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ON THE POWERFUL X RAY EMISSION OF RADIOGALAXIES

(REVIEW)

by

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SUMMARY

This is a review paper on the state of X-ray astronomy. After describing its origin and reviewing the various experiments with the aid of space probes, the author analyses with some detail the fundamental results achieved, illustrating them with figures and tables.

The nature of cosmic X-radiation is then examined in detail, namely by discussing the various processes having given its emergence, with special emphasis on bremmstrahlung, magnetic bremmstrahlung and the characteristic X-ray radiation forming during transitions in atoms (bound-bound transitions). The paper ends with concluding remarks and addenda with ample bibliography.

INTRODUCTION

The major discovery of exceptionally powerful X-ray emission from known radiogalaxies, Cygnus A, Virgo A (galaxy NGC 4486 ≡ M 87) was the object of a quite recent announcement in the field of X-ray astronomy [1].

The X-ray luminance (emission power) for Cygnus A is $L_X \simeq 3 \cdot 10^{46}$ erg/sec, which is almost one hundred times greater than the radioluminance of that galaxy, which is $L_r \sim 4 \cdot 10^{44}$ erg/sec and which belongs to the most powerful known cosmic radiosources (note that for Cygnus A the optical luminance is $L_0 \sim 10^{44}$ erg/sec). For Virgo A the luminance $L_X \simeq 3 \cdot 10^{43}$ erg/sec, and $L_r \simeq 3 \cdot 10^{41}$ erg/sec.

Therefore, Cygnus A and Virgo A, and to a lesser extent also other radiogalaxies, may all be designated as X-ray (Roentgen) galaxies. The fact that we are confronted here with entirely unusual objects is clear from the comparison with our own stellar system - the Galaxy. The latter's radioluminance is $L_r \sim 3 \cdot 10^{38}$ erg/sec.* The optical luminance of the Sun is $L_{\odot} = 3.86 \cdot 10^{33}$ erg/s which is by 10 ÷ 11 orders higher than the X-ray luminance of the quiet Sun, which is $L_{\odot,X} \sim 10^{23}$ erg/sec.

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* O MOSHCHNOM RENTGENOVOSKOM IZLUCHENII RADIOGALAKTIK (Report to the Scientific Session of the Division of General and Applied Physics of the USSR Ac.of Sc. 20 April 1966). ** Its X-ray luminance is apparently of same order, and the optical luminance of the Galaxy is $L \sim (3 \div 5) \cdot 10^{43}$ erg/sec.

Thus, the X-ray luminance of Cygnus A is 10^{13} times (!) higher than the total (practically optical) luminance of the Sun, several hundred times higher than the total (optical) luminance of the Galaxy and 10^8 times greater than the X-ray and the radioluminances of the Radiogalaxy.

Even before these discoveries were made hypotheses were brought forth on the possibility of existence of powerful X-ray emission of radiogalaxies, and specifically of Cygnus A (see [2, 3]). However, the respective estimates could not be sufficiently accurate and convincing. Thus with the detection of X-ray emission of extragalactic objects (radiogalaxies) the X-ray astronomy enters a new period of its development.

In the present work we obviously cannot make a somewhat complete and detailed review of the state of X-ray astronomy. We should like, however, to pause at the history of the question if only briefly*, and also on the most important results of observations, and, finally, on the possible mechanisms of cosmic X-ray emission (for details, see reviews [4 - 6]).

2. EMERGENCE OF X-RAY ASTRONOMY

The X-ray emission of the Sun was already discovered in 1948 [7]. Since then the study of the Sun in X-rays moved much further ahead [8, 9], and this method now plays an important role in solar physics. In the 1 to 10 A spectrum interval the energy flux from the quiet Sun on the ground fluctuates within the limits from 10^{-4} to 10^{-5} erg/cm$^2\cdot$sec, which is $10^{10} \div 10^{11}$ times less than the total flux of solar radiation, $F_\odot = 1.4 \cdot 10^6$ ergs/cm$^2\cdot$sec (of which the greater part corresponds to the visible part of the spectrum). In the periods of high solar activity, particularly at times of flares, the X-ray emission of the Sun rises very rapidly, but with still $F_\odot^{max} \lesssim 10^{-6} F_\odot \sim 1$ erg/cm$^2\cdot$sec.

