

Radiative Cycle with Stimulated Emission from Atoms and Ions in an Astrophysical Plasma

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(Received 20 August 2002; published 6 January 2003)

We propose that a radiative cycle operates in atoms and ions located in a rarefied gas in the vicinity of a hot star. Besides spontaneous transitions the cycle includes a stimulated transition in one very weak intermediate channel. This radiative “bottleneck” creates a population inversion, which for an appropriate column density results in amplification and stimulated radiation in the weak transition. The stimulated emission opens a fast decay channel leading to a fast radiative cycle in the atom (or ion). We apply this model by explaining two unusually bright Fe II lines at 250.7 and 250.9 nm in the UV spectrum of gas blobs close to η Carinae, one of the most massive and luminous stars in the Galaxy.

DOI: 10.1103/PhysRevLett.90.011101

PACS numbers: 95.75.Fg, 95.85.Jq, 95.38.Gt, 98.58.Bz

Radiative processes play a key role in atomic astrophysics as stellar radiation controls the primary activity in the immediate surroundings of a star. Radiative mechanisms in low-density, nonequilibrium astrophysical plasmas manifest themselves in the spectrum by the appearance of unusually bright, sometimes time-variable, emission lines [1]. Enhanced lines are produced through “photoexcitation by accidental resonance” [2], in which an accidental (but not rare) wavelength coincidence between a strong line of the most abundant elements (H, He) and an absorption line from another element makes the photoexcitation possible. The most famous case is the Bowen mechanism [3]. However, in many cases such a coincidence cannot solely explain anomalous emission lines. For example, the resonant photoexcitation of an atom (ion) and the subsequent spontaneous decay may lead to an accumulation of atoms in an intermediate long-lived state, in which the atom resides for a long time (“a dark state”). Such a bottleneck in the spontaneous decay chain limits the cycling rate of photoexcitation + fluorescence, i.e., limits the efficiency of the conversion of UV photons into less energetic fluorescence from the absorbing atom. This effect is illustrated in Fig. 1 in a simplified scheme of a four-level atom, which represents a number of real cases in multilevel atoms (ions).

The bottleneck in the radiative decay chain, e.g., level 3 in Fig. 1(a), is fed by photoexcitation in $1 \rightarrow 4$ and a fast spontaneous decay, $4 \rightarrow 3$. This leads to an accumulation of atoms in the pseudometastable state 3 having a lifetime $\tau_3 \gg \tau_4$. For a high photoexcitation rate $W_{14}^{\text{exc}} \gg A_{32}$, the intensities of the fluorescent lines $4 \rightarrow 3$ and $2 \rightarrow 1$ are limited by the intensity of the “weak” transition $3 \rightarrow 2$ due to the transfer of atoms from the initial state 1 to the long-lived state 3. In a stellar atmosphere, for example, the density is high enough for collisional relaxation $3 \rightarrow 2$ to take place [Fig. 1(b)]. It is, however, effective in a cyclic process [4] only if state 2 is the ground state of the atom. Otherwise, the collisions will open the closed cycle by relaxation from state 3 to other excited states.

The goal of the present Letter is to demonstrate that in an ensemble of atoms under certain astrophysical conditions the radiative bottleneck leads to amplification and stimulated isotropic radiation in the spectral line λ_{32} . The accumulation of atoms in state 3 creates a population inversion in the transition $3 \rightarrow 2$ at an appropriate column density $\Delta N_{32}L$, where ΔN_{32} is the population density and L is the size of the ensemble of atoms. If $W_{14}^{\text{exc}} \gg A_{32}$, the rate of stimulated transitions $W_{32}^{\text{st}} \gg A_{32}$, and the channel of weak spontaneous decay will be filled up by fast stimulated decay [Fig. 1(c)]. Thus, the rate for radiative cycling becomes enhanced as well as the energy transfer from the pumping UV line to the fluorescence lines. We show that such a radiative cycle with stimulated radiation operates in Fe II pumped by intense H Ly α radiation in compact gas condensations (the so-called Weigelt blobs

