LASER ACTION IN NON-LTE ATMOSPHERES

by

Donald H. Menzel

Harvard College Observatory
and
Smithsonian Institution Astrophysical Observatory

ABSTRACT

The radiative transfer equation is written in microscopic form, and from some simplifications on the ratio of occupation numbers for upper and lower level, a laser action is suggested.

Key words: radiative transfer, laser action.

I like to write the equation of radiative transfer for line absorption in a plane-parallel atmosphere in the following exact form:

$$\mu \frac{dI}{dr} = -\left(n_1 - n_2 \frac{\tilde{\omega}_1}{\tilde{\omega}_2}\right) I\alpha + \frac{2h\nu^3}{c^2} \; n_2 \frac{\tilde{\omega}_1}{\tilde{\omega}_2} \alpha \; , \qquad (1)$$

where I is the specific intensity and α is the atomic absorption coefficient at frequency, ν. The quantities n_1 and n_2 are the atomic populations of the lower and upper levels, whose respective statistical weights are $\tilde{\omega}_1$ and $\tilde{\omega}_2$.

In thermodynamic equilibrium, a single parameter, the absolute temperature T, governs the Boltzmann and Planck formulas, so that

$$\frac{n_2}{n_1} = \frac{\bar{\omega}_2}{\tilde{\omega}_1} e^{-h\nu/kT} \text{ and } I = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \; . \qquad (2)$$

When these equations are substituted into (1) the right-hand side vanishes, as it must for thermodynamic equilibrium, since the intensity is isotropic and independent of position.

In equation (1), the second term in the parenthesis represents the stimulated emission or, as it should more properly be called, the negative absorption. Too many astrophysicists either combine it with the random emission, the second term on the right-hand side, or neglect it altogether. The true source function takes the form of the second term on the right-hand side of (1), which in no sense resembles a Planck function except when $h\nu >> kT$.

The quantities n_1 and n_2 are to be calculated from the equations of statistical equilibrium, which involve collisional excitation and de-excitation as well as radiational processes.

Many years ago, in problems related to gaseous nebulae, I introduced a dimensionless parameter, b, to indicate the degree of departure of a gas from thermodynamic equilibrium at temperature T of the electron gas. This parameter equalled unity for thermodynamic equilibrium. Thus I could write

$$\frac{n_2}{n_1} = \frac{b_2\bar{\omega}_2}{b_1\tilde{\omega}_1} e^{-h\nu/kT} \qquad (3)$$

with which expression (1) becomes

$$\frac{dI}{dh}\cos\theta = -n_1\alpha\left[\left(1 - \frac{b_2}{b_1} e^{-h\nu/kt}\right)I + \right. \left. + \frac{2h\nu^3}{c^2}\frac{b_2}{b_1} e^{-h\nu/kT}\right] \qquad (4)$$

As long as $h\nu/kT >> 1$, we can usually neglect the term representing the stimulated emissions. And, as long as b_2/b_1 does not depart too far from unity, the second term on the right-hand side is approximately equal to the source function.

Many studies have shown that the b's exhibit the following behavior for nebulae and, presumably, also for stars with highly distended atmospheres. First of all, b's for ground or metastable levels

https://doi.org/10.1017/S025292110015122X Published online by Cambridge University Press

tend to be high. Second, the first excited levels directly above the ground level tend to have b's much less than unity. Third, the b's for still higher levels slowly tend to unity at the series limit.

For all lines except those from the ground or metastable levels, then, b_2/b_1 will exceed unity. And when the temperature is high enough, the stimulated emission may exceed the ordinary absorption so that

$$\frac{dI}{dh}\cos\theta \sim n_1\alpha \frac{b_2}{b_1} e^{-h\nu/kT}\left(\frac{2h\nu^3}{c^2} + I\right) \quad . \qquad (5)$$

Since this term is essentially positive, the emission line increases in intensity with depth.

This process is truly a laser action, analogous to those responsible for the high-level radio emission of atomic hydrogen. I believe this process can explain many of the anomalies referred to by Miss Underhill as occurring in stars of exceptionally high temperatures.

The process is self-limiting, however, since an increase in the intensity of the incident radiation causes the medium to approach local thermodynamic equilibrium. However, as long as the energy is "diluted," some sort of laser action will occur.

DISCUSSION

Hearn: It is important to know the electron density. In the case of the higher levels you get an equilibrium distribution because of electron collisions. If the electron density is large enough even the lower levels will have a Boltzmann population. For the lower levels the spontaneous emissions are much more important than the induced emissions. In the case of Hα the induced emission is very small. If the electron density is of the order 10^{10} or 10^{12} the lower levels follow the Boltzmann distribution and there is no induced emission at all.

Menzel: There is a cooling effect by forbidden

https://doi.org/10.1017/S025292110015122X Published online by Cambridge University Press

transitions, which will also cause strong deviations from LTE.

Underhill: In the main part of the atmospheres of WR stars, the electron densities are of the order of 10^{11} to 10^{12} and the electron temperatures are of the order of 30000° to 50000° K. These values are not suitable for efficient laser action, which you have described.

Rybicki: To my knowledge, no non-LTE solutions in multi-level atoms have shown inverted populations for stellar atmospheres extended or not, even when stimulated emissions have been properly included. Of course one should always be aware of this possibility, since, if it occurs, it can be a dominant effect in the formation of the spectrum. It should be noted that any laser action will build up intensities that will tend to destroy the action by returning the population ratios to their normal order. This is particularly true in a strict plane-parallel atmosphere where any negative opacity in a region between two planes would build up infinite intensities, since infinite path lengths exist within the negative opacity region.