The star, nearest to us, is at a distance $R \sim 4 \cdot 10^{18}$ cm, while the astronomical unit (distance from Earth to Sun) is $1.5 \cdot 10^{13}$cm. Hence it is clear that the Sun, placed at the distance of the nearest star, would induce on Earth even in the period of the stormiest activity, an X-ray radiation with a flux

$$F \sim \left(\frac{1,5\cdot 10^{13}}{4\cdot 10^{18}}\right)^2 F^{max}_{\odot, X} \lesssim 10^{-11} \text{ erg/cm}^2 \text{ sec.}$$

Such a value corresponds in all to 10^{-2} photon/cm^2 sec, even for photons with energy $E_X \sim 10^3$ ev ($\lambda \sim 10$ A)**.

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* The first stage in the development of X-ray astronomy was illustrated in popular form in the paper by H. Friedman (UFN, 84, 3, 505, 1964).

** It is obvious that the wavelength (in A) is linked with the energy E (in ev) of the photon, by the relation

$$\lambda = \frac{hc\cdot 10^8}{1,6\cdot 10^{-12} E_X \text{ (eV)}} \approx \frac{12\,400}{E_X \text{ (eV)}}$$

The X-ray emission of stars similar to the Sun does not lend itself to detection for a presently attained threshold response of the apparatus; this inference was still more categorical several years back. The estimates of X-ray emission from supernova shells, from "outbursting" stars etc., also led to fluxes many times weaker than for the Sun. As a result, the conviction apparently prevailed everywhere that the X-ray astronomy holds little promise for the future.

Such a prognosis was found to be erroneous. But at the same time it becomes clear why the galactic X-ray emission was to a known extent casual. In any case the first successful rocket observations of cosmic X-ray radiation were performed in an attempt to detect an entirely different radiation - the X-ray radiation of the Moon [10], which could have set in when comparatively high-energy electrons of the solar wind hit the surface of the Moon, or under the action of harder solar X-rays (Roentgen fluorescence).

This first successful rocket experiment in the region of extra-solar X-ray astronomy [10], materialized on 12 July 1962, led to the detection of cosmic X-rays, of which the flux attained by order of magnitude 10 photons/cm sec (such a flux, as we have seen, is $10^7 \div 10^8$ times greater than the flux from the quiet Sun, if it were placed at the distance of the nearest star). The measurements were repeated by two groups in 1963 [11, 12], after which it could already be asserted without any doubt that a powerful cosmic (nonsolar) X-ray radiation did exist.

From there on a series of spinning rockets and balloons were flown* and significant achievements were attained in the perfection of the apparatus. As a result a series of important results were obtained (see [1, 4-6] and the literature indicated there). We shall limit ourselves here to the remark that it is possible at present to recognize the sources of which the X-ray flux constitutes only $0.2 \div 0.3$ photon/cm^2 sec. The angular resolution, obtained in [1], constituted near 1.5°, but in certain cases a much higher resolution was attained. For sufficiently powerful sources a resolution of 1' is already workable; it may be even higher with the help of X-ray telescopes and collimators, etc. [4, 32]. A still better resolution is attained when utilizing the Moon covering of the source; this was already materialized [13] relative to Crab Nebula on 7 July 1964.* Very important polarization measurements have not yet been materialized (see below), but they are already quite possible. Most realistic apparently is the creation of polarization apparatus utilizing X-ray scattering in LiH or in liquid hydrogen (see [14]).

3. BASIC RESULTS OF X-RAY ASTRONOMY

Let us turn to the results obtained in the field of galactic and extragalactic X-ray astronomy.

The existence of powerful galactic and extragalactic sources of X-rays has been established. The brightest of them (for observations from the Earth) is

* For observations from the ground the covering of the source of the Moon is a rare event. The next one for Crab Nebula may be only observed in 1972. However, with the aid of rockets it is possible to observe the phenomenon any time.

Sco XR-1 (Scorpion XR-1). Up to only very recently (provided we do not take into account the work [1]) only nine more sources were known; they are compiled in Table I (from data of [15], see also [6]), alongside with data concerning two earlier known sources: Cyg XR-1 and Cyg XR-2, and also of three rediscovered sources: Cyg A, Vir A (M 87) and Cas A (Cassiopea A). In reality, however, a whole series of new sources were also discovered during the flight of the rocket having taken in April 1965 (of which some results are brought out in [1]); for example, the source Leo XR-1 and, apparently, not less than ten others, for which details still remain witheld.

