Electron optical depths and temperatures of symbiotic nebulae from Thomson scattering

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ABSTRACT

Symbiotic binaries are comprised of nebulae, whose densest portions have electron concentrations of \(10^8 - 10^{12}\) cm\(^{-3}\) and extend to a few astronomical units. They are optically thick enough to cause a measurable effect of the scattering of photons on free electrons. In this paper, we model the extended wings of strong emission lines by electron scattering with the aim of determining the electron optical depth, \(\tau_e\), and temperature, \(T_e\), of symbiotic nebulae. We have applied our profile-fitting analysis to the broad wings of the O\(\text{VI}\) 1032, 1038 Å doublet and the He\(\text{II}\) 1640 Å emission line, measured in the spectra of symbiotic stars AG Dra, Z And and V1016 Cyg. The synthetic profiles fit the observed wings well. In this way, we have determined \(\tau_e\) and \(T_e\) of the layer of electrons, throughout which the line photons are transferred. During quiescent phases, the mean \(\tau_e = 0.056 \pm 0.006\) and \(T_e = 19200 \pm 2300\) K, while during active phases, the mean quantities of both parameters increase to \(\tau_e = 0.64 \pm 0.11\) and \(T_e = 32300 \pm 2000\) K. During quiescent phases, the faint electron-scattering wings are caused mainly by free electrons from/around the accretion disc and the ionized wind from the hot star with the total column density, \(N_e \lesssim 10^{23}\) cm\(^{-2}\). During active phases, the large values of \(\tau_e\) are caused by a supplement of free electrons into the binary environment, as a result of the enhanced wind from the hot star, which increases \(N_e\) to \(\sim 10^{24}\) cm\(^{-2}\).

Key words: line: profiles – scattering – binaries: symbiotic.

1 INTRODUCTION

Symbiotic stars are long-period interacting binaries with orbital periods in the range of years. In their spectra, we can recognize three main sources of radiation. The first is represented by a giant star of spectral type (G-)K-M, and the second is a very hot \((T_h \gtrsim 10^7\) K) compact star, which is in most cases a white dwarf accreting from the wind of the giant. The third component of radiation is produced by a nebula, which represents the ionized fraction of the circumstellar material in the binary (e.g. Boyarchuk 1967; Seaquist, Taylor & Button 1984, hereafter STB; Kenyon 1986; Nussbaumer & Vogel 1987; Corradi, Mikolajewska & Mahoney 2003; Skopal 2005, and references therein). As a result, the circumstellar environment of symbiotic binaries comprises energetic photons from the hot star with luminosities of \(10^5 - 10^7\) L\(_\odot\) (e.g. Mürset et al. 1991; Greiner et al. 1997; Skopal 2005), neutral particles produced by the cool giant at rates of a few times \(10^{-7}\) M\(_\odot\) yr\(^{-1}\) (e.g. STB, Mikolajewska, Ivison & Omont 2002; Skopal 2005) and ions and free electrons resulting from the processes of ionization. Thus, symbiotic stars represent ideal objects for studying the effects of Rayleigh, Raman and Thomson scattering. Both Raman and Rayleigh scattering result from interactions between the photons of the hot star and the neutral atoms in the giant’s wind. They are important tools in mapping the ionization structure of symbiotic binaries (e.g. Isliker, Nussbaumer & Vogel 1989; Nussbaumer, Schmid & Vogel 1989; Schmid 1998; Birriel 2004; Lee 2009, 2012). In contrast, the Thomson scattering of photons by free electrons acts within the ionized part of the environment of symbiotic stars, and thus it can diagnose symbiotic nebula. In the spectrum, we can indicate this effect in the form of shallow, wide wings of the strongest emission lines, whose photons are scattered by free electrons and are thus Doppler-shifted by their thermal motion to both the red and blue sides of the line. The effect of this process is weak and wavelength-independent, because of a very small and constant value of the Thomson cross-section, \(\sigma_T = 6.652 \times 10^{-25}\) cm\(^2\). Nevertheless, the densest portions of symbiotic nebulae with electron concentrations of \(\log (n_e) \sim 8 - 12\) (n\(_e\) in cm\(^{-3}\)) could be optically thick enough to cause a measurable effect of the electron scattering. From this point of view, strong emission lines of highly ionized elements, which are formed in the densest part of the ionized medium in the vicinity of the hot white dwarf, represent the best candidates.

Originally, Schmid et al. (1999) suggested that the broad wings of the O\(\text{VI}\) 1032 and 1038 Å resonance lines could be explained by scattering of the O\(\text{VI}\) photons by free electrons. Young et al. (2005) successfully compared a model of the electron-scattering
wings with the O\textsc{vi} doublet in the AG Dra spectrum. Jung & Lee (2004) also used this process to model the broad He\textsc{ii} wings in the spectrum of the symbiotic star V1016 Cyg, as an alternative to the Raman scattering of Ly\textsc{\beta} photons on atomic hydrogen. Skopal et al. (2009) used the electron scattering of the O\textsc{vi} 1032, 1038 Å doublet and the He\textsc{ii} 1640 Å line in the AG Dra spectrum to support the origin of the X-ray–ultraviolet (UV) flux anticorrelation, revealed by modelling the spectral energy distribution (SED).

In this paper, we describe a simplified method for fitting the broad wings of intense emission lines using the electron-scattering process (Section 3). We have applied our profile-fitting procedure to the O\textsc{vi} resonance doublet and the He\textsc{ii} 1640 Å line, observed in the spectra of symbiotic stars AG Dra, Z And and V1016 Cyg, with the aim of determining the electron optical depth, $\tau_e$, and temperature, $T_e$, of their nebulae. In Section 4 we present the results and a discussion, and we give our conclusions in Section 5.

2 OBSERVATIONS AND DATA TREATMENT

For the purposes of this paper, we have used the extremely intense emission lines of the O\textsc{vi} 1032, 1038 Å doublet in the spectra of AG Dra, Z And and V1016 Cyg observed with the Far-Ultraviolet Spectroscopic Explorer (FUSE), the Berkeley Extreme and Far-Ultraviolet Spectrometer (BEFS) and the Tübingen Ultraviolet Echelle Spectrograph (TUES). We have also used the strong emission line He\textsc{ii} 1640 Å in the high-resolution International Ultraviolet Explorer (IUE) spectra of AG Dra. The spectra were obtained from the satellite archives with the aid of the Multimission Archive at the Space Telescope Science Institute (MAST). They are summarized in Table 1.

The FUSE spectra were processed using the calibration pipeline versions 3.0.7, 3.0.8 and 2.4.1. We used the calibrated time-tag observations (TTag photon collecting mode). Before adding the flux from all exposures, we applied an appropriate wavelength shift relative to one, in order to obtain the best overlapping of the absorption features. Then, we co-added the spectra of individual exposures and weighted them according to their exposure times. The wavelength scale of the spectra was calibrated with the aid of the interstellar absorption lines (e.g. Rogerson & Ewell 1984). The accuracy of such calibration is ±0.05 Å. Finally, we binned the resulting spectrum within 0.025 Å.

All the spectra were corrected for heliocentric velocity, including that of the satellite, and dereddened with $E(B-V) = 0.30$ (Z And; Mürset et al. 1991), 0.28 (V1016 Cyg; Nussbaumer & Schild 1981) and 0.08 (AG Dra; Birriel, Espey & Schulte-Ladbeck 2000), using the extinction curve of Cardelli, Clayton & Mathis (1989).

3 MODEL

3.1 Assumptions and simplifications

Thomson scattering represents a special case of the scattering of a photon off a free electron, which is fully elastic (i.e. the photon energy does not change). In the real case, the photon always transfers some of its energy to the electron, which shifts its wavelength by $\sim 0.024$ Å, the so-called Compton wavelength of the electron. However, the Doppler effect arising from the thermal motion of free electrons leads to significantly larger shifts to both sides of the spectrum. Therefore, the elastic Thomson scattering is a good approximation for studying the scattering of low-energy photons ($h\nu \ll m_e c^2$) off non-relativistic electrons (e.g. Rosswog & Brüggen 2007, in detail).

To model the effect of the electron scattering, we have to know how the scattered photons are redistributed in frequencies and directions. Hummer & Mihalas (1967) have shown that it is convenient and sufficiently accurate to regard the radiation field, from which scattering occurs, as isotropic, so that the direction can be averaged out. Therefore, for the sake of simplicity, we consider isotropic scattering with a Maxwellian distribution of electron velocities. Under these assumptions, the redistribution function can be expressed in the form (Mihalas 1970)

$$ R_e (\nu, \nu') = \frac{1}{w} \left[ \frac{\exp \left( -\frac{(\nu - \nu')^2}{2w^2} \right)}{\nu} - \left( \frac{\nu - \nu'}{2w} \right) \text{erfc} \left( \frac{\nu - \nu'}{2w} \right) \right] $$

(1)

Here, $\nu$ and $\nu'$ are the frequencies of radiation before and after the scattering, respectively, $w$ is the electron Doppler width,

$$ w = \frac{v_0}{c} \sqrt{\frac{2kT_e}{m_e}}, $$

(2)

and the complementary error function $\text{erfc}(x)$ is defined as

$$ \text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-z^2} \, dz. $$

(3)

To calculate the profiles of the electron-scattering wings, we have adopted a simplified scheme of Münch (1950), which assumes that a plane-parallel layer of free electrons of optical thickness $\tau_e$ and temperature $T_e$ is irradiated by the line photons, and that the electrons are segregated from the other opacity sources, which implies no change in the equivalent width of the line. In our case, this assumption corresponds to modelling the wings of highly ionized O\textsc{vi} and He\textsc{ii} lines, which are formed within the O\textsc{viii} and/or He\textsc{ii}

| Table 1. Log of spectroscopic observations. |
|---------------------------------------------|
| Date (yyyy/mm/dd) | Julian date | Orbital phase$^a$ | Observing satellite | Line$^b$ |
| AG Dra | 1981/12/11 | 44949.5 | 0.38 | IUE | He\textsc{ii} |
| 1993/09/18 | 49248.5 | 0.22 | BEFS | O\textsc{vi} |
| 1994/06/29 | 49532.5 | 0.74 | IUE | He\textsc{ii} |
| 1994/07/09 | 49542.5 | 0.76 | IUE | He\textsc{ii} |
| 1994/07/12 | 49545.5 | 0.79 | IUE | He\textsc{ii} |
| 1994/07/28 | 49561.5 | 0.79 | IUE | He\textsc{ii} |
| 1994/09/17 | 49612.5 | 0.88 | IUE | He\textsc{ii} |
| 1995/07/28 | 49927.5 | 0.46 | IUE | He\textsc{ii} |
| 1996/02/14 | 50127.5 | 0.82 | IUE | He\textsc{ii} |
| 1996/11/22 | 50409.5 | 0.33 | IUE | He\textsc{ii} |
| 2000/03/16 | 51619.5 | 0.54 | FUSE | O\textsc{vi} |
| 2001/04/25 | 52024.5 | 0.28 | FUSE | O\textsc{vi} |
| 2003/11/14 | 52957.5 | 0.98 | FUSE | O\textsc{vi} |
| 2004/06/24 | 53180.5 | 0.38 | FUSE | O\textsc{vi} |
| 2004/12/25 | 53364.5 | 0.72 | FUSE | O\textsc{vi} |
| 2007/03/15 | 54174.5 | 0.20 | FUSE | O\textsc{vi} |
| Z And | 2002/07/05 | 52460.5 | 0.90 | FUSE | O\textsc{vi} |
| 2003/08/04 | 52855.5 | 0.42 | FUSE | O\textsc{vi} |
| V1016 Cyg | 2000/08/10 | 51766.5 | – | FUSE | O\textsc{vi} |

$^a$According to Fekel et al. (2000).

$^b$He\textsc{ii} 1640 Å, O\textsc{vi} 1032, 1038 Å doublet.

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zone close to the hot white dwarf photosphere. The layer of free electrons, where the Thomson scattering arises, is located above the line-formation region.

According to the radiative transfer equation, assuming that the electron scattering is the only process attenuating the original line photons, the observed line flux can be expressed as
\[ F_{\text{obs}} = F_0 e^{-\tau_e}, \]
where \( F_0 \) is the line flux before scattering, \( \tau_e = \sigma_T N_e \) is the electron optical depth and \( N_e \) is the column density of free electrons along the line of sight. Because the scattered fraction of the original flux is redistributed into the line wings so that the equivalent width before and after the scattering is constant, \( F_{\text{wing}} = F_0 - F_{\text{obs}} = F_0(1 - e^{-\tau_e}) \). Then, the line profile after it emerges from the layer of scattering electrons can be approximated by (see also Castor, Smith & van Blerkom 1970)
\[ \Psi(x) = e^{-\tau_e} \Phi(x) + (1 - e^{-\tau_e}) \int_{-\infty}^{\infty} \Phi(x') R_{\text{sc}}(x', x) \, dx', \]
where \( \Phi(x) \) is the incident line profile, \( R_{\text{sc}}(x', x) \) is the redistribution function for Thomson scattering (equation 1) and \( x' \) is a frequency displacement from the line centre units of electron Doppler width before and after the scattering, respectively. So, the first term on the right-hand side of equation (5) represents the original flux at \( x \) attenuated by the scattering (equation 4), and its scattered \( (1 - e^{-\tau_e}) \) fraction is redistributed in the wings (the second term). Note that the scattered profile used previously by, for example, Castor et al. (1970) represents a special case of equation (5) for \( \tau_e \ll 1 \).

In order to fit the theoretical profile (5) to observations, it is necessary to determine its variables \((\tau_e, T_e)\) and those of the incident profile \( \Phi(x) \).

3.2 Incident profile
First, we have estimated the continuum level from a large wavelength interval around the \text{O vi} lines by a linear fit to the noise in the spectrum. In the case of the \text{He ii} 1640 Å line, the continuum level was estimated with the aid of the corresponding low-resolution spectrum. Secondly, we have approximated the incident profile \( \Phi(\lambda) \) in the model (5) as follows. It was possible to fit the \text{He ii} 1640 Å line with a single Gaussian curve. The fit of the observed emission core provided the first estimate of its position, width and height. The \text{O vi} 1032 Å line is in most cases asymmetric with respect to its reference wavelength. Its blue emission wing is steeper than the red one, being cut by an absorption component (see Fig. 1). It is probably caused by the scattering in the line in the close vicinity of the white dwarf within the densest part of the wind moving to the observer. This absorption can be more pronounced during active phases, when a higher mass-loss rate is observed (Skopal 2006). The observation of AG Dra from 2007 May 3, made during the 2006–2008 active phase, is consistent with this view (see the left panel of Fig. 1). The scattering in the line operates within the line-formation region. Therefore, we take the incident profile of the \text{O vi} 1032 Å line as a sum of emission and absorption Gaussians. It was not possible to reconstruct the incident emission of the \text{O vi} 1038 Å line using a direct fitting of its observed remainder, because of the strong influence by the absorption of the interstellar molecular hydrogen \( H_2 \) (e.g. Schmid et al. 1999). Therefore, we reconstructed the incident \text{O vi} 1038 Å profile with the aid of the theoretical ratio of the doublet lines, with the assumption that they have the same width (see below).

3.3 Profile-fitting analysis
First, we selected the flux points of the observed profile(s), \( F_{\text{obs}}(\lambda_i) \), for fitting with the function (5). These were selected from the observed profiles by omitting some artificial (sharp) emission/absorption features and the depression around the Ly\( \beta \) line, caused by the Rayleigh scattering (see Fig. 2). To find the best solution, we calculated a grid of models for reasonable ranges of the fitting parameters: \( I_n, \sigma_n \) and \( \lambda_n \) for the original profile \( \Phi(x) \) and its incident profile \( \Phi(\lambda) \).
Figure 2. The top panel shows the $U$ light curve of AG Dra from 1977. Active phases are characterized by outbursts with multiple maxima. The data are from Skopal et al. (2012). The bottom panels compare the observed (dotted + enhanced line) and modelled (solid smooth line) broad wings of the OVI 1032, 1038 Å doublet and the He II 1640 Å line at different stages of activity. The enhanced parts of the observed profile were fitted with function (5). The horizontal dotted line represents the level of the continuum. Timings of individual observations are given in Table 1 (arrows in the top panel). Fluxes are in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. 

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and $\Delta \lambda$ with steps of 0.001 Å. Finally, we selected the model corresponding to a minimum of the function

$$\chi^2_{\text{red}} = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{F_{\text{obs}}(\lambda_i) - \Psi(\lambda_i)}{\Delta F_{\text{obs}}(\lambda_i)} \right]^2, \tag{7}$$

where $F_{\text{obs}}(\lambda_i)$ are the observed fluxes of the profile, $N$ is their number ($\approx 200$), $N$ is the number of degrees of freedom (d.o.f.), $\Delta F_{\text{obs}}(\lambda_i)$ are their errors and $\Psi(\lambda_i)$ are theoretical fluxes.

Errors in the selected flux points were around 10–15 per cent of the line wings. Based on these, we determined uncertainties in $T_e$ and $\tau_e$ for individual spectra. To obtain a rough estimate of the corresponding range of $T_e$, we fixed other fitting parameters and varied $T_e$ in order to fit fluxes $F_{\text{obs}}(\lambda_i) = \Delta F_{\text{obs}}(\lambda_i)$. Similarly, we proceeded to estimate the limits for $\tau_e$. Such estimated ranges of fitting parameters can be as large as $\approx 50$ per cent of the best model value and they are asymmetrically placed with respect to it (see Table 2). This is a result of the non-uniformly distributed fluxes determining the profile of electron-scattered wings (see the beginning of Section 3.3.). In the case of the AG Dra spectrum from 1996/02/14, the relatively small uncertainties in $T_e$ and $\tau_e$, but the large value of $\chi^2_{\text{red}}$ in the AG Dra spectrum, probably reflect underestimated flux errors, $\Delta F_{\text{obs}}(\lambda_i)$. Large flux uncertainties on the spectrum from 1996/11/22 and a poorly defined continuum level did not allow us to estimate the upper limit of $T_e$ (see Fig. 2).

### Table 2. Best solutions of equation (7) for $T_e$ and $\tau_e$ and their ranges $\Delta T_e$ and $\Delta \tau_e$, corresponding to $\Delta F_{\text{obs}}(\lambda_i)$ (see Section 3.3).

| Date (yyyy/mm/dd) | Stage | $\tau_e$ | $\Delta \tau_e$ | $T_e$ (K) | $\Delta T_e$ (K) | $\chi^2_{\text{red}}$ |
|-------------------|-------|----------|-----------------|----------|-----------------|-------------------|
| AG Dra            | A     | 0.39     | 0.26–0.55       | 40 100   | 22 500–47 200   | 0.6               |
| 1993/09/18        | T     | 0.18     | 0.15–0.21       | 20 200   | 14 600–23 100   | 1.9               |
| 1994/06/29        | A     | 0.39     | 0.34–0.44       | 32 700   | 29 700–34 900   | 1.6               |
| 1994/07/09        | A     | 1.17     | 1.0–1.4         | 31 000   | 28 800–34 500   | 3.6               |
| 1994/07/12        | A     | 0.86     | 0.70–1.1        | 29 100   | 25 300–38 700   | 3.0               |
| 1994/07/28        | A     | 0.80     | 0.69–0.95       | 41 300   | 40 100–46 700   | 2.5               |
| 1994/09/17        | A     | 0.49     | 0.36–0.66       | 25 400   | 14 900–27 400   | 1.2               |
| 1995/07/28        | A     | 0.39     | 0.33–0.46       | 28 800   | 27 500–33 500   | 0.9               |
| 1996/02/14        | T     | 0.30     | 0.26–0.35       | 14 300   | 13 700–15 800   | 12.1              |
| 1996/11/22        | T     | 0.23     | 0.13–0.34       | 23 900   | 18 600–39 000   | 11.6              |
| 2000/03/16        | Q     | 0.044    | 0.033–0.056     | 12 800   | 7 600–18 500    | 1.0               |
| 2001/04/25        | Q     | 0.065    | 0.051–0.078     | 23 100   | 22 900–25 200   | 1.9               |
| 2003/11/14        | T     | 0.084    | 0.073–0.096     | 29 900   | 16 200–41 900   | 1.2               |
| 2004/06/24        | T     | 0.063    | 0.051–0.074     | 20 300   | 11 200–24 000   | 0.8               |
| 2004/12/25        | Q     | 0.078    | 0.066–0.091     | 30 700   | 29 100–38 900   | 1.8               |
| 2007/03/15        | T     | 0.20     | 0.16–0.25       | 21 300   | 9 600–27 900    | 2.3               |
| Z And             | Q     | 0.050    | 0.042–0.058     | 16 500   | 8 600–22 300    | 2.3               |
| 2003/08/04        | Q     | 0.051    | 0.045–0.056     | 15 300   | 10 300–22 400   | 1.5               |
| V1016 Cyg         | Q     | 0.038    | 0.031–0.044     | 16 000   | 8 200–26 100    | 2.0               |

$^a$A, Q and T denote active phase, quiescent phase and transition to quiescence, respectively.
significant increase of free electrons on the line of sight in the direction to the hot star during active phases. The origin of this change is discussed in Sections 4.2. and 4.3.

4.1 Application to selected symbiotic stars

4.1.1 AG Dra

AG Dra is a yellow symbiotic star, comprising a cool giant of a K2 III spectral type (Müts & Schmid 1999). It is located at a high galactic latitude of $41^\circ$, which implies that its spectrum is less affected by interstellar matter. As a result, the line ratio $I(1038\text{ Å})/I(1032\text{ Å})$ was close to its theoretical value of 0.5, which made the modelling of the O VI doublet more trustworthy (Section 3.2).

By modelling the UV/infrared continuum of AG Dra, Skopal (2005) found that the mean electron temperature of the nebula during the quiescent phase and/or small bursts is between 18 000 and 21 800 K, while during major outbursts (1980–1981, 1994–1995 and 2006–2007; see Fig. 2), the nebula significantly strengthens and increases its mean $T_e$ to $\sim 35 000$ K. In this work, we have confirmed these results independently using the profile-fitting analysis of the electron-scattered wings. We have found that during a quiescent phase, the mean $T_e = 21 700 \pm 3600$ K, while during active phases, $T_e = 32 300 \pm 2000$ K. Also, $\tau_e$ is a function of the star’s activity. Our analysis has revealed $\tau_e = 0.063 \pm 0.007$ and $0.64 \pm 0.11$ during quiescence and activity, respectively (see Table 2 and Figs 2 and 3).

In the 2007/03/15 spectrum, a relatively high value of $\tau_e = 0.20$ – but with very faint wings of the O VI doublet (see Fig. 2) – is caused by the weak incident line flux, $F_0$, because $F_{\text{wing}}/F_0 = 1 - e^{-\tau_e}$ (see Section 3.1 and Fig. 1). So, the easily detectable electron-scattering wings reflect a relatively large amount of free electrons on the line of sight during the transition from the major 2006 outburst.

4.1.2 Z And

Z And is considered to be a prototype of symbiotic stars. Here, the white dwarf accretes from the stellar wind of an M3–4 III red giant (e.g. Fernandez-Castro et al. 1988). During active phases, the light curve shows 2–3 mag brightenings, while the quiescent phase is characterized by a wave-like orbitally related variation (e.g. Belyakina 1985; Formiggini & Leibowitz 1994; Skopal et al. 2006).

The two FUSE spectra used in this work were observed at the end of the major 2000–2003 outbursts: on 2002/07/05 and just after the optical rebrightening on 2003/08/04 (see Fig. 1 of Skopal et al. 2006). The electron-scattering wings observed on both dates (Fig. 3) corresponded to very similar quantities of the fitting parameters, $T_e \approx 16 500$ K, $\tau_e \approx 0.050$ and $T_e \sim 15 300$ K, $\tau_e \sim 0.051$, respectively (Table 2). The electron temperatures are consistent with those derived from modelling the SED in the continuum (Skopal 2005).

4.1.3 V1016 Cyg

V1016 Cyg is a member of a small group of symbiotic stars called symbiotic novae. In 1964, it underwent a nova-like outburst (McCuskey 1965), during which the star’s brightness increased from $m_B \approx 15.5$ to $\sim 10.5$ mag in 1971, after which there was a gradual small decrease to $\sim 11.7$ in 2000 (see fig. 1 of Parimucha et al. 2002).

There is only one well-exposed spectrum in the FUSE archive, from 2000/08/10. The wings of the O VI doublet are clearly visible, although the contamination of the 1038 Å line is significant: $E(B - V) = 0.28$ mag. In this spectrum, we have also been able to fit the sharp absorption component in the P Cyg profile of the 1032 Å line (Fig. 3). The fitting parameters of the nebula ($\tau_e = 0.038$ and $T_e = 16 000$ K) are similar to those derived from observations during quiescent phase of AG Dra. The very small value of $\tau_e$ is a result of very weak wings with respect to the strong central emission core. $F_{\text{wing}}/F_0 = 0.037$.

4.2 Thomson scattering during quiescent phases

The fitting of the extended faint wings of the O VI and He II lines using Thomson scattering suggests that there is a connection between $\tau_e$ and the level of the star’s activity (Fig. 2).

During the quiescent phase, it is assumed that the symbiotic nebula arises from ionizing a portion of the neutral wind from the giant only (i.e. the wind from the hot star is neglected). When the source of neutral particles and that of ionizing photons are separated, the nebula is spread asymmetrically around the hot star in the binary. This implies that the column densities of free electrons on the line of sight to the hot star, and thus $\tau_e$, will also be a function of the orbital phase $\varphi$. Here, we investigate the function $\tau_e(\varphi)$ for the simplest (idealized) case, as outlined by STB. In particular, we assume a spherically symmetric unperturbed wind from the giant, whose particles are accelerated along the $\beta$-law, and the stationary situation (i.e. no binary rotation and no gravitational attraction of the accretor to the wind are included). Under these assumptions, the extent of the ionized zone during quiescence can be obtained from the parametric equation

$$X = f(r, \varphi).$$

The solution of this equation defines the boundary between neutral and ionized gas at the orbital plane, determined by a system of polar coordinates, $r, \varphi$, with the origin at the hot star. STB were the first to treat the function $f(r, \varphi)$ for a steady-state situation and pure hydrogen gas. Nussbaumer & Vogel (1987) have also considered a contribution of free electrons from singly ionized helium, because its zone nearly overlaps that of the H II region. This increases the electron concentration in the ionized zone by a factor of $[1 + \alpha(\text{He})]$, where $\alpha(\text{He})$ is the abundance by number of He relative to H. Following the derivation of Nussbaumer & Vogel (1987), but replacing the terminal velocity of the wind, $v_{\infty}$, by its $\beta$-law distribution

$$v_{\text{wind}}(r) = v_{\infty} \left(1 - \frac{R_s}{r}\right)^{\beta},$$

Here, $r$ is counted from the centre of the cool giant with the radius $R_s$ (= the beginning of the wind). We can express the terms of equation (8) as

$$X \propto \frac{4\pi u^2 m_H}{M_\odot} \frac{I(\Theta) \left(v_{\infty}\right)^2}{\alpha(\text{He}) [1 + \alpha(\text{He})]} p L_H \left(\frac{v_{\infty}}{M_\odot}\right)^{1/2},$$

and

$$f(u, \Theta) = \int_0^{u_0} \int_0^{\pi} \left[1 - R_s/\left[R_s - (\Theta)\right]\right] \frac{du}{u^2}.$$
correctly for AG Dra, we have considered its orbital inclination \(i = 60^\circ\) (Schmid & Schild 1997). The function \(\tau_e(\psi)\) is plotted in Fig. 4. A maximum value of \(\tau_e(\sim 0.03)\) is around \(\psi = 0.1\), when the line of sight passes the ionization region as an asymptote to the boundary (the direction B in the figure). A minimum of \(\sim 0.007\) corresponds to the position with the hot star in front (\(\psi = 0.5\)), because of the lowest densities of the wind from the giant. Fig. 4 demonstrates that the theoretical \(\tau_e(\psi)\) function is significantly below the values derived from observations during quiescent phases (crosses in the figure; see Table 2). This implies that the ionized fraction of the unperturbed wind from the giant is not capable of producing the observed electron-scattering wings.

In a more realistic case, the density distribution in a binary with a mass-losing giant is determined mainly by the rotation of the binary and accretion by its compact companion, as demonstrated by several hydrodynamical simulations (e.g. Theuns & Jorissen 1993; Bisikalo et al. 1995; Mastrodemos & Morris 1998; Nagae et al. 2004). In these studies, it was shown that the regions with highly increased density around the accretor, around the mass-losing star and the whole binary, and behind the accretor (opposite to its orbital motion) were in the form of a disc, a spiralling arm and an elongated accretion wake, respectively. As a result, the column density of free electrons in the direction to the accretor can be enriched by the ionized material accumulated around the accretion disc on each position of the binary. Additional extremes can be expected for highly inclined orbits, when the line of sight passes throughout a higher density structure (e.g. see fig. 6 of Dummm et al. 2006). A lower orbital inclination smooths out the density contrasts at different phases (see fig. 2 of Theuns & Jorissen 1993). Accordingly, in the real case, the faint electron-scattering wings during quiescent phases with \(\tau_e = 0.044–0.078\) can be caused mainly by free electrons from around the accretion disc and the ionized wind from the hot star. This corresponds to the total column density, \(N_e = \tau_e/\sigma_T \lesssim 10^{23} \text{ cm}^{-2}\). The presence of the latter has been proved by several authors (e.g. Vogel 1993; Nussbaumer, Schmutz & Vogel 1995; Skopal 2006).

### 4.3 Thomson scattering during active phases

It is well known that during active phases the hot stars in symbiotic binaries significantly enhance the mass-loss rate (e.g. Fernández-Castro et al. 1995; Nussbaumer et al. 1995; Crocker et al. 2002; Skopal 2006). The ejected material is ionized by the luminous central hot star, which thus enhances radiation from the symbiotic nebula. For example, Skopal (2005) has derived nebular emission in the continuum that is stronger by a factor of \(\approx 10\) during active phases compared to values measured during quiescence. Thus, the enhanced mass-loss rate from the hot star represents a significant supplement of free electrons into the nebula. As a result, the electron optical depth, \(\tau_e = \sigma_T N_e\), will be considerably larger during active phases (Table 2). Here, this is well documented by the series of the AG Dra spectra (Fig. 2). The model SED demonstrates that the nebular radiation also dominates the spectral region of the photometric \(U\) filter (see the top panels of Fig. 5). Therefore, the level of AG Dra activity is well mapped with the \(U\) light curve (top panel of Fig. 2), which thus explains the relationship between \(\tau_e\) and the star’s brightness in \(U\) (bottom panel of Fig. 5). A large scatter around \(\tau_e = 0.2\) is probably connected with the transition phase, when the nebula can be partially optically thick in the continuum.

We can conclude that during active phases the large values of \(\tau_e = 0.39–1.17\) (i.e. \(N_e = 0.58–1.8 \times 10^{24} \text{ cm}^{-2}\)) are caused by a

\[\tau_e = \sigma_T \int_0^\infty n_e(s) \, ds.\]  

Here, the electron concentration \(n_e(s) = [1 + a(\text{He})] n(r)\) and \(n(r)\) is the density of hydrogen atoms in the wind from the giant. If the line of sight does not pass through the neutral region, \(s_0 \rightarrow \infty\) (in practice, we have adopted \(s_0 = 100 \times p\)). To calculate \(\tau_e(\psi)\)
supplement of free electrons into the binary environment, as a result of the enhanced mass-loss rate from the hot star.

5 CONCLUSIONS

We have investigated the effect of Thomson scattering of the strong emission lines, O vi 1032 Å, 1038 Å and He II 1640 Å, observed in the spectra of the symbiotic stars, AG Dra, Z And and V1016 Cyg. Our models of their profiles are in good agreement with those observed by FUSE, BEFS, TUES and IUE (Figs 2 and 3). This supports the idea that the broad wings of these lines result from the scattering of the line photons on free electrons. Their profile is given supports the idea that the broad wings of these lines result from the activity of the hot star. During quiescent phases, the presence of the electron-scattering wings in the line profiles is well explained by the hypothesis that the electron-scattering cross-section is dominant in the scattering region (i.e. the symbiotic nebula). The particular results of our analysis can be summarized as follows.

(i) The presence of the electron-scattering wings in the line profiles of highly ionized elements means that they originate mostly in the vicinity of the hot star in the binary, with the highest density on the line of sight.

(ii) During quiescent phases, the mean $T_e = 19200 \pm 2300$ K, while during active phases $T_e = 32300 \pm 2000$ K. This finding agrees well with quantities derived independently by modelling the SED.

(iii) The electron optical depth also depends strongly on the star’s activity. During quiescent phases, $\tau_e = 0.056 \pm 0.006$, while during active phases, $\tau_e = 0.64 \pm 0.11$ (see Table 2 and Figs 2 and 3). Uncertainties in the results given in (ii) and (iii) represent rms errors of the average values.

(iv) During quiescent phases, the ionized fraction of the wind from the giant within a simple (STB) model (Section 4.2) is not capable of producing a measurable effect of the Thomson scattering. In the real case, the faint electron-scattering wings with $\tau_e = 0.044-0.078$ are caused mainly by free electrons from/around the accretion disc and the ionized wind from the hot star, with a total column density of a few $10^{22} \text{ cm}^{-2}$ (see Section 4.2 and Fig. 4).

(v) During active phases, the large values of $\tau_e$ are caused by a supplement of free electrons into the nebula from the enhanced wind of the hot star, which increases $N_e$ to $\sim 10^{23} \text{ cm}^{-2}$ (see Section 4.3 and Fig. 5).

The presumed relationship between $\tau_e$ and the level of the activity, as suggested by our profile-fitting analysis, could be used to probe the mass-loss rate from hot stars in symbiotic binaries.

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