Non-LTE spectroscopic analysis of the wind of the central star of NGC 6543

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Abstract. Using ISA-WIND non-LTE unified model atmospheres, we have determined the basic parameters of the central star of NGC 6543. We have also shown that the wind of this Wolf-Rayet type star can be driven by radiation pressure, resolving an eight-year-old problem posed by Lucy & Perinotto.

1. Introduction

The Wide Field Planetary Camera-2 composite color picture of the planetary nebulae NGC 6543 shows an extremely intricate structure including concentric gas shells, jets and bright knots of gas (Harrington, priv. comm.). To fully understand this system it is imperative that we know the properties of the central star NPN 6543, which is responsible for the genesis, dynamics and ionization structure of the nebula. Several studies have focussed on determining the basic parameters, but have not yielded a definite answer (Table 1). In order to derive reliable basic parameters, we have modeled the UV and optical spectrum of this star using the most recent version of the non-LTE unified model atmosphere code ISA-WIND (de Koter et al. 1993). The UV observations are obtained with IUE, and the optical data is an echelle spectrogram secured at Kitt Peak.

2. Current best model of the UV & optical spectrum

In this paper, we present those results that can be derived from a purely spectroscopic analysis, i.e. the effective temperature $T_{\text{eff}}$, the helium mass fraction $Y$, the terminal velocity of the wind $v_{\infty}$, the wind acceleration parameter $\beta$, and the mass flux $\mathcal{F}_M = \dot{M}/4\pi R^2$. We can thus deduce the ratio, $L/\dot{M}$, because it is proportional to $T_{\text{eff}}^4/\mathcal{F}_M$. This yields the performance number $\eta = \dot{M} v_{\infty}/(L/c)$. However, the luminosity cannot be derived from spectroscopy only.

To derive the above listed parameters, we took the following approach: using a grid of H-He models, spanning a range in $T_{\text{eff}}$ from 40 to 80 kK, we first determined reasonable starting values for $T_{\text{eff}}$, $\mathcal{F}_M$ and $Y$. For a given $T_{\text{eff}}$ and solar helium abundance, we used the He II $\lambda 1640$ and $\lambda 4686$ emission lines to determine the mass flux. We then determined $Y$ by comparing the H$\gamma$ profile to the predicted one. Although H$\gamma$ is dominated by the sharp nebular emission,

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Table 1. Previous studies on NPN 6543

<table>
<thead>
<tr>
<th>Reference</th>
<th>$T_{\text{eff}}$ [K]</th>
<th>$L/L_\odot$</th>
<th>$M/M_\odot$</th>
<th>$\dot{M}$ [$M_\odot$ yr$^{-1}$]</th>
<th>$v_{\infty}$ [kms$^{-1}$]</th>
<th>$\beta$</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castor et al. (1981)</td>
<td>43000</td>
<td>2000</td>
<td>0.55</td>
<td>$9 \times 10^{-8}$</td>
<td>2150</td>
<td>1</td>
<td>4.8</td>
</tr>
<tr>
<td>Bianchi et al. (1986)</td>
<td>80000</td>
<td>15100</td>
<td>1.06</td>
<td>$32 \times 10^{-8}$</td>
<td>1900</td>
<td>2</td>
<td>2.0</td>
</tr>
<tr>
<td>Perinotto et al. (1989)</td>
<td>60000</td>
<td>5600</td>
<td>–</td>
<td>$4 \times 10^{-8}$</td>
<td>1900</td>
<td>1.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

the red-shifted emission (at $v > 250$ km s$^{-1}$) and the blue-shifted absorption are of stellar origin. We adjusted $Y$ by fitting the red wing of H$\gamma$, changing $F_M$ appropriately to keep the fits to the He II lines. We thus obtained a consistent set of $Y$ and $F_M$ for every value of $T_{\text{eff}}$ in our grid.

In the second step, we used detailed models including H, He, C, N, O and Si to derive the effective temperature from simultaneously fitting the O IV $\lambda\lambda1338, 1343$ vs. O IV $\lambda1371$, Si IV $\lambda\lambda1394, 1403$ and N IV $\lambda1718$ vs. N V $\lambda\lambda4604, 4620$ lines. Using the oxygen lines, we found the effective temperature to lie within $45 \lesssim T_{\text{eff}} \lesssim 50$ kK. At $T_{\text{eff}} \approx 40$ kK, the O V line is too weak. Temperatures higher than 60 kK are excluded as the O IV lines disappear quickly. The Si IV lines are much too strong at $T_{\text{eff}} \approx 40$ kK; a best fit is achieved at 45 kK, while the lines disappear at 55 kK. The nitrogen lines yield 45 $\lesssim T_{\text{eff}} \lesssim 55$ kK. The optical N V doublet only starts to appear at $T_{\text{eff}} \approx 43$ kK and reaches the observed strength at 50 kK. The N IV line disappears at $T_{\text{eff}} \gtrsim 55$ kK.

