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Laser action in a gas condensation in the vicinity of a hot star

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In the region around 1 μm we have found laser action in a quantum transition between highly excited states in Fe II, with its higher levels being optically pumped by the intense H Lyα radiation (1215 Å) formed in the ionized HII region of a gas condensation (blob B) in the close vicinity of the central star in η Carinae.

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Following the discovery of space microwave masers operating in the OH radicals [1] and H_2O molecules [2], such masers were found to be operative in more than 100 molecular species [3], as well as in highly excited hydrogen atoms [4] in the submillimeter wavelength region. In the IR region of the spectrum, the effect of stimulated emission of radiation in the CO_2 molecule was discovered in the Martian and Venus's atmospheres [5, 6]. In this letter, we report on the laser action in the optical region of the spectrum – a possibility that was discussed as far back as in 1972 [7].

The probability to find a laser effect in the optical region differs considerably from that in the microwave region as a result of the enormous difference (10^{15} to 10^{18} times) between the spontaneous emission rates and inverse population production mechanisms in the two wavelength regions. This follows from simple qualitative considerations of the steady-state saturation regime of the isotropic maser/laser action.

The stimulated emission of radiation in a space maser occurs as a result of the pumping of the upper maser level, which is not associated with spontaneous emission in microwave radiative transitions. It may therefore have a decay rate much in excess of the spontaneous emission rate, which lies in the region $A_{mn} \cong 10^{-9}–10^{-7}\,s^{-1}$. Therefore, the intensity of the stimulated radiation can be many orders of magnitude higher than the intensity of the spontaneous radiation and it is only limited by the pumping rate. This is exactly the reason why the brightness temperature of maser microwave lines reaches as high a value as $10^{10}–10^{15}$ K. The intensity of maser lines is not borrowed from other microwave spectral lines, which are very weak, but from other pumping sources.

In the optical region of the spectrum, the rate of allowed spontaneous transitions is high ($A_{mn} \cong 10^{8}–10^{9}\,s^{-1}$), and it is precisely spontaneous transitions that provide for the pumping of the upper level in an optical space laser at a sufficiently high rate to exceed the rates of collisional pumping mechanisms. This is especially true for the case considered here where the space laser is being indirectly pumped by H Lyα in the vicinity of η Car, one of the most luminous stars of our Galaxy. Therefore, the intensity of the stimulated radiation in the optical region generated by the occurrence of an inversion population and significant amplification cannot in the steady-state regime to any substantial extent exceed the intensity of the pumping spectral lines, formed by spontaneous emission in allowed radiative transitions of atoms or ions. This fact presents difficulties in detecting laser action by a large enhancement of the intensity of the radiation, but it should manifest itself in comparatively moderate changes of the branching ratios of spectral lines, having a common source of pumping.

One exception is the case of quantum transitions having a relatively low spontaneous emission probability ($A_{mn} \cong 1 - 10^5\,s^{-1}$), and consequently the spontaneous radiation lines are weak. Once an inverted level population has developed in such a transition with a significant amplification in a properly sized cloud, a stimulated emission channel opens up. The stimulated transition rate cannot be much higher than the spontaneous emission rate, which is limited by the pumping rate of the upper laser level. Thus, the intensity of the laser line should become comparable with the intensity of the lines, which are due to allowed spontaneous emission of radiation and resulting from the optical pumping (direct or indirect) of the upper level. This takes place only in the inverted population volume with size $L \gg 1/\alpha$, where α is the amplification coefficient per unit length. In such a case, a spectral line, expected to be weak, must appear as a spectral line of normal intensity, typical for an allowed transition. This is exactly what we have found to be the case with several spectral lines of Fe II pumped indirectly by the intense H Lyα radiation (1215 Å) in a dense gas condensation (blob) in the vicinity of η Car.

Using the Space Telescope Imaging Spectrograph (STIS) onboard the Hubble Space Telescope, the authors of [8] have recorded spectra of blob B in the vicinity of η Car in high angular and spectral resolution. The spectrum contains the intense 9997 Å line, as well as other Fe II lines at 9391, 9617, and 9913 Å, which can be excited by HLyα radiation in a cascade fashion [9] shown schematically in Fig.1. All these spectral lines have long-lived (from a few microseconds to a few milliseconds) upper states and a short-lived (3,7 ns) lower state, i.e., an inverted population always exists in these transitions. The gain by these inverted-population transitions is governed by the rate of photoexcitation of the upper levels by the HLyα radiation.

