# THE CONTINUOUS SPECTRUM OF HYDROGEN IN A LOW-DENSITY ENVELOPE

by

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## ABSTRACT

A progress report on theoretical work on the formation of a continuum in low-density stellar envelopes. Preliminary results are given on a comparison between the recombination case and the case for a semi-empirical approach including the effect of collisions from the ground state.

Key words: recombination case, collisional excitation, low-density envelope.

This note is a progress report on the theoretical work concerning the problem of formation of the continuum in low density stellar envelopes excited essentially by collisions. By low density envelope is meant an envelope in which emission lines are formed.

When collisions are important for ionization and excitation essentially two facts must be considered, which may give the following significant differences with respect to the normal radiative recombination theory:

(1) the metastable level of hydrogen, 2s, may be

populated directly from the ground level, which is by far the most populated level in typical nebular conditions. This is the difference with respect to the solely radiative excitation situation, when the 2s level may be reached only from the upper levels;

(2) for the same values of electron temperature and density, the product of the electron density and neutral hydrogen concentration is much higher in the collisional case than in the radiative case.

These facts lead one naturally to consider the effects of two emission processes:

(i) the two-photon continuous emission in the decay of the 2s level;

(ii) the continuous emission in the reaction for the formation of the negative hydrogen ion.

The effect of two-photon emission in the case of pure collisional excitation was studied by the authors in a previous paper (Gerola and Panagia, 1968), with the usual approximation of cases A and B due to Baker and Menzel (1938).

If the degree of ionization is considered, it is found that, for the same values of electron density and electron temperature, the ionization in the collisional case is smaller than in the radiative case. This fact opens the possibility that another process may lead to an important contribution to the continuous spectrum only in the collisional excitation case: this process is the continuous emission in the reaction for the formation of the negative hydrogen ion. The rate of this reaction is proportional to the product of electron density and neutral hydrogen density and this product is larger in envelopes when collisions are responsible for ionization. It is to be expected that the efficiency of this process will be greater at temperatures lower than $10^4$°K.

Greenstein and Page (1951) found that $H^-$ emissivity is unimportant for planetary nebulae; it should be remembered that typical planetary nebulae seem to be definitely radiatively excited.

It has been verified that in low density conditions an abundance of $H^-$ ions high enough to give a finite opacity for the continuum of the Balmer and higher series and to modify the neutrality condition is never reached. What is found instead is that the $H^-$ concentration is of the order of $10^{-7}N_e$ and can therefore be neglected.

So the continuum is simply the sum of recombination plus two-photon plus $H^-$ free-bound emission.

To see the problem, let us write the statistical equilibrium equation for the levels with $n \geq 3$ in the form:

$$\sum_{n''=n+1}^{\infty} F_{n''n} + \int_{\nu}^{\infty} F_{kn} d\nu + \mathcal{H}\,\mathfrak{F}^{*}_{1n} + F_{1n} = \sum_{n'=1}^{n-1} F_{nn'}$$

where $\sum_{n''=n+1}^{\infty} F_{n''n}$ is the radiative cascade rate from upper levels to level n;

$\int_{\nu_n}^{\infty} F_{kn} d\nu$ is the recombination rate from the continuum;

$\mathfrak{F}^{*}_{1n}$ is the collisional rate of excitation from ground level for the pure collisional case;

$F_{1n}$ is the radiative rate of excitation from ground level,

and $\sum_{n'=1}^{n-1} F_{nn'}$ is the radiative rate of decay from level n.

Now we shall discuss the $\mathcal{H}$ factor, which was introduced in 1953 by Chamberlain in his first study of the collisional Balmer decrement, where it was pointed out that all intermediate cases between $\mathcal{H} = 0$ and $\mathcal{H} = 1$ are physically possible. This factor assumes the value 0 in the radiative case and 1 in the collisional case and represents the amount of collisional ionization from ground level relative to the total amount of ionization.

