Spectroscopy of the post-AGB star HD 101584 (IRAS 11385-5517) *

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Abstract. From an analysis of the spectrum (4000 Å to 8800 Å) of HD 101584 it is found that most of the neutral and single ionized metallic lines are in emission. The forbidden emission lines of [OI] 6300 Å and 6363 Å and [CI] 8727 Å are detected, which indicate the presence of a very low excitation nebula. The Hα, FeII 6383 Å, NaI D1, D2 lines and the CaII IR triplet lines show P-Cygni profiles indicating a mass outflow. The Hα line shows many velocity components in the profile. The FeII 6383 Å also has almost the same line profile as the Hα line indicating that they are formed in the same region. From the spectrum synthesis analysis we find the atmospheric parameters to be $T_{\text{eff}} = 8500\text{K}$, $\log g = 1.5$, $V_{\text{turb}} = 13\text{km s}^{-1}$ and [Fe/H] = 0.0. From an analysis of the absorption lines the photospheric abundances of some of the elements are derived. Carbon and nitrogen are found to be overabundant. From the analysis of Fe emission lines we derived $T_{\text{ex}} = 6100\text{K} \pm 200$ for the emission line region.

Key words: stars: abundances-stars: evolution-stars: supergiants-stars: post-AGB-stars: circumstellar matter-stars: individual: HD 101584

1. Introduction

Humphreys and Ney (1974) found near-infrared excess in HD 101584 and suggested that it is a massive F-supergiant with an M-type binary companion star (Humphreys 1976). However, HD 101584 ($V=7.01$, F0 Iape (Hoffleit et al. 1983)) was found to be an IRAS source (IRAS 11385−5517) (Parthasarathy and Pottasch 1986). On the basis of its far-infrared colors, flux distribution and detached cold circumstellar dust shell, Parthasarathy and Pottasch (1986) suggested that it is a low mass star in the post-Asymptotic Giant Branch (post-AGB) stage of evolution.

CO molecular emission lines at millimeter wavelengths were detected by Trams et al. (1990). The complex structure of the CO emission shows large Doppler velocities of 130 km s$^{-1}$ with respect to the central velocity of the feature indicating a very high outflow velocity. Te Lintel Hekkert et al. (1992) reported the discovery of OH 1667 MHz maser emission from the circumstellar envelope of HD 101584. The OH spectrum has a velocity range of 84 km s$^{-1}$ and shows two unusually broad emission features. Te Lintel Hekkert et al. (1992) found from the images obtained from the Australian Telescope, that the OH masers are located along the bipolar outflow. The post-AGB nature of HD 101584 is also suggested by the space velocity of the star derived from the central velocity of the CO and OH line emission. This velocity of $V_{\text{rad}} = 50.3 \pm 2.0$ km s$^{-1}$ does not agree with the galactic rotation curve assuming it to be a luminous massive population I F supergiant.

Bakker et al. (1996a) studied the low and high resolution ultraviolet spectra and the high resolution optical spectra of HD 101584. Based on the strength of HeI (see also Morrison and Zimba 1989) N II, C II lines and Geneva photometry, Bakker et al. (1996a) suggest that HD 101584 is a B9 II star of $T_{\text{eff}} = 12000\text{K}$ ± 1000K and $\log g = 3.0$. Bakker et al. (1996b) also found small amplitude light and velocity variations and suggested that HD 101584 is a binary with an orbital period of 218 days.

The optical spectrum of HD 101584 is very complex and shows many lines in emission. In this paper we report an analysis of the high resolution optical spectrum of HD 101584.
2. Observations and analysis

High resolution and high signal to noise ratio spectra of HD 101584 were obtained with the European Southern Observatory (ESO) Coude Auxiliary Telescope (CAT) equipped with the Coude Echelle Spectrograph (CES) and a CCD as detector. The spectra cover the wavelength regions 5360-5400Å, 6135-6185Å, 6280-6320Å, 6340-6385Å, 6540-6590Å, 7090-7140Å, 7420-7480Å, 8305-8365Å and 8680-8740Å. The spectral resolution ranged from 0.165 ˚A at 6150Å to 0.210˚A at 8700Å. We have also obtained 2.5˚A extended atmosphere and NLTE effects.