Photoselective pumping of Fe II by HLyα Radiation

Dense gas condensations (Weigelt blobs [10]) in the neighborhood of the luminous, blue variable (LBV) and massive star η Carinae are capable of absorbing all the photospheric radiation in the wide Lyman continuum region ($\lambda < \lambda_c = 912$ Å) incident upon them from the central star. This occurs because of the high Lyman-continuum optical density $\tau(\lambda_c)$ of the neutral hydrogen component in the ionized HII/HI region of the blob. Since the gas condensations are very close to the central star [11, 12], the density of the radiative energy deposited in them proves so high that the spectral brightness temperature $T_{br}(\text{Ly}\alpha)$ of the more narrow Lyα line at 1215 Å inside the blobs can be very high. The magnitude of $T_{br}(\text{Ly}\alpha)$ can become commensurable with that of the brightness temperature of the photosphere of η Car, $T_s = (20-30) \cdot 10^3$ K. This is a unique situation for the photoselective excitation of those atoms and ions whose absorption lines from the ground state or low-lying metastable states coincide with Lyα.

It is exactly such a situation that occurs for the Fe II ions formed in the HI region of the blob by complete photoionization of Fe I by the radiation from η Car in the spectral region $I_{\text{Fe}} = 7.6\,\text{eV} < h\nu < I_H = 13.6\,\text{eV}$. The concentration of iron in typical nebulae is about 0.01% of the hydrogen concentration. When Fe I undergoes photoionization, a substantial portion of the Fe II ions formed occupy low-lying long-lived metastable states with energies $E < I_{\text{H}} - I_{\text{Fe}} \approx 6\,\text{eV}$ as a result of decay from numerous autoionization states. There are about 90 such metastable and pseudo-metastable states in Fe II. Some of them have absorption lines coinciding in wavelength with the extremely bright spectral line Lyα.

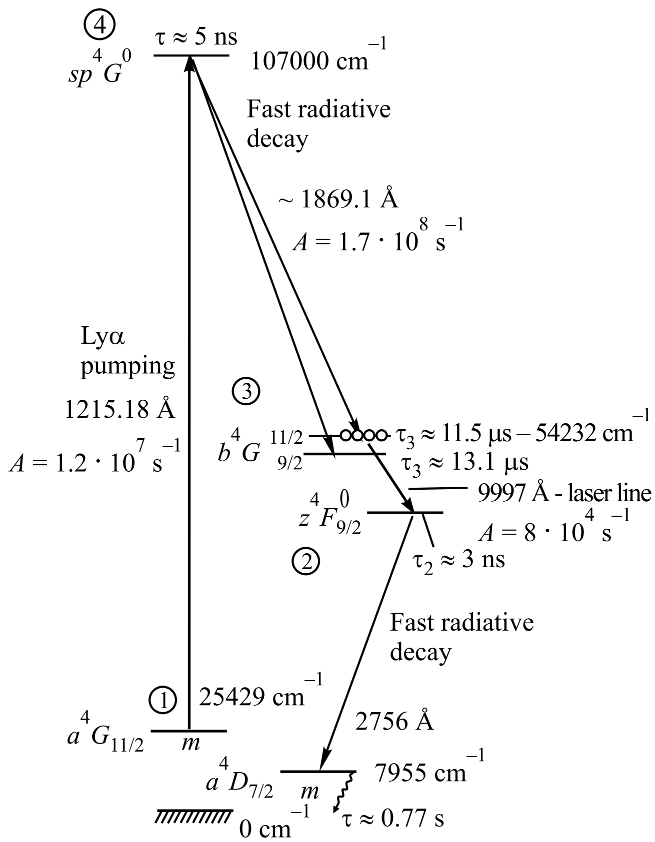

Fig.1. Schematic diagram of the relevant energy levels and radiative transitions of Fe II illustrating the formation of an inverse population of levels *3* and *2* and amplification in the transition *3* → *2* owing to the photoselective pumping of the level *4* by the intense Lyα radiation

The large number of low-lying long-lived states and the high density of spectral lines (≈ 15 lines/Å in the Lyα region) result in several such coincidences in Fe II. Several of them are similar to those shown schematically in Fig.1, which lead to photoselective excitation of energy levels in Fe II, and the subsequent cascading decay gives rise to population inversion.

The Lyα line at $\lambda = 1215.671$ Å almost coincides with the absorption line of Fe II in the transition $a^4G_{11/2}$ (level *1* in Fig.1) → sp^{4}G° (level *4*), the frequency difference (detuning) between them being $\Delta\nu = +30\,\text{cm}^{-1}$. This difference is compensated by the broadening of the line profile when the Lyα radiation is passing through the HI region with an optical density of $\tau \cong 3 \cdot 10^5$. Thus, the transfer broadening of the Lyα radiation makes the photoselective excitation of the state *4* in Fig.1 quite possible.

