an evolutionary phase, which has never been observed before. We present the first spectroscopic evidence of the blueward motion of a cool super/hypergiant on the HR diagram.

1. Introduction

The yellow hypergiants, of which ρ Cas and HR 8752 are the best studied members, are characterized by their near-unstable atmospheres, fairly extended envelopes and a large rate of mass loss, properties that are related to their position in the Hertzsprung-Russell diagram, where they occupy an area (Fig. 1) near to the low-temperature border of the Yellow Evolutionary Void (de Jager 1998, Fig. 1). A typical aspect of their instability is the 'bouncing' against the low-temperature border of the Void (de Jager and Nieuwenhuijzen 1997). There are indications (relatively small mass; overabundance of Na and N with respect to the Sun) that yellow hypergiants are evolved stars, evolving from the red supergiant phase to the blue phase. Stellar evolutionary computations (e.g. Maeder & Meynet 1988) place cool hypergiants in a certain area on the H-R diagram ($3.6 < \log T_{\rm eff} < 3.9$, $5.3 < \log L/L_{\odot} < 5.9$) and predict that redward loops down to 4000±1000 K occur only for stars with $M_{\rm ZAMS} \leq 60\ M_{\odot}$. Once in the red supergiant phase ($T_{\rm eff} \sim 3000$–4000 K), stars with $M_{\rm ZAMS} \geq 10\ M_{\odot}$ shrink again and evolve to become blue supergiants. Already in 1958 Böhm-Vitense (1958) has noted that stars with $T_{\rm eff}$ near 9000 K have density inversions, which may indicate instability. This has led to research on the *yellow evolutionary void*; the area on the H-R diagram which occupies the region $3.8 < \log T_{\rm eff} < 4.0$, $5.2 < \log L/L_{\odot} < 5.9$ (de Jager & Nieuwenhuijzen 1997). Inside the void the atmospheres are unstable, which is shown in various ways. The atmospheres have a negative density gradient at a certain depth level, the sonic point of the stellar wind is situated in photospheric levels, and the sum of all accelerations is directed outwards during part of the pulsational cycle (Nieuwenhuijzen & de Jager 1995). It is expected that stars, when approaching the void during their blueward evolution, may show signs of instability, but the very process of approaching the void has not yet been studied. A monitoring of stars approaching the void will help to understand the nature of the instabilities and finally to answer the most important question of whether or not these stars can pass the void.

The Galactic hypergiants HR 8752, ρ Cas and IRC+10420 are presently "bouncing" against the "yellow evolutionary void" (de Jager 1998) at $\sim 7500 \pm 500$ K. However, there were periods when these stars had $T_{\rm eff} \sim 4000$ K. The brightness of IRC+10420 in V-band increased by 1 mag from 1930 to 1970 (Jones et al. 1992) and its $T_{\rm eff}$ has increased by 1000 K over the last 20 years (Oudmaijer et al. 1996). The changes of $T_{\rm eff}$ are accompanied by variations in the mass loss (de Jager 1998). There are other hypergiants that appear to have a similar position on the HR diagram; Var A in M33 and V382 Car (Humphreys 1978). The maximum $T_{\rm eff}$ ever observed in HR 8752 is 7170 K (de Jager 1999, private communication). Previous ground-based spectroscopic observations of HR 8752 and ρ Cas have been carried out only in the optical and near IR region (4000–9000 Å). High-resolution *IUE* spectra of ρ Cas and HR 8752 have been discussed by Lobel et al. (1998) and Stickland & Lambert (1981), respectively.