TABLE 1

Sources of X-Rays

Denomination	(cm^2 sec) Number of readings [15]	Denomination	Number of readings in cm^2 sec [15]	[1]
Tau XR-1 (Crab Nebula	2.7	Sgr XR-2	1.5	--
		Ser XR-1	0.7	--
Sco XR-1	18.7	Cyg XR-1	3.6	0.9
Sco XR-2	1.4	Cyg XR-2	0.8	1.0
Sco XR-3	1.1			
Oph XR-1	1.3	Cyg A (XR-3)	--	0.4
Sgr XR-1	1.6	Vir A (M 87)	--	0.2
		Cas A	--	0.3

The number of readings indicated in Table 1 refers to specific-type counters; therefore, the data brought out characterize the relative intensity of the sources. Note that in [1] still another important discovery was made (besides the detection of X-ray emission of radiogalaxies), namely the variability of the source Cyg XR-1. Indeed, the data of [15] were obtained in June 1964, and at that time Cyg XR-1 gave 3.6 counts/cm^2 sec. In April 1965 this source gave already only 0.9 count/cm^2 sec. Incidentally, this circumstance constituted precisely the cause of detection of Cyg A (Cyg XR-3), which is very close in direction to Cyg XR-1, and it could not have been detected earlier, when the latter was significantly brighter.

The first optically identified X-ray source was the Crab Nebula (radiosource Taurus A), which, as is well known, constitutes a supernova 1054 shell (which belongs to supernovae of type-I or is some rare supernova of a very peculiar type). Presently X-ray emission is revealed also from the brightest radiosource, Cassiopea A [1], which constitutes the shell of a type-II supernova, having outbursted in the Galaxy some 250 years ago. There exists no doubt that most of other detected X-ray sources are also within the bounds of the Galaxy. This is clearly seen from Fig.1, where the position of the first 10 sources of Table 1 is indicated. The sources are clearly concentrated near the galactic equator, that is, in the region of the galactic disk. Meanwhile, the extragalctic sources must have been distributed by the sky more or less uniformly.

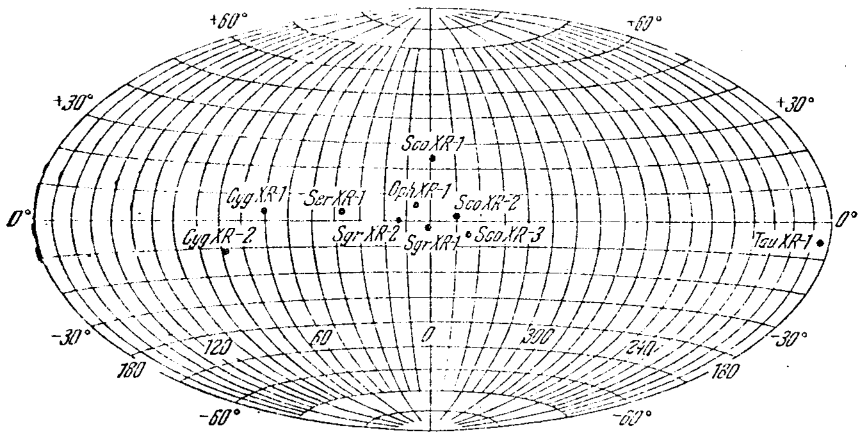

Fig.1. Position of X-ray sources over the celestial sphere (only 10 sources of Table 1 are indicated). (The line 0°-0° responds to the galactic equator.)

Quite significant is the fact that so far no optical or radio source could be noted at the place of the brightest X-ray source Sco XR-1 (of which the angular dimension in a direction parallel to the galactic equator is less than 7', and according to the latest data [32], less than 20"; see annotation at the end of the paper).

In case of Crab Nebula it has been possible to establish (by the method of lunar covering [13]) that the X-ray source Tau XR-1 lies within the bounds of the nebula and has the dimension near 1', which constitutes about $^1/_5$ of the optical and radio dimensions of the Crab (for details see [16]). The position of the X-ray source is shown by a circle in Fig.2. Inasmuch as Crab is located at a distance of 3300 light years = $3.3\ 10^{21}$ cm, the diameter of the X-ray source constitutes near 1 light year = 10^{18}cm $\simeq 10^5$ a.u. For the three other sources identified with known objects (Cas A, Cyg A, Virgo A), nothing is known as regards the position and dimension of X-ray sources. Considering, however, that the identification itself is reliable, we obtain outright the distance to the sources (Table II).

As to the fluxes of X-rays near the Earth and X-ray luminances L_X of the sources, the result depends on the emission spectrum on which only quite approximate data are available. Generally they are not in contradiction with the assumption that the X-ray spectrum coincides within the range 1 - 10 A with the spectrum of a transparent, optically thin layer of gas with temperature $T > 5 \cdot 10^7$ °K $\simeq 5$ kev. The values indicated in Table I respond to such a thermal radiation with $T = 5 \cdot 10^7$ °K. If we consider the emission as bremmstrahlung with spectral index $\alpha = 1$ (the intensity $I \sim \nu^{\alpha}$, where ν is the frequency), the flux varies insignificantly (for example, for Cyg A in this case $L_X = 2 \cdot 10^{46}$; see [1]).

