LYMAN-α RADIATION FROM NEBULAR OBJECTS

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Abstract. For a simplified model of a gaseous nebula, that is spherical, isothermal, homogeneous and composed of pure hydrogen, the amount of Lyman-α radiation emitted from the surface of the nebula is evaluated for various physical conditions. The problem of observability of the Lyman-α emission line is examined, taking into account absorption by dust and by interstellar neutral hydrogen.

In this note preliminary results of a theoretical study of the Lyman-α radiation from nebular objects are presented.

The great difficulty in observing the Lyman-α line is that the flux is much reduced by interstellar absorption, due not only to interstellar dust but also to neutral hydrogen.

For the present analysis we have assumed a simple model nebula, namely one that is spherical, isothermal, homogeneous and composed of pure hydrogen. This model corresponds to that of Gerola and Panagia (1969), so that the calculations of level populations were performed using the same procedure.

The Lyman-α line intensity radiated from the nebula is obtained by integrating the radiative transfer equation in the direction of the line of sight throughout the whole sphere. Assuming complete redistribution in frequencies, the transfer equation along a line can be written as:

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu - k_\nu I_\nu, \tag{1}$$

where

$$j_\nu = j_0 H(a, x); \qquad k_\nu = k_0 H(a, x). \tag{2}$$

In (2) one has:

$$x = \frac{\nu - \nu_0}{\Delta\nu_{\text{Doppler}}}; \qquad a = \frac{A(2p, 1s)}{4\pi\Delta\nu_{\text{Doppler}}}, \tag{3}$$

where ν_0 indicates the central frequency of the line and $A(2p, 1s)$ is the Einstein coefficient of spontaneous emission for the transition $2p - 1s$ which generates the Lyman-α line; $H(a,x)$ represents the well known Voigt profile (Hummer, 1965). Clearly for the adopted model, j_0 and k_0 do not depend on the position into the nebula.

Integrating (1) throughout the sphere, along the line of sight, one obtains:

$$I(\nu)\,\mathrm{d}\nu = 2\pi R^2 \frac{j_0}{k_0}\, p(x)\,\mathrm{d}\nu \tag{4}$$

$$p(x) = \frac{1}{2} + \frac{\exp[-2\tau(x)]\,[2\tau(x) + 1] - 1}{[2\tau(x)]^2} \tag{5}$$

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$$\tau(x) = \tau_0 H(a, x); \qquad \tau_0 = k_0 R, \tag{6}$$

where R is the radius of the nebula.

The profile of the emergent line is then determined by the function $p(x)$. In Figure 1 are plotted some profiles (dashed lines) as functions of x, corresponding to various values of τ_0 and for $a = 4.72 \times 10^{-4}$. The lines have a flat and broad core with constant value $\frac{1}{2}$, which extends approximately until $\tau(x)$ becomes less than 4; then for a given value of a, the width of the core is determined by the value of τ_0.

In these calculations the continuous radiation was not included explicitly; however, some evaluations of this factor were made. The results were that, in nebular conditions, the contribution of the continuous emission is always negligible in a large region of the spectrum centred on the Lyman-α line.

To take into account interstellar absorption, it is still possible to use Equation (1), referred to interstellar conditions, putting:

$$j_v = 0 \tag{7}$$

$$k_v = k_{0i} H(a_i, x_i) + k_{\text{dust}}, \tag{8}$$

where the subscript 'i' denotes quantities referred to interstellar conditions. The quantity x_i is simply related to x as follows from the definition (3a):