2. Observations

The observations of ρ Cas and HR 8752 were carried out in 1998 August 4 using the Utrecht Echelle Spectrograph (UES) at the Nasmyth focus of the 4.2-m WHT at the ORM (La Palma). A UV-sensitive CCD detector EEV 42 4200×2148 (pixel size: 13.5×13.5 μm) with 60% quantum efficiency at 3200 Å provided superb sensitivity down to the atmospheric cut-off at 3050 Å. We obtained spectra which cover the wavelength range between 3050 and 3920 Å in 40 orders at a spectral resolving power of $R = \lambda/\Delta\lambda \sim 55,000$. For the data

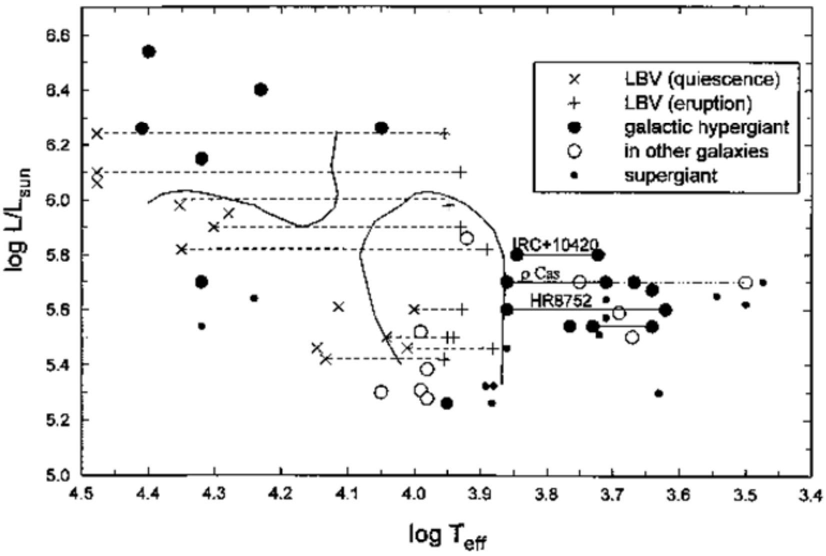

Figure 1. The H-R diagram for blueward evolution of massive stars.

reduction we used standard IRAF procedures. The wavelength calibration was performed with a Th–Ar lamp. The final signal-to-noise (S/N) ratio varies for the different echelle orders, being in the range 80–160 for both stars. Additional high resolution spectra of these stars in the wavelength range 3500-11 000 Å were acquired with SOFIN echelle spectrograph at the 2.5-m NOT (La Palma) in 1998 October 9-10. The archival spectra from 1969 Sep. 7, 1976 July 15 and 1978 August 8 were obtained at the Dominion Astronomical Observatory, Victoria, Canada using the 1.2 m telescope in the coude focus (Smoliński et al. 1994). The dispersion of the spectrograms was about 6 Å/mm and signal-to-noise ratio at the level of 30 to 50.

3. Spectral Analysis

Simple comparison of the near-UV spectra of HR 8752 and ρ Cas shows that these stars are no longer spectroscopic "twins". It is enough to overplot their spectra and to identify a number of lines in order to be convinced that the atmosphere of HR 8752 is hotter than that of ρ Cas. Most of the absorption lines in this spectral range belong to α (like Ti, Si) and Fe-group (Cr, Sc, V, Mn. Fe etc.) elements. Note that the spectrum of HR 8752 is considerably *clean* from blends compared with ρ Cas because of a displacement of the ionization equilibrium. This is illustrated in Fig. 2, where we compare one of the near UV echelle orders and two unblended optical Fe I lines (selected by Lobel et al. 1998) in our targets. We have also found that many absorption lines in the near-UV spectrum of ρ Cas are split. This phenomenon has been first reported by Bidelman & McKellar (1957). We confirm findings by Sargent (1961) and Lobel (1997) that these splits in absorption appear only in lines with $\chi_{\rm up} \leq$ 3 eV. Various explanations for the split absorption cores have been suggested in the literature. The explanation of this phenomenon has been given recently by Lobel (1997), who showed that the line splitting is caused by static emission emerging from detached and cool circumstellar shells, modeled for a fast bi-polar wind.