T A B L E II

Identified X-ray Sources

Denomination	Flux near Earth in the region 1-10 A in 10^{-8} erg/cm^{2}sec	Distance light-years	Luminance. erg/sec		
			Roentgen	radio	optics
Cyg A (Cyg XR-3)	0.5	$660 \cdot 10^6$	$3 \cdot 10^{46}$	$4.4 \cdot 10^{44}$	$\sim 10^{44}$ *
Virgo A (Vir XR-1) (M 87 ≡ NGC 4486)	0.2	$33 \cdot 10^6$	$3 \cdot 10^{43}$	$3 \cdot 10^{41}$	$\sim 10^{44}$ **
Crab Nebula Tau A (Tau XR-1)	3.2	$3.3 \cdot 10^3$	$4.5 \cdot 10^{36}$	$8 \cdot 10^{33}$	$10^{36} \div 10^{37}$
Cassiopea A (Cas XR-1)	0.4	$100 \cdot 10^3$	$5 \cdot 10^{36}$	$2.6 \cdot 10^{35}$	$10^{35} \div 10^{36}$

* To the share of magnetic bremmstrahlung correspond $10^{42} \div 10^{43}$.
** Principally magnetic bremmstrahlung emission.

The question of X-ray spectrum has a first degree importance for the establishment of the mechanism responsible for the emission. Unfortunately, measurements with monochromators have not yet been materialized to-date and some information on the spectrum are obtained only with the aid of various filters, and also of scintillation and proportional counters (see [4, 6, 18]). Following is the procedure to deal with the insuffiency of data: the observation data are compared with three theoretical spectra. Namely, the intensity for a blackbody is

$$I_{BB,\nu} = \text{const} \cdot \frac{\nu^3}{e^{h\nu/kT} - 1}$$

In case of bremmstrahlung emission of an optically thin layer of gas with temperature T, the intensity is

$$I_{b,\nu} = \text{const} \cdot e^{-h\nu/kT}$$

(see below), and for magnetic bremmstrahlung emission of electrons with the spectrum $I_e = KE^{-\gamma}$, the X-ray spectrum is

$$I_{m,\nu} = \text{const} \cdot \nu^{-\alpha}, \qquad \alpha = \frac{\gamma - 1}{2}$$

(see [17, 18]).

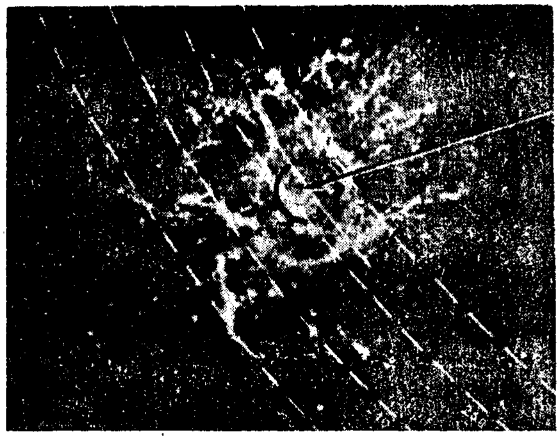

Fig.2. Crab Nebula (optical photograph in the rays of one of the spectral lines).

The circle shows the position of the X-ray source. The dashed lines indicate the position of the lunar limb (the numerals indicate the time in seconds from the launching time of the rocket).

For the Crab (Tau XR-1) the data are visibly compatible with both the magnetic bremmstrahlung $I_{m,\nu}$ and the bremmstrahlung $I_{b,\nu}$ spectra, but the index or the temperature T must be somewhat changed for various parts of the spectrum (such a situation might take place for a nonhomogenous source). In case of Sco XR-1 the latest data [19] are evidence against the blackbody spectrum and they are completely compatible with the bremmstrahlung spectrum $I_{b,\nu}$ for $T = 5.8 \cdot 10^7$°K. The radiation flux from Sco XR-1 on Earth in the 2 - 20 kev energy interval of photons constitutes 74.6 photons/cm sec or $4.8 \cdot 10^{-7}$ erg/cm sec (see [19]). According to [4], the flux from Sco XR-1 is somewhat lesser: in the interval $1 < E_X < 10$ kev., $F_X = (1.6 \pm 0.4) \cdot 10^{-7}$ erg/s (according to the same data for Crab $F_X = 2 \cdot 10^{-8}$). If Sco XR-1 is at a distance of 10^3 light years from us, its luminance is

