



Soviet-era science, translated into English

ASTRONOMY

1961

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Abstract

Full Text

ASTRONOMY

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THE POSSIBILITY OF OBSERVING GASEOUS NEBULAE IN THE LYMAN-ALPHA LINE

(Presented by Academician V. A. Ambartsumian, 19 IX 1960)

Extra-atmospheric observations of planetary and diffuse nebulae, hot stars with gaseous envelopes, certain types of galaxies, and others, in the frequency of the first line of the Lyman series of hydrogen (L_α) by means of satellites and high-altitude rockets are of particular interest; such observations may solve a number of important problems connected with the nature of the objects indicated. However, the practical opacity of the interstellar medium at the wavelength $\lambda 1216 \text{ \AA}$, caused by absorption by interstellar neutral hydrogen, seems to call into question the possibility of observing any objects at all in the L_α line, even at distances close to the Sun. Indeed, according to observations of monochromatic radio emission at a wavelength of 21 cm, the mean concentration of neutral interstellar hydrogen is of the order of $n \sim 1 \text{ cm}^{-3}$. Taking also, for the coefficient of selective absorption in the L_α line, calculated per one neutral hydrogen atom, the value $s_\alpha \approx 10^{-14} \text{ cm}^2$, corresponding to a temperature of interstellar hydrogen of the order of 100° , we find that already at a distance of 1 parsec from the Sun the optical thickness of the interstellar medium t_0 (without taking the dust component into account) in the frequency of L_α radiation will be of the order of 10,000!

Let us first consider the question of what happens to absorbed L_α quanta in the Galaxy.

Under the conditions of the interstellar medium, L_α quanta cannot be transformed into quanta of other discrete frequencies. However, because of the large value of the optical thickness t_0 of this medium at the frequency of the center of the L_α line (of the order of 10^6 – 10^7 at distances of the nebula from us of 100–1000 pc), the probability of splitting of L_α quanta (two-photon emission) is considerably increased in the following processes: a) transitions $2P \rightarrow 1S$ with the emission of two quanta; b) the transition $2S_{1/2} \rightarrow 1S_{1/2}$, again with the emission of two quanta, preceded by the transition $1S_{1/2} \rightarrow P_{1/2,3/2}$, accompanied by absorption of an L_α quantum, and then the transition $2P_{1/2,3/2} \rightarrow 2S_{1/2}$, caused by an elastic collision. The probability of conversion of an L_α quantum into two quanta in the first case was determined by A. Ya. Kipper and V. M. Tait; it does not depend on the physical conditions of the medium and is of the order of 10^{-14} per single scattering event ⁽¹⁾. In the second case, this probability, as

Spitzer and Greenstein have shown, depends on the electron concentration of the medium and is of the order of 10^{-10} in planetary nebulae ($n_e \sim 10^4 \text{ cm}^{-3}$) and 10^{-17} in the interstellar medium ($n_e \sim 10^{-3} \text{ cm}^{-3}$), again per single scattering event ⁽²⁾. It follows from this, among other things, that under the conditions of interstellar neutral hydrogen the first of the indicated mechanisms for the splitting of L_α quanta is the more effective. At $t_0 \sim 10^7$, the probability of splitting (destruction) of an L_α quantum in this case becomes of the order of unity (the total number of scatterings is approximately equal to the square of the optical thickness).

However, there is one reason which, generally speaking, must eliminate the possibility of even a partial transformation of L_α -quanta into quanta of a continuous spectrum. This is the absorption of L_α -quanta by interstellar dusty matter. The point is that, for those values of t_0 that exist under the conditions of the interstellar medium, the duration of stay (diffusion) of L_α -quanta in this medium will be very large, as a result of which they will sooner or later be absorbed by cosmic dust particles.