In order to proceed with spectral analysis of our targets, we have employed a grid of LTE, plane–parallel, constant flux, and blanketed model atmospheres (Kurucz 1993), computed with ATLAS9 without overshooting. These models are interpolated for several values of $T_{\rm eff}$, $\log g$. For ρ Cas we used [Fe/H]=0.3 (Lobel et al. 1998) and for HR 8752 [Fe/H]=−0.5 (Schmidt 1998). Synthetic spectra were computed first, using the LTE code WITA3 (Pavlenko 1991) which takes into account molecular dissociation balance (note that our targets may have $T_{\rm eff}$ as low as 4000 K) and all important opacity sources. Atomic data were obtained from the VALD-2 database (Kupka et al. 1999). Molecular bands of OH, CH and NH in the near-UV can be used to derive CNO abundances and constrain the range of the atmospheric parameters. Molecular data for the CH (3145 Å), NH (3360 Å) and OH (0,0) (3120-3260 Å) bands were taken from Kurucz (1993), Cottrell & Norris (1978) and Israelian et al. (1998), respectively. To minimize the effects associated with errors in the transition probabilities of molecular lines, the oscillator strengths (gf-values) have been modified from their original values to match the solar atlas (Kurucz et al. 1984) with solar abundances (Anders & Grevesse 1989). Synthetic spectra of the Sun were computed using a model with $T_{\rm eff}$=5777 K, $\log g$=4.4, [Fe/H]=0.0, microturbulence $\xi = 1$ km s^{-1}.

We have attempted to fit the spectral lines located in the CH and NH regions assuming solar CNO abundances and found that these molecules are simply not present in the spectra. Even by increasing the abundance of nitrogen 10 times we still found no effect on the measured equivalent widths. We considered this as clear evidence that both stars had $T_{\rm eff} > 6200$ K (given the values of dissociation energies of CH, NH and OH molecules) at the time of our observation. In fact, at $T_{\rm eff}$=6200 K we still expect 10–20 mÅ lines of the OH molecule located between 3100–3200 Å (Israelian et al. 1998) even if oxygen is slightly underabundant in ρ Cas with [O/H]=−0.3 (Takeda & Takeda-Hidai 1998). Given the S/N of the data, we could easily detect a minimum of 3-4 unblended OH lines if they were present in the spectra. We confirm a microturbulent velocity $\xi = 11 \pm 2$ km s^{-1} in both stars (de Jager 1998). Figure 3 shows the comparison between synthetic and observed spectra of both stars corresponding to the regions surrounding the CH and NH lines. We stress that these plots should not be considered as "best fits". We only want to show basic features and blends in these regions and demonstrate the effect of varying $T_{\rm eff}$ on the synthetic spectra. We did not convolve synthetic spectra with Gaussian macro-broadening because it is not affecting the EWs and therefore our final values of $T_{\rm eff}/\log g$. However, we convolved them with a Gaussian (FWHM=0.12 Å) to reproduce the instrumental profile. The differences between the observed and calculated equivalent widths have been minimized for the best set of $T_{\rm eff}$, $\log g$ and ξ (i.e. the same method as used by Lobel et al. 1998). We have selected 16 spectral lines of Sc, Cr, Ti, etc. (Fig. 3), located in the windows 3130–3170 (near the CH band) and 3340–3380 (near the NH band) and measured their EWs (typically 300–800 mÅ) with a multi-Gaussian function of the SPLOT task of IRAF.

The spectrum of HR 8752 from 1969 was analyzed with a different approach. Due to the limited spectral region, covering wavelengths from 4800 till 6060 Å, severe blending and a low signal-to-noise ratio, only a limited number of relatively unblended lines were accessible for the analysis - 27 Fe I and 6 Fe II lines. Equivalent widths were typically in range from 200 to 600 mÅ. The atmospheric parameters have been found by forcing an independence of the determined single line abundance on the excitation potential and the equivalent width, with a unique value of iron abundance for both neutral and ionized lines.

The analysis was made using atmospheric models computed with a modified version of the TLUSTY code. The use of ATLAS9 opacity sources and ODF functions enables us to treat these models as an extension of the existing grid of ATLAS9 models (Kurucz, 1993). Both plane-parrallel and spherically symmetric models have been calculated. For spherically symmetric models a luminosity value of log $(L/L_\odot) = 5.50$ has been utilized, as was determined by Schmidt (1998).

