The O I] 1641Å line as a probe of symbiotic star winds

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ABSTRACT

Context. The neutral oxygen resonance \(\lambda1302\)Å line can, if the optical depth is sufficiently high, de-excite by an intercombination transition at \(\lambda1641\)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 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 I \(\lambda1302\)Å and O I \(\lambda1641\)Å lines.

Results. The intercombination 1641Å 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 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. Stars-symbiotic stars, physical processes

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 multicolor observations, and the incident spectra are simple at ultraviolet (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 \(\lambda16825, 7082\)Å that are produced by the near coincidence of the resonant O VI doublet \(\lambda11301, 1037\)Å and H Ly\(\beta\). 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 \(\lambda1302\) resonance 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 O I has a slightly higher ionization potential than neutral hydrogen. In addition to the ground state, the O I \(^3P^o - ^3P\) \(\lambda11302, 1304, 1305\)Å multiplet 5 is connected to two long-lived states through emission at \(\lambda1641\)Å and \(\lambda2324\)Å, both spin forbidden (intercombination) transitions (see Fig. 1), and their associated decay channels to the ground state. One such decay channel, \(\lambda6300\)Å, is well known from terrestrial auroral spectra. Also, the \(\lambda1641\) 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 (Grandi 1983) and the determination of
Fig. 1. Grotrian diagram for the principal transitions of O I involving all levels up to $10^5 \text{ cm}^{-1}$. Each multiplet in the figure is labeled with the shortest wavelength (in Å) in the multiplet, the number of lines of the multiplet (in parentheses) and the total Einstein $A$ transition probability (in italics, units of $s^{-1}$). The transition coincident with H Lyα is shown as a long dash, while lines of the prominent decay path and the O I $\lambda1641$ Å line are presented in bold. For clarity, the transition $^5P(99092 \text{ cm}^{-1}) - ^3S^o(96225 \text{ cm}^{-1}) (\lambda134860 \text{ Å}, A = 1.1e01 \text{ s}^{-1})$ has not been included. Atomic data are taken from Ralchenko et al. (2008).

the oxygen abundance in cool stars ([O I] $\lambda6300$, Nissen et al. 2002).

A difficulty presented by any neutral or singly-ionized resonance transitions 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 $\lambda1640$ relatively early in the outburst and identified this as O I $\lambda1641$. This line was also identified by Aufdenberg (1993) in the IUE 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 features (Shore, Wahlgren, Genovali, et al. 2010). This survey included an examination of archival material as well as optical high-resolution spectra. The absence of the [O I] $\lambda6300$ line was noted but it was suggested that it would be worthwhile checking the existing archive of high resolution UV data for O I $\lambda1641$. This symbiotic is a special case, having a radial velocity of $-144 \text{ km s}^{-1}$; any resonance line originating from the star is well shifted in wavelength with respect to its ISM components. In this paper we report on our search of the archives for the presence of O I $\lambda1641$, as well as other O I lines, in the spectra of symbiotic stars. As mentioned above, the O I spectrum originates in the vicinity of the red-giant star. Observations of the O I line may prove to be useful diagnostics of the red-giant wind and its sources of excitation. Correlation of the UV lines with optical and near-infrared (near-IR) O I lines would therefore enable studies of symbiotic star properties and behavior in the absence of UV spectra.

2. Observations

We retrieved all MAST archival spectra for symbiotic stars taken with the International Ultraviolet Explorer (IUE) satellite at high resolution ($R \approx 10000$, 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 $\lambda1641 + \text{He II } \lambda1640$ line profiles for six symbiotics from HST/STIS spectra. The high spectral resolution of the STIS instrument clearly shows that the O I $\lambda1641$ line can be located either within or outside of the He II $\lambda1640$ 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 $\lambda1641$ and its possible excitation mechanisms. 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 both eclipsing (as for CH Cyg) and 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 (Mikolajewska 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
2.2. Notes and correlations

For the stars AS210, S190, R Aqr, AE Ara, T CrB, BF Cyg, and AX Per the O I\(\lambda 1640\) line was either absent or too weak to measure in all cases only based on the Fe-curtain absorption (derived from the narrow-line components of C IV, see Shore et al. (1996)). Its radial velocity is only one STIS spectrum (2003 Apr. 19, see Shore et al. 2010), for which the O I\(\lambda 1641\) flux is \(8.13 \times 10^{-14}\) erg s\(^{-1}\)cm\(^{-2}\) and the (O I\(\lambda 1302\)/O I\(\lambda 1641\)) ratio is 10.2. Mikolajewska et al. (1995) propose a moderately small inclination and no eclipses.

- **RX Hya:** There is one STIS spectrum but no detectable emission at O I\(\lambda 1640\), which is very strong. The line is also strong in all IUE spectra, especially in SWP29816.

- **HM Sge:** Only high resolution IUE spectra exist. Based on the available spectra mentioned, two-thirds of the symbiotic star spectra by Evans et al. (2007), and Mikolajewska et al. (1995) propose a moderately small inclination and no eclipses.

- **RR Tel:** The most studied of the symbiotic stars in this sample, spectra were taken with GHRS and STIS for calibration of wavelengths and comparisons between instruments. The O I\(\lambda 1640\) line is very strong. The line is also strong in IUE spectra.

