final compression stage. This sets limits on the plasma parameters, both in density and in temperature ('smearing' them and mixing the material), in comparison with those which would be expected under ideal cumulation.

The above circumstances cast some doubt upon the correctness of choosing this line of implementing ignition. This brings up the natural question: is it warranted to expend so highly organized a form of energy as laser radiation for a 'brute-force' approach? That is why I believe that alternative schemes and techniques should be contrived, which may prove to be more efficient.

I feel certain that the last word in the field under discussion has not yet been uttered and there exist routes that lead beyond the province of the scheme now being elaborated. A long time ago, we considered at the P N Lebedev Physics Institute (Moscow) the possibility of directly heating frozen DT, enclosed in a heavy shell, with the aid of a short laser pulse fed through tiny openings in the shell. Later on there emerged proposals for a target design which has come to be known as a 'greenhouse', wherein laser radiation is delivered to a low-density material layer. Lastly, six years ago scientists (including scientists from our P N Lebedev Physics Institute) came up with the idea that the processes of compression and heating should be 'separated'. This approach is now referred to as 'fast ignition' and implies the ignition of a compressed target with a very short, well-focused laser pulse. The latter deserves attention and invites thorough investigation, especially so because it involves new physics, though with a yet uncertain outcome.

The heart of the concept developed at LLL (Livermore) is as follows. For extremely high flux densities, in a thin channel through which laser radiation is propagated, one might expect the formation of conditions that favor a deep penetration of the light energy into the above-critical high-density plasma.

It is anticipated that electrons together with ions would be forced out of the light beam due to the ponderomotive forces directed opposite to the gradient of the laser field amplitude squared. Furthermore, a tremendous force also acts on the electrons in the longitudinal direction. There forms a reduced-density channel (the so-called self-focusing) and it is reasonable to expect that the density would be subcritical and the energy would be delivered to the dense precompressed target core. The absorbed light energy would heat the material, thus causing ignition.

This concept is now being experimentally investigated in model conditions. The fundamental fact discovered is the production of a large number of fast electrons with energies ranging into the hundreds of kiloelectron-volts, which are ejected from the field localization region. These data, however, are as yet insufficient for a definitive prediction.

The optimistic view on the solution of the LF problem may, I belive, be based upon the fact that we are witnessing an impetuous (without exaggeration) advancement in generation techniques of high-power laser radiation. Two fundamental advances were made in this field approximately five-to-six years ago, which will undeniably have a strong impact on the future development of the LF program as well as on other fields of laser application. I have in mind, first, the implementation of semiconductor pumping (by means of injection semiconductor lasers) of crystal and glass lasers. It is likely that the total efficiency will be as high as 30 – 35%, and this has already been reached at a level of several kilowatts of continious wave (CW) output power.

Second, it has been possible to realize the mode of ultrashort (femtosecond range) pulse lasing. Few-cycle laser pulses have been produced (few wavelengths in space). Furthermore, impressive energy flux densities were produced in the focal region — up to 10^{18} W cm^{-2}. The feasibility of designing a laser facility with an energy ranging into the hundreds of kilojoules and a pulse duration of several tens-to-hundred femtoseconds is being considered in all seriousness!

Should these projects be realized, the LF program will have unique instruments at its disposal, which would call for a reconsideration of present-day approaches and invite the development of new ideas. One possibility involves going over to ultrarelativistic conditions, when the energy of electron oscillations in the electric field exceeds mc^2. This occurs at energy flux densities higher than 10^{18} W cm^{-2} (for radiation with a wavelength of 1 μm). Under ultrarelativistic conditions the plasma oscillation frequency decreases with an increase in the electron 'mass', resulting in the plasma transparence cutoff shift to higher densities. Moreover, the response of the medium becomes strongly nonlinear, which should be accompanied by rescattering of the laser radiation to high-order harmonics. In any case, going over to a very short pulse duration would allow a more efficient employment of laser radiation energy.

Needless to say that the above considerations are not a simple prediction for the future, but I have been greatly impressed by the fact that 42 years after the first implementation of optical lasing we are witnessing a major 'breakthrough' in the realm of practical laser applications. When did optical fiber communication lines make their appearance? When did compact disks emerge, which ousted mechanical and magnetic recording? Or semiconductor-pumped lasers, which have found use in various technologies? and so on. We have seen all this in recent years, and the results have been achieved owing to the combination of new ideas and technologies. That is why I believe that unexpected and maybe quite simple solutions will emerge in the realm of laser fusion.

