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Resonance-enhanced two-photon ionization (RETPI) of Si II and an anomalous, variable intensity of the λ1892 Si III] line in the Weigelt blobs of η Carinae

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ABSTRACT

Context. The Si III] 1892 Å intercombination line shows an anomalously high intensity in spectra of the radiation-rich Weigelt blobs in the vicinity of Eta Carinae. The line disappears during the 100 days long spectral events occurring every 5.5 years.
Aims. The aim is to investigate whether resonance-enhanced two-photon ionization (RETPI) is a plausible excitation mechanism for the Si III] λ1892 line.
Methods. The possible intensity enhancement of the λ1892 line is investigated as regards quasi-resonant intermediate energy levels of Si II.
Results. The RETPI mechanism is effective on Si II in the radiation-rich Weigelt blobs where the two excitation steps are provided by the two intense hydrogen lines Lyα and Lyγ.

Key words. atomic processes – radiation mechanisms: non-thermal – HII regions – stars: individual: η Carinae

1. Introduction

Johansson & Letokhov (2001a) have considered the possibility that ions can be created by resonance-enhanced two-photon ionization (RETPI) in a low-density ($N_{\rm H} < 10^{10}\,{\rm cm}^{-3}$) astrophysical plasma, in which the HLyα line is supposed to have a sufficiently high intensity. In subsequent papers, this possibility was examined for the elements C, N, O (Johansson & Letokhov 2001b, 2002) and the rare gases Ne, Ar (Johansson & Letokhov 2004b), with the involvement of intense H Lyα, β, γ as well as HeI and HeII lines.

The RETPI process can compete with ionization by collisions between atoms (ions) and free electrons in a radiation-rich astrophysical plasma, in which the radiation energy density is comparable with or even higher than the energy density of free electrons. Such an astrophysical plasma can, for example, be represented by a gas cloud ejected from a hot star. The best-known case is the Weigelt blobs (WB's) near one of the most massive and brightest stars in the Galaxy, Eta Carinae (HD 93308) (Weigelt & Ebersberger 1986). The emission line spectra of these blobs have been resolved from the radiation of the central star by means of the STIS two-dimensional spectrograph aboard the Hubble Space Telescope (Gull et al. 2001). The STIS observations show that the blobs are located only a few hundred stellar radii from the central star, and that their size and hydrogen density imply a high optical depth in the Lyman continuum (Davidson & Humphreys 1997; van Boekel et al. 2003).

Simple estimates show that the effective spectral temperature of Lyα inside the blobs $T_\alpha^{\rm eff} \simeq (10 \text{ to } 15) \times 10^3$ K (Johansson & Letokhov 2004a). This value is comparable to or even higher than the electron temperature, which implies a sharp change of the energy balance in the WB's in comparison with classical planetary nebulae. This change is explained by the fact that the dilution factor of the radiation reaching the blobs from the central star is compensated by the effect of "spectral compression". Thus, the Lyman-continuum radiation, which is absorbed in the photoionization of hydrogen, is emitted in the relatively narrow lines HLyα, β, γ as a result of radiative recombination. The WB's may therefore be regarded as *radiation-rich* nebulosities to distinguish them from *thermal* planetary nebulae (Aller 1984).

The WB's represent naturally a suitable astrophysical plasma in which the RETPI effect may occur. To verify this fact, one can, in principle, investigate the ionization equilibrium among various elements in the blobs aiming at finding some indications of the RETPI process. Such indications could be abundance depletion or enhancement of some particular ion compared to predictions from an ionization equilibrium governed by electronic ionization. Another possibility is to investigate spectral anomalies that are apparent for some ions. This approach is especially valuable, since RETPI is a purely radiative process depending on the intensity of the H Lyα, β, γ radiation. At the same time, there is the well-known "spectral event" in η Car, a periodic attenuation of the intensity of some lines occurring every 5.5 years and having a duration of about three months (Damineli 1996). For many of these lines it has been shown that their intensities depend on H Lyα, β, γ radiation. Thus, data recorded during these three months allow for a discrimination of the excitation mechanism of the spectral lines in the WB's (Hartman et al. 2005). In general, the radiatively excited lines should vanish during the spectral event, whereas the recombination lines should remain, as the recombination time in the HI zone of the WB's exceeds three months.