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

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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 \( \lambda 1302 \) line from within the interstellar absorption, it is possible to study the long term variation of the \( \lambda 1302 \) to \( \lambda 1641 \) line flux ratio, shown in Fig. 7. There is an apparently asymptotic trend with \( \frac{F(\lambda 1302)}{F(\lambda 1641)} \approx 0.4 \) 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 \( \lambda 1641 \) line for Z And (Fig. 8) shows 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 \( \lambda \lambda 1302, 1304, 1305, 1355, 1358, 1641 \). The \( \lambda 1304 \) line is nearly entirely removed by saturated absorption from the ISM feature Si II \( \lambda 1304.370 \), while the O I \( \lambda 1302 \) emission line is impinged upon by its saturated ISM counterpart (as an example we show the 1300Å region of AG Dra in Fig. 9). Several lines (\( \lambda \lambda 12324, 8446, 9204, 9260 \)) may have marginal detections, and no evidence exists for the presence of others (\( \lambda \lambda 5577, 6300, 6363, 6391 \)). The \( \lambda 2324 \) line is suspect due to broadening of the 2324 Å feature (C II + O I).

For EG And the \( HST \) data are limited to UV wavelengths, showing emission for \( \lambda \lambda 1302, 1304, 1305, 1355, 1358 \). Emission in O I \( \lambda 2324.738 \), if present, is blended with the emission feature C II \( \lambda 12324.69 \), which is one of five lines that comprise the C II UV2 2s\(^2\)2p\(^2\)P\(^o\) - 2s 2p\(^2\)4P multiplet, all of which are found in emission. O I \( \lambda 1727.106 \) does not appear to be present. Emission is not found for lines at the longer wavelengths (\( \lambda \lambda 2958, 2972 \)) as the continuum flux of the cool star, the increased number of absorption lines, and the lower transition probabilities render these lines difficult to detect. The RR Tel data set clearly shows emission from O I \( \lambda \lambda 1302, 1304, 1305, 1641, 5577, 6300, 6363 \). The detection of \( \lambda 2324 \) line is complicated by blending with C II, with the lines of this multiplet not
1304, and 1306 and Si II -150 km s⁻¹ being in proportion to their relative obscures the nance line from within the ISM profile but a chance coincidence calculated with the O VI Raman emission at at ORFEUS spectra, Schmid et al. (1999) compared emission on this region. Crowley et al. (2008), for instance, find that this lies about the wind. The O I] line samples the same warm neutral H wind, that are Raman scattered by Lyβ absorption at the red giant wind, and surrounding ionized cavity within the red giant wind, which decays to the 76794 cm⁻¹ level through the chain λλ14110, 4368 Å, among others. 2) H Lyβ 430.748 and He II λ930.342 can pump the O I 8s 3S⁰ 107497 cm⁻¹ level, which decays to the 76794 cm⁻¹ level through the chains λλ112790, 4368 or λλ5298, 8446. 3) C II λ2324.69 emission is coincident with O I λ2324.738 and can pump the O I 76794 cm⁻¹ level from the metastable O I level 33792 cm⁻¹. 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 76794 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 λλ1302, 1304, 1305, 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 λ11289 (Evans et al. 2007). Absorption lines at λλ7771, 7773, 7774 are commonly used in abundance analysis in a variety of stars. There is also the curious appearance of an undiscussed weak emission line near 2.9 μm (Schild, Boyle & Schmid 1992) in spectra of several symbiotics. Conspicuous by their absence from discussion and published spectra are lines of large transition probability (λλ14368, 9204, 9260 for example) and small transition probability (λλ1727, 1729).
The incidence of Lyman lines is a useful tool for studying the optical depth as large as $10^{25}$ that pumps the UV4 transition at $\lambda 1302.77$ and the O I resonance line (UV4) at $\lambda 1641$ line for the symbiotics is the same order of magnitude as the column density in absorption to explain the narrow UV emission line variations. The optical depth expected for the red-giant wind in the FUV is large enough to displace the O I $\lambda 1302$ 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, suggests that this is not a dominant mechanism in producing the O I opacity fluxes.

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Kwan, W & Krolik 1981, we can estimate the required column density in the resonance line. The observed branching ratio is $\approx 1$ for all systems in which the O I $\lambda 1641$ line is detected in our survey, the implied optical depth for $\lambda 1302$ is $\tau_{1302} \approx 7 \times 10^{-4} f_{\lambda 1302} N_\text{O} = 2 \times 10^{2}$, where $f$ is the oscillator strength and $v_{\text{O}}$ is the wind velocity in km s$^{-1}$, that for a solar O/H ratio ($5 \times 10^{-4}$, see Asplund et al. 2009) gives a column density $N_{\text{O}} \approx 10^{23}$ cm$^{-2}$ for the neutral absorption region. This is the same order of magnitude as the column density in absorption required to explain the narrow UV emission line variations during the early RS Oph outburst (Shore et al. 1996) and similar to that derived by Crowley et al. (2008) from eclipse spectra of EG And. Using the length scale from the photoionization modeling in 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 $R_{\text{13}} = (R/10^{13})$ cm gives an estimate of the mass loss rate for the giant of $10^{-6} R_{\text{13}} M_\odot$ yr$^{-1}$. This estimate is different between systems (there are several with lower branching ratios, others with higher,