The OI triplet lines (Fig. 2) are very strong indicating an outflow. The CII lines at 6578˚A and 6582˚A are weak. The Na line profiles. The blue wing is shallow compared to the red wing. The NI lines are strong and show asymmetric profiles. The OI lines at 6156˚A are blended with emission lines of FeI. The CaII H and K absorption lines are strong. The CaII IR triplet lines are due to neutral and single ionized lines of Ti, Cr and Fe. The CaII H and K absorption lines are strong. The CaII IR triplet lines (Fig. 3) show an outflow velocity of 100±10 km s⁻¹. The Hα line also shows a P-Cygni profile. It has a broad emission wing at the red end. This indicates that the line forming region is extended. The Hβ, NaI D1, D2 and the CaII IR triplet lines (Fig. 3) show an outflow velocity of 75±20 km s⁻¹. The velocity structure seen in these P-Cygni profiles could be due to emission from different shells formed during the episodic mass-loss events.

All the spectra were analyzed using IRAF software. The equivalent widths of lines were found by fitting a gaussian. For blended lines de-blending was done by fitting multiple gaussians. We carried out spectrum synthesis calculations using KURUCZ stellar models (1994). SYN-SPEC code (Hubeny et al. 1985) was used for calculating the theoretical line profiles. The gf values were taken from Wiese et al. (1966), Wiese and Martin (1980), Hibbert et al.(1991), Parthasarathy et al. (1992) and Reddy et al. (1997 and references therein). For the analysis of forbidden lines we have used the IRAF software package NEBULAR under STSDAS.

3. Description of the spectrum

The remarkable characteristic of the optical spectrum of HD 101584 is the fact that different spectral regions resemble different spectral types. The spectrum in the UV region is similar to that of α Lep which is an F-supergiant (Bakker 1994). The optical spectrum in the range 3600Å-5400Å is dominated by absorption lines. Most of them are due to neutral and single ionized lines of Ti, Cr and Fe. The CaII H and K absorption lines are strong. The strength of the absorption lines are similar to that observed in an A2 supergiant. In the yellow and red spectral regions, most of the lines are in emission (Fig. 1). The emission lines show complex line profiles. The absorption lines of NI, OI, CII and SII are broad. The Paschen lines are in absorption. Some of these absorption lines are blended with emission lines and many have asymmetric profiles. The OI lines at 6156Å are blended with emission lines of FeI. The NI lines are strong and show asymmetric line profiles. The blue wing is shallow compared to the red wing. The CII lines at 6578Å and 6582Å are weak. The Na D lines, KI 7700 Å (Fig. 2), the CaII IR triplet lines (Fig. 3), [OI], [CI] and MgI 6318.7Å lines are found in emission. The OI triplet lines (Fig. 2) are very strong indicating an extended atmosphere and NLTE effects.

3.1. P-Cygni profiles

The Hα line has a very strong P-Cygni profile indicating an outflow. The profile looks very complex. It shows at least 6 velocity components. The FeII line at 6383Å is in emission and the profile is very similar to that of Hα (Fig. 4). Similar behaviour of the 6383Å FeII line and Hα line is also noticed in the post-AGB F supergiant IRAS 10215-5916 (García-Lario et al. 1994). The Hα and the FeII 6383Å line show an outflow velocity of 100±10 km s⁻¹. The Hβ line also shows a P-Cygni profile. It has a broad emission wing at the red end. This indicates that the line forming region is extended. The Hβ, NaI D1, D2 and the CaII IR triplet lines (Fig. 3) show an outflow velocity of 75±20 km s⁻¹. The velocity structure seen in these P-Cygni profiles could be due to emission from different shells formed during the episodic mass-loss events.

