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 Eta Carinae

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Abstract. 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. The aim is to investigate whether resonance-enhanced two-photon ionization (RETPI) is a plausible excitation mechanism for the Si III] λ1892 line. The possible intensity enhancement of the λ1892 line is investigated as regards quasi-resonant intermediate energy levels of Si II. 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: two-photon ionization – HII regions – stars: individual: Eta Carinae – Line: formation

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 ($N_\text{H} < 10^{10}$ cm$^{-3}$) astrophysical plasma, in which the H Lyα 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 (HD93308) [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 $T_\alpha^{\text{eff}} \approx (10$ to $15) \cdot 10^3$ 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 H Lyα, β, γ as a result of radiative recombination. The WB’s may therefore be regarded as radiation-rich nebulae 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
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 3s2 1S0–3s3p 1P1 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.

3. Scheme of RETPI operating on Si ii and Involving Excitation of the Si III] Intercombination Line

The ionization potential of Si ii is 8.12 eV, i.e. it is lower than the ionization potential of HI. Therefore, ionization of Si ii can be achieved by means of stellar Planck radiation in the spectral range 912 Å < λ < 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 3s3p 3P1 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 Figure 2.

The coupling between the excited state in the Si iii continuum and the 3s3p 3P1 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 3s3p 3P1 state, and because of a relatively strong LS coupling the transition probability of this LS-forbidden lines is A = 1.67·10^5 s⁻¹ (Kwong et al. 1983).

Considering that the Lyα and Lyγ spectral lines are generated in the HI 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 ($\approx 16\,\text{Å}$). With the terminal velocity $v_{\text{term}}$ 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, Ly\(\alpha\) and Ly\(\gamma\), irradiating the WB from the opposite side, reduce the difference to 10 Å, which increases the coupling between the continuum states of Si\(\text{II}\) and the triplet state of Si\(\text{III}\).

Energetically, the RETPI process proposed could also populate the J=0 and J=2 levels of the 3s3p \(^3\)P term, yielding an energy difference $E = 0.022$ eV ($\approx 6\,\text{Å}$) 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 \(\lambda\)1892 intercombination line. The forbidden \(\lambda\)1882 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\(\text{II}\) by the Ly\(\alpha\) and Ly\(\gamma\) Radiation

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

$$W_{\text{R}}^a \approx \frac{2}{\pi} \frac{\delta \nu_\alpha \delta \nu_\gamma}{(\Delta \nu_{\text{eff}})^2} \frac{\sigma_\alpha^a}{\lambda^2} A^a_{\text{eff}} \exp \left( -\frac{h \nu_\alpha}{k T_{\text{eff}}} \right) \exp \left( -\frac{h \nu_\gamma}{k T_{\text{eff}}} \right)$$ (1)

and

$$W_{\text{R}}^b \approx \frac{2}{\pi} \frac{\delta \nu_\alpha \delta \nu_\gamma}{(\Delta \nu_{\text{eff}})^2} \frac{\sigma_\alpha^b}{\lambda^2} A^b_{\text{eff}} \exp \left( -\frac{h \nu_\alpha}{k T_{\text{eff}}} \right) \exp \left( -\frac{h \nu_\gamma}{k T_{\text{eff}}} \right)$$ (2)

where $\delta \nu_\alpha$ and $\delta \nu_\gamma$ are the spectral widths of the Ly\(\alpha\) and Ly\(\gamma\) lines, $\Delta \nu_{\text{eff}} = 1800$ cm$^{-1}$ and $\Delta \nu_{\text{eff}} = 2920$ cm$^{-1}$ are the frequency detunings of the Ly\(\alpha\) and Ly\(\gamma\) lines relative to the 4d $^2$D$_{3/2}$ and 3d $^2$D$_{3/2}$ intermediate quasi-resonant levels, respectively. $\lambda_\alpha$ and $\lambda_\gamma$ are the wavelength of the Ly\(\alpha\) and Ly\(\gamma\) lines, $\sigma_\alpha^a$ and $\sigma_\alpha^b$, the cross-sections for photoionization from the 4d $^2$D and 3d $^2$D, $A^a_{\text{eff}}$ and $A^b_{\text{eff}}$ the Einstein coefficients for the 4d $^2$D $\to$ 3p $^2$P and 3d $^2$D $\to$ 3p $^2$P radiative transitions, and $T_{\text{eff}}$ and $T_{\text{eff}}$ are the effective (spectral) temperatures of the Ly\(\alpha\) and Ly\(\gamma\) radiation, respectively. In the scheme in Fig.2 we have only included parameter values for the ground state transitions, 3p $^2$P$_{1/2}$ $\to$ 4d $^2$D$_{3/2}$ and 3p $^2$P$_{1/2}$ $\to$ 3d $^2$D$_{3/2}$, 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 $W_{\text{R}}^a$ and $W_{\text{R}}^b$ of the RETPI of Si\(\text{II}\) under the effect of the Ly\(\alpha\) and Ly\(\gamma\) radiation with the spectral widths $\delta \nu_\alpha \approx \delta \nu_\gamma \approx 500$ 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 $\sigma_\alpha^a \approx 10^9$ s$^{-1}$ and $\sigma_\alpha^b \approx 10^{-18}$ cm$^2$, we obtain the following estimate:

$$W_{\text{R}}^a \approx W_{\text{R}}^b \approx 0.2 \cdot \exp \left( -\frac{h \nu_\alpha}{k T_{\text{eff}}} \right) \exp \left( -\frac{h \nu_\gamma}{k T_{\text{eff}}} \right) \left[ s^{-1} \right]$$ (3)

Figure 3 presents the relationship between the total rate of the RETPI process involving the two pathways, $W_{\text{R}} = W_{\text{R}}^a + W_{\text{R}}^b$, and the effective temperatures $T_{\text{eff}}^a$ and $T_{\text{eff}}^b$ in the range (10$^{-9}$–10$^{-6}$) K. The approximate estimate of the rate of the RETPI of Si\(\text{III}\) accompanied by the excitation into its ionized continuum close to the triplet state of Si\(\text{III}\) 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\(\text{III}\) \(\lambda\)1892 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\(\text{III}\) and the ionization continuum of Si\(\text{II}\). Nevertheless, one can note that with the total volume of the WB and the surrounding stellar wind region being $V \approx 10^{27}$ cm$^3$, the Si abundance $N_{\text{Si}} = 5 \cdot 10^{-5}$N$_{\text{H}}$, with N$_{\text{H}} \approx 10^{8}$ cm$^{-3}$, and the coupling constant of the order of unity, the Si\(\text{II}\) RETPI rate $W_{\text{R}} \approx 10^{-7} - 10^{-8}$ s$^{-1}$ explains fairly well the observed intensity of the 1892 Å Si\(\text{III}\) line, which from the blobs is 7.10$^{-12}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ (Gull et al. 2001).
Fig. 3. Rate of RETPI (s$^{-1}$) of Si ii as a function of the effective (spectral) temperatures of Lyα and Lyγ.

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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