Let us first determine the mean duration T of stay of an L_α -quantum inside a sphere of radius r , filled with neutral hydrogen atoms. We have ⁽³⁾

$$T = \frac{3t_0^2}{2cns_\alpha} = \frac{3ns_\alpha r^2}{2c},$$

where $t_0 = ns_\alpha r$ has been substituted. From this relation, for $n = 1 \text{ cm}^{-3}$, $s_\alpha \approx 10^{-14} \text{ cm}^2$, and $r = 100 \text{ pc}$, we find $T \approx 5 \cdot 10^{16} \text{ sec.} \approx 10^9 \text{ years}$. This is at least 3-4 orders of magnitude greater than the lifetime of the nebulae themselves. Hence one can already draw the first conclusion: from a given nebula, neither the direct nor the diffuse component of L_α -radiation can reach the observer simultaneously.

In 10^9 years a quantum traverses a zigzag path with a total length of about 10^{27} cm , or 10^8 pc (!). Thus even a very small amount of interstellar dust in the volume of the Galaxy under consideration is sufficient for complete absorption of the L_α -quanta to occur long before the indicated time has elapsed.

Of course, interstellar dust can also cause scattering of L_α -quanta. But it is known that for small particles (such as particles of interstellar dust) the absorption coefficient considerably exceeds the scattering coefficients ⁽⁴⁾. Only in one case, when the dusty medium consists exclusively of ferromagnetic particles (i.e., particles with a very high value of the dielectric constant), can diffusion of L_α -quanta from this medium occur without absorption of the quanta. However, more or less extensive dusty regions in the Galaxy consisting of ferromagnetic particles apparently do not exist. In any case, we know of no reflecting diffuse nebulae consisting only of ferromagnetic particles; otherwise we would have to observe a very high degree of polarization of the light from these nebulae, which is not the case.

One may nevertheless expect the existence in the Galaxy of individual hydrogen clouds several tens of parsecs in diameter, “uncontaminated” by dust. In such clouds the diffusion of L_α -quanta may indeed end with the splitting of such a quantum into two, as a result of which the cloud becomes a source of continuous radiation whose total energy must be equal to the energy of the initial flux of L_α -quanta. However, this can take place in individual volumes, but not in the general field of the Galaxy, where, as is known, absorbing matter is present. It is important that, in the general case, diffusion of L_α -quanta in the Galaxy cannot occur without their absorption by interstellar dust particles.

Thus, any more or less prolonged stay of L_α -quanta in the interstellar medium must inevitably lead to their extinction. Hence we arrive at the following important conclusion: the diffuse component of L_α -radiation (the L_α -background) in the Galaxy should practically be absent. The consequences following from this conclusion are not difficult to foresee.

Since the L_α -background is absent in the Galaxy, even a very small amount of direct L_α -radiation from the object under consideration is sufficient for it to stand out quite contrastively against this “dark” background (when photographed). Some L_α -background may be produced by the direct component

the L_α -radiation of ordinary stars, in which this radiation is of chromospheric origin. It is not difficult, however, to see that the L_α background arising in this way will, to a first approximation (without allowing for interstellar absorption), be weaker than the total background of the Galaxy at visible-light frequencies by the same factor by which the flux of L_α -radiation from ordinary stars is less than their flux at visible-light frequencies. According to rocket observations (^{5,6}), the intensity of the L_α -radiation arriving from the Sun is of the order of $5 \text{ erg/cm}^2 \cdot \text{sec}$, i.e., several hundred thousand times less than the intensity of the Sun’s radiation in visible light. Allowance for interstellar absorption will further increase the indicated ratio for stars.

The half-width of the L_α emission line emitted by a nebula is determined by the Doppler effect associated with the thermal motions of absorbing and emitting atoms in the nebula at a temperature $T = 10\,000^\circ$; it is of the order of 0.05 \AA . The half-width of the absorption line caused by interstellar neutral hydrogen is determined by the effect of natural damping and by the total number of hydrogen atoms in a column of unit cross section and height equal to the distance from the nebula to us. For $r = 100 \text{ pc}$, $n = 1 \text{ cm}^{-3}$, the half-width of the absorption line at $\lambda 1216 \text{ \AA}$ is obtained as approximately 1 \AA —it exceeds the half-width of the L_α emission line many times over, and the optical thickness at the center of the L_α line is of the order of 10^6 . Therefore the L_α line emitted by a nebula will be completely absorbed by interstellar hydrogen. However, one may hope that, for sufficiently large values of the radial velocities of nebulae, at least a small part of the L_α -energy emitted by the nebula will nevertheless reach the observer. A calculation of one example shows that, for a radial velocity of the nebula of the order of 50 km/sec and $r = 100 \text{ pc}$, about 1% of the L_α -energy emitted by the nebula reaches the observer. Even such an apparently