The photoselective excitation rate of state *4* is defined by the expression

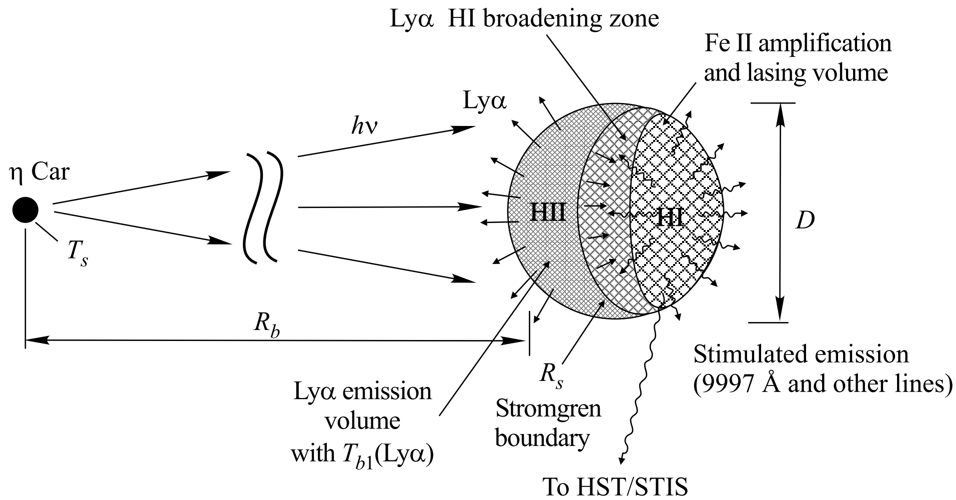

Fig.2. Physical model of the photoionization-resonance photoexcitation pumping of Fe II in the gas condensation by the radiation emitted by ηCar with a brightness temperature of T_s

$$W_{\rm exc}^{14} = A_{41}\left[\exp\left(\frac{h\nu_{14}}{T_{bl}}\right) - 1\right]^{-1}, \qquad (1)$$

where the indices 1 and 4 correspond to the level designations of Fig.1, $A_{41} = 1.2\cdot 10^7\,\mathrm{s}^{-1}$ is the Einstein coefficient for the spontaneous decay of state *4* to state *1*, and T_{bl} is the brightness temperature of the Lyα radiation inside the blob B. For $kT_{bl} \approx 1.0-1.5\,\mathrm{eV}$ ($T_{bl} \approx (12-18)\cdot 10^3\,\mathrm{K}$), the photoselective excitation rate $W_{\rm exc}^{14} \approx 10^3 - 10^4\,\mathrm{s}^{-1}$.

The main decay channel (branching fraction = 0.97) of state *4* is radiative transitions to two fine-structure levels of b^4G, one of which ($b^4G_{11/2}$ is level *3*) has a channel of spontaneous radiative decay with a probability of $A_{32} = 8\cdot 10^4\,\mathrm{s}^{-1}$ to level *2* ($z^4F^0_{9/2}$) with a much shorter lifetime ($\approx 3\,\mathrm{ns}$). It is exactly in this $3\to 2$ transition that a steady-state population inversion is reached, its density being

$$\Delta N = N_3 - N_2 = N_3 = (W_{\rm exc}^{14}\tau_3)N_1, \qquad (2)$$

where $N_2 \ll N_3$ because of the much faster decay of the level *2*, $\tau_3 = 11.5\,\mu\mathrm{s}$, and N_1 is the population of the initial metastable state with a lifetime of $\tau_1 = 0.77\,\mathrm{s} \gg \tau_3$.

The linear amplification coefficient for the $3\to 2$ transition at 9997 Å is defined by the standard expression

$$\alpha_{32} = \sigma_{32}\Delta N, \qquad (3)$$

where ΔN is the inverted population density defined by Eqn. (2). The stimulated emission cross section σ_{32} is given by

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

where $\Delta\nu_D$ is the Doppler width of the $3\to 2$ transition in Fe II. At a temperature of $T \approx 100-1000\,\mathrm{K}$ in the relatively cold HI region, $\Delta\nu_D \approx (300-1000)\,\mathrm{MHz}$, i.e., $\sigma_{32} = (0.6-2)\cdot 10^{-13}\,\mathrm{cm}^2$. Thus, the amplification coefficient may be estimated by the expression

$$\alpha_{32} = \alpha_{32}(W_{\rm exc}^{14}\cdot\tau_3)f\cdot N_0, \qquad (5)$$

where f is the fraction of the Fe II ions in their initial state relative to all Fe II ions (all the iron atoms in the HI region of the blob are ionized).