PACS numbers: **42.55.–f**, **97.20.–w**
DOI: 10.1070/PU2002v045n12ABEH001326

Lasing in space

V S Letokhov

Lasing in a CW mode is implemented under selective or preferential excitation of any appropriate excited quantum level, resulting in disturbance of the equilibrium with the production of inverse population and amplification. With positive feedback, the active medium transforms to a laser [1], but in the absence of the feedback it remains a laser amplifier of both its intrinsic spontaneous radiation and an external light signal. Though making a pulsed-mode laser proved to be an easier task than making a CW laser [2], in the astrophysical conditions of an interstellar medium (nearstellar medium, stellar atmosphere) all characteristic equilibrium-disturbance times are much longer than the characteristic relaxation times for level populations of a quantum system (atom, ion, molecule). That is why in astrophysical conditions the case in point is possible in a CW mode of a maser or laser.

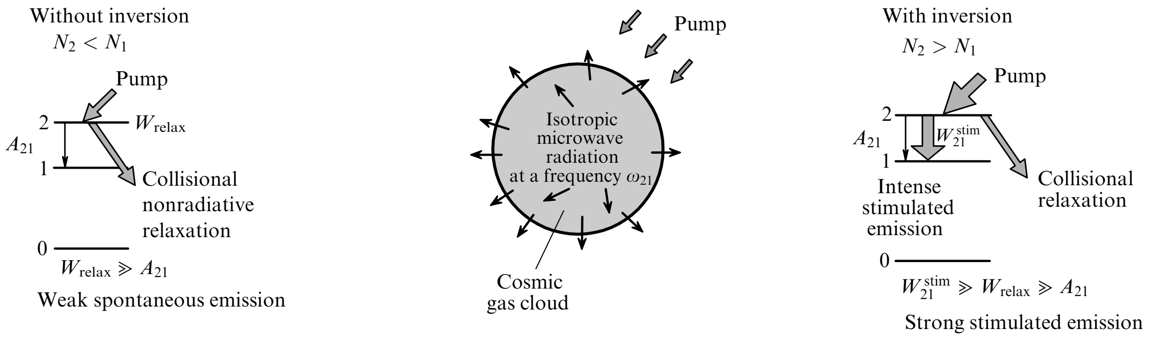

Figure 1. Passage from the mode of weak isotropic spontaneous emission in a medium without inversion (left) to the mode of strong isotropic stimulated emission in a medium with inversion (right) in the microwave case.

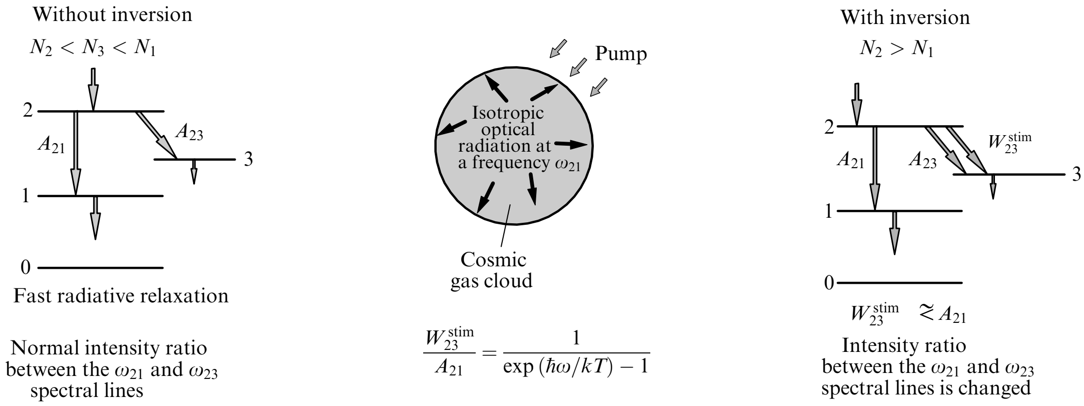

Figure 2. Passage from the mode of isotropic spontaneous emission in a medium without inversion (left) to the mode of isotropic spontaneous and isotropic stimulated emission in a medium with inversion (right).

