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High-resolution spectroscopic observations of the D′-type symbiotic stars HD 330036 and AS 201⋆

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Abstract. We present high-resolution spectroscopic analyses of two stars classified as D′-type symbiotic stars, HD 330036 and AS 201. These two stars display both rapid rotation and enhancements of the s-process elements that are synthesized via slow neutron captures during stellar evolution along the asymptotic giant branch (AGB). Both characterisitics of rapid rotation and s-process overabundances have also been discovered recently in another D′-type symbiotic, S190. The stellar parameters derived here for HD 330036 are $T_{\rm eff}$ = 6200 K and log g = 2.4, while AS 201 has $T_{\rm eff}$ = 6000 K and log g = 2.3. Resulting luminosity and distance estimates are 650 $L_{\odot}$ and 2.3 kpc for HD 330036, and 700 $L_{\odot}$ and 4.3 kpc for AS 201. Both HD 330036 and AS 201 have evolved away from the main sequence and are approaching the base of the red-giant branch. These stars have near-solar abundances of iron and calcium, but substanial enhancements (by about +0.9 dex for HD 330036 and +1.7 dex for AS 201) of the s-process element barium. The observed barium overabundances in the current cool-star members of these two binary systems probably resulted from mass-transfer when the current white dwarf was an AGB star. The rapid rotation found in the cool stars may also be due to mass-transfer, with the mass-gaining stars being spun up with the transfer of angular momentum from the AGB winds. As only a few (six) D′-type symbiotics are known, the fact that the 3 studied to date at high-spectral resolution all display rapid rotation and s-process elemental overabundances may indicate that these two traits are signatures of these rare binary systems.

Key words. stars: binaries: symbiotic – stars: abundances

1. Introduction

Of the 188 symbiotic stars known (Belczyński et al. 2000) there are very few systems (only six) that are classified as D′-type. This notation was first introduced by Allen (1982) in order to distinguish these types of objects from the D-type Mira symbiotics: in the D-type the cool component is a M-type star (or in a few cases a carbon star), while in the D′-type systems the cool components are warmer stars of F-G spectral types. Both the D′ and D-types exhibit infrared dust emission. However, the dust color temperatures of the D′-types are typically lower than in the D-types. The basic properties of these peculiar binary systems are discussed in Allen (1982) and Schmid & Nussbaumer (1993). One interesting characteristic of one D′-type symbiotic that has been recently studied at high spectral resolution, S190, (Smith et al. 2001; Munari et al. 2001) was the discovery that this star rotates fast and that it shares with the yellow symbiotics (also labelled as S-type; Allen 1982) the trait of enhancement in the s-process element abundances. In this paper we probe through high-resolution spectroscopy, the nature of the cool components of two additional D′-type symbiotics in order to investigate their rotational velocities as well as chemical compositions.

2. Observations

The high resolution spectra of the two D′-type symbiotics analyzed in this work were obtained with the 1.52 m telescope at the European Southern Observatory (ESO) plus the fiber-fed coudé cross-disperser echelle spectrometer FEROS and a CCD detector (Kaufer et al. 1999). The FEROS spectral resolving power is R = 48 000 corresponding to 2.2 pixels of 15 μm and the wavelength coverage is from 4000 Å to 9200 Å. Table 1 summarizes the details of the observations. Our analysis relied mainly on the spectra taken where the exposure time was the greatest. We used the other to check for the presence of possible cosmic rays. The observed spectra were reduced using the FEROS pipeline reduction (Kaufer et al. 2000). Final S/N ratios were evaluated from the measurements of rms flux fluctuations around a continuum region near 6130 Å, with values

⋆ Based on observations made with the 1.52 m telescope at the European Southern Observatory (La Silla, Chile) under the agreement with the CNPq-Observatório Nacional (Brazil).

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Table 1. Observation log of target stars.