In reality a combination of the two excitation mechanisms is possible and the effective value of $\mathcal{H}$ depends not only on the present geometry and the ultraviolet radiation field, but also on the past history of the system nebula plus the exciting star. So, for example, the envelope of a star that has recently flared actually has an energy input due to the present radiation of the star and to the energy

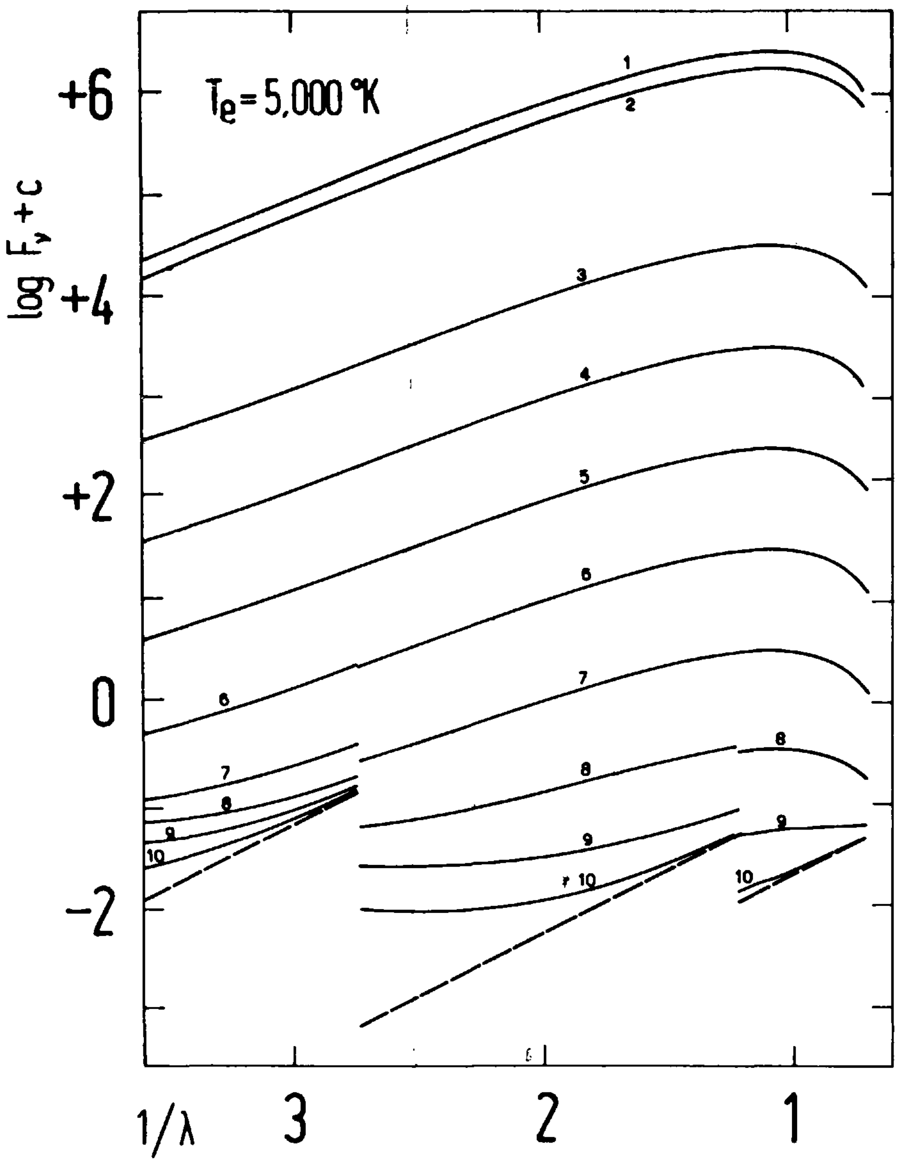


*Figure 1.* The dashed curve represents the recombination spectrum; for the other continua (solid lines) the number attached to each curve refers to the values of $\mathcal{H}$ which are listed in Table 1. All the continuous spectra were computed for $N_e = 10^4$ cm$^{-3}$ and $R = 10^{16}$ cm.