Following the discovery of OH-radical [3] and H_2O-molecule [4] space microwave masers, the same masers were discovered to utilize more than 100 molecules [5], and then a maser radiation from highly excited hydrogen atoms was detected in the millimeter range [6]. In the IR spectral range (10 μm), the stimulated emission of the CO_2 molecule was observed in the atmospheres of Mars and Venus [7, 8]. Quite recently, lasing on the transitions of the FeII ion was discovered in gas condensations in the neighborhood of *Eta Carinae* [9] — the brightest and most massive star in our Galaxy.

It has been a rather long time since the laser effect in stellar atmospheres was proposed [10], but for two reasons lasing is much harder to discover than the maser effect. First, it manifests itself less clearly than the maser effect. Second, it is more likely to occur in the neighborhood of a star, where the rate of selective excitation of a particular quantum level becomes comparable with the relaxation rate of the metastable levels of a quantum system. That is why lasing is hard to observe against the background of the photospheric radiation of the star itself. Indeed, stimulated microwave radiation has a high brightness temperature owing to the conversion of unobservable collisional pumping to the radiation undergone without participation in the pumping process of extremely weak lines of spontaneous microwave radiation (Fig. 1). In the optical range, the most likely mechanism of selective excitation of a certain level is the presence of strong spontaneous emission lines of another element (accidental Bowen coincidence [11]). That is why the intensity of stimulated emission cannot exceed the intensity of spontaneous emission which affects the pumping. This is the specific feature of stimulated laser emission into an angle of 4π sr in an astrolaser, which distinguishes it from the stimulated emission of a laboratory laser into a narrow solid angle defined by the design of the optical resonator. The laser effect in astrophysical conditions makes itself evident in the fact that a weak spontaneous emission line arising from a transition with a small value of the Einstein coefficient A_{21} comes, due to inversion and amplification, to be a strong stimulated emission line comparable in intensity to the strong spontaneous emission line of the pump transition (Fig. 2). This is precisely the circumstance which determines the strategy of the search for lasing. As for the observation of the lines emitted by the gas medium in the vicinity of the star separately from the photospheric stellar emission, it became possible quite recently, after putting into operation the Hubble space telescope (HST) possessing an 0.1-arcsecond angular resolution. With the aid of a special spectrograph (STIS), this telescope makes it possible to study spectra in a broad spectral range (1640 – 10300 Å) [12].

In the neighborhood of the Eta Carinae star, it has been possible to discover gas condensations (GCs) [13] with a hydrogen number density of no less than 10^8 cm^{-3}, located rather close (within several hundred stellar radii) from the star and therefore exposed to a strong VUV radiation of the star with a photospheric temperature $T_{ph} \simeq 30{,}000$ K. Due to the high hydrogen density, the Lyman continuum radiation ($\lambda < 912$ Å) is completely absorbed in the front part of the GC through the photoionization of hydrogen (Fig. 3), and approximately 70% of this radiation is reradiated at a

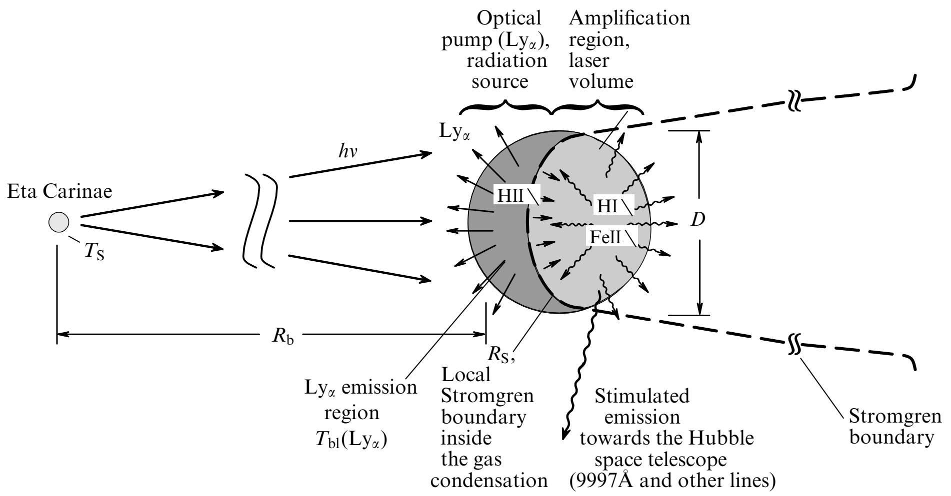

Figure 3. Photophysical model of compact gas condensation (GC) in the neighborhood of the hot bright Eta Carinae star with a local Stromgren boundary between the photoionized HII and neutral HI domains inside the GC (borrowed from Refs [9, 15]).