4. Results and Conclusions

The final values of the atmospheric parameters are $T_{\rm eff}$=7900±200 K and $\log g = 1.1 \pm 0.4$ for HR 8752 and $T_{\rm eff}$=7300±200 K and $\log g = 0.8 \pm 0.4$ for ρ Cas. The resulting parameters for the 1969 spectrum of HR 8752 are $T_{\rm eff}$=5250±250 K, $\log g$=−0.5±0.5, [Fe/H]=−0.55±0.25, microturbulence ξ_μ=10±1 km s^{-1} derived for plane-parallel models, and $T_{\rm eff}$=5630±200 K, $\log g$=−0.7±0.5, [Fe/H]=−0.46±0.25 and ξ_μ=11±1 km s^{-1} with spherically symetric models. For the latter case we found that the atmospherical extension was 23 percent (being measured as the ratio of the geometrical distance between optical depths 10^{-4} and 1 and the stellar radius).

Hα is often cited as the best indicator for global changes in the outer part of the envelope where the wind is accelerating in a typical cool supergiant. Variations in the velocity and density structure of the upper layers produce changes in the asymmetry of the line, while an increase of the temperature (quasi-chromosphere) can force the wing to go appear in emission. This effect has been clearly observed in ρ Cas (de Jager et al. 1997). However, changes in Hα may reflect those in the chromospheric structure rather than wind variations. For this reason it is desirable to study wind variations in other absorption lines. In general, winds of cool stars are subtle and difficult to detect. Far shortward extended wings due to the wind absorption have been observed in many Fe I lines of ρ Cas in the phase when $T_{\rm eff}$=7250 K (Lobel et al. 1998) and the upper limit of the mass-loss rate was derived as 9.2 $10^{-5} M_\odot$ yr^{-1}. These wings are also seen in many lines in the near-UV (Fig. 4). In addition, we have also found violet wings extending up to 120 km s^{-1} in the spectrum of HR 8752. Assuming $\log(L/L_\odot)$=5.6 (de Jager 1998) and ρ=7 10^{-15} gr cm^{-3} as an upper limit of the density for the outermost layers of the atmosphere (from the model with $T_{\rm eff}$=7900 K and $\log g$=1.1), we estimate from $\dot{M} = 4\pi R_* \rho V_\infty$ an upper limit $\dot{M}_{\rm max}$=6.7 10^{-6} $M_\odot$ yr^{-1} assuming spherically symmetric mass loss. We derived for ρ Cas almost the same $T_{\rm eff}$ as it had in Dec. 21 1993 (Lobel et al. 1998) suggesting that ρ Cas makes small "oscillations" with an amplitude $\Delta T_{\rm eff} \sim 500$ K near the void. However, the effective temperature of HR 8752 has risen sharply over the last 2-3 decades and places the star on the border of the void. When deriving the mass loss rates one should keep in mind that the real distribution of the matter around these hypergiants is very complex and asymmtertic (Lobel 1997, Petrov & Herbig 1992, Humphreys et al. 1997).

We are inclined to think that the large variations with $\Delta T_{\rm eff} \sim 3000$–$4000$ K observed in HR 8752 are not caused by pulsations but reflect some complex *evolutionary* changes due to the active reconstruction of the stellar interior. It is striking that a number of stars moving to the blue is clustering at the low-temperature side of the void while none of them occurs inside the void. Approaching the instability border the star may show excessive mass loss and the development of an envelope, associated with a reduction of the effective temperature. How frequently this will happen before the star eventually passes through the void is an open question. It is quite possible that the final passage of the most massive stars through the void never takes place and that these stars finally explode as Type II supernovae.