The fraction f is governed by the excitation rate of the level *1* and its lifetime τ_1. The rates of the collisional excitation mechanisms of the level *1* (i.e., the recombination of the Fe^{2+} ions and electron collisional excitation) are negligible in comparison with the decay rate $1/\tau_1$ of the state *1* because of the low electron concentration in the HI region ($n_e \cong 10^4 - 10^5$ due to the photoionization of iron, as well as other elements with an ionization potential of $I < 13.6\,\mathrm{eV}$). Most important for the laser action observed are the following radiative channels: (1) the radiative decay of the high-lying states of Fe II excited by the Lyα or other intense radiation lines and (2) the decay of the autoionization states of Fe I excited by the radiation emitted by η Car in the spectral region $I_{\rm Fe} + E_1 = 10.6\,\mathrm{eV} < h\nu < 13.6$ eV, where E_1 is the energy of the state *1*. These excitation channels can provide for an excitation rate $> 1/\tau_1 \approx 1\,\mathrm{s}^{-1}$ and hence sustain the relative population of the state *1* at a level, for example, of $f \approx 10^{-2}$. This would correspond to an approximately equal distribution of the Fe II ions among their 90 metastable and pseudo-metastable states, including the state *1*. Leaving the calculation of the magnitude of the fraction f for the future consideration, we will restrict ourselves here to the qualitative estimate of $f \approx 10^{-2}$.

In this approximation, the amplification coefficient for the transition $3 \to 2$ may be estimated, according to Eqn.(5), as $\alpha_{32} \approx (3 \cdot 10^{-18}$ to $10^{-16}) N_0\,[\mathrm{cm}^{-1}]$, where $N_0 \approx 10^{-4} N_{\mathrm{H}}$ is the density of the Fe atoms, N_{H} being the density of the hydrogen atoms in the blob. According to the data presented in [11] and the results of a calculation of the critical density of hydrogen atoms [13], the density N_{H} of the hydrogen atoms in the blob is obviously higher than $10^8\,\mathrm{cm}^{-3}$. Thus, for $\alpha_{32} \geq 3 \cdot 10^{-14}{-}10^{-12}\,\mathrm{cm}^{-1}$ and a blob diameter $D \approx 10^{15}\,\mathrm{cm}^{-3}$ [11], which can be regarded as the size L of the amplifying region (Fig.2), $\alpha L \approx (30{-}1000)$ at a blob temperature of $T_{bl} = (12$ to $18) \cdot 10^3\,\mathrm{K}$.

These numbers correspond to fairly high linear amplification coefficients $K = \exp(\alpha L)$. However, at an amplification coefficient of $K \approx A_{41}/A_{32} \approx 10^3$ for an isotropic radiation, the intensity of the weak line λ_{32} (in photons/cm^2·s) approaches that of the strong line λ_{43}, i.e. the rate of stimulated transition approaches the pumping rate of level *3*. Thereafter, the amplification regime becomes saturated, and the intensity of the laser line λ_{32} becomes equal to that of the pumping line λ_{43}. Under such saturated amplification conditions the intensities of both these lines grow in proportion to the propagation length L.

We believe that laser amplification and stimulated emission of radiation is a fairly common and widespread phenomenon, at least for gaseous condensations in the vicinity of bright stars. This is due to the occurrence of two types of processes (fast radiative and slow collisional) in the very rarefied gas of the condensations, whereby the populations of electronic levels in atoms (ions) can relax. These relaxation processes occur on highly different time scales, radiative relaxation operating on a time scale of $10^{-9}{-}10^{-3}\,\mathrm{s}$ (sometimes even within $10^{-3} - 1\,\mathrm{s}$), and collisional relaxation on a time scale of over 100 s (at gas densities $< 10^9\,\mathrm{cm}^{-3}$). In the case of photoselective excitation of some high-lying levels of an atom or ion with a complex energy-level structure, radiative relaxation takes place as a consequence of downward transitions with spontaneous emission of radiation, in the course of which there inevitably develops an inverse population of some pair (pairs) of levels. If the size of a gas cloud is large enough, large amplification of the inverted-population transition automatically switches on the radiative relaxation channel, which leads to faster stimulated quantum transitions until collisional relaxation becomes important. Thus, the laser action is an intrinsic characteristic of the radiative cooling of gas clouds near bright stars by stimulated emission for inverted transitions along with spontaneous emission for normal non-inverted transitions.

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