wavelength $\lambda = 1215$ Å (the Ly_α-line) in the course of recombination. This monochromatic radiation is strongly broadened during the radiative transfer in the optically thick medium of the GC and is capable of exciting several quantum transitions of the FeII ion in the nonionized (rear) part of the GC, as is shown in Fig. 3. The FeII ions arise due to the photoionization by stellar radiation in the $\lambda > 912$ Å range, which passes unimpeded through the photoionized front part of the GC (see Fig. 3).

The excitation of the $1 \to 4$ transition in FeII by the Ly_α radiation at $\lambda = 1215.671$ Å is diagrammed schematically in Fig. 4a [14]. The frequency mismatch is only $\Delta\nu = +30$ cm^{-1} and is compensated for by the strong Ly_α broadening (up to 300 cm^{-1}) in the course of radiative transfer. The principal decay channel of state 4 is the radiative decay to state 3 which has a relatively small value of the coefficient $A_{31} \simeq 8 \times 10^4$ s^{-1}. Since level 2 decays very fast (Fig. 4a) and level 3 is the 'bottleneck' of the radiative relaxation of highly excited FeII, there always exists population inversion on the $3 \to 2$ transition. According to simple estimates in the context of the model of the GC photoprocesses in the vicinity of Eta Carinae considered in Ref. [15], the gain coefficient at $\lambda \simeq 9997$ Å is $\alpha \simeq 3 \times 10^{-14} - 10^{-12}$ cm^{-1}. For a GC diameter $D \simeq 10^{15}$ cm, the gain-length product is $\alpha D \simeq 30 - 1000$, i.e., the linear amplification factor is very large. However, in reality the intensity of the weak $3 \to 2$ line rises only by a factor $A_{41}/A_{32} \simeq 10^3$ (in the number of photons per unit area per unit time) owing to the amplification saturation. It is precisely this effect that has been observed for several weak lines of FeII according to the data of Refs [14, 16].

Laser amplification and stimulated emission in the optical range are likely to be widely occurring processes in gas media in the vicinity of bright stars. They emerge due to the specific features of relaxation of excited electron energy levels of atoms (ions) in a rarefied nearstellar gas. The relaxation processes have various characteristic times (Fig. 4b). The radiative relaxation due to spontaneous emission proceeds in a time of $10^{-9} - 10^{-3}$ s (sometimes even $10^{-3} - 1$ s), while the collisional relaxation proceeds in a time of over 100 s (for a gas number density below $< 10^9$ cm^{-3}). In the case of selective excitation of an atom (ion) with a complex structure of electron energy levels, the spontaneous radiative relaxation is realized without participation of collisions, in a purely radiative way, in an isolated atom (ion) to produce population inversion on a particular level pair due to the 'bottleneck' effect. When the GC dimension is large enough to afford a