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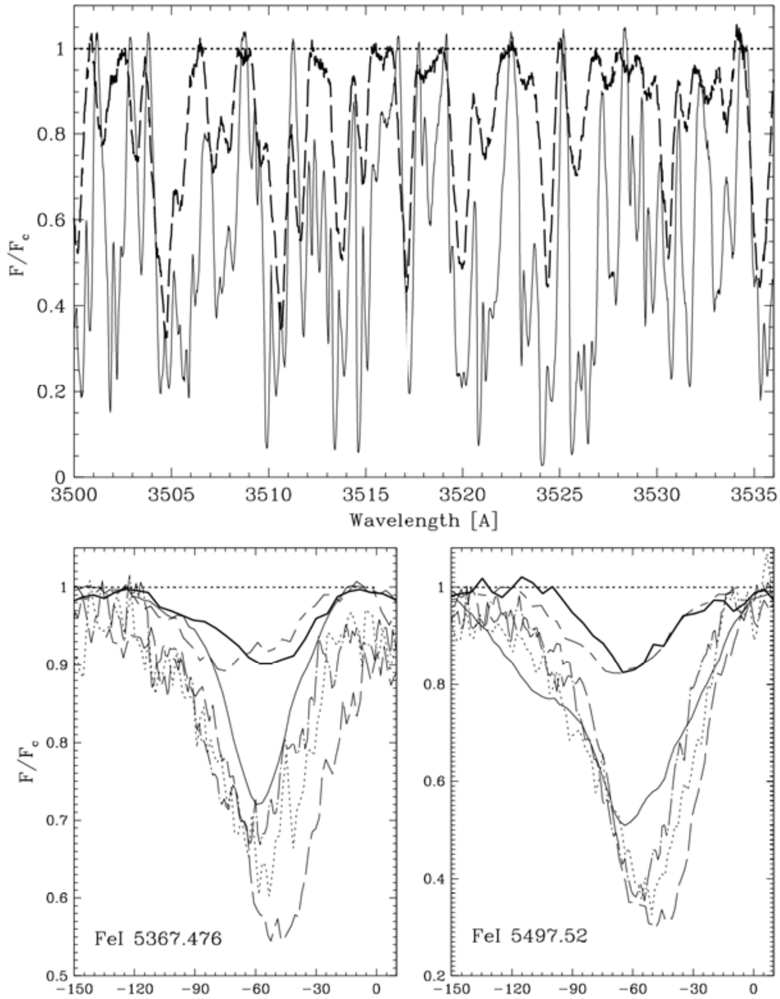

Figure 2. **upper panel:** High resolution near-UV spectra of HR 8752 (bold line) and of ρ Cas (thin line) observed on Aug. 4 '98 with UES. Note the single absorption cores in HR 8752 which appear to split in ρ Cas. **lower panels:** Two unblended FeI lines in both stars. The lines of HR 8752 developed violet wing extensions (bold line: NOT Oct. 1998, short dashed line: UES April 1995), which was also observed in ρ Cas in Nov.-Dec. 1993 when its $T_{\rm eff}$=7250 K (thin line: UES). Note the strong weakening of these neutral lines over the past three decades (Dominion Obs.: long dashed line: Sept. 1969, dotted line: July 1975 and dash-dotted: Aug. 1978). The spectral resolutions are equal but note that both stars have different systemic velocities of −69 to −50 kms^{-1} and −47±2 kms^{-1} respectively.