Star	Date	Exp time (s)	S/N
AS 201	1999 Apr. 17	3600	60
	1999 Dec. 19	6600	120
HD 330036	1999 Apr. 23	3600	60
	2000 Fev. 21	6600	120

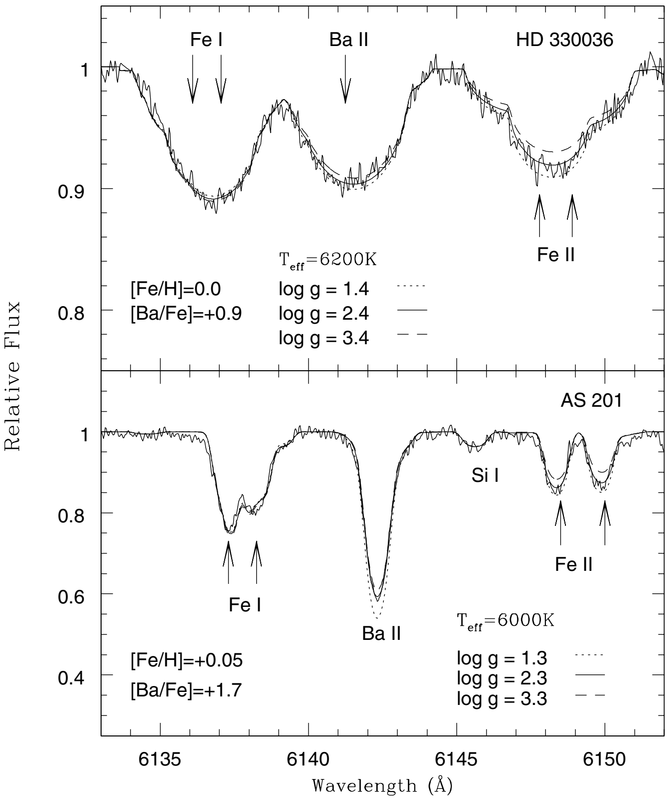

Fig. 1. Observed and synthetic spectra for HD 330036 and AS 201 displaying broad lines and indicating rotationally broadened profiles. The observed spectra (*solid lines*) are plotted along with three synthetic spectra computed for three different surface gravities (*dotted lines*) showing the sensitivity of the Fe II (and Ba II) to log g.

ranging from 80 to 120 (Table 1). A small portion of the observed spectra illustrating their quality is shown in Fig. 1.

3. Stellar parameters and projected rotational velocities

The spectra of these targets exhibit absorption lines broadened by large rotational velocities as can be seen in Fig. 1. Due to this fact, spectrum synthesis techniques were adopted here in order to derive chemical abundances, as well as to obtain spectroscopic estimates of their stellar parameters. In particular, we followed a similar methodology to that used in the study of S190 (Smith et al. 2001) and computed synthetic spectra in selected spectral regions around 6140 Å and 6430 Å, where there are relatively unblended Fe I and Fe II lines. In Fig. 1 we show the observed, as well as synthetic spectra for the 6140 Å region, computed using the MOOG LTE

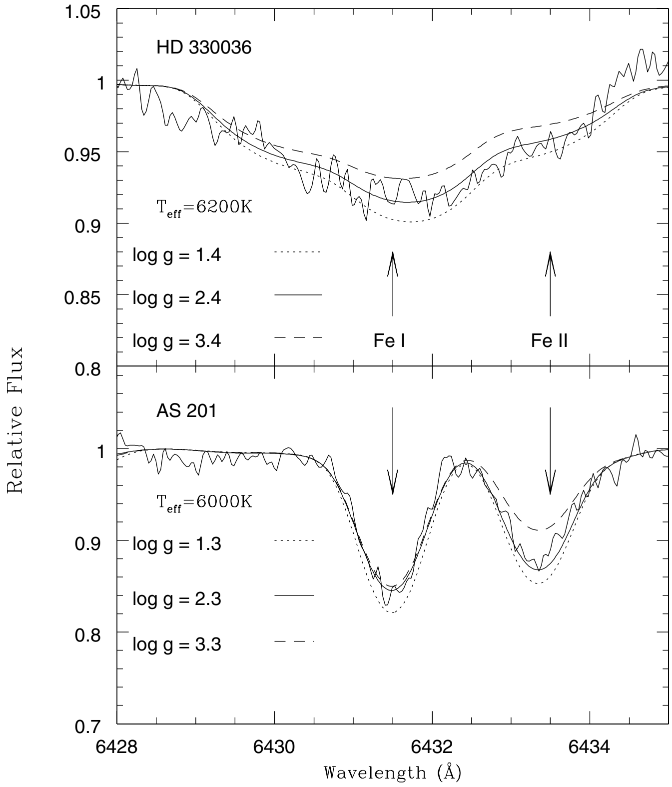

Fig. 2. The same as in Fig. 1 but for a region around 6430 Å.

synthesis code (Sneden 1973), plus a Kurucz & Bell (1995) linelist and Kurucz ATLAS9 model atmospheres. The projected rotational velocities (V sin i's) had also to be adjusted in order to produce the best fit synthetic spectra for all lines. Note that the features present in the spectrum of HD 330036 are broader than in AS 201 indicating that the latter rotates at a lower projected rotational velocity. Our best fits were obtained for $v \sin i = 100 \pm 10$ km s^{-1} and 25 ± 5 km s^{-1} for HD 330036 and AS 201, respectively.