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TABLE 1.

VALUES OF $\mathcal{H}$

| Number of the curve | 5000 (Fig.1) | 10000 (Fig.2) | 20000 (Fig.3) |
|---|---|---|---|
| | $T_e$ (°K) | | |
| 1 | $1.00 \times 10^{0}$ | $1.00 \times 10^{0}$ | $1.00 \times 10^{0}$ |
| 2 | $6.67 \times 10^{-1}$ | $6.21 \times 10^{-1}$ | $5.70 \times 10^{-1}$ |
| 3 | $1.22 \times 10^{-1}$ | $2.01 \times 10^{-1}$ | $1.26 \times 10^{-1}$ |
| 4 | $1.22 \times 10^{-2}$ | $2.01 \times 10^{-2}$ | $1.26 \times 10^{-2}$ |
| 5 | $1.22 \times 10^{-3}$ | $2.01 \times 10^{-3}$ | $1.26 \times 10^{-6}$ |
| 6 | $1.22 \times 10^{-4}$ | $2.01 \times 10^{-6}$ | —— |
| 7 | $1.22 \times 10^{-5}$ | $2.01 \times 10^{-10}$ | —— |
| 8 | $1.22 \times 10^{-6}$ | —— | —— |
| 9 | $1.22 \times 10^{-7}$ | —— | —— |
| 10 | $1.22 \times 10^{-10}$ | —— | —— |

injected into the envelope by the recent flare of the star. Only a detailed model of the evolution of this system would permit the determination of $\mathcal{H}$ from other physical parameters. We have chosen an empirical approach, being interested here on the actual appearance of the continuum, that is in the spectroscopic problem; so $\mathcal{H}$ was let free to run as an independent parameter, and the computed spectra were compared with observations.

A detailed description of the calculations will be found in a paper that will be published soon.

Figures 1, 2 and 3 represent some computed continua for different values of electron temperature. Dashed curves correspond to the recombination spectrum while the other curves represent the total continuum for the values of $\mathcal{H}$ given in Table 1.

It is to be noted that even with a small value of $\mathcal{H}$ the behaviour of the continuum is very different from the pure recombination spectrum. This is so