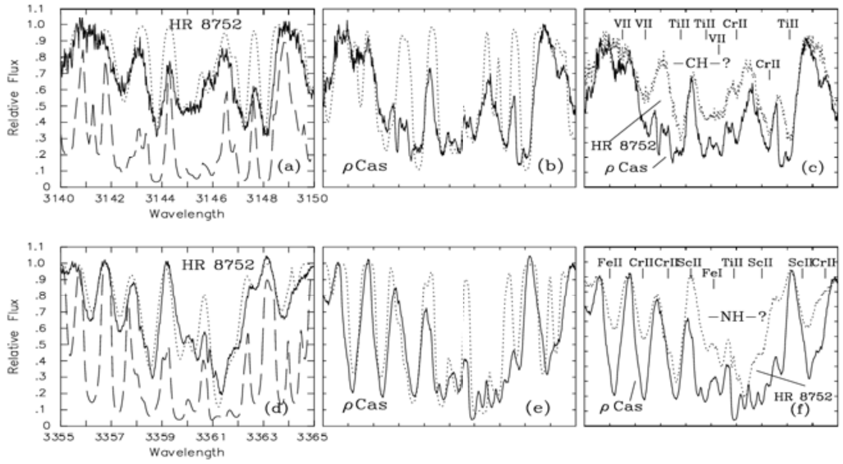

Figure 3. Theoretical (dotted lines) and observed (solid lines) spectra of the regions near the CH (top row) and NH (bottom row) molecular bands. Theoretical spectra are computed for $T_{\rm eff}$=8100 K, $\log g$=1.0 for HR 8752 (panels (a) and (d)) and for $T_{\rm eff}$=7500 K, $\log g$=1.0 for ρ Cas (panels (b) and (e)). These temperatures are the upper limits obtained from our analysis. Dashed lines in panels (a) and (d) correspond to the model $T_{\rm eff}$=6250 K, $\log g$=0.5. In panels (c) and (f) we compare the observations of HR 8752 and ρ Cas. To illustrate the effect of rotation we have convolved the synthetic spectrum (dotted) in panel (d) with $v \sin i$=20 km s^{-1}. The observed spectra have been corrected for the system velocities.

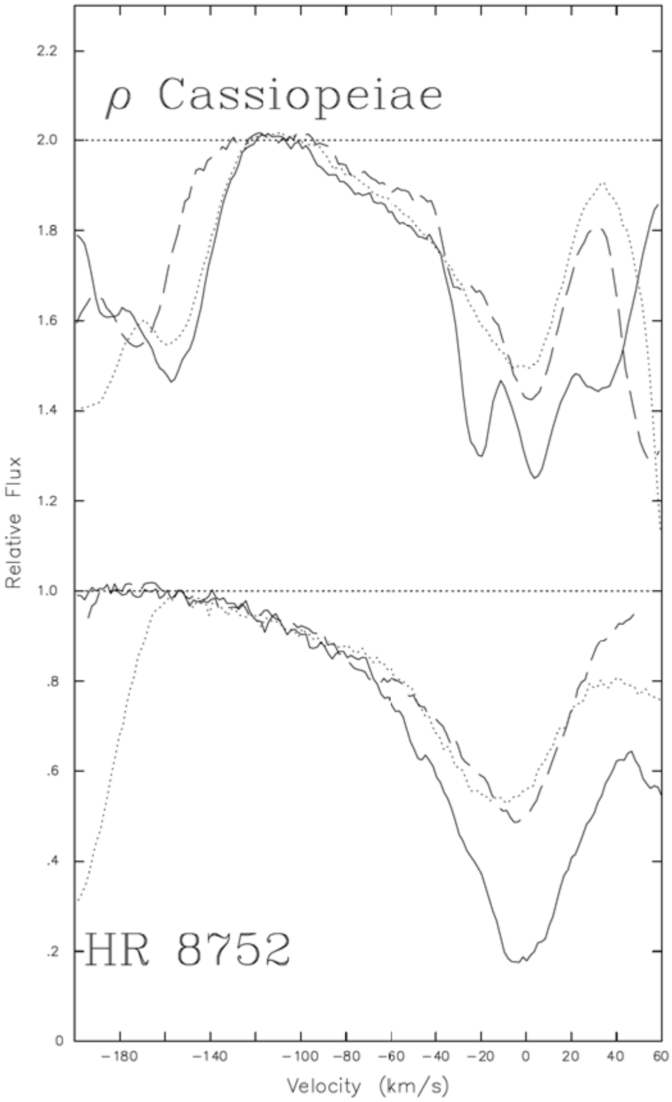

Figure 4. The violet-extended wings of Fe II 3448.43 (solid line), Fe II 3436.107 (dotted line) and Fe I 3640.390 Å (dashed line) lines in the spectrum of ρ Cas (shifted upwards by 1.0 in upper panel) and the violet wings of Ti II 3335.2 (solid line), Ti II 3500.34 (dashed line) and Si II 3862.6 Å (dotted line) in the spectrum of HR 8752 (lower panel). All lines have been shifted to their laboratory wavelengths.