In this work we confined our analysis to the visible and red part of the spectrum for three main reasons. First, since all symbiotic stars contain Balmer lines in emission in their spectra, the flux due to recombination may increase the continuum level. Pereira & Porto de Mello (1997) showed using photoionization models that the ratio of the observed to calculated Hα equivalent widths is about 0.004, this means that the observed continuum around the Hα line is dominated by stellar, not nebular, continuum. The other two reasons were pointed out in Smith et al. (2001) and here we only make a few comments. The number of absorption lines decreases strongly from blue to red, allowing for a much clearer analysis in spectra broadened by rotation. The other point is related to the first one mentioned above; the possiblility of light contamination due to the nebular continuum from a gas, or due to the hot companion diminishes towards the red. This point was also raised by Schmid & Nussbaumer (1993) in their analysis of yellow symbiotics.

The determination of the atmospheric parameters, effective temperature ($T_{\rm eff}$) and surface gravity (log g), are prerequisites for obtaining chemical abundances. $T_{\rm eff}$'s and log g's were derived spectroscopically and relied on Fe I lines at 6136.62 Å

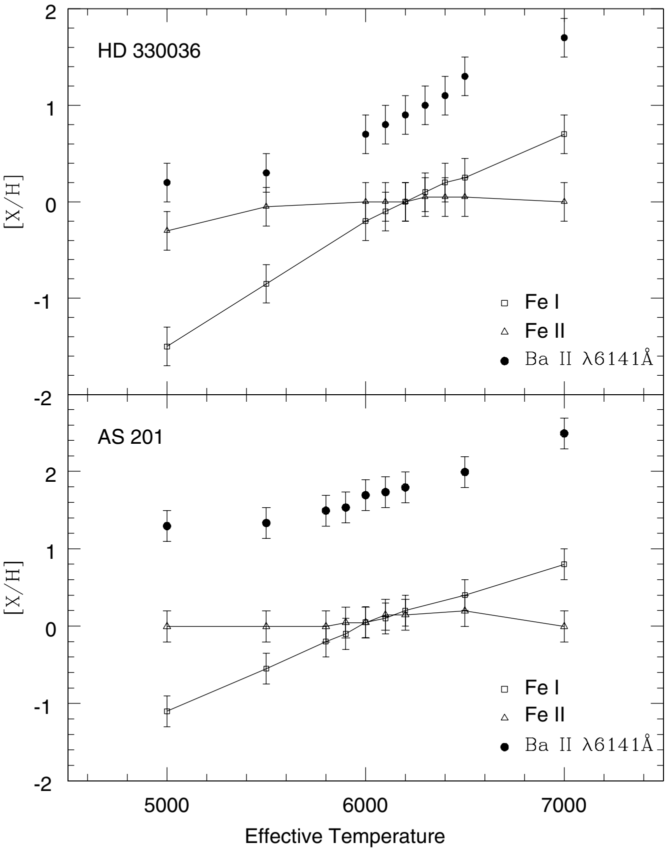

Fig. 3. Derivations of abundances and stellar parameters. Abundances of [Fe I/H], [Fe II/H] and [Ba II/H] versus Effective Temperature for model atmospheres with log g = 2.4 and 2.3, respectively for HD 330036 and AS 201 and microturbulence ξ = 2.0 km s^{-1}. Fe I and Fe II give the same abundances for $T_{\rm eff}$ = 6200 K and 6000 K respectively for HD 330036 and AS 201. The [Ba II/H] is always larger than [Fe/H].