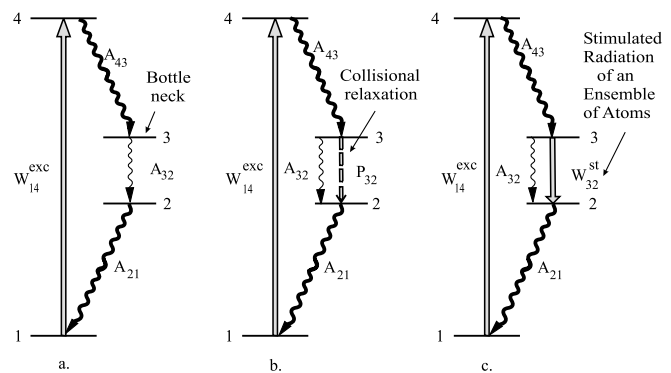


FIG. 1. A radiative cycle in a four-level atom having allowed radiative transitions $1 \rightarrow 4$, $4 \rightarrow 3$, $2 \rightarrow 1$ and a metastable (pseudometastable) state 3 with a slow spontaneous radiative decay $3 \rightarrow 2$: (a) An isolated atom without collisions (on the time scale A_{32}^{-1}), (b) an atom in a high-density environment, which provides a fast collisional relaxation in the transition $3 \rightarrow 2$, (c) a collision-free ensemble of atoms with an inverted population in the $3 \rightarrow 2$ transition and a significant amplification, which provides a fast stimulated radiative relaxation $3 \rightarrow 2$.

[5]) close to η Carinae, one of the most luminous and massive stars in our Galaxy. This mechanism explains the origin of two unusually bright fluorescence lines at 250.7 and 250.9 nm observed in spectra of high spectral and spatial resolution recorded with the Hubble Space Telescope [6].

The diagram in Fig. 2 includes a few of the known energy levels of Fe II, which together with the indicated transitions are relevant in the present study. The broad (a few hundreds cm^{-1}) H Ly α line at 121.57 nm almost coincides in wavelength with two Fe II transitions from the low level $a^4D_{7/2}$ (level 1 in Fig. 2) to the close levels $(^5D)5p^6F_{9/2}^0$ and $(b^3F)4p^4G_{9/2}^0$ (marked 4 in Fig. 2), the frequency difference (detuning) being $\Delta\nu = -160$ and -185 cm^{-1} , respectively. The detuning is compensated by the broadening of H Ly α when it penetrates the HI region having an optical depth of $\tau \geq 10^7-10^8$. This fluorescence channel was suggested and identified in the early work on IUE observations [8] and has later been confirmed by Hubble Space Telescope (HST) observations of the bright lines at 250.7 and 250.9 nm [6] corresponding to the transition 4 \rightarrow 3 (see Fig. 2 for notations). The line at 250.91 nm to state 3 ($c^4F_{7/2}$) is the main decay channel from $(b^3F)4p^4G_{9/2}^0$

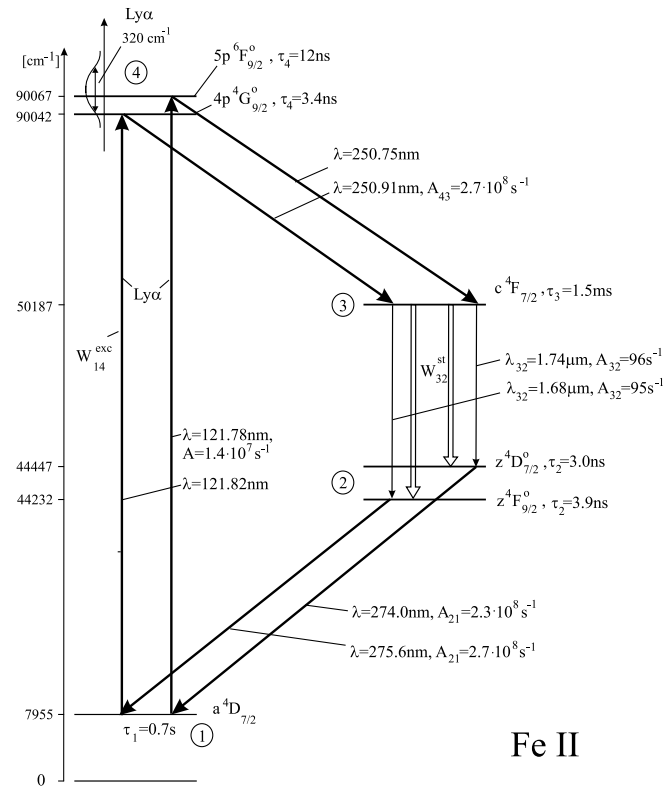


FIG. 2. A partial level diagram of the very complex multi-level ion Fe II forming an almost closed (on the time scale τ_1) radiative cycle, which includes a selective photoexcitation of the uppermost level by intense H Ly α radiation. (References to the atomic data are given in [7].)