3.2. FeI and FeII emission lines

The presence of numerous emission lines of FeI and FeII makes it possible to derive the physical conditions of the line forming region. From the curve of growth analysis of the FeI and FeII emission lines (Viotti 1969), we have derived $T_{\text{exi}}=6300\pm1000$K and $5550\pm1700$K respectively (Fig. 5). The scatter found could be due to the fact that the lines are not optically thin. On the other hand, there are only few emission lines of FeII present in the spectra and thus the estimate from FeII might not be accurate. In order to determine whether the large scatter observed in Fig. 4 is reflecting optical thickness effects we have done self-absorption curve (SAC) analysis (Friedjung and Murrario 1987) for the FeI emission lines.

SAC is a kind of curve of growth applied to emission lines, but it has certain advantages as compared to the classical emission line curve of growth analysis. This method of analysis is valid also for optically thick lines. It deals with each transition separately, so that it is possible to get the population of different levels without assuming a Boltzmann distribution. In this curve, a function of the line flux emitted in the different transition of a given multiplet is taken in such a way that it is constant for a reference multiplet. Fig. 6(b) and Fig.6(c) shows the self-absorption curve (SAC) in Fig. 6(a) shows the line forming region. From the curve of growth analysis of the FeI and FeII emission lines (Viotti 1969), we have derived $T_{\text{exi}}=6300\pm1000$K and $5550\pm1700$K respectively (Fig. 5). The scatter found could be due to the fact that the lines are not optically thin. On the other hand, there are only few emission lines of FeII present in the spectra and thus the estimate from FeII might not be accurate. In order to determine whether the large scatter observed in Fig. 4 is reflecting optical thickness effects we have done self-absorption curve (SAC) analysis (Friedjung and Murrario 1987) for the FeI emission lines.
3.3. Forbidden lines

The forbidden emission lines at 5577Å, 6300Å and 6363Å of neutral oxygen are present in the spectra. The forbidden line of neutral carbon at 8727Å is also seen. The 6300Å line is blended with ScII line and the 5577Å line is very weak. We have calculated the I(6300)+I(6363)/I(5577) to be 13.3. From the flux ratio we can calculate T_{e} (Osterbrock 1989). This flux ratio is not very accurate because of very the weak 5577Å line and poor signal to noise spectrum. For the flux ratio of 13.3 we derived a function depending on the electron density N_e and temperature T_{e}. Figure 7 shows the N_{e} and T_{e} contours for different values of flux ratio around 13.3. Since we do not see any other forbidden lines which are sensitive to the electron density, we could not fix both N_{e} and T_{e} uniquely. But assuming a temperature derived from the Fe emission lines, an electron density of 1 x 10^7 is obtained. For this value of electron density and temperature the C/O = 0.5± 0.2 has been obtained.

4. Radial velocities

There are very few absorption lines and most of these are affected by emission and or a shell component, therefore we derived the average radial velocity from the well defined emission lines. The average radial velocity from the emission lines is found to be 50 ± 2 km s^{-1}. Morrison and Zimba (1989) using 14 best absorption lines found the radial velocity to be 69±1 km s^{-1}. From the equivalent widths of Fe absorption lines given by Rosenzweig et al. (1997) we find no correlation between log gf - \chi_{\Theta} and heliocentric radial velocity (Fig. 8). However, Bakker et al. (1996a) found a correlations between log gf - \chi_{\Theta} and heliocentric radial velocities of HD101584 in the UV. The discrepancy could be due to the poor resolution of Rosenzweig et al. (1997) data compared to that of Bakker et al. (1996a). The large scatter seen in the radial velocities could be due to pulsation. Similar velocity variations were noticed in other post-AGB supergiants (García-Lario et al. 1997, Hrivnak 1997).

5. Atmospheric parameters and chemical composition

The UV (IUE) low resolution spectrum of HD 101584 matches well with that of an A6Ia star (HD 97534) (Fig. 10) indicating a T_{eff} of 8400K (Lang 1992). The presence of ClI lines at 6578Å and 6582Å indicates a T_{eff} > 8000K. For T_{eff} ≤ 8000K the ClI lines would be very weak or absent. The Paschen lines also indicates a low gravity (Fig. 11). The luminosity class Ia also indicates a very low gravity. From the analysis of several nitrogen lines around 7440Å and 8710Å we derived the microturbulence velocity V_{turb}=13km s^{-1}. We synthesised the spectral region from 4000Å to 4700Å (Fig. 9) with low gravity (log g =1.5 )models of Kurucz (1993) with temperatures 8000K, 8500K and 9000K. The best fit was found for T_{eff} = 8500K, log g =1.5, V_{t}=13km s^{-1} and [Fe/H] = 0.0.