We finally adopt $T_{\text{eff}} = 48 \pm 3$ kK and a helium abundance by mass, $Y = 0.96^{+0.2}_{-0.3}$. The metal abundances are assumed to be solar, except for nitrogen. The lines of this element are relatively strong, showing that it is enriched. We have taken a nitrogen abundance of three times solar for the final model. We determined the terminal velocity from the edge of the C IV $\lambda\lambda1548, 1551$ line. We find $v_{\infty} = 1600 \pm 100$ km s$^{-1}$. For the wind acceleration parameter we found $\beta = 1.5$ from the width of the He II $\lambda4686$ profile. We derived for the mass flux $F_M = 1.5 \times 10^{-4}$ g s$^{-1}$ cm$^{-2}$ from the strength of the He II $\lambda1640$ and $\lambda4686$ line. The effective temperature and mass flux yield a performance number, $\eta = 2.4$.

Figure 1 compares the observations with our current best model. All lines in the UV part of the spectrum fit properly. The same conclusion can be drawn for the optical lines, except for the He II Pickering series ($n=4 \rightarrow l$). While the latter are predicted to be in absorption, they appear almost filled in in the observed spectrum. These lines are formed in the region ranging from the photosphere to the sonic point. The discrepancy may point to an imperfection in the density structure in this regime, e.g. due to the neglect of clumping.

3. Can the wind be driven by radiation pressure?

Lucy & Perinotto (1987, henceforth LP) tested the hypothesis of radiative driving for NPN 6543. Using a Monte-Carlo technique developed by Abbott & Lucy (1985) and adopting the stellar parameters of Castor, Lutz and Seaton (1981, henceforth CLS; cf. Table 1), they calculated that the maximum mass flux that can be driven by radiation pressure is only $\sim 10\%$ of the value derived by CLS. They concluded that, if their adopted basic parameters are not significantly in error, the hypothesis of radiative driving is not correct for NPN 6543.

We have re-investigated this problem using the same technique, which allows for multiple scattering and line overlap. The method allows one to derive the
Figure 1. Current best model for the UV and optical spectrum of NPN 6543. Basic parameters are: $T_{\text{eff}} = 48$ kK, $F_M = 1.5 \times 10^{-4}$ g s$^{-1}$cm$^{-2}$, $v_\infty = 1600$ km s$^{-1}$ and $\beta = 1.5$. For this model we adopted $L = 5200$ $L_\odot$ and $M = 1.6 \times 10^{-7} M_\odot$ yr$^{-1}$. The helium mass fraction is $Y = 0.96$. All metal abundances are solar except nitrogen, which is three times solar. All modeled lines give good fits, except for the lines of the He II Pickering series. These are predicted to be in absorption, however, they are observed to be almost filled in. Modeled lines are labeled in the figure.
maximum sustainable performance number $\eta_{\text{max}}$, using the assumption that all energy removed from the radiation field by the wind is present in the mechanical energy of the terminal flow. To assure consistency, we used the structure of our current best model. This could not be achieved by LP, because CLS analysed the line profiles using only the moments $W_0$ and $W_1$. The ionization and excitation of the metals is treated as in Schaerer & Schmutz (1994). When using all of our 12 available ionization ratios (see Schaerer & Schmutz) in assigning ionization temperatures to the metals, we find a maximum sustainable performance number of $\eta_{\text{max}} = 1.04$. An ionization temperature equal to the electron temperature, which drops to 0.4 T$_{\text{eff}}$ in the outer parts of the wind, would yield $\eta_{\text{max}} = 1.63$. In both calculations, approximately 14,000 lines contribute to the wind acceleration.

These results for $\eta_{\text{max}}$ show that the discrepancy between the performance number derived from spectroscopic analysis and from the global dynamics argument is not an order of magnitude as found by LP, but only a factor of two. The first cause is that our required $\eta$ of 2.4 is only half of that required by CLS, due to a somewhat lower $v_{\infty}$ and higher T$_{\text{eff}}$. Secondly, our higher T$_{\text{eff}}$ favours a stronger line force. Thirdly, our treatment is consistent in that we don't need to make any artificial assumptions on the wind structure. The remaining discrepancy is small in view of the assumptions made in the Monte-Carlo calculation, e.g. on ionization and excitation structure of metals and on the number of selected lines. We conclude that the dominant mechanism driving the wind of NPN 6543 is radiation pressure.

4. Conclusions

Using ISA-WIND non-LTE extended and expanding model atmospheres, we have determined the basic stellar parameters of the central star of NGC 6543 by fitting the UV and optical spectrum. All lines fit the current best model, except those of the He II Pickering series. The line ratios O IV/\lambda and N IV/\lambda and the Si IV resonance lines yield the same effective temperature, T$_{\text{eff}} = 48 \pm 3$ kK. We have also shown that the wind of NPN 6543 can be driven by radiation pressure, which resolves a problem posed by Lucy & Perinotto (1987). In a future study, we intend to test whether our model predicts the correct nebular spectrum.

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References