$$x_i = \left(\frac{T_{\text{neb}}}{T_i}\right)^{1/2} \cdot x. \tag{9}$$

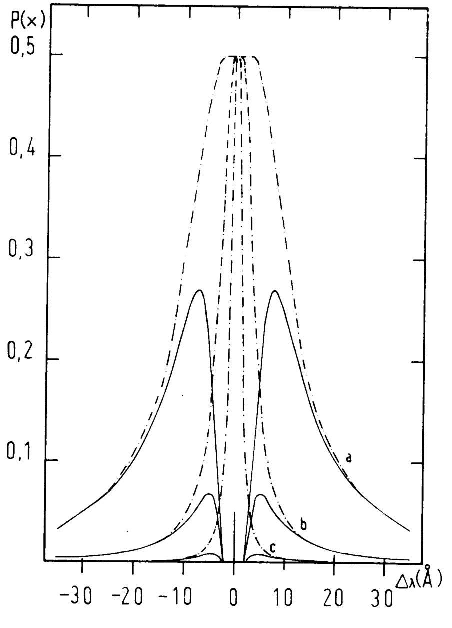

Fig. 1. Solid lines show profile of the Lyman-α line after absorption by a column of neutral hydrogen of 5.4×10^{20} atoms cm^{-2} at a kinetic temperature of 110 K. The curves refer to nebulae with $T_e = 10^4$ K and (a) $\tau_0 = 10^8$; (b) $\tau_0 = 10^7$; (c) $\tau_0 = 10^6$ respectively. For comparison the emergent profiles (broken lines) are shown for the same cases.

Finally the flux per unit wavelength that is received outside the atmosphere is given by:

$$F(\lambda)\,\mathrm{d}\lambda = \frac{c}{\lambda^2}\frac{I(\nu)}{4\pi d^2}\exp\left[-\tau_i(x) - 0.921\,A_\lambda\,d_{\mathrm{kpc}}\right]\mathrm{d}\lambda$$
$$= 4.16\times 10^{18}\left(\frac{R}{d}\right)^2 \frac{N_{2p}}{N_{1s}}\,p(x)\exp\left[-\tau_i(x) - 0.921\,A_\lambda\,d_{\mathrm{kpc}}\right]\mathrm{d}\lambda\,, \tag{10}$$

where the term 0.921 $A\,d_{\mathrm{kpc}}$ in the exponential factor accounts for the absorption due to dust, A being monochromatic extinction in magnitudes per pc and d_{pc} the distance in pc. The factor $(4\pi d^2)^{-1}$ represents the geometrical dilution of the radiation.

In Figure 1 some profiles of the received flux of Lyman-α radiation are shown (solid lines): they correspond to the fluxes after absorption by a column of neutral hydrogen of 5.4×10^{20} atoms cm^{-2} with a kinetic temperature of 110 K. It is evident that the greater τ_0, the broader the emergent line from the nebula and then the total flux will be less affected by interstellar hydrogen absorption.

Of course, the amount of radiation received, for given conditions of interstellar medium, depends not only upon the received profile, which is determined by τ_0, but also essentially on the ratio of the populations of the levels $2p$ and $1s$ of hydrogen. These are determined not only by self-absorption or Lyman-α radiation within the nebula, but also by other physical parameters, particularly the electron temperature and density and the mean degree of ionization.

Examining the equilibrium equation for the $2p$ level and the transfer problem through the interstellar medium, one finds that in the range of conditions typical of planetary nebulae, for given values of R, N_e, T_e, that is for a nearly constant behaviour of the optical spectrum, the lower the degree of ionization of hydrogen the greater the flux of Lyman-α radiation.

In Figure 2 the fluxes of the Lyman-α line are plotted corresponding to a nebula of four sq sec of area on the sky with $T_e = 10^4$ K, $N_e = 10^4$ cm^{-3}, $R = 10^{17}$ cm and which is 1 kpc from the Sun. A kinetic temperature of 110 K and a mean density of interstellar neutral hydrogen of 0.2 atoms cm^{-3} are assumed. A mean extinction by dust of 3.75 magnitudes per kpc was adopted; this value is consistent with a reasonable extrapolation of Stecher's data (1965), having assumed 3 for the ratio of visual absorption to color excess and an extinction of 1 magnitude par kpc in the visual.

The abscissa shows wavelengths in Å and the ordinate gives the logarithm of the flux, in units of 10^{-11} ergs cm^{-2} s^{-1} Å^{-1}.