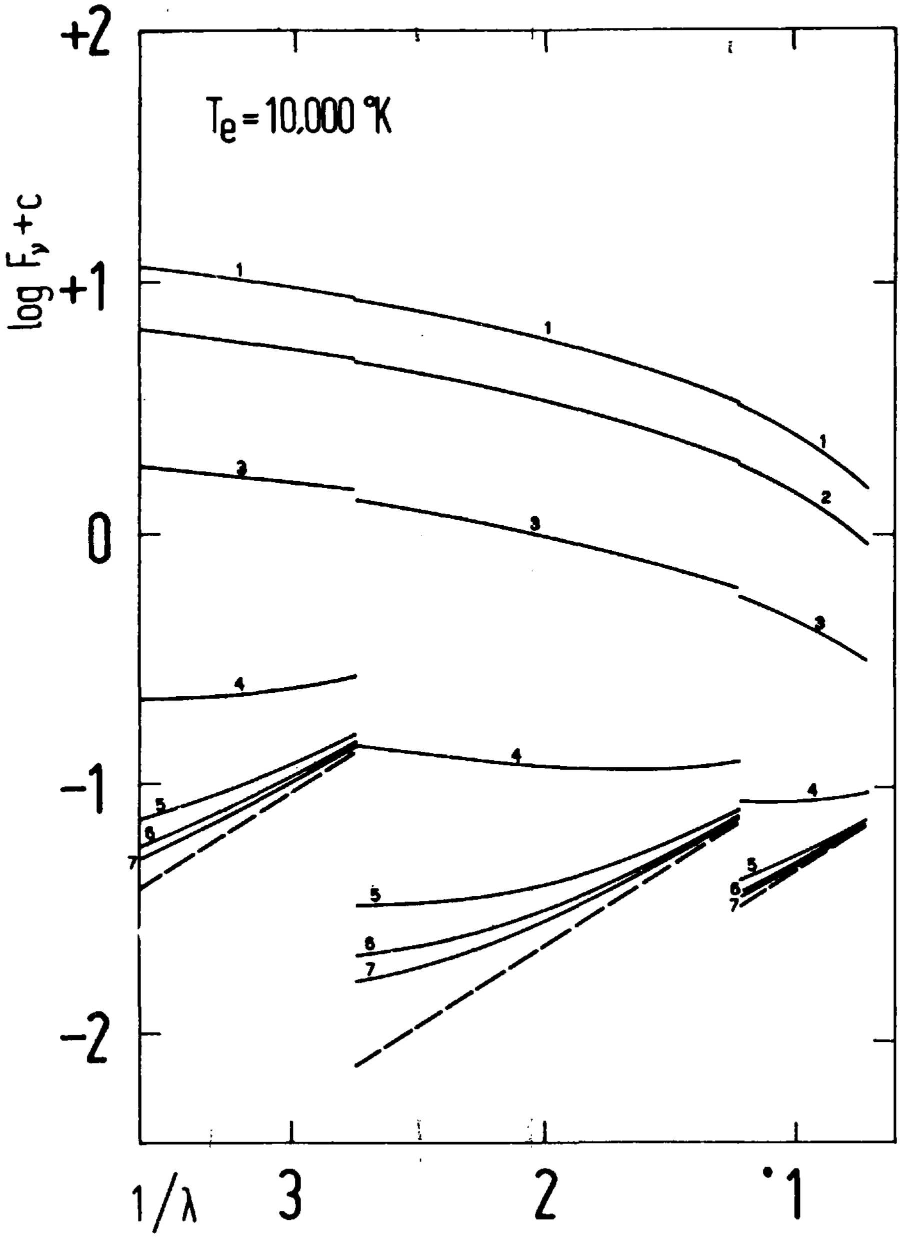


*Figure 2.* As in Figure 1.

because the ground level is so highly populated that a small collisional contribution is sufficient to affect profoundly the 2s level population, with all the consequences for the continuous spectrum. Clearly for very small values of $\mathcal{H}$ , that is, for those values, corresponding to the radiative case, our results are very similar to those obtained by Spitzer and Greenstein (1951) and by Seaton (1960).

Regarding the comparison with observations, Pagel (1969) and Viotti (1969) found that the continuous emission spectrum of the peculiar object η Car and the intensity of the Hα-line can be explained in terms of a collisional case spectrum.