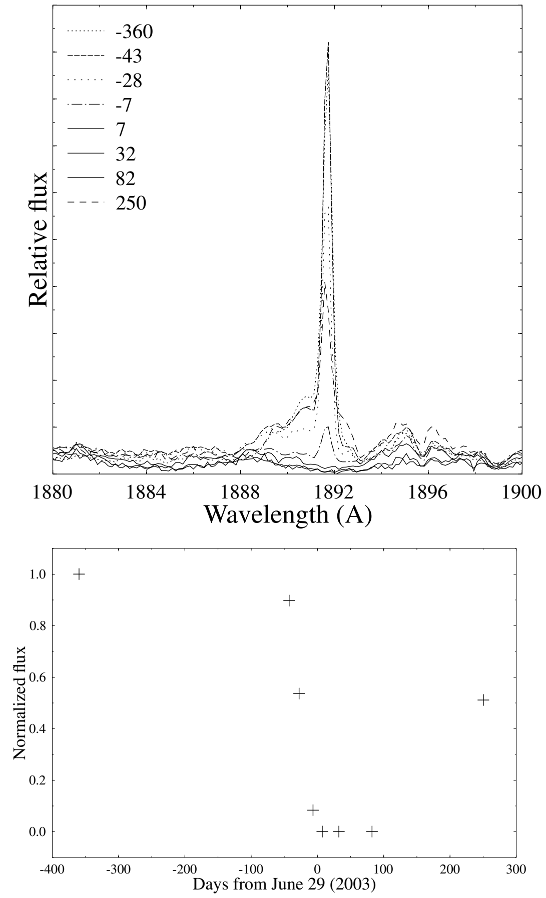

Fig. 1. Time variation of the intensity of the anomalous intercombination Si III] line at 1892 Å observed in the Weigelt blobs of Eta Carinae during the spectral event 2003. Upper: spectral profiles of the line; lower: the intensity change during a period of two years around the event. The data are part of the HST Treasury Project of Eta Carinae.

In the present paper, following the above-described strategy of finding proofs of the existence of the RETPI effect, we propose an explanation of the spectral anomaly of the Si III] intercombination line in spectra of the Weigelt blobs.

2. Striking spectral feature: the 1892 Å Si III] intercombination line

The emission lines of various elements in the WB's were summarized by Zethson (2001). In particular, he noted that in 1999 the Si III] 3s^2 ^{1}S$_0$–3s 3p ^{3}P$_1$ intercombination line at 1892 Å was the third strongest emission feature in the satellite UV region of the observed spectrum (only surpassed by the 2507 and 2509 Å FeII fluorescence lines). However, there is no sign of the Si III] line in the data recorded during the spectral event in 1998. This is perhaps the most striking example of the influence that the spectral event imposes on the WB spectrum.

The same effect was observed during the spectral event of 2003. Figures 1a and b show the drop of the intensity of the Si III] λ1892 line according to the *HST*/STIS CCD-data of the Weigelt blobs taken during the event in June 2003, as part of the HST Treasury Project of Eta Carinae. The slit of the spectrograph was centered on Weigelt blob D, which is the main contributor to the observed line emission. For some position angles of the slit, the adjacent blobs B and C are not fully excluded from the field of view. Thus, B and C also contribute to the observed flux, but this contribution does not change the general behavior of the curves in Figs. 1a and 1b. The rate of the intensity decrease for the Si III] line coincides approximately with that of twelve FeII spectral lines excited by Lyα radiation (Hartman et al. 2005). This fact suggests that the excitation of the Si III] λ1892 line should also be associated with Lyα radiation.

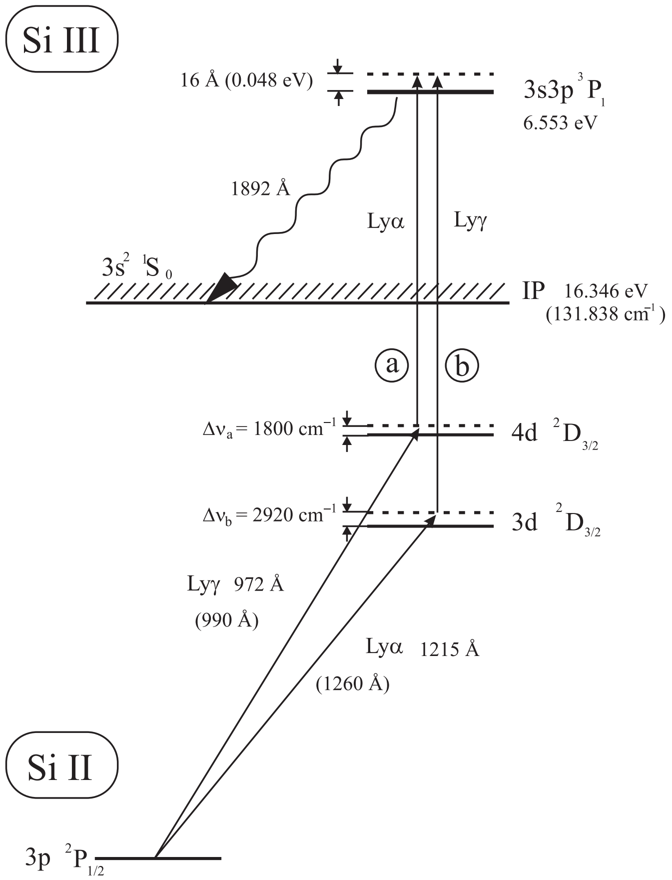

Fig. 2. Two possible pathways of resonance-enhanced two-photon ionization (RETPI) of Si II by HLyα and HLyγ radiation providing excitation of the 1892 Å Si III] intercombination line.

3. Scheme of RETPI operating on Si II and involving excitation of the Si III] intercombination line

The ionization potential of Si I is 8.12 eV, i.e. it is lower than the ionization potential of HI. Therefore, ionization of Si I can be achieved by means of stellar Planck radiation in the spectral range 912 Å $< \lambda <$ 1527 Å that penetrates inside the WB. The RETPI of Si II to form Si III can occur as a result of two-photon absorption of H Lyα radiation (Johansson & Letokhov 2001b). But in that case, the excess of energy provided by the two Lyα photons after ionizing Si II to Si III, 2hν(Lyα)-IP(Si II), amounts to 4.06 eV. This is insufficient to populate the 3s 3p ^{3}P$_1$ state of Si III whose excitation energy is 6.553 eV. However, the RETPI of Si II under the effect of a combination of two different Lyman lines, Lyα and Lyγ, provides for the excitation of a state in the Si II continuum at an energy of E = 6.608 eV. This is E = 0.055 eV higher than the excitation energy of the triplet state. Based on this fact two possible pathways of the RETPI of Si II are illustrated in Fig. 2.

The coupling between the excited state in the Si II continuum and the 3s 3p ^{3}P$_1$ triplet state of Si III may prove quite enough for its excitation, followed by a radiative transition to the ground state in Si III, i.e. emission of the Si III] λ1892 intercombination line. This is the only allowed radiative decay channel of the 3s 3p $^3P_1$ state, and because of a relatively strong LS coupling the transition probability of this LS-forbidden lines is $A = 1.67 \times 10^4$ s^{-1} (Kwong et al. 1983).

Considering that the Lyα and Lyγ spectral lines are generated in the HII zone of the stellar wind as well, the energy difference in the excitation of the triplet state is even smaller than $E = 0.055$ eV ($\approx$16 Å). With the terminal velocity $\upsilon_{\rm term}$ of the stellar wind from Eta Carinae being as high as +625 km s^{-1} (Hillier et al. 2001; Smith et al. 2003) the two photons, Lyα and Lyγ, irradiating the WB from the opposite side, reduce the difference to 10 Å, which increases the coupling between the continuum states of Si II and the triplet state of Si III.

Energetically, the RETPI process proposed could also populate the $J = 0$ and $J = 2$ levels of the 3s 3p ^{3}P term, yielding an energy difference $E = 0.022$ eV ($\approx$6 Å) for the $J = 2$ level. However, the radiative decay of this level involves a forbidden transition at 1882.7 Å whose gA-value is 6 orders of magnitude smaller than the value for to the observed λ1892 intercombination line. The forbidden λ1882 line is not observed, which could partly be due to a collisional ion-electron coupling between the $J = 2$ and $J = 1$ levels.

4. Rate of the RETPI of Si II by the Lyα and Lyγ radiation

The rate W_{1i}(s^{-1}) of the RETPI of Si II under the effect of the Lyα + Lyγ two-frequency radiation for each of the pathways, (a) and (b), of Fig. 2 is defined by the following expressions (Johansson & Letokhov 2001b):

$$W^a_{1i} \simeq \frac{2}{\pi} \cdot \frac{\delta\nu_\alpha \delta\nu_\gamma}{(\Delta\nu_a)^2} \cdot \frac{\sigma^a_{2i}}{\lambda^2_\alpha} A^a_{21} \exp\left(-\frac{h\nu_\gamma}{kT^{\rm eff}_\gamma}\right) \exp\left(-\frac{h\nu_\alpha}{kT^{\rm eff}_\alpha}\right) \qquad (1)$$

and

$$W^b_{1i} \simeq \frac{2}{\pi} \cdot \frac{\delta\nu_\alpha \delta\nu_\gamma}{(\Delta\nu_b)^2} \cdot \frac{\sigma^b_{2i}}{\lambda^2_\gamma} A^b_{21} \exp\left(-\frac{h\nu_\alpha}{kT^{\rm eff}_\alpha}\right) \exp\left(-\frac{h\nu_\gamma}{kT^{\rm eff}_\gamma}\right) \qquad (2)$$

where $\delta\nu_\alpha$ and $\delta\nu_\alpha$ are the spectral widths of the Lyα and Lyγ lines, $\Delta\nu_a = 1800$ cm^{-1} and $\Delta\nu_b = 2920$ cm^{-1} are the frequency detunings of the Lyα and Lyγ lines relative to the 4d $^2D_{3/2}$ and 3d $^2D_{3/2}$ intermediate quasi-resonant levels, respectively. λ_α and λ_γ are the wavelength of the Lyα and Lyγ lines, σ^a_{2i} and σ^b_{2i} the cross-sections for photoionization from the 4d ^{2}D and 3d ^{2}D, A^a_{21} and A^b_{21} the Einstein coefficients for the 4d $^2D \to 3p\ ^2P$ and 3d $^2D \to 3p\ ^2P$ radiative transitions, and $T^{\rm eff}_\alpha$ and $T^{\rm eff}_\gamma$ are the effective (spectral) temperatures of the Lyα and Lyγ radiation, respectively. In the scheme in Fig. 2 we have only included parameter values for the ground state transitions, 3p $^2P_{1/2} \to$ 4d $^2D_{3/2}$ and 3p $^2P_{1/2} \to$ 3d $^2D_{3/2}$, but there are also contributions from the $3/2 \to 5/2$ and $3/2 \to 3/2$ fine structure transitions.

Let us make a very approximate estimate of the rates W^a_{1i} and W^b_{1i} of the RETPI of Si II under the effect of the Lyα and Lyγ radiation with the spectral widths $\delta\nu_\alpha \simeq \delta\nu_\gamma \simeq 500$ cm^{-1}, which corresponds to the widths of these lines in the HII region of the stellar wind in the vicinity of the WB. Assuming approximately that $A_{21} \simeq 10^9$ s^{-1} and $\sigma_{2i} \simeq 10^{-18}$ cm^2, we obtain the following estimate:

$$W^a_{1i} \simeq W^b_{1i} \simeq 0.2 \cdot \exp\left(-\frac{h\nu_\alpha}{kT^\alpha_{\rm eff}}\right) \exp\left(-\frac{h\nu_\gamma}{kT^\gamma_{\rm eff}}\right) \quad [\rm s^{-1}]. \qquad (3)$$