insignificant amount of L_α -energy is sufficient for the nebula to become visible on photographic plates (in the L_α line), because, first, in this case the brightness of the nebula will be only 3.5 magnitudes (and not 5) fainter than the brightness of the nebula in photographic rays—taking into account that the main part (75%) of the L_c -energy emitted by the central star is converted into L_α -energy, whereas less than 20% of the star's L_c -energy is transformed into visible (photographic) rays. Secondly, the L_α background in the Galaxy, as we saw above, is practically absent, as a result of which the limiting brightness of celestial objects that can still be detected on photographs in L_α rays is considerably (probably by as much as 10 magnitudes!) reduced.

More than 35% of the total number of planetary nebulae for which radial velocities are known have velocities greater than 50 km/sec. In addition, a considerable fraction of planetary nebulae is located outside the layer of interstellar neutral hydrogen, whose half-thickness is estimated to be of the order of 100 pc ⁽⁷⁾. Therefore the possibility of studying at least some planetary nebulae in the L_α line should apparently not be regarded as entirely hopeless.

The gaseous shells ejected during outbursts of novae and supernovae (the Crab Nebula, N Persei 1901, N Aquilae 1918, N Herculis 1934, and others) should be well observed in the L_α line; the Doppler shift caused by their expansion will in this case be almost two orders of magnitude greater than in the case of planetary nebulae. Gaseous nebulae in other galaxies should also be well observed in the L_α line.

Observations of nebulae, gaseous shells of stars, and so forth in the L_α line make it possible, comparatively easily and quite convincingly, to reveal some of their structural features which appear extremely weakly or are not visible at all on ordinary photographs. This applies in particular

to the peripheral regions of nebulae. Examples of such problems include, for instance, establishing the presence of secondary (outer) gaseous envelopes around the main nebula, detecting weak spiral arms, etc. Because of the large optical depth of a nebula in the L_α line (10^3 — 10^4), its overall image should have the appearance of a patch of uniform brightness; apparently one should not expect to detect any structural features in the central parts of the nebular image in the L_α line.

In some cases, observations of planetary nebulae in the L_α line make it possible to determine the value of their optical depth in the frequencies of ultraviolet radiation (τ_c), which is one of the important parameters of nebulae.

As for the other lines of the Lyman series of hydrogen (L_β, L_γ , etc.), these lines can be observed in those nebulae which are practically transparent at the frequencies of the lines of this series, i.e., for which $\tau_c \sim 10^{-4}$. For most planetary and diffuse nebulae this requirement is apparently not satisfied, and their Lyman series will be represented in the form of the single line L_α .

The situation is otherwise with observations of stars and nebulae at the frequen-

cies of L_c -radiation (shorter than $\lambda 912 \text{ \AA}$). The optical depth of interstellar hydrogen at the frequencies of L_c -radiation is also very large (at a distance of 100 pc it is already of order 1000) and does not depend on the kinematic state of this medium. Therefore the Lyman continuum of all types of nebulae, the gaseous envelopes of stars, and also the continuous radiation of all hot stars in the region of the spectrum shorter than $\lambda 912 \text{ \AA}$, in principle, cannot be observed. The starry sky and the Milky Way should appear practically dark in photographs at the frequencies of L_c -radiation.

In the spectral region from wavelengths longer than $\lambda 912 \text{ \AA}$ to $\lambda 1500 \text{ \AA}$, images of intermediate-temperature and cool stars should be extremely weak. In contrast, hot stars in the indicated wavelength interval should appear very bright. Therefore, by photographing the sky in the wavelength region $\lambda \lambda 912\text{--}1500 \text{ \AA}$, we obtain a simple and convincing method for detecting clusters of hot stars and stellar associations.

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Received
16 IX 1960

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