(state 4) with a branching fraction of about $\eta \approx 0.9$. Because of the small energy difference the two energy levels in state 4 [$(^5D)5p^6F_{9/2}^0$ and $(b^3F)4p^4G_{9/2}^0$] are strongly mixed and show the same decay pattern [9]. Level 3 is pseudometastable; i.e., it has a long lifetime (1.5 ms), but in contrast to metastable states it can decay slowly by electric dipole radiation to the short-lived states 2 ($z^4D_{7/2}^0$ and $z^4F_{9/2}^0$). It is essential that the decay of state 2 returns a large fraction of the Fe $^+$ ions to the initial state 1, which is metastable with a radiative lifetime of about 1 s. Let us emphasize that we are considering a gas blob close to a star, the density (mainly hydrogen) is less than 10^{10} cm^{-3} and the time scale for collisions is hence much longer than the time scale for radiative decay of state 3. Under these conditions the nearly closed radiative cycle 1 \rightarrow 4 \rightarrow 3 \rightarrow 2 \rightarrow 1 has a bottleneck in the 3 \rightarrow 2 transition. If the rate of pumping W_{14}^{exc} is larger than the decay rate $1/\tau_3$ of state 3 ($\tau_3 = 1.5 \text{ ms}$), an inverted population is created for the transition 3 \rightarrow 2. The rate of selective photoexcitation of state 4 by isotropic H Ly α radiation is defined by the expression

$$W_{14}^{\text{exc}} = A_{41} \left[\exp\left(\frac{h\nu_{14}}{kT_\alpha}\right) - 1 \right]^{-1}, \quad (1)$$

where the Einstein coefficient $A_{41} = 1.4 \times 10^7 \text{ s}^{-1}$, and T_α is the brightness temperature of H Ly α . Inversion of population ($W_{14}^{\text{exc}} > 1/\tau_3$) is achieved for $T_\alpha > 12000 \text{ K}$.

The steady-state population inversion in the 3 \rightarrow 2 transition is

$$\Delta N_{32} = N_3 - N_2 \approx N_3 = \frac{W_{14}^{\text{exc}} \tau_3}{1 + W_{14}^{\text{exc}} \tau_3} N_1, \quad (2)$$

where $N_2 \ll N_3$ because of the much faster decay of level 2, and N_1 is the concentration of Fe $^+$ in state 1 having a lifetime $\tau_1 = 0.7 \text{ s} \gg \tau_2, \tau_3, \tau_4$. At the brightness temperature $T_\alpha \approx (1.5-2.0) \times 10^4 \text{ K}$ of H Ly α in the Weigelt blob [10] the pumping rate $W_{14}^{\text{exc}} \gg 1/\tau_3$, leading to a full transfer of Fe $^+$ ions from state 1 to state 3. Using “laser” terminology this means that a strong saturation of the three-level system 1 \rightarrow 4 \rightarrow 3 occurs due to the action of intense isotropic H Ly α radiation.

The linear amplification coefficient for the 3 \rightarrow 2 transitions at $\lambda_{32} = 1.74$ and $1.68 \mu\text{m}$ (Fig. 2) is defined for $W_{14}^{\text{exc}} > (2-3)/\tau_3$ by the standard expression

$$\alpha_{32} = \sigma_{32} \Delta N_{32} \approx \sigma_{32} N_3 \approx \sigma_{32} N_1. \quad (3)$$