6137.69 Å and 6430.85 Å and on Fe II lines at 6147.74 Å 6149.26 Å and 6432.68 Å. We computed a grid of synthetic spectra covering a range in $T_{\rm eff}$ (from 4500 to 7000 K), log g (from 2.0 to 4.0) and microturbulent velocities (from 1.0 to 3.0 km s^{-1}). The best fits were obtained from comparisons between the computed and observed spectra through a least-squares fit procedure. Figure 3 shows the Fe I, Fe II and Ba II results (with the Ba II abundances derived from the 6142 Å Ba II line) from a set of models with log g = 2.4 and 2.3 respectively for HD 330036 and AS 201. The solution is found when the Fe I and Fe II curves intercept each other or, at 6200 for HD 330036 and 6000 for AS 201. Estimates of the 1σ uncertainties in the derived stellar parameters would indicate that log g can be constrained to about ±0.7 and ±0.3 respectively for HD 330036 and AS 201 and to about ±150 K and ±100 K respectively for HD 330036 and AS 201. These derived $T_{\rm eff}$'s suggest a spectral type of F8 III for HD 330036 and F9 III for AS 201 (Schmidt-Kaler 1982), to be compared with F5 III-IV (Lutz 1984) for HD 330036 and G2 III (Kohoutek 1987) and G5 (Mürset & Schmid 1999) for AS 201.

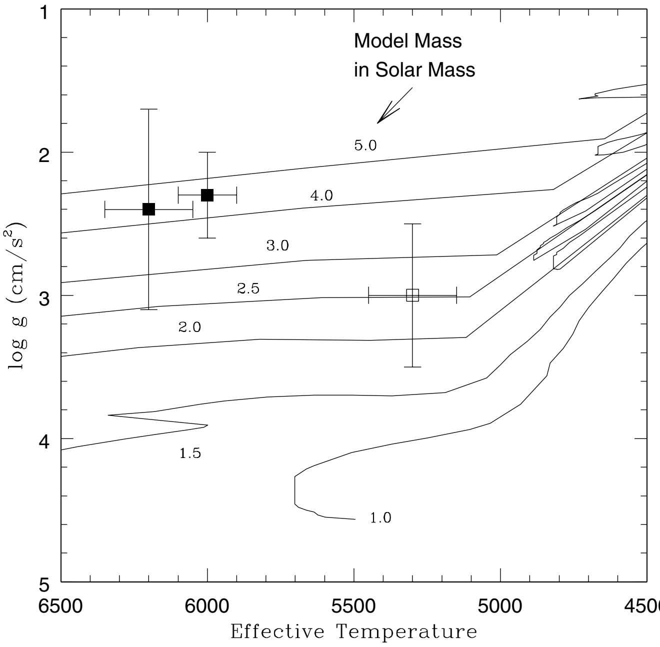

Fig. 4. The positions of HD 330036 and AS 201 (filled squares) in a log $g - T_{\rm eff}$ diagram along with stellar model evolutionary tracks from Scharer et al. (1993). The position of S 190 (open square) (Paper I) is also shown. This comparison indicates that the yellow component of HD 330036 and AS 201 it is a giant massive star.

4. Evolutionary status and distances

With the stellar parameters in hand, the primaries of HD 330036 and AS 201 can be located on a log $g - T_{\rm eff}$ plane and compared to stellar evolutionary model tracks. Figure 4 shows the positions of these two stars in such a diagram where the model tracks were computed by Schaerer et al. (1993) for solar composition. The position of S 190 is also shown for comparison (Smith et al. 2001). The parameters derived for our targets place them on the giant branch with roughly similar masses around $M \simeq 4 - 5\ M_{\odot}$.

Given the derived stellar parameters ($T_{\rm eff}$, log g, and mass as estimated from the model tracks) for the cool components of HD 330036 and AS 201, their luminosities can be calculated from Lα $(M \times T_{\rm eff}{}^4)/g$. We find for HD 330036 and AS 201, respectively, $L \sim 650\ L_{\odot}$ and $L \sim 700\ L_{\odot}$. Adopting V = 11.0 (Lutz 1984; Munari et al. 1992) for HD 330036, plus $E(B-V)$ = 0.41 (Bhatt & Mallik 1986) and our estimated luminosity leads to a distance of $d \sim 2.3$ kpc. Lutz (1984) estimate a much smaller distance of ∼450 pc based upon the color excess versus distance for stars within 20′ of HD 330036. Part of the difference in distance is caused by different values of the reddening, with Lutz (1984) using $E(B-V)$ = 0.28. Using the Bhatt & Mallik (1986) value of $E(B-V)$ = 0.41 and the Lutz "Distance – $E(B-V)$" relation would yield d = 640 pc. Inspection of Fig. 3 from Lutz (1984), with distance versus $E(B-V)$, shows that there are only 2 points to guide this relation for color excesses greater than 0.35, and a linear trend across the entire reddening range may not be well-constrained. On the other hand, due to the rapid rotation of HD 330036, our derived surface gravity is also uncertain (as can be seen

Table 2. Stellar parameters, luminosities and distances for HD 330036 and AS 201 and their respective uncertainties.