$$L = 4\pi R^2 F_X \sim 3 \cdot 10^{36} \text{ erg/sec.}$$

Note finally, that aside from discrete X-ray sources a diffusive cosmic X-ray background was also detected. The intensity of background in the interval $2 \text{ Å} \leqslant \lambda \leqslant 8 \text{ Å}$ is $I_\phi \cong 10$ photons/cm^2 sec sterad. According to [4] it is still not quite certain that the observed background has a cosmic nature, though it is quite probable. Inasmuch as the background is isotropic, it must have an extragalactic origin (obviously if the background is cosmic, that is extraterrestrial). It is possible that the background may constitute a combined X-ray emission of galaxies, not resolved by the apparatus (see [1]). However, the background could also have been induced as a result of bremmstrahlung emission of hot intergalactic gas, or constituted the X-ray radiation forming the thermal photon scattering on relativistic electrons. Important problems are connected with the question of X-ray background and also with X-ray absorption in the intergalactic space; we shall not pause at them (see [5, 6, 20 - 25]).

4. ON THE NATURE OF COSMIC X-RAY RADIATION

The most important question with which we are confronted through observations consists in ascertaining the character of the sources and the nature of cosmic X-ray radiation emitted by them. It is then also essential that we refer here to very powerful radiations competing with optical and radio-emission. This is precisely the aspect that was found to be most unexpected, for a weak cosmic X-ray emission might already have been evidently expected on the basis of data on solar X-ray radiation. It is interesting to note that precisely the same situation took place 15 - 20 years ago, when powerful radioemission of supernova shells and radiogalaxies was discovered.

We mentioned above the character of the sources and the nature of their X-ray emission. We shall now make more precise what we have in mind.

By their character the sources can be conveniently subdivided into "compact" and "extended" sources. The star is a classical example of a compact source; when the question evolves about the X-ray band, of particular interest are the neutron stars. As a matter of fact, in general, the "standard" stars are relatively poor X-ray emitters. But the neutron stars may be so hot ($T > 10$ °K) that despite their small dimensions (radius $r \sim 10$ km), they can be powerful X-ray sources. In this regard, see the reviews [5, 26] with the indicated literature. Another possible example of compact X-ray sources is the magnetospheres of quasar nuclei and analogous formations (see [5, 26, 27, 28]).

To the extended sources belong the large clouds of hot gas, and also, for example, a cluster of relativistic electrons in some extended region. Radiogalaxies and supernova shells constitute precisely such extended sources of radioemission. Speaking of the nature of the source, we shall understand the mechanisms and processes that are responsible for its X-ray emission. It is obvious that compact as well as extended sources may have an entirely different nature.

Indeed, X-rays may emerge as a result of a series of processes, among which the most important are:

1. The bremmstrahlung radiation occurring during collisions of electrons with nuclei. According to the astrophysical (and simultaneously quantum) terminology, it is referred here to free-free transitions, that is, to transitions of an electron from level to level in a continuous spectrum with emission of a photon.

2. The characteristic X-ray radiation, forming during transitions in atoms from discrete to discrete level (bound-bound transitions). Obviously, in the X-ray region proper there lie only the lines of elements not lighter than nitrogen and oxygen (for a hydrogen-like ion with charge Z, the ionization potential from the ground state is $13.6\ Z^2$ v; for the ion C VI this responds to about 500 v or to wavelength $\lambda \cong 25$ A).

3. The magnetic bremmstrahlung (synchrotron) emission of relativistic electrons occurring during their motion in magnetic fields.

4.. The Compton (or, as sometimes described, the inverse Compton) X-ray emission which is generated during the scattering of relativistic electrons on optical and radio photons.

A somewhat more detailed discussion of these mechanisms is impossible here, and we shall limit ourselves to certain remarks concerning the processes 1, 2 and 3 (for details see [5, 6]; the characteristic emission is discussed in [6] and in the references indicated in that paper).

The spectrum of the magnetic bremmstrahlung of an electron with energy E has a maximum in the frequency (see, for example [18])

$$\nu_m = 0.07 \frac{eH_\perp}{mc}\left(\frac{E}{mc^2}\right)^2 = 1{,}2\cdot 10^6 H_\perp \left(\frac{E}{mc^2}\right)^2 = 4.6 \cdot 10^{-6} H_\perp [E\ (ev)]^2 \text{ cps} \quad (1)$$

where $H_\perp$ is a projection of the magnetic field perpendicularly to the visual ray.

So long as we do not refer to small regions, the field H in supernova shells and radiogalaxies is $H < 10^{-3}$ oe; this is why electrons with energy $E \gtrsim 10^{13}$ ev would be those mainly responsible for the magnetic bremmstrahlung emission with $\nu \sim 10^{18}$ ($\lambda = \frac{c}{\nu} \sim 3$ A, $E_X = h\nu \sim 4$ kev).