The cross section σ_{32} for stimulated emission of the 3 \rightarrow 2 transitions in Fe II is

$$\sigma_{32} = \frac{\lambda_{32}^2 A_{32}}{2\pi \Delta\nu_D}, \quad (4)$$

where $\Delta\nu_D$ is the Doppler width. At a kinetic temperature of $T = 100-1000 \text{ K}$ in the relatively cold HI region (Fig. 3), $\Delta\nu_D \approx (200-600) \text{ MHz}$, i.e., $\sigma_{32} \approx (1.2-3.7) \times 10^{-16} \text{ cm}^2$. The population in state 1, N_1 , is determined

by the fraction $f = N_1/N_0$, where N_0 is the total concentration of Fe^+ ions. The fraction f is governed by the excitation rate of level 1 and its lifetime τ_1 . Most important for excitation of level 1 is the radiative decay of the high-lying states of Fe II excited by H Ly α in about ten transitions [8]. These decay channels can provide an excitation rate that is greater than $1/\tau_1 \approx 1.5 \text{ s}^{-1}$ and, hence, sustain the relative population of state 1 at a level of $f \approx 0.01$. This would correspond to an approximately equal distribution of the Fe^+ ions among their 90 metastable and pseudometastable states, including state 1. Leaving the calculation of the magnitude of f for future considerations, we adopt a qualitative estimate of $f \approx 0.01$.

The amplification coefficient for the $3 \rightarrow 2$ transition may, according to Eq. (3), be estimated to $\alpha_{32} \approx (1.2\text{--}3.7) \times 10^{-18} N_0 \text{ cm}^{-1}$, where $N_0 \approx 10^{-4} N_H$ is the density of iron, which is fully photoionized, and N_H is the hydrogen density in the gas blob. According to data in [11] and calculations of the critical density of hydrogen [10], N_H is estimated to be higher than 10^8 cm^{-3} . Thus, for $a_{32} \geq (1\text{--}4) \times 10^{-14} \text{ cm}^{-1}$ and a diameter $D \approx 10^{15} \text{ cm}$ of the gas blob [11], which can be regarded as the length L of the amplifying region (Fig. 3), we get $\alpha_{32}L \approx (10\text{--}40)$ at a Ly α temperature $T_a \geq 12\,000 \text{ K}$, which corresponds to a large linear amplification coefficient $\exp(\alpha_{32}L)$. The large amplification coefficient α_{32} implies that stimulated emission occurs in the $3 \rightarrow 2$ transition (the λ_{32} lines), and in the steady-state saturation regime the rate of stimulated transitions at 1.74 and 1.68 μm will be equal to the rate of photoselective pumping W_{14}^{exc} of state 3 ($W_{14}^{\text{exc}} \ll A_{43}$). The intensity (in photons/ $\text{cm}^2 \cdot \text{s}$) of these isotropic laser lines should be enhanced by $W_{14}^{\text{exc}}/A_{32}$ relative to their intensity associated with spontaneous emission.

For an ensemble of atoms with sufficient density and size the channel $3 \rightarrow 2$ will open for fast stimulated

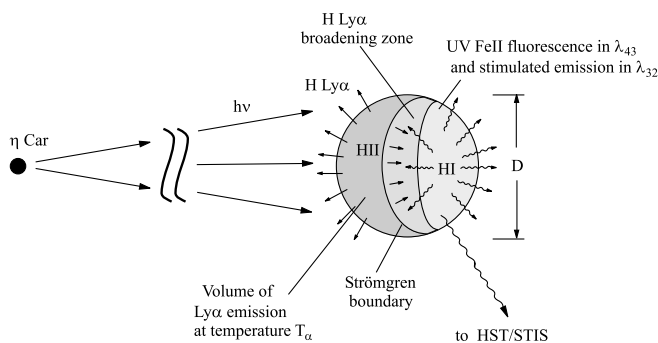


FIG. 3. An illustration of a physical model of a compact gas condensation in the vicinity of η Carinae showing the internal boundary between the ionized HII and neutral HI zones (the Strömgen boundary). Ly α radiation from the HII zone irradiates Fe^+ ions in the HI zone, resulting in a radiative cycle in Fe II with spontaneous as well as stimulated emission and a large enhancement of the spontaneous line λ_{43} .

decay, and the duration of the whole cycle is determined by the rate of the slowest excitation channel $W_{14}^{\text{exc}} = W_{32}^{\text{st}}$ rather than by the rate of the slowest spontaneous decay A_{32} . For a brightness temperature of Ly α in the range $T_a \approx (1.5\text{--}2.0) \times 10^4 \text{ K}$ the excitation rate appears in the range $W_{14}^{\text{exc}} \approx 5 \times 10^3\text{--}2 \times 10^4 \text{ s}^{-1}$ giving a duration of the total radiative cycle in Fe II of $t_{\text{cycle}} = 50\text{--}200 \mu\text{s}$. The Fe^+ ions can undergo a number of cycles ($\tau_{\text{cycle}}/\tau_1 \approx 3.5 \times 10^3\text{--}1.4 \times 10^4$) during the lifetime of state 1. A detailed study of the branching ratio effects and the anomalous intensity ratio of the strong UV lines and their satellites will be the subject of a forthcoming paper.