Star	$T_{\rm eff}$	log g	$L/L_{\odot}$	Distance (kpc)
HD 330036	6 200 ± 150 K	2.4 ± 0.7	650^{+3370}_{-560}	$2.3^{+4.5}_{-1.1}$
AS 201	6 000 ± 100 K	2.3 ± 0.3	700^{+630}_{-480}	$4.3^{+2.2}_{-1.9}$

in Fig. 4), with larger surface gravities leading to lower luminosities. Taking our estimated upper limit of log $g \sim 3.0$ would result in a luminosity for the cool component of $L \sim 165\ L_{\odot}$, with a resulting distance of 1.2 kpc; much closer to a Lutz estimate of 640 pc if $E(B-V) = 0.41$. It is fair to say that the distance to HD 330036 is uncertain, but within probable limits of ~0.6 to 2.3 kpc.

Another data point in constraining the distance to HD 330036 is provided by the hot white dwarf star in the system. Schmid & Nussbaumer (1993) derive $T_{\rm eff} = 60\,000$ K and, if its distance is 450 pc, then $L_{\rm WD} \sim 60\ L_{\odot}$ (following the discussion of Bhatt & Mallik 1986). This point in a log $L -$ log $T_{\rm eff}$ plane would suggest a cooling age of the white dwarf of about 500 000–10^6 yr, based upon the evolutionary tracks of Blocker & Schoenberner (1990). This age may be at odds with the large nebular density ($N_{\rm e} = 10^6$ cm^{-3}) observed by Lutz (1984). If the larger distance is adopted (2.3 kpc), then $L_{\rm WD}$ ~1700 $L_{\odot}$ (from Eq. (1) of Bhatt & mallik 1986), and its position in the log $L-$ log $T_{\rm eff}$ plane falls on the cooling curve for a young (50 000–100 000 yr) $0.55 M_{\odot}$ white dwarf (Schonberner 1983).

In the case of AS 201, our estimated distance is $d \sim 4.3$ kpc based upon its luminosity (from our stellar parameters) of 700 $L_{\odot}$ and $V = 12.0$ (Munari et al. 1992) with $E(B-V) = 0.33$ (Gutierrez-Moreno & Moreno 1996). This distance is within the range derived by Schwarz (1991) of $d \sim 2.0$ to 4.5 kpc, based on the bolometric luminosity of the hot white dwarf. This places the hot component at ≈0.57 $M_{\odot}$, according to Schönberner (1983). Table 2 gives the stellar parameters, luminosities and distances for the stars analyzed in this work with their respective uncertainties.

5. Abundances

Our next step was to determine abundances for a sample of chemical elements of interest via spectral synthesis. High projected rotational velocity is a limiting factor in the determination of abundances from weak lines that become washed away in rotationally broadened profiles. In both our targets we derived abundances of Fe, Ba and Ca. However, Since AS 201 has a relatively low projected rotational velocity, we could derive abundances of additional elements using lines that were free from blends. In Table 3 we list all the studied elements and atomic transitions together with their respective atomic parameters (excitation potentials and gf-values). The adopted linelists in the calculations are from Kurucz & Bell (1995). In the top panel of Fig. 5 we show synthetic spectra for the spectral region around 7115 Å where several C I lines are found. In the bottom panel of this figure we show fits to the observed spectra of Fe I, S I and N I lines in the region around 8690 Å for AS 201.

Table 3. Abundances of some elements in AS 201.

λ(Å)	Species	χ(eV)	gf	Ref.
7113.180	C I	8.64	1.117e−01	LRB
7115.190	C I	8.64	1.175e−01	LRB
7116.990	C I	8.64	8.318e−01	LRB
7119.660	C I	8.64	4.500e−01	LRB
8683.400	N I	10.3	1.288e+00	LL85
8686.150	N I	10.3	4.467e−01	LL85
8736.040	Mg I	5.94	4.571e−01	WSM
5772.139	Si I	5.08	1.560e−02	LB85
8693.960	S I	7.87	3.890e−01	LL85
8694.640	S I	7.87	1.148e+00	LL85
6449.808	Ca I	2.52	2.820e−01	S86
6471.660	Ca I	2.51	2.061e−01	S86
6767.770	Ni I	1.83	6.761e−03	MFW
5087.430	Y II	1.08	5.395e−01	LB85
5200.410	Y II	0.99	2.692e−01	H82

H82: Hannaford et al. (1982); LB85: Luck & Bond (1985) LRB: Lambert et al. (1982); LL85: Luck & Lambert (1985); MFW: Martin et al. (1988) S86: Smith et al. (1986); WSM: Wiese et al. (1969).

Table 4. Abundance results (in the scale log ϵ(H) = 12.0).

Species	AS 201	HD 330036	Sun*
C I	8.72 ± 0.20	–	8.41
N I	8.02 ± 0.20	–	7.80
Mg I	7.68 ± 0.10	–	7.58
Si I	7.05 ± 0.11	–	7.55
S I	7.13 ± 0.11	–	7.33
Ca I	6.47 ± 0.10	6.33 ± 0.2	6.36
Fe I	7.57 ± 0.10	7.52 ± 0.2	7.50
Ni I	6.25 ± 0.10	–	6.25
Y II	3.24 ± 0.15	–	2.24
Ba II	2.83 ± 0.10	3.03 ± 0.2	2.13

∗ Grevesse & Sauval (1998) plus Asplund (2003) for C and N.

Table 4 assembles the abundance results for the target stars. These indicate that the D′ type symbiotics studied here have roughly solar compositions of non-s-process elements. In particular, the average of the abundances with respect to solar for AS 201 of Mg, Si, S, Ca, Fe and Ni is +0.01 ± 0.26: the dispersion of 0.26 dex is representative of the expected abundance uncertainties of analyzing these rotationally broadened spectral lines. It is important to note, however, that the s-process elements Ba and Y have enhanced abundances in AS 201, while Ba is also enhanced significantly in HD 330306. It seems that s-process enrichment is a common feature in three D′ type symbiotics analyzed to date.

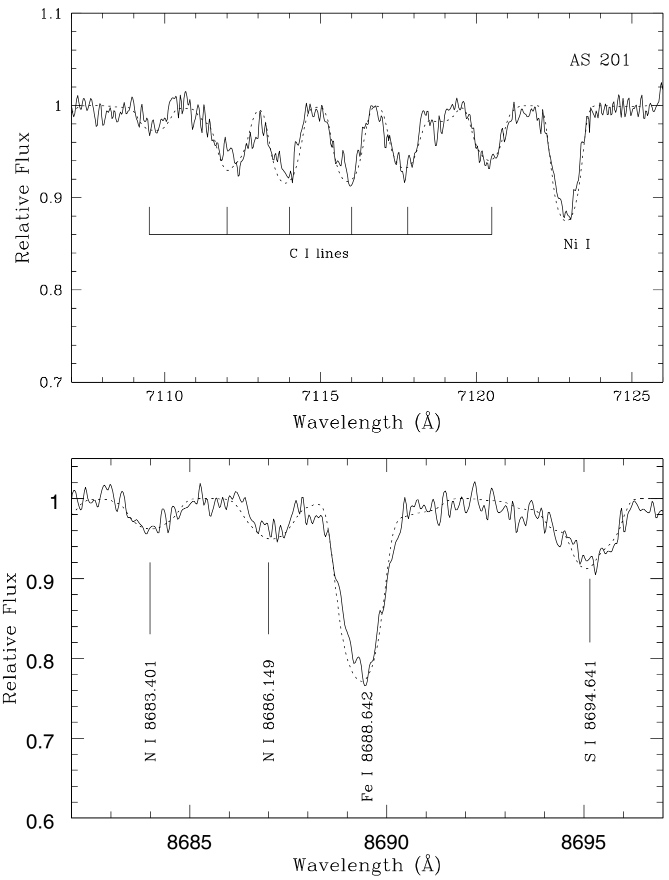

Fig. 5. Spectrum-synthesis fit to the 7107 Å–7126 Å region (*top*) and to the 8680 Å–8695 Å (*bottom*) region of AS 201. Thick line represesnts the observed spectrum and the dotted line is a synthetic spectrum calculated for $\log \epsilon(\mathrm{C})$ = 8.72 (*top*) and $\log \epsilon(\mathrm{N})$ = 8.02 ([N/Fe] = +0.1), $\log \epsilon(\mathrm{S})$ = 7.13 ([S/Fe] = −0.2) (*bottom*) for T_{eff} = 6000 K and $\log g$ = 2.3.

6. D′-type yellow symbiotics or binary planetary-nebulae?

In the late 70's Lutz (1977) singled out a small class of objects in the Catalogue of Planetary Nebulae (Perek & Kohoutek 1967) that seemed peculiar because they had nebular emission lines in combination with the absorption spectrum of a cool (spectral type A to K) central star. Since these central stars are not hot enough to account for the ionization of the nebular shell, some of these peculiar central stars must be components of binary systems in which the fainter star (in the visual) is hot and produces the observed ionization while the brighter star (in the visual) is cool and is the source of the observed absorption spectrum.

Today it is known that some objects in Lutz's (1977) list belong to a small subsample of symbiotic stars, called yellow symbiotics (Schmid & Nussbaumer 1993). These binaries are interesting, in particular, because mass-transfer may have occurred from the former AGB star that now is the hot star component of the system. When the white dwarf was a thermally pulsating asymptotic giant branch (AGB) star, it was s-process enriched during the third dredge-up phase of its stellar evolution. s-process enhancements have been found in all yellow symbiotic stars that have been studied in high-resolution so far, AG Dra (Smith et al. 1996), BD-21°3873 (Smith et al. 1997) and Hen 2-467 (Pereira et al. 1998).

Another interesting subsample of yellow symbiotics, also from Lutz's (1977) sample, is the D′-type symbiotics. Little was known about them until the study by Schmid & Nussbaumer (1993) on a sample of four objects. More recently, Smith et al. (2001) and Munari et al. (2001) discovered that the cool central star of the D′ system S190 is a rapidly rotating ($v \sin i = 100 \pm 10$ km s^{-1}) subgiant-giant star showing enhanced abundances of carbon and heavy elements produced by s-process neutron-capture reactions. In this study, we derived the abundance patterns in two additional D′ type symbiotics and found that they are also s-process enriched and fast rotators.

Rapidly rotating stars showing enhancements of elements created by neutron-capture reactions have already been reported in the literature. Thévenin & Jasniewicz (1997) show that the central stars of Abell 35 and LoTr 5 have [Ba/Fe] ratios of +0.5 and rotational velocities respectively of 55 and 60 km s^{-1}. These observed features of rapidly rotation and enhancements of elements due to neutron capture reactions observed both in the D′-type symbiotics and in "Abell-35 type" objects suggests that these categories of objects may have originated from the same mechanism. As discussed by Jeffries & Stevens (1996) there is a class of wide binaries having white-dwarfs with cool and radiply rotating companions. These authors proposed a mechanism in which the companion star accreates matter from the wind of an AGB star (now the white dwarf of the system) and starts to spin-up. Although these two classes of binaries discussed here have two important spectroscopic features in common, their emission spectra are different. The "Abell-35 type" displays emission spectra similar to RS-CVn stars, H&K lines of Ca II, Mg II and Hα (Thévenin & Jasniewicz 1997) while in D′-type clearly show emission-lines of [O III]4959, 5007 Å [N II] and Hα (Kohoutek 1987; Lutz 1984; Downes & Keyes 1988). The most recent discovered barium star candidate in a binary planetary nebula WeBo1 also displays a similar emission spectra as "Abell 35-type" (Bond et al. 2003).

7. Conclusions

We present further evidence that the absorption spectra in the D′-type symbiotic stars are broadened due to rapid rotation after analyzing the high-resolution spectra of AS 201 and HD 330036. Their [Fe/H] and [Ca/H] abundances indicate near-solar metallicities, while carbon, barium and yttrium are enhanced. Thus, both HD 330036 and AS 201 are s-process enriched and probably accreted matter from their companions, now white-dwarfs, when they were s-process enriched thermally pulsing AGB stars. Further studies would be important to understand the evolution of these binary systems, not only D′-type but also the "Abell 35-type" objects, with the determination of the age of the nebula and the orbital period. Regarding the age of the nebula it seems that the "Abell 35-type" objects are older than the D′-type symbiotics. Corradi & Schwartz (1997) obtained 4000 years for the age of the nebula around AS 201, being much younger than in WeBo 1 which is 12 000 years old (Bond et al. 2003). It is interesting to note that another D′-type system, V417 Cen is 40 000 years old with an optical spectrum exhibiting only a few emission lines (van Winckel et al. 1994).

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