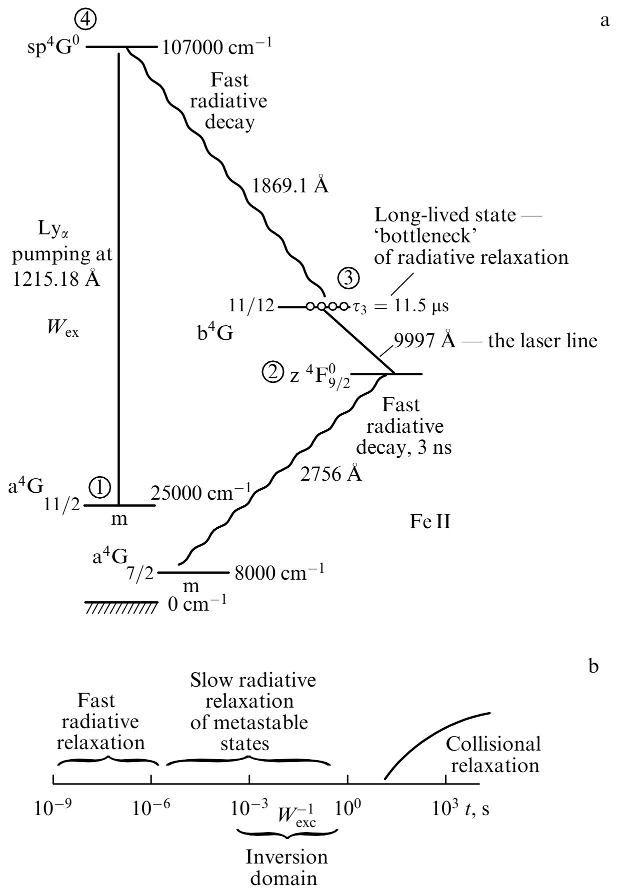

Figure 4. The origin of the population inversion on the $3 \to 2$ transition of FeII due to the resonance photoexcitation of the high level 4 and its subsequent cascade radiative decay to the long-lived 'pseudo-metastable' level 3 (the 'bottleneck' of radiative decay): (a) diagram of the levels and transitions pertaining to inversion production, and (b) characteristic radiative and collisional relaxation times of excited FeII levels (borrowed from Refs [9, 14]).

significant amplification factor on the inverted transition, there comes into effect the mechanism of a faster radiative relaxation arising from stimulated emission. Therefore, the laser effect is a mechanism of radiative cooling due to stimulated GC emission on inverted transitions in parallel with spontaneous emission on ordinary transitions without population inversion.

The effect of resonance scattering in an amplifying medium can lead to the lasing mode reliant on an incoherent (nonresonator) energy feedback [17]. For astrophysical masers and lasers, this mode was considered in Ref. [18].

References

1. Schawlow A L, Townes C H *Phys. Rev.* **112** 1940 (1958)
2. Maiman T H *Nature* **187** 493 (1960)
3. Weinreb S et al. *Nature* **206** 440 (1965)
4. Cheung A C et al. *Nature* **221** 626 (1969)
5. Townes C H *Kvantovaya Elektron.* **24** 1063 (1997) [*Quantum Electron.* **27** 1031 (1997)]
6. Strelnitski V et al. *Science* **272** 1459 (1996)
7. Johnson M A et al. *Astrophys. J. Lett.* **208** L145 (1976)
8. Mumma M J et al. *Science* **212** 45 (1981)
9. Johansson S, Letokhov V S *Pis'ma Zh. Eksp. Teor. Fiz.* **75** 591 (2002) [*JETP Lett.* **75** 495 (2002)]
10. Letokhov V S *IEEE J. Quantum Electron.* **QE-8** 615 (1972); Lavrinovich N N, Letokhov V S *Zh. Eksp. Teor. Fiz.* **67** 1609 (1974) [*Sov. Phys. JETP* **40** 800 (1975)]
11. Bowen I S *Astrophys. J.* **81** 1 (1935)
12. Kimble R A et al. *Astrophys. J.* **492** L83 (1998)
13. Weigelt G, Ebersberger J *Astron. Astrophys.* **163** L5 (1986)
14. Johansson S et al., in *Eta Carinae and Other Mysterious Stars: the Hidden Opportunities of Emission Line Spectroscopy* (ASP Conf. Ser., Vol. 242, Eds T R Gull, S Johansson, K Davidson) (San Francisco, Calif.: Astron. Soc. of the Pacific, 2001) p. 297
15. Johansson S, Letokhov V S *Astron. Astrophys.* **378** 266 (2001)
16. Gull T R et al., in *Eta Carinae and Other Mysterious Stars: the Hidden Opportunities of Emission Line Spectroscopy* (ASP Conf. Ser., Vol. 242, Eds T R Gull, S Johansson, K Davidson) (San Francisco, Calif.: Astron. Soc. of the Pacific, 2001) p. 391
17. Letokhov V S *Zh. Eksp. Teor. Fiz.* **53** 1442 (1967) [*Sov. Phys. JETP* **26** 835 (1968)]
18. Letokhov V S, in *Amazing Light: A Volume Dedicated to Charles Hard Townes on His 80th Birthday* (Ed. R Y Chiao) (Berlin: Springer-Verlag, 1996) p. 409