Astronomy

G. A. Gurzadyan

1960

SovietRxiv

Abstract

Full Text

Astronomy

G. A. Gurzadyan

SYNCHROTRON RADIATION IN COMETARY NEBULAE

(Presented by Academician V. A. Ambartsumian on 11 IX 1959)

A small but interesting group among galactic nebulae is formed by cometary nebulae. The distinguishing features of these objects are, above all, their external form (comet-like or cone-shaped), as well as the irregular variability of their brightness and structure. The bright part of cometary nebulae usually has dimensions comparable with the apparent dimensions of large planetary nebulae, while the star causing their luminosity, as a rule, belongs to stars of low luminosity (type A and later); the latter circumstance is also difficult to reconcile with the fact that emission lines of hydrogen are present in the spectra of some cometary nebulae. Finally, characteristic of cometary nebulae is the emission of a strong continuous spectrum, sometimes interrupted by hydrogen absorption lines.

V. A. Ambartsumian was the first to draw serious attention to the peculiarities of the radiation of cometary nebulae, showing that the luminosity of these objects is not of thermal nature (1). Further investigation of this question shows that the luminosity of cometary nebulae may be due to the bremsstrahlung of relativistic electrons in the magnetic fields of the nebula (synchrotron radiation). At the same time we consider it necessary to note that consideration of the proposed hypothesis is by no means limited to a simple calculation of the concentration of relativistic electrons and determination of their spectrum. The hypothesis of relativistic electrons, it turns out, explains well a number of facts relating to cometary nebulae, whereas, for example, the widely accepted hypothesis of reflection of the light of the nucleus by dust particles of the nebula does not give such an explanation. In the present article some of the results obtained by the author on this question are presented.

Sometimes, on the opposite side of the cone of a cometary nebula, symmetrically to the nucleus, a protrusion of the same cometary form is observed (for example, in NGC 2261, 2245). In this way the nebula acquires the character of a kind of bipolarity, which, however, should not be identified with the bipolarity of the structure of some planetary nebulae (2), but at the same time cannot be regarded as a chance phenomenon. From this fact one may conclude that a cometary nebula "rests" with its end on definite regions of the surface of the stellar nucleus, most probably on the region of the magnetic pole. However, the structure of the magnetic field in this case differs somewhat from that usually assumed for stars. It can be shown that, in order to explain the form and the observed extent of a cometary nebula, its nucleus must possess either a dipole magnetic field located eccentrically with respect to the center of the star, or, what is difficult to reconcile with our present ideas about the nature of magnetism, a unipolar magnetic field. If the dependence of the magnetic-field strength in a given direction is represented in the form $H \sim r^{-n}$, then $n = 3$ for a dipole field and $n = {}^{3}/_{2} \div 2$ for a unipolar field, i.e. the gradient of the magnetic field in the po-

in the latter case will be considerably smaller than in the first case. The gradient of the magnetic field is further decreased because the matter itself, ejected from the region of the star' s pole, can carry away the magnetic field with it. For these reasons, the relativistic electrons emitted from the region of the pole may produce synchrotron radiation even at large distances from the nucleus, if the magnetic-field strength at the pole is of the order of 10^4 gauss.

The magnetic lines of force emerging from the pole in the direction of the magnetic axis (or of the star' s rotation axis, since they are close to one another) have approximately the form of straight rays. Electrons flying out from the pole at some angle to the lines of force will wind around them, describing a spiral trajectory. The radius of the trajectory should gradually increase as the electron moves away from the pole, since the field strength decreases with distance. A change in the radius means a change in the radiation frequency of the relativistic electron. Therefore an electron, for a given value of its energy E, emits invisible ultraviolet waves in regions close to the nucleus, and invisible infrared and radio waves in regions far from the nucleus. It follows from this that only within a certain interval of distances from the nucleus can an electron with a given energy produce radiation in the optical range. For example, for $E = 10^{11}$ eV, the optical range from $\lambda 3200$ Å to $\lambda 7000$ Å is emitted in the field-strength interval from $H_1 = 2.2 \cdot 10^{-2}$ gauss to $H_2 = 5 \cdot 10^{-3}$ gauss. Although we do not know the exact law by which the star' s magnetic-field strength decreases with distance, there is no doubt that at some distance from the nucleus r_1 the first condition will be satisfied, and at another r_2 the second condition. For another value of E, different values of r_1 and r_2 are obtained.