The line at 5876Å was identified as a H line by Bakker et al.(1996a) who also state that the lines at 5047Å and 5045Å as due to HeI and NII respectively. However, we find that the 5047 and 5045 lines are in fact due to FeII. Except HeI 5876Å, we have not found any other helium lines in the spectrum and nor have we found any NII or OII lines. In fact, Hibbert et al. (1991) indicate the presence of a Cl line at 5876Å. It is likely that the line at 5876Å may be due to Cl instead of HeI.

If we assume that the 5876Å line is due to HeI then for a solar helium abundance and log g = 1.5, T_{eff} = 9000K is found. Since we do not see any other helium lines, if 5876Å line is due to helium, it is likely that it may be formed in the stellar wind or in the chromosphere of the star. On the basis of the presence of this helium line Bakker et al. (1996a) suggested that HD 101584 is a B9II star of T_{eff} 12000K. On the basis of the analysis of our spectra we have not found any evidence for such a high temperature. We have also analysed the equivalent widths of absorption lines in the spectrum of HD 101584 given by Bakker et al.(1996a). The final abundances of some of the elements are listed in Table 2. The abundances listed in Table 2 show that the star is overabundant in carbon and nitrogen. It appears that the material processed by the triple alpha C-N and O-N cycle has reached the surface.

6. Discussion and Conclusions

The optical spectrum of the post-AGB star HD 101584 is rather complex. We find several emission lines and P-Cygni profiles indicating an ongoing mass-loss and the presence of a circumstellar gaseous envelope. From the analysis of the absorption lines we find the atmospheric parameters to be T_{eff}=8500K , log g=1.5, V_{t}=13km s^{-1} and [Fe/H]=-0.0.

Carbon and Nitrogen are found to be overabundant indicating that material processed by triple alpha C-N and O-N cycle has reached the surface. Since our blue spectra are of relatively low resolution and because of the presence of emission and shell components it is difficult to estimate reliable abundances of s-process elements. The OI line at 6156Å is blended with a weak FeI emission line. The OI triplet at 7777Å is very strong and affected by NLTE. In any case it appears that the oxygen abundance is nearly solar. A NLTE analysis of the high resolution OI 7777Å triplet may yield a more reliable oxygen abundance.

The nitrogen abundance is based on 6 lines in the 7440Å and 8710Å region. We have not used the strong nitrogen lines. Nitrogen seems to be clearly overabundant. The carbon abundance is based on two CN lines at 6578Å and 6582Å. There is a clear indication that carbon is overabundant. The abundance of Mg, Ti, and Fe are nearly solar. The Ti abundance is based on 15 lines and the Fe abundance is based on 6 lines. Many of the other atomic
lines are affected by emission and shell components. In our opinion, the line at 5876 Å might be due to CI (Hibbert et al. 1991) and not to He I, as previously suggested by Bakker et al. (1996a). We have not found any other He I, N II or O II lines. Our analysis shows that the $T_{\text{eff}}$ is 8500±500K.

Bakker et al. (1996b) found small amplitude light and velocity variations and suggested that HD 101584 is a binary with an orbital period of 218 days. The radial velocity variations may be due to pulsation, macroturbulence motions or shock waves in the outer layers of the stellar atmosphere. Many post-AGB supergiants show small amplitude light and velocity variations (Hrivnak 1997). These variations may not be interpreted as due to the presence of a binary companion. Long term monitoring of the radial velocities is needed in order to understand the causes for these variations.

The spectrum and the brightness of HD 101584 appears to remain the same during last two or three decades. There is no evidence for significant variations in brightness similar to those observed in Luminous Blue Variables (LBVs). The chemical composition and all the available multiwavelength observational data collected during the last two decades by various observers indicates that HD 101584 is most likely a post-AGB star.