A large number of radiative cycles with a stimulated channel provide a large enhancement of the UV fluorescence lines ($4 \rightarrow 3$) due to a suppressed accumulation of Fe^+ ions in the pseudometastable state 3 and the corresponding depletion of state 1. If the density N_0 and the size L are not sufficiently large, the amplification will be small and the stimulated channel will not operate. In such a case the radiative bottleneck limits the rate of the radiative cycling in Fe II to the time $\tau_1 = 1.5 \text{ ms}$ and the intensities of the two UV lines λ_{43} become normal.

In fact, high-resolution spectra of the gas blobs outside η Carinae, which are spatially resolved from the central star, show an anomalous brightness of the two UV lines [12]. A further observational evidence for the radiative cycle proposed in this Letter is the observation of the bottleneck lines around 1.7 μm in ground-based spectra of η Carinae [13]. The $3 \rightarrow 2$ transition from $c^4F_{7/2}$ at $\lambda_{32} = 1.74$ and 1.68 μm appear relatively stronger than lines from the other fine structure levels of c^4F . Since the ground-based spectra contain integrated light from a larger region than the gas blob discussed here, the absolute intensities cannot be compared with the intensities measured in the HST spectra. Moreover, according to the observations made in [12], the UV lines of the $2 \rightarrow 1$ transition at 274 and 275.6 nm have an integral intensity comparable with that of the bright $4 \rightarrow 3$ lines. Of course, the width of these lines is great because of the substantial optical density in the $2 \rightarrow 1$ transition and the corresponding resonance transfer radiation broadening. Resonance radiation trapping increases the effective lifetime of level 2, but still it remains much shorter than the lifetime of level 3 and does not prevent the formation of an inverted population in the $3 \rightarrow 2$ transition.

The present Letter is related with the problem of astrophysical lasers, considered in [14] and recently discovered [15] in other Fe II transitions around 1 μm in the same gas blob outside η Carinae as studied here. However, the new features in the present case compared to the case studied in [15] are the closed radiative cycle with stimulated emission transitions and the explanation of the two extremely bright UV lines. The astrophysical lasers discovered have no extreme brightness, but they transform very weak spectral lines of spontaneous emission to strong lines of stimulated isotropic radiation

having intensities comparable to the intensity of allowed spectral lines. In the saturation regime the intensity of an astrophysical laser is limited by the rate of optical pumping, i.e., the intensity of the pumping Ly α line and the subsequent fast spontaneous decay to the upper laser level. There is an essential difference between an astrophysical laser [14,15] and an astrophysical maser [16–18]. The maser has an extraordinary brightness and effective temperature of microwave radiation due to the conversion of an unobservable pumping (without involvement of weak spontaneous microwave emission) into observable stimulated maser radiation. The effect of a cycle with both spontaneous and stimulated radiation proposed in this Letter enhances greatly the efficiency of optical excitation and, hence, the intensity of the optical lines involved in the cycle.

In conclusion, let us emphasize that stimulated emission at optical and near-infrared wavelengths forming noncollisional, radiative cycling of atomic particles in astrophysical media gives a natural explanation to the anomalous behavior of spectral lines of two types: (i) The transformation of a very weak line from a pseudometastable state having a low transition probability A_{32} (line λ_{32} in Fig. 2) into a strong line with an intensity comparable to that of an allowed transition and (ii) the transformation of a normally intense line into an anomalously bright line (line λ_{43} in Fig. 2) due to radiative cycling, which is possible only if stimulated emission drives the weakest link in the cycle.

We thank T. Gull and K. Ishibashi for providing reduced HST/STIS data. V.S.L. acknowledges financial support through a grant (S.J.) from the Royal Swedish Academy of Sciences and Lund Observatory for hospitality. The research project is supported by a grant (S.J.) from the Swedish National Space Board.

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