Thus, depending on the composition and homogeneity of the beam of relativistic electrons, the brightness maximum may be located at any distance from the nucleus. If several more or less homogeneous (monochromatic) beams are present simultaneously, but with different values of E, there will be several brightness maxima of different intensity and at different distances from the nucleus. With fluctuations, even small ones, in the composition of the beams, the bright regions (spots) will drift and may even disappear. If, finally, the energy spectrum of the relativistic electrons is continuous, then instead of spots there will be a continuous nebula with a brightness monotonically decreasing with distance from the nucleus.

Irregular changes in the brightness and structure of cometary nebulae have been considered one of the incomprehensible phenomena of their nature. As we see, the hypothesis of relativistic electrons injected from the nucleus of the nebula gives a simple and convincing explanation of this phenomenon. The picture of variability of the brightness and structure will become even more pronounced if one also takes into account the effect of stellar rotation and the effect of possible fluctuations in the magnetic-field strength.

The mean concentration of relativistic electrons N_e in the nebula is determined from the assumption that the integral brightness of the nebula is due to continuous synchrotron radiation. Assuming that the spectrum of relativistic electrons is continuous and is represented in the form $N_e = KE^{-\gamma}$, we shall have for the concentration in the nebula of relativistic electrons possessing energies greater than E_0:

$$N_e(E > E_0) = \frac{1}{\gamma - 1} \frac{K}{E_0^{\gamma-1}}, \tag{1}$$

where K is determined from the relation

$$K = \frac{H^{-\frac{\gamma+1}{2}}}{c(\gamma)} \frac{F_\odot}{\Omega \Delta\nu_{pg} R} 10^{-0.4\,(m_{pg} - m_\odot)}\, \nu^{\frac{1-\gamma}{2}}, \tag{2}$$

where H is the magnetic-field strength in the middle parts of the nebula; R is the mean linear extent of the nebula along the line of sight; Ω is the apparent surface area of the nebula in steradians; $m_\odot$ is the bolometric apparent magnitude of the Sun; $F_\odot$ is the total radiation flux of the Sun; m_{pg} is the integral photographic stellar magnitude of the nebula; $\Delta\nu_{pg}$ is the width of the spectral interval in frequency units; ν is the mean frequency of the photographic region of the spectrum.

$C(\gamma)$ is a function depending on γ and taking the following values:

γ	2	3	4	5
$C(\gamma)$	$0.47 \cdot 10^{-13}$	$0.95 \cdot 10^{-4}$	$2.85 \cdot 10^{5}$	$8.70 \cdot 10^{14}$

Application of (1) and (2) to the known cometary nebula NGC 2261 gives, for $\Omega = 5' \times 5'$, $m_{pg} \simeq 10^m$ (^{3}), $R = 10^{18}$ cm, and $\gamma = 3$, $N_e(E > 10^{12}) \simeq 10^{-12}$ cm^{-3} for $H = 10^{-3}$ gauss.

Ionization of hydrogen atoms in cometary nebulae is effected under the influence of the ultraviolet synchrotron radiation that is produced in the nebula. On this basis one may derive the following formula for determining the electron concentration of ordinary (thermal) electrons in the nebula:

$$n_e^2 = \frac{\omega_a A(\gamma)}{z_3 A_{32} h}\,\nu_a^{-\frac{1+\gamma}{2}}, \tag{3}$$

where $A(\gamma) = C(\gamma)KH^{\frac{\gamma+1}{2}}$; ω_a and ν_a are the equivalent width and the frequency of the emission line H_a; $z_3 = n_3/n^+n_e$ and is taken from (^{4}); A_{32} is Einstein' s coefficient of spontaneous transition $3 \to 2$ of hydrogen. For NGC 2261 this formula gives, at $\omega_a = 126$ Å $= 0.88 \cdot 10^{13}$ sec^{-1} (^{5}) and $\gamma = 3$, $n_e = 13$ cm^{-3}, which is two orders of magnitude less than the electron density of planetary nebulae.