The presence of several P-Cygni lines with significant outflow velocities, the OH maser and CO emission profiles (Te Lintel Hekkert et al. 1992, Trams et al. 1990) and the IRAS infrared fluxes and colours (Parthasarathy and Pottasch 1986) indicates the possibility that HD 101584 is a post-AGB star with a bipolar outflow with a dusty disk. Since HD 101584 shows a strong Hα emission line, high resolution imaging with the Hubble Space Telescope (HST) may reveal the bipolar nebula and the presence of a dusty disk similar to that observed in other post-AGB stars like IRAS 17150-3224 (Kwok et al. 1998) or IRAS 17441-2411 (Su et al. 1998).

References

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Fig. 1. High resolution spectra of HD 101584 obtained with the ESO CAT-CES
Fig. 1(contd.). High resolution spectra of HD 101584 obtained with the ESO CAT-CES
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Fig. 2. The spectrum in the upper panel shows several nitrogen lines and emission lines of Fe. The lower panel shows the KI 7699Å in emission and the strong absorption due to OI triplet at 7777Å.
Fig. 3. CaII IR triplet lines showing P-Cygni emission. This spectrum is of 2.5Å resolution, obtained from VBO, Kavalur.
Fig. 4. P-Cygni profile of Hα and FeII(6383Å) lines showing similar velocity structures
Fig. 5. Curve of growth analysis of Fe emission lines. + represents the FeI lines and ♦ represents FeII lines. The slope gives $T_{\text{exi}}=6300\pm1000\text{K}$ for FeI lines and $T_{\text{exi}}=5550\pm1700\text{K}$ for the FeII lines. The large dispersion is because the lines are optically thick. The errors bar show the error in the least square fit.
Fig. 6(a). The plot shows the shape of the SAC. The + sign indicates multiplets 167,168,169,204,207,208 of Fe I having similar excitation potential. ♦ indicates multiplets 1002,1005,1014,1077,1105,1140,1153,1220,1229,1277 of FeI. The fit was obtained after shifting higher multiplets 1002,1005,1014,1077,1105,1140,1153,1220,1229,1277 w.r.to the lower multiplets 167,168,169,204,207,208.
Fig. 6 (b). The fit shows the distribution of upper level population of different multiplets of FeI with respect to the multiplet 207, versus the upper excitation potential.
Fig. 6 (c). The fit shows the distribution of lower level population of different multiplets of FeI with respect to the multiplet 207, versus the lower excitation potential.
Fig. 7. Plot of electron density $N_e$ and electron temperature $T_e$. The dotted line is the contour for the observed ratio (13.3) of [O]I lines 5577Å, 6300Å, and 6363Å. Each contour in the plot is for a change in the flux ratio of 0.5.
Fig. 8. The plot in the upper panel does not show any correlation between the optical depth and the heliocentric radial velocity for the FeI absorption lines of HD 101584 in the wavelength region 3600Å-4500Å. The plot in the lower panel shows the normalized strength of FeI absorption lines in the wavelength region 3600Å to 4500Å versus the optical depth. It shows clearly that the lines are forming at different optical depths. The equivalent widths are taken from the paper by Rosenzweig et al. (1997)
Fig. 9. IUE low resolution spectrum of HD 101584 is compared with that the A6Ia star HD 97534. The dotted line corresponds to the spectrum of HD 97534 while the solid line is HD 101584.
Fig. 10. Observed and synthetic spectra in the Paschen line region. 1-observed, 2-Teff=8000K, log $g$=1.0, 3-Teff=8000K, log $g$=2.0, 4-Teff=8500K, log $g$=1.5. The peaks are FeI emission lines.
Fig. 11. Synthesis spectra for different models are compared with the observed spectrum. The observed spectrum is of 2.5Å resolution taken at VBO kavalur. Observed spectrum matches well for $T_{\text{eff}}=8500\text{K}$, $\log g=1.5$, $V_{\text{turb}}=13\text{km s}^{-1}$ and $[\text{Fe/H}]=0.0$. 