The characteristic time of magnetic bremmstrahlung losses (time during which the energy of the electron decreases by half as much)

$$T_m = \frac{5{,}1\cdot 10^8}{H_\perp^2} \frac{mc^2}{E} \text{ sec} \quad (2)$$

For $H_\perp \sim 10^{-3}$oe and $E \gtrsim 10^{13}$ ev, the time $T_m \lesssim 3 \cdot 10^7$ sec $\cong$ 1 year. Meanwhile the age of the Crab Nebula (supernova 1054 shell) is more than 900 years and the active phase for radiogalaxies is of the order of 10^6 years and more. Hence it is already clear that the X-ray radiation of supernova shells and radiogalaxies could have a magnetic bremmstrahlung nature only with a continuous "pumping" of electrons with very high energy. For the Crab Nebula and Virgo A, where the optical and magnetic bremmstrahlung emission is unquestionably observed, the question of electron "pumping" arises anyway. This is why the magnetic bremmstrahlung nature of X-ray emission of these sources (particularly of Crab Nebula) is possible. The most convincing evidence of this hypothesis would be found by the detection of polarization of X-ray radiation. For the Crab Nebula one may expect a polarization reaching in the case of magnetic bremmstrahlung up to 15%. Speaking in terms of real conditions, no other mechanism can provide such a polarization.

For the brightest source Sco XR-1, and also for all other galactic sources besides Crab, the magnetic bremmstrahlung hypothesis seems to be of little probability. It should be sufficient to state that these sources do not provide notable optical bremmstrahlung emission, and, except for Cassiopea A, not even noticeable radioemission. Under such conditions, the X-ray emission can be considered as magnetic bremmstrahlung only at a price of far-reaching additional assumptions. (We assumed here that the question evolved around extended sources. For the compact ones the situation will change; see annotation at the end).

During the scattering of electrons with energy

$$E \ll \frac{mc^2}{\varepsilon} mc^2 \qquad (3)$$

on photons with energy ε, photons with energy

$$E_x \sim h\nu \sim \varepsilon \left(\frac{E}{mc^2}\right)^2. \qquad (4)$$

are formed. For thermal optical photons ($\varepsilon \sim 1$ ev) condition (3) has the form $E \ll 3 \cdot 10^{11}$ ev and $E_x \sim 10^3 \div 10^4$ ev for $E \sim 2 \div 5 \cdot 10^7$ ev. For relict metagalactic photons (see [21]) $\varepsilon \sim 10^{-3}$ ev ($T \simeq 3°K$) and $E_x \sim 10^3 \div 10^4$ ev for $E \sim$ $\sim 5 \cdot 10^8 \div 2 \cdot 10^9$ ev. In the region (3) the Compton losses differ from magnetic bremmstrahlung losses in isotropic field with intensity H by the substitution of $H^2/8\pi$ by w_{ph}, which is the density of energy of thermal (scattering) photons (this result has a simple physical sense; see [4, 17]).

For extended sources $w_{ph} < 5 \cdot 10^{-12}$ erg/cm^3 (we have in mind the density of thermal radiation in the optical and radio regions; the energy density of the black radiation with T = 3°K constitutes $w_{ph} \simeq 0.6 \cdot 10^{-12}$ erg/cm^3). Therefore, Compton losses are less than the magnetic bremmstrahlung losses so long as

$$w_{ph} < 5 \cdot 10^{-12} < \frac{H^2}{8\pi} \quad \text{or} \quad H > 10^{-5} \text{ oe}.$$

In radiogalaxies and supernova shells this inequality is usually observed; hence it is already clear that the X-ray Compton emission is, generally speaking, weaker than the total magnetic bremmstrahlung emission from the source. Developing similar considerations we may see that the Compton mechanism is as improbable as the magnetic bremmstrahlung as a mechanism of X-ray emission of Cassiopea A, Cygnus A and of a series of other X-ray sources, provided only they are extended.

For extended sources great attention is deserved by the bremmstrahlung mechanism, or, to be more precise, the bremmstrahlung emission of a quasiequilibrium hot plasma, that is, plasma with distribution of electrons by velocities close, or practically coinciding with Maxwellian velocities.

