The O \textsc{i} \,\lambda1641 Å line as a probe of symbiotic star winds

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ABSTRACT

Aims. The neutral oxygen resonance \textsc{i}\lambda1302 Å line can, if the optical depth is sufficiently high, de-excite by an intercombination transition at \textsc{i}\lambda1641 Å to a metastable state. This has been noted in a number of previous studies but never systematically investigated as a diagnostic of the neutral red giant wind in symbiotic stars and symbiotic-like recurrent novae.

Methods. We used archival IUE high resolution, and \textit{HST} GHRS and STIS medium and high resolution, spectra to study a sample of symbiotic stars. The integrated fluxes were measured, where possible, for the O \textsc{i}\lambda1302 Å and O \textsc{i}\lambda1641 Å lines.

Results. The intercombination \textsc{i}\lambda1641 Å line is detected in a substantial number of symbiotic stars with optical depths that give column densities comparable with direct eclipse measures (EG And) and the evolution of the recurrent nova RS Oph 1985 in outburst. In four systems (EG And, Z And, V1016 Cyg, and RR Tel), we find that the O \textsc{i} variations are strongly correlated with the optical light curve and outburst activity. This transition can also be important for the study of a wide variety of sources in which an ionization-bounded H II region is imbedded in an extensive neutral medium, including active galactic nuclei, and not only for evaluations of extinction.

Key words. binaries: symbiotic – atomic processes – galaxies: active – circumstellar matter

1. Introduction

Symbiotic stars present the unusual situation of a nearly neutral, stable environment centered on a cool giant star, in which a hot source, along with its surrounding ionized region, is imbedded. The radius of the H II region is determined only by the mass gainer’s effective temperature and luminosity, which in turn depend only on the accretion rate from the wind (or in the cases where a disk forms, from the flux distribution of the surrounding disk along with that of the underlying star). Since these can be separated using multiwavelength observations, and the incident spectra are ultra-violet (UV) wavelengths (a hot white dwarf and/or an accretion disk continuum and emission line continuum), it is possible to model the formation of the spectrum comparatively easily. This is mainly because the wind of the companion red giant is at nearly its terminal velocity (see Vogel 1991; Pereira et al. 1999) and, even if structured by the orbital motion and hydrodynamic processes related to the accretion (e.g. Dumm et al. 2000; Walder et al. 2008) this happens on a length scale far larger than the gainer and its ionized zone.

In such an environment several radiative processes, not usually encountered under nebular conditions, are observable. Principal among these are fluorescence due to various scattering mechanisms. Accidental resonances account for much of the down-conversion of UV emission to emission in the optical and near infrared. Perhaps the best known are those Fe II and related ions that can be excited by UV resonance transitions of highly-ionized species, e.g. C IV and its coincidence with ground state multiplets of Fe II that de-excite through optical forbidden transitions (Johansson 1983, 1988). Raman scattering (e.g. Schmid 1989), a nearly coincident resonance process that produces broad, down-converted emission lines, is particularly spectacular in the symbiotics, the most notable lines being those of O VI \textsc{i}\lambda6825, 7082 Å that are produced by the near coincidence of the resonant O VI doublet \textsc{i}\lambda1031, 1037 Å and H Lyβ. There is, in addition, a process whereby the UV resonance line of a neutral species can, by virtue of absorption in a surrounding neutral gas, produce both optical and UV emission lines through otherwise inaccessible forbidden transitions. This happens because the ionization potential of several neutral atoms, in particular oxygen, is slightly higher than that of hydrogen and can therefore form in the H II region along with those formed by recombination. Furthermore, resonant absorption by the neutral gas at energies significantly below the ionization limit can, if the optical depth is sufficiently large, lead to emission in alternate channels even in the resonant scattering case.

The O I spectrum is a case in point. The \textsc{i}\lambda1302 line is one of the strongest emission features in the spectrum of late-type symbiotics. It forms in the H II region around the degenerate gainer since neutral oxygen has a slightly higher ionization potential than neutral hydrogen. In addition to the ground state, the O \textsc{i} 3\,S^\textsc{i} \rightarrow \textsc{p} \,(\lambda\lambda 1302, 1304, 1305 Å) multiplet 5 is connected to two long-lived states through emission at \textsc{i}\lambda1641 Å and \textsc{i}\lambda2324 Å, both spin forbidden (intercombination) transitions (see Fig. 1), and their associated decay channels to the ground state. One such decay channel, \textsc{i}\lambda6300 Å, is well known from terrestrial auroral spectra. Also, the \textsc{i}\lambda1641 line has been used as a proxy measure of solar activity variability and its effect on the atmosphere (e.g. Bowers et al. 1987, see below). These lines are also well known from planetary nebulae (e.g. Feibelman 1997) and have been discussed in the literature for studies of interstellar...
extinction in Seyfert galaxies (Grandy 1983) and the determination of the oxygen abundance in cool stars ([O I] λ6300, Nissen et al. 2002).

A difficulty presented by any neutral or singly-ionized resonance transition is that the interstellar medium, possessing the same resonance transitions, is opaque along many lines of sight, especially for distances of several kiloparsecs that are typical of symbiotic and planetary nebular targets. This is exacerbated for cosmological distances where the intervening Lyα forest potentially contaminates the whole redshift range from that of the host galaxy to nearly the local standard of rest. These systems should, therefore, present sufficient line of sight optical depths to produce detectable O I emission.

In a study of the UV spectra of the recurrent nova RS Oph during its 1985 outburst, Shore & Aufdenberg (1991) noted the presence of a transient emission line on the red wing of He II λ1641. This line was also identified by Aufdenberg (1993) in the STIS spectrum of RR Tel. In a recent study of the 2006–2009 outburst of the S-type symbiotic star AG Dra, we discussed the variations of the optical spectra, concentrating on the optical Raman emission line originating from the star is well shifted in wavelength with respect to its ISM components. In this paper we report on studies of symbiotic stars. For AG Dra, these were supplemented with Telescopio Internazionale Ultraviolet Explorer ([IUE] satellite at high resolution (R ≈ 10 000, large aperture) and Hubble Space Telescope ([HST] G140M, G160M) spectra. No HST echelle spectra exist for symbiotic stars. For AG Dra, these were supplemented with Telescopio Nazionale Galileo (TNG) high resolution optical spectra. Note was taken of literature sources presenting symbiotic spectra that included O I lines. Figure 2 presents a sample of O I λ1641 + He II λ1640 line profiles for six symbiotics from HST/STIS spectra. The high spectral resolution of the STIS instrument clearly shows that the O I λ1641 line can be located either within or outside of the He II λ1640 profile.

2. Observations

We retrieved all MAST archival spectra for symbiotic stars taken with the International Ultraviolet Explorer ([IUE] satellite at high resolution (R ≈ 10 000, large aperture) and Hubble Space Telescope ([HST] GHRS and STIS medium resolution (G140M, G160M) spectra. No HST echelle spectra exist for symbiotic stars. For AG Dra, these were supplemented with Telescopio Nazionale Galileo (TNG) high resolution optical spectra. Note was taken of literature sources presenting symbiotic spectra that included O I lines. Figure 2 presents a sample of O I λ1641 + He II λ1640 line profiles for six symbiotics from HST/STIS spectra. The high spectral resolution of the STIS instrument clearly shows that the O I λ1641 line can be located either within or outside of the He II λ1640 profile.

2.1. Stellar sample

The available data sets are not of a homogeneous quality, since they were obtained for various scientific purposes, as well as serving as a calibration target. In addition, these data neither represent a thorough nor even sampling of light curves or eruptive events. Therefore, statistics and correlations are directed to the observed occurrence of O I λ1641 and its possible excitation mechanism. Stars for which the line was detected or suspected of being present in the available spectra are the following:

- Z And: The line is visible in high resolution [IUE] spectra, its variations are discussed in the following section. The system is a very active variable with jet-like outflows having been detected.
- EG And: Two GHRS spectra show the He II and O I lines. The forbidden line is strong and easily visible on the lower resolution spectra. There are five STIS pointings, see Crowley et al. (2008) for details. They note the presence of the line but do not study its variations relative to the orbital phase. The main point is that there is almost no variability in the STIS spectra while the He II line is strongly Fe-curtained.
The line is present in all spectra taken outside of eclipse, its variation, based on the IUE data, is discussed in the next section.

- CH Cyg: The UV absorption Fe-curtain spectrum is among the strongest of any symbiotic star. Although cited by Hack & Selvelli (1982), the O I] line is weak when present, blended with He II, and visible in two IUE high resolution spectra, SWP8940 (MJD 44365) and SWP10878 (MJD 44596).

- CI Cyg: There is one GHRS spectrum, showing one of the strongest and most unusual O I] lines; the intensity relative to He II is very high. There is one published study (Mikołajewska et al. 2006) that discusses the O I], but it does not discuss the line formation. Possibly present in IUE spectra during the mid-1990s.

- V1016 Cyg: For the high resolution IUE spectra, many are saturated at He II and partially mask any weaker emission lines, but the O I] line is apparent in spectrum SWP05612 and possibility detected in other spectra. Only a single GI40L STIS spectrum is available from the archives, the resolution of which is insufficient to detect the O I]. The line variations are discussed in the next section.

- V1329 Cyg: The O I] line is possibly present at a level just above the approximate continuum noise level for several IUE spectra, especially in SWP29816.

- AG Dra: O I] is strong, one STIS spectrum shows this perfectly. Weakly present in the red wing of He I λ1640 in the IUE spectrum SWP25444. The O I] line is, however, too weak to measure in the archival IUE spectra and there is only one STIS spectrum (2003 Apr. 19, see Shore et al. 2010), for which the O I] λ1641 flux is $8.13 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ and the (O I $\lambda$1302/O I] λ1641) ratio is 10.2. Mikołajewska et al. (1995) propose a moderately small inclination and no eclipses.

- RW Hya: Two GHRS and one STIS low resolution spectra show only a hint of O I] mainly as a redward-extended wing on He II that could mask the unresolved line.

- SY Mus: High resolution IUE spectra (including SWP14236) show the O I] line.

- AG Peg: Two GHRS spectra give a possible indication of the line, but it is clearly weak. Possibly present in the IUE spectrum SWP37420, the shortest exposure available.

- RX Pup: There is one STIS spectrum but no detectable emission at O I]. An IUE spectrum (SWP14240) shows the line.

- HM Sge: Only high resolution IUE are available, and there is a possibility that these show the O I] line.

- RR Tel: The most studied of the symbiotic stars in this sample, spectra were taken with GHRS and STIS as a standard for calibration of wavelengths and comparisons between instruments. The O I] line is very strong. The line is also strong in IUE spectra.

- KX TrA: Weakly present in the IUE spectra SWP38741, SWP38742.

### 2.2. Notes and correlations

For the stars AS210, S190, R Aqr, AE Ara, T CrB, BF Cyg, and AX Per the O I] line was either absent or too weak to measure in the available data, in all cases only IUE spectra exist. Based on the available spectra mentioned, two-thirds of the symbiotic stars have shown the presence of O I] λ1641. Among the remaining classical symbiotics from Kenyon (1986), Allen (1984), and Belczyński et al. (2000), Y CrA, V443 Her, BX Mon, IAR Pav, CL Sco, HK Sco, CL Sco, and AS296 have only low resolution IUE archival spectra, and are therefore not useful for detecting O I] λ1641.

Although not measured in the previous studies (especially the outburst analysis by Shore et al. (1996)), the O I] line is detected in IUE high dispersion spectra of the 1985 outburst of the symbiotic-like recurrent nova RS Oph. In Fig. 3 we show three early spectra, from 10 days (SWP 25248), 25 days (SWP 25290), and 30 days (SWP 25328) after optical maximum. The O I] line is clearly detected in only one of these, SWP 25290, which was obtained during the broad-line phase of the permitted lines and when the inferred neutral column density was about $10^{23}$ cm$^{-2}$ based on the Fe-curtain absorption (derived from the narrow line components of C IV, see Shore et al. (1996)). Its radial velocity is consistent with that of the binary system, $v_{\text{rad}} = -10$ km s$^{-1}$. To our knowledge, the line O I $\lambda$1.12895 $\mu$m has only been identified in symbiotic and related star spectra by Evans et al. (2007), where it was recorded in post outburst spectra of RS Oph.

We show four examples of long term variability of this line in Fig. 4 for EG And, Fig. 5 for V1016 Cyg, Figs. 6 and 7 for RR Tel, and Fig. 8 for Z And. The precipitous drop in the RR Tel flux corresponds to a step in the visual magnitude light curve, obtained from the AAVSO website. Similarly, the spike in the
Z And O I] flux corresponds to a spike in the visual magnitude light curve. The AAVSO visual magnitude light curve for V1016 Cyg shows a weak correlation with peaks in the O I] flux in Fig. 5. The sparser EG And data in Fig. 4 is more difficult to correlate with its light curve; however, the amplitude of the O I] flux is similar to the visual magnitude amplitude over a period that is similar to the 482 day period of its (orbit/pulsation). This latter is an eclipsing system in which the line of sight optical depth is so large, due to the absorption line and Rayleigh scattering opacities, as to obscure the entire region, including the O I] line. For non-eclipsing systems, the optical depth appears never to be so large that the O I], which is always optically thin, is not seen. As with the Raman feature, the line is formed close to the ionized-neutral interface in the red giant wind and for low inclination systems should always be visible.

Parimucha et al. (2002) have shown that the fluxes for resonance lines of ionized species (C III-C IV, N III-N V, etc.) in V1016 Cyg showed a well defined minimum at around MJD 47000. It is possible that the O I] line, which shows an almost lightcurve, may reach minimum strength slightly earlier.

The secular development of the O I] strength in RR Tel is the same as the slow decline of the V magnitude, according to the AAVSO light curves, for the entire period of the IUE measurements. In addition, since in this system the stellar radial velocity suffices to displace the O I 1302 Å line from within the interstellar absorption, it is possible to study the long term variation of the 1302 Å to 1641 Å line flux ratio, shown in Fig. 7. There is an apparently asymptotic trend with $F(\lambda 1302)/F(\lambda 1641) \approx 0.4$ at late times in the IUE data set. This flux ratio agrees with the STIS observations from almost a decade later.

The integrated flux variations of the $\lambda 1641$ Å line for Z And (Fig. 8) show a strong correlation with the long term optical variations (based on the AAVSO archive), especially the strong outburst between MJD 46000 and 47000. In the figure, the zero flux values are the conjunctions when it is heavily obscured (according to Friedjung et al. 2010) that were otherwise well exposed (not, as in several symbiotic stars, over- or underexposures that we have ignored in the analysis).

The HST data set includes extended wavelength coverage at high spectral resolution and signal-to-noise for the stars AG Dra,
EG And, and RR Tel. This allows for a search of multiple lines from O I for the purpose of investigating emission line excitation mechanisms. STIS spectra for AG Dra extend from the vacuum UV to the red. Emission is observed for lines that might lead to population enhancement of this O I level are: 1) H Lyβ 937.803 Å coincident with O I 1302 Å line, which can decay to the 76 794 cm\(^{-1}\) level from the metastable O I level. Direct excitation by the resonance line should, however, be more effective in symbiotics, as in the terrestrial case since the Ly lines are so optically thick and the illumination is from the companion, not in situ from the chromosphere (there will, of course, be a contribution from the spectrum of the late-type component but this is small compared to that from white dwarf environment).

Population of the O I 1302 Å line arises from recombination in the H II region, whose boundary is virtually the same for the two species, the 1641 Å line probes the same region as the Raman feature. During outburst events, for instance for Z And around MJD 46700 (Fig. 7), the O I line notably and briefly strengthened and when the He II line was hidden by a sufficient optical depth in the Fe-curtain absorption the O I line was also obscured.

3. Discussion

Several fluorescence processes can lead to the population of levels that will ultimately lead to emission of O I 1641 Å. Coincidence of H Lyβ 1025.722 with O I 1025.762 will populate the O I 3d 3D\(^{+}\) (97488 cm\(^{-1}\)) level from the ground level. The dominant decay chain (according to their Einstein transition probabilities, see Fig. 1) from the 3d 3D\(^{+}\) level (λ11285 and 8446) will populate the 3s 3S\(^{+}\) (76 794 cm\(^{-1}\)) level, which subsequently decays through three channels (λ1302, 1641, 2324), two of which are commonly detected in symbiotic star spectra. In addition to the Lyβ O I pumping, McMurry & Jordan (2000) identified CO emission fluorescingly-excited by O I UV 2 resonance line emission near λ1302 in the UV spectrum of α Tau.

A second pumping mechanism for the O I 76 794 cm\(^{-1}\) level is He II λ1640 for those stars which have a broad He II line. This is evident for RR Tel and EG And, and less so for RW Hya and AG Peg, in Fig. 2. Other possible pumping mechanisms that might lead to population enhancement of this O I level are: 1) H Lyβ 937.803 Å coincident with O I λ1302 Å line in the O I 106 765 cm\(^{-1}\) level, which can decay to the 76 794 cm\(^{-1}\) level through the chain λ112790, 4368 Å, among others. 2) H Lyβ 937.803 Å and H II λ930.342 can pump the O I 8s 3S\(^{-}\) 107 497 cm\(^{-1}\) level, which decays to the 76 794 cm\(^{-1}\) level through the chains λ112790, 4368 or λ15298, 8446. 3) C II λ2324 Å emission is coincident with O I λ2324 Å and can pump the O I 76 794 cm\(^{-1}\) level from the metastable O I level λ2324 Å.

The five lines of C II multiplet 2 are seen in emission in a number of symbiotics and symbiotic novae (RR Tel). Direct excitation by the resonance line should, however, be more effective in symbiotics, as in the terrestrial case since the Ly lines are so optically thick and the illumination is from the companion, not in situ from the chromosphere (there will, of course, be a contribution from the spectrum of the late-type component but this is small compared to that from white dwarf environment).

Population of the O I 76 794 cm\(^{-1}\) level via electron recombination is possible through additional decay chains. Spectral observations at infrared wavelengths may offer a means of determining the dominant excitation mechanisms by detecting other emission lines. The number of lines from the O I spectrum that have been observed in astronomical targets, in particular symbiotic stars and novae, are few. Common UV lines detected include transitions at wavelengths λ1302, 1304, 1305, 1355, 1358, 1641. At optical wavelengths λ6300, 6363 are found in planetary nebula spectra with λ6300 commonly used for abundance analysis in cool stars. For near-IR wavelengths, detections, or suspicions of detections, have been mentioned for 8446 Å in AG Dra (Iijima et al. 1987), and 11289 (Evans et al. 2007). Absorption lines at λ17771, 7773, 7774 are commonly used in abundance analysis in a variety of stars. There is also the curious appearance of an undiscovered weak emission line near 2.9 μm (Schild et al. 1992) in spectra of several symbiotics.
Conspicuous by their absence from discussion and published spectra are lines of large transition probability ($\lambda \lambda 14368, 9204, 9260$ for example) and small transition probability ($\lambda \lambda 1727, 2324, 2958, 2972$). A full accounting of O I lines for any target would be useful for determining the excitation conditions and better enable the physical modeling.

The importance of the O I $\lambda 1641$ line for the symbiotics as a possible tool for as long as ultraviolet spectroscopy is available. Oddly, although this line has been included in a number of identification lists at high resolution, it has never been exploited as a diagnostic for symbiotics or related systems. It has, however, been noted as a contributor to the energetics of AGN when the O I resonance line is sufficiently optically thick. Grandi (1983), in discussing reddening determinations for AGN using the resonance and Bowen fluorescence O I UV2 lines ($\lambda \lambda 1302, 1304$ vs. $\lambda \lambda 8446$) noted that the line ratio O I $\lambda 1641$ (UV146) to the resonance multiplet is often unusually large, given the branching ratio. This can be accounted for by a large enough optical depth to strongly self-absorb the ground state lines. With a Lyα optical depth as large as 10$^6$ the reduction in $\lambda 1302$ is sufficient to produce an integrated flux of only a factor of 2 larger than the forbidden transition. The inhomogeneous regions around the central engine often show such large opacities while still permitting observation of the nucleus along a given sight line. More recently, the chromospheric O I spectrum has been discussed for a few main-sequence and evolved F, G, and K stars.

The importance of the O I $\lambda 1641$ line is another mode to produce the O I $\lambda 1641$ line for the symbiotics is sufficient to displace the $^3P_0$ $\rightarrow$ $^3S_1$ emission line variations during the early RS Oph outburst (Shore et al. 1996) and similar to that derived by Crowley et al. (2008), who obtain a standoff distance for the neutral region from the white dwarf in EG And of about 10$^{13}$ cm, gives a characteristic number density of about 10$^{10}$ cm$^{-3}$. For a wind velocity of 50 km s$^{-1}$ and using $R_{13} = (R/10^{13}$ cm) gives an estimate of the mass loss rate for the red giant of $\approx 10^{-6}$ $M_\odot$ yr$^{-1}$. This estimate is different between systems; there are several with lower branching ratios, others with higher, and in many cases the stellar radial velocity is not sufficient to displace the $\lambda 1302$ line from within the interstellar absorption. The optical depth expected for the red-giant wind in the FUV O I doublet, combined with the opacity of the Lyβ transition, suggest that this is not a dominant mechanism in producing the $\lambda 1641$ line and that the O I opacity suffices.

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