There is reason to suppose that the optical thickness τ_c at the frequencies of ultraviolet radiation (L_c) for some cometary nebulae (NGC 2261) is considerably greater than unity. The formula for ionization of hydrogen in a nebula, when the ionization is effected by synchrotron short-wave radiation, has, for $\tau_c \gg 1$, the form

$$\frac{n^+}{n_1} n_e = \frac{1}{4\pi}\,\frac{A(\gamma)}{\gamma+3}\,\frac{c^2(2\pi\mu)^{3/2}(kT_e)^{1/2}}{n_1\chi_c h^3}\,\nu_0^{-\frac{\gamma-3}{2}}. \tag{4}$$

Proceeding from observations of the equivalent width of the absorption line H_δ in the spectrum of a cometary nebula, one can determine the concentration of neutral hydrogen atoms in it by means of the formula

$$n_1^2 = 0.115\,\frac{X_0(\omega_\lambda)}{R^2\omega s_1 s_2}\,\frac{\gamma-1}{RA(\gamma)}\,\nu_0^{\frac{\gamma-1}{2}}, \tag{5}$$

where $X_0(\omega_\lambda)$ is determined from the formula for the curve of growth (^{6})

$$\frac{\omega_\lambda}{\lambda} = 2X_0\frac{\Delta\nu_D}{\lambda}\int_0^\infty (e^{p^2}+X_0)^{-1}\,dp; \tag{6}$$

s_1 and s_2 are the coefficients of selective absorption, respectively at the frequencies of the lines L_α and H_δ; $\omega = 5 \cdot 10^4$; ν_0 is the ionization frequency of hydrogen; χ_c is the coefficient of continuous absorption per hydrogen atom.

Application of (4), (5), and (6) to NGC 2261 gives, for $\omega(H_\delta) = 3$Å (^{5}) and $\gamma = 3$, $n_1 = 170$ cm^{-3}, $n^+/n_1 \simeq 0.1$.

Thus, in NGC 2261 the overwhelming majority of hydrogen atoms are in the neutral state, and the degree of ionization is very low. Under these conditions the optical depth of the nebula at the frequencies of L_c-radiation is $\sim 10^3$, while at the frequencies of the lines of the Balmer series of hydrogen it is of order unity.

Synchrotron radiation must be polarized, and the plane of polarization must be perpendicular to the magnetic line of force at the given point; the theoretical degree of polarization is very high—of the order of 70% (7). Since the magnetic lines of force of a unipolar field in the region of the cone of a cometary nebula have approximately the form of straight rays, its continuous radiation must, to a first approximation, be polarized radially with respect to the nucleus, and the degree of polarization must be fairly high.

What has been said is confirmed by the data of polarimetric studies carried out for NGC 2261 by E. E. Khachikyan (^{3}) and N. A. Razmadze (^{8}); they obtained radial polarization. The mean degree of polarization over the entire nebula proved to be, respectively, 16 and 19%, while at some points of the nebula it reached 50-60%. Thus, the results of polarimetric studies also speak in favor of the synchrotron nature of the glow of cometary nebulae.

The hypothesis of synchrotron radiation as the source of the glow of cometary nebulae also gives a satisfactory explanation of other phenomena observed in them, in particular, the formation in their spectra of emission lines and absorption lines.

Byurakan Astrophysical Observatory
Academy of Sciences of the Armenian SSR

Received
3 IX 1959

CITED LITERATURE

[1] V. A. Ambartsumian, *Communications of the Byurakan Observatory*, **13**, 3 (1954). [2] G. A. Gurzadyan, *DAN*, **120**, No. 4, 734 (1958). [3] E. E. Khachikyan, *Communications of the Byurakan Observatory*, **25**, 67 (1958). [4] G. Cillié, *M.N.*, **92**, 771 (1936). [5] J. Greenstein, *Ap. J.*, **107**, 375 (1948). [6] V. A. Ambartsumian, E. R. Mustel, A. B. Severnyi, V. V. Sobolev, *Theoretical Astrophysics*, Moscow, 1952. [7] G. M. Garibyan, I. I. Goldman, *Izv. AN ArmSSR, ser. phys.-matem. natural and technical sciences*, **7**, 31 (1954). [8] N. A. Razmadze, *Bull. Abastuman Observatory*, No. 25 (1959).

Note: Figure translations are in progress. See original paper for figures.

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.