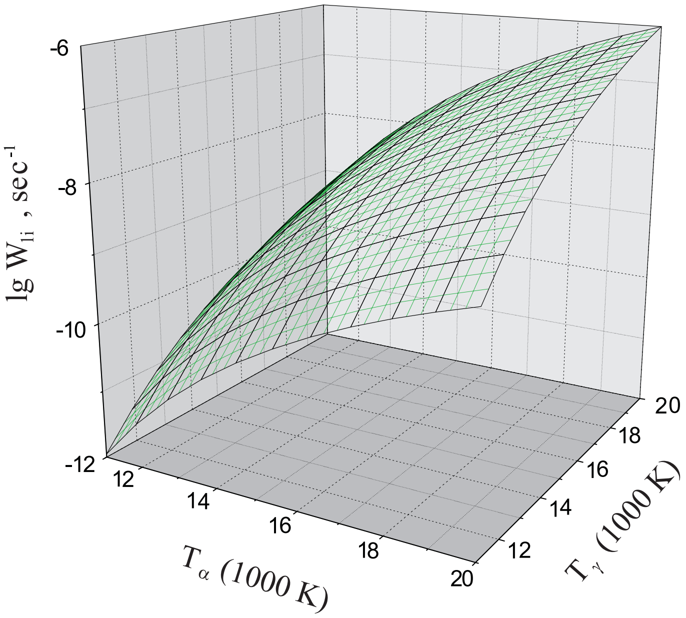

Fig. 3. Rate of RETPI (s^{-1}) of Si II as a function of the effective (spectral) temperatures of Lyα and Lyγ.

Figure 3 presents the relationship between the total rate of the RETPI process involving the two pathways, $W_{1i} = W^a_{1i} + W^b_{1i}$, and the effective temperatures $T^{\rm eff}_\alpha$ and $T^{\rm eff}_\gamma$ in the range (10–20) $\times$ 10^3 K. The approximate estimate of the rate of the RETPI of Si II accompanied by the excitation into its ionized continuum close to the triplet state of Si III lies in the range 10^{-9}–10^{-6} s^{-1}.

To use this estimate to get an explanation of the intensity observed for the Si III] λ1892 line (Fig. 1) seems rather natural. However, such an estimate would be rather approximate, since the volumes of the WB's and stellar wind regions wherein this intercombination line is generated by the RETPI process are unknown. The abundance of Si in the WB is only approximately known, as is the degree of coupling between the triplet state of Si III and the ionization continuum of Si II. Nevertheless, one can note that with the total volume of the WB and the surrounding stellar wind region being $V \simeq 10^{47}$ cm^3, the Si abundance $N_{\rm Si} = 5 \times 10^{-5} N_{\rm H}$, with $N_{\rm H} \simeq 10^8$ cm^{-3}, and the coupling constant of the order of unity, the Si II RETPI rate $W_{1i} \simeq 10^{-7}$–10^{-8} s^{-1} explains fairly well the observed intensity of the 1892 Å Si III line, which from the blobs is 7×10^{-12} erg cm^{-2} s^{-1} Å^{-1} (Gull et al. 2001).

5. Conclusion

This is the first attempt to use the rich observational data on emission line spectra of the radiation-rich Weigelt blobs in the vicinity of Eta Carinae and search for evidence for resonance-enhanced two-photon ionization (RETPI) in an astrophysical object. This object is special for this purpose for several reasons. Firstly, the availability of spectral data from *HST*/STIS with excellent spatial resolution (no overlap with the radiation from the central star). Secondly, the effect of a periodical reduction of the ionizing radiation from the central star during "spectroscopic events" allows to distinguish the radiative (collisionfree) and recombination (collisional) excitation mechanisms (Hartman et al. 2005). It is rather tempting to search for other anomalies in the spectra of the Weigelt blobs to reveal possible contributions from the RETPI process in the ionization of elements.

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