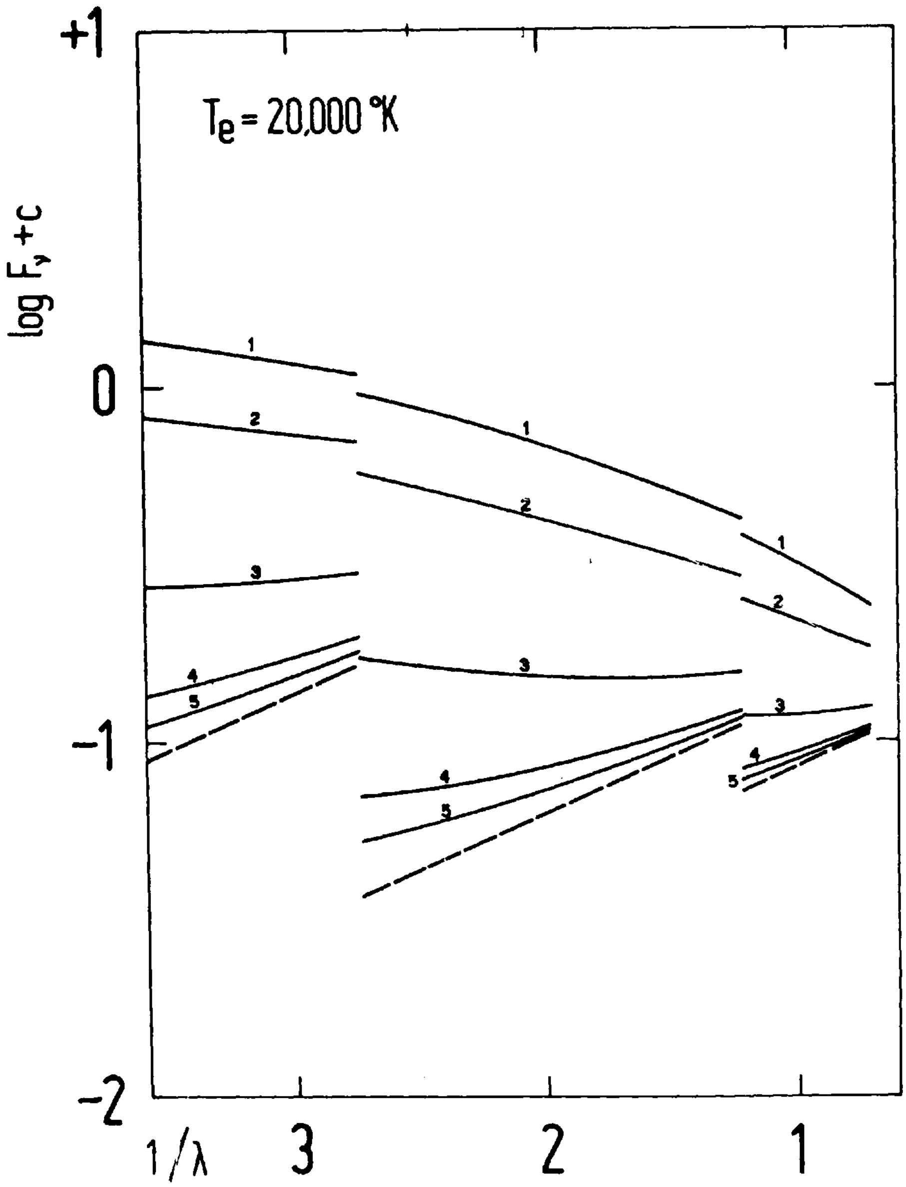


*Figure 3.* As in Figure 1.

Another object with similar features is MHα 328-116. Up to 1964 its appearance was that of a normal M star with some emission features superimposed on the M spectrum; in 1965 this star abruptly rose in luminosity, changing also the spectral characteristics.

O'Dell's measurements of the continuum (1967) and those independently obtained by Caputo et al. (1969) can be fitted very well with a continuous spectrum corresponding to a mixed case of excitation ($\mathcal{K} \simeq .6$).

What is to be noted is that these spectra cannot be explained by means of any other emission mechanism.



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Studies of the Balmer decrement, taking into account the reabsorption from 2s and 2p levels, in the cases of a mixed excitation, are being considered.

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## DISCUSSION

*Swings*: Collision terms were already introduced in the statistical equilibrium equation by Menzel.

*Gerola*: The notation I used is due to Chamberlain.

*Editorial remark*: In the paper by Gerola and Panagia the definition of $\mathcal{H}\,\mathcal{F}^*_{1n}$ is not explained in detail although the reason for introducing this term can be seen. Confusion exists about what is meant by the factor $\mathcal{H}$, which was not introduced in precisely this manner by Chamberlain (1953 *Ap. J.* 117, 387) and about what the expression is, for "the collisional rate of excitation from the ground level for the pure collisional case." In the examples presented the parameter $\mathcal{H}$ is used only as an arbitrary multiplying factor. To understand fully the meaning of the results one must know the precise definition of $\mathcal{F}^*_{1n}$. It is presumed that this definition will be given in the unpublished work by Gerola and Panagia to which reference is made.