The curves correspond, from top to bottom, to degrees of ionization from 5.0×10^{-1} to 5.0×10^{-4} (corresponding to τ_0 between 2.9×10^7 and 2.9×10^4). One can see that the separations between successive curves are nearly the same on the logarithmic scale: this means that the flux is proportional to some nearly constant power of the degree of ionization which in this case is about the square root. Indeed these profiles all correspond to cases in which ionization and excitation of nebular hydrogen are due essentially to radiation from the central star.

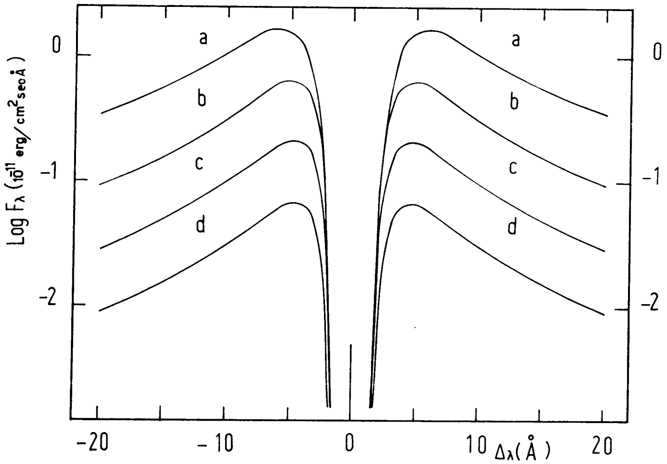

Fig. 2. Fluxes of Lyman-α radiation received from an area of a nebula subtending four square second of arc with $T_e = 10^4$ K, $N_e = 10^4 \text{cm}^{-3}$, $R = 10^{17}$cm which is 1 kpc from the Sun. Mean density of neutral hydrogen of 0.2 atoms cm–^{3} with kinetic temperature of 110 K, and mean dust extinction of 3.75 magnitudes per kpc are assumed. The abscissa shows wavelengths in Å and the ordinate the logarithm of the flux in units of 10^{-11} ergs cm^{-2} s^{-1} Å^{-1}. The curves correspond to:

(a) $N_1/N_p = 5.0 \times 10^{-1}$, $\tau_0 = 2.9 \times 10^7$;
(b) $N_1/N_p = 5.0 \times 10^{-2}$, $\tau_0 = 2.9 \times 10^6$;
(c) $N_1/N_p = 5.0 \times 10^{-3}$, $\tau_0 = 2.9 \times 10^5$;
(d) $N_1/N_p = 5.0 \times 10^{-4}$, $\tau_0 = 2.9 \times 10^4$.

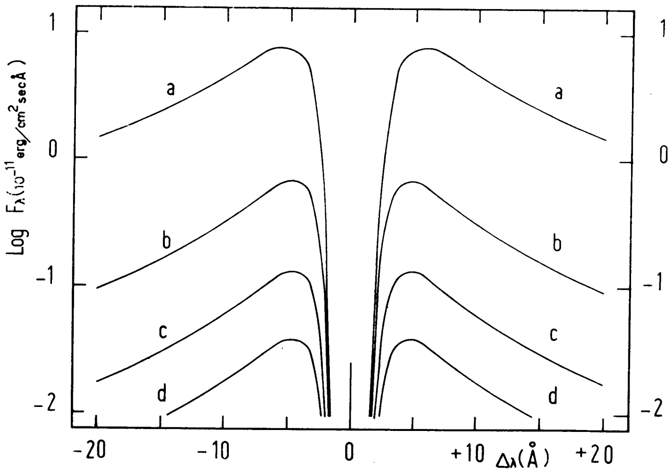

Fig. 3. Fluxes of Lyman-α radiation received from an area of a nebula subtending four square second of arc with $T_e = 1.4 \times 10^4$K; the other parameters and the units of the plots are the same as for Figure 2. The same assumptions on the interstellar matter are also made. The curves correspond to:

(a) $N_1/N_p = 3.6 \times 10^{-1}$, $\tau_0 = 1.8 \times 10^7$;
(b) $N_1/N_p = 3.6 \times 10^{-2}$, $\tau_0 = 1.8 \times 10^6$;
(c) $N_1/N_p = 3.6 \times 10^{-3}$, $\tau_0 = 1.8 \times 10^5$;
(d) $N_1/N_p = 3.6 \times 10^{-4}$, $\tau_0 = 1.8 \times 10^4$.

Incidentally the two lower curves are representative of the physical conditions of planetary nebulae.

In Figure 3 the fluxes of the Lyman-α line received are shown for the case of a nebula with $T_e = 1.4 \times 10^4$ K and with the other parameters the same. Identical conditions of interstellar matter have also been considered.

The curves correspond, from top to bottom, to degrees of ionization from 3.6×10^{-1} to 3.6×10^{-4}, corresponding to τ_0 from 1.8×10^7 to 1.8×10^4.

It is to be noted that the separation of the upper curve from the one immediately beneath is greater than the separation between the other successive curves. In fact, the upper curve corresponds to a nebula in which collisions are responsible for about 10% of the total ionization, whereas the other profiles correspond to a nearly radiative situation.

Summarizing, we can conclude that:

(1) In suitable but not severe conditions the Lyman-α emission line can be detected, although it suffers considerable interstellar absorption;

(2) In the range of physical conditions typical of planetary nebulae, the intensity is very sensitive to the degree of ionization; therefore measurements of Lyman-α radiation can give much more accurate determinations of the true degree of ionization of hydrogen than those which can be obtained from the ground-based optical spectrum;

(3) A larger Lyman-α emission by low excitation nebulae with respect to other nebulae is to be expected.

References

Gerola, H. and Panagia, N.: 1969, Rapp. Int. 69/17, Laboratorio di Astrofisica, Frascati.
Hummer, D. G.: 1965, *Mem. Roy. Astron. Soc.* **70**, 1.
Stecher, T. P.: 1965, *Astrophys. J.* **142**, 1683.

Discussion

Sunyaev: Have you the estimation of Hα emission from nebulae?

Panagia: I have no detailed results corresponding to the same conditions for which I have shown Lyman-α line profiles. These calculations are right now being carried out in collaboration with H. Gerola of Buenos-Aires University. However I can say that, for given values of radius electronic temperature and density of the nebula, in collisional cases Hα emission is greater than in radiative cases by a factor twenty, more or less (see for instance R. A. R. Parker, 1964, *Astrophys. J.* **138**, 208), just as well as Lyman-α radiation.

Sunyaev: The observations of profile and intensity of Hα emission from nebulae and the Milky Way can give us the choice between different models of observed α-emission from the Milky Way. I think Courtès (France) and Tscheglor from Sternberg Astronomical Institute can find the answer to this question.

Courtès: The width of Hα in the classical galactic nebulae is of the order of 0.4 Å. There exists in the inner part of the galaxy (Sagittarius clouds) a faint extended general emission which is broadened by differential rotation but this emission is not very broad, 1 Å approximately.

We find the same order of width in the central disks of M33 and the Large Magellanic Cloud; some other local group galaxies show a similar Hα emission.

The emission suggested by Sunyaev is perhaps observable in the periphery of the Milky Way if we try to look in the directions of the largest geometrical depth.

Of course with poor resolution nebulae spectrographs it is difficult to select all these emissions from the Hα geocoronal emission, but with the use of the Pérot-Fabry interferometer it is easy to separate the general galactic emission from the geocoronal Hα emission owing to the difference of their profile.

Hekela: This is interesting theoretical work but has a lack. It is not possible to compare this procedure with observation and check it. I suggest you to solve it in a little bit difficult manner together with equations of ionization structure.

Panagia: You are right; however I have presented here only preliminary results, using a very simplified model, to give some evaluations of the expected flux of the Lyman-α line. On the other hand it is easy to see that the values I obtained are lower limits for the true flux: in fact, if ionization structure is taken into account, the emergent line has not longer flat core and monotonically decreasing wings, but it has in the center a relative minimum and presents some symmetric prominent feature before to decrease (C. M. Walmsley and W. C. Mathews 1969, *Astrophys. J.* **155**, 57). In this case clearly, being the same as the total energy emitted in the line, the received flux, after absorption of interstellar neutral hydrogen, is greater than that I have shown here.