An electron with energy E induces bremmstrahlung emission lying in the entire frequency interval below $\nu_{max} = \frac{E}{\hbar}$. The spectrum of plasma bremmstrahlung emission depends at the same time not only on the emission spectrum of one electron, but also on the distribution function of electrons by velocities. If this distribution is Maxwellian with temperature T, we may conclude that from a unit of volume of fully ionized hydrogen plasma there is emitted per unit of time the energy

$$\varepsilon = \frac{64\sqrt{2\pi}\, e^6 n^2}{3mc^3 h}\left(\frac{kT}{m}\right)^{1/2} \cong 1{,}6 \cdot 10^{-27} n^2 \sqrt{T} \ \text{erg/cm sec} \qquad (5)$$

where n is the concentration of electrons (and protons), whereas in the last expression as well as everywhere below, the temperature T is measured in absolute degrees; if the gas consisted of ions with charge Z (or to be more precises eZ), it would be necessary to substitute in (5) n^2 by $nn_Z Z^2 = n^2 Z$, where n is the electron concentration, and on the strength of quasineutrality of ions $n_Z = \frac{n}{Z}$. Formula (5) is valid in the Borne approximation, when $\frac{e^2 Z}{\hbar v} \ll 1$; for hydrogen plasma this means that the velocity of electrons $v \gg 3 \cdot 10^8$ cm/sec or

$$T \sim \frac{mv^2}{3k} \gg \frac{e^4 m}{3k\hbar^2} \sim 10^5\,^\circ\mathrm{K}. \qquad (6)$$

In the frequency region $\frac{h\nu}{kT} \gg 1$ the spectral density of bremmstrahlung radiation is determined by the formula

$$\varepsilon_\nu \cong \varepsilon \frac{h}{kT} e^{-h\nu/kT} = 7{,}7 \cdot 10^{-38} \frac{n^2}{\sqrt{T}} e^{-h\nu/kT} \text{ erg/cm}^3 \text{ sec cps} \qquad (7)$$

where ε is given by expression (5). If we integrate expression (7) over the spectrum $\int_0^\infty \varepsilon_\nu d\nu$, the result coincides with expression (5), though formula (7) is also approximate. As a matter of fact formula (5) is also approximate. This approximation is good because the region of small frequencies $h\nu/kT \ll 1$ contributes only little to ε (in this region, expression (7), multiplied by $\frac{\sqrt{3}}{\pi} \ln \frac{4kT}{1{,}781\,h\nu}$ is valid for ε_ν). Expressions (5) and (7) were obtained without accounting for the reabsorption, that is, they are related to the case of optically thin (transparent) gas layer. Taking reabsorption into account the radiation decreases and becomes black for a thick layer. By virtue of the Kirchhof theorem $\varepsilon_\nu = \varepsilon_{0,\nu}\,\mu_\nu$, where μ_ν is the radiation's absorption coefficient and $\varepsilon_{0,\nu}$ is the spectral density of blackbody radiation:

$$\varepsilon_{0,\nu} = \frac{8\pi}{c^2} \frac{h\nu^3}{e^{h\nu/kT} - 1}. \qquad (8)$$

This is why we obtain from (5), (7), (8)

$$\mu_\nu = \frac{\varepsilon_\nu}{\varepsilon_{0,\nu}} = \frac{8\sqrt{2}e^6 n^2}{3\sqrt{\pi} m^{3/2} ch (kT)^{1/2} \nu^3} (1 - e^{-h\nu/kT}) = \frac{4 \cdot 10^8 n^2}{\sqrt{T}\nu^2} (1 - e^{-h\nu/kT}). \qquad (9)$$

The layer may be considered as thin so long as its optical thickness

$$\tau_\nu = \int_0^L \mu_\nu dl \ll 1$$

or, for a uniform layer with thickness L, so long as $\mu_\nu L \ll 1$. From a unit of blackbody surface (in particular, from the surface of an optically thick layer of equilibrium plasma), the following flux is emitted:

$$F = \sigma T^4, \qquad \sigma = \frac{\pi^2 k^2}{60\hbar^3 c^2} = 5{,}67 \cdot 10^{-5} \text{ erg/cm sec deg}.$$

Estimates show (see [29]) that in the cases under discussion reabsorption is still very small.

The equilibrium plasma cloud with volume V has by virtue of the above considerations the luminance

$$L_X = \varepsilon V = 1.6 \cdot 10^{-27}\, n^2\sqrt{T}\, V \text{ erg/sec} \qquad (10)$$

whereupon the plasma is considered uniform (for definiteness we proceed in the same way below, where in order to obtain the mean concentration $\bar{n}$ of the gas we shall postulate $n \sim \sqrt{\overline{n^2}}$); the index of X and L points to the fact that we are interested in the case when $h\nu \sim kT \gtrsim 10^3$ ev ($T \gtrsim 10^7$ °K) and the fundamental part of radiation lies in the X-ray region of the spectrum.

From (6) it is clear that, knowing the luminance L and the temperature T, we may express n^2, the gas mass M and its inner energy W_T by V :

$$n^2 = \frac{L_X}{1{,}6 \cdot 10^{-27}\sqrt{T}V}, \quad M \sim 2 \cdot 10^{-24}\sqrt{n^2}\,V \sim \frac{(L_X V)^{1/2}}{2 \cdot 10^{10} T^{1/4}} \text{ g}, \qquad (11)$$

$$W_T \sim \sqrt{n^2}\,kTV \sim 3 \cdot 10^{-3}(L_X V)^{1/2}\,T^{3/4} \text{ erg}.$$

In the case of the Crab $L_X \sim 5 \cdot 10^{36}$ ergs, and the volume V is known to be

$V \sim \frac{4\pi}{3} r^3 \sim 5 \cdot 10^{53}$ cm^3. Hence for $T \sim 10^8$ we have $n^2 \sim 10^6$, $M \lesssim M_\odot$ and W $\sim 5 \cdot 10^{48}$ ergs. As far as can be judged, such a possibility cannot be denied; it was more than once discussed in literature (see for example, [6]). The inner energy of the gas $W_T \sim W_{cr}$, where W_{cr} is the energy of cosmic rays in the source. Such a relation is not only consistent, but is even natural (see [20, 22, 29]). A possible objection to the assumption of existence in the Crab of a large amount of gas consists in that a strong depolarization would, as a result, be observed in Crab's magnetic bremmstrahlung centimeter and decimeter emission. However, this objection fails to be convincing, as far as we are concerned, inasmuch as the volume of the X-ray source in the Crab is by one order smaller than the volume of the source responsible for the polarized optical and radio emissions (see [16, 29]).

By virtue of the above considerations the question of the nature of Crab's X-ray radiation is now open. Both bremmstrahlung and magnetic bremmstrahlung mechanisms are possible for it, though the latter is visibly somewhat more probable. Decisive here will apparently be only polarization measurements.

In case of Virgo A, both the bremmstrahlung and magnetic bremmstrahlung mechanisms compete here basically too, but here the situation is more complex, inasmuch as the size of the X-ray source is unknown. The greater the source, the more probable its bremmstrahlung nature. This hypothesis is met with difficulties that are mainly connected with the requirements of having a large reserve of hot gas (see [29, 30]).

For Cas A and Cyg A the bremmstrahlung mechanism seems precisely to be the most likely. The alternative assumption would consist in that the respective X-ray sources would be very small by comparison with radiosources (compact sources). Though there are no indications of any sort on the existence of such compact sources in Cas A and Cyg A, this is, however, not excluded. If we consider that the

the X-ray emission of Cyg A as bremmstrahlung with $T \cong 5 \cdot 10^7\,°K$, we obtain from (11):

$$n^2 \sim \frac{3 \cdot 10^{69}}{V}, \quad M \sim 10^{11}\sqrt{V}, \quad W_T \sim 3 \cdot 10^{26}\sqrt{V} \qquad (12)$$

or at $V = 3 \cdot 10^{68}$ cm^3 (radius $r \sim 5 \cdot 10^{22}$ cm) and $V = 10^{62}$ cm^3 ($r \sim 3 \cdot 10^{20}$ cm) we have

$$V \sim 3 \cdot 10^{68}\ cm^3, \quad n \sim 3, \quad M \sim 10^{45}\ g \sim 5 \cdot 10^{11} M_\odot, \quad W_T \sim 5 \cdot 10^{60}\ \text{ergs},$$
$$V \sim 10^{62}\ cm^3, \quad n \sim 5 \cdot 10^3, \quad M \sim 10^9 M_\odot, \quad W_T \sim 3 \cdot 10^{57}\ \text{ergs}.$$

Even in the second variant, without even speaking of the first, the gas mass is large. On the other hand, even for the first variant the energy $W_T \sim W_{cr}$ is the energy of cosmic rays in Cyg A (see [17]); therefore, the mechanism of X-ray emission of Cyg A does not lead to additional difficulties of energetic character (see [29]).

Thus, in the present state of the matter, it seems to us that in case of Cyg A only two possibilities are at present likely:

a) the presence of a great amount of hot gas leading to the formation of bremmstrahlung X-ray emission;

b) the existence in Cyg A of some compact X-ray source in radio and optical regions that went unnoticed (active galactic nucleus, X-ray quasar etc.); such a source could have provided X-ray radiation as a result of action of a whole series of mechanisms.

Only observations could provide the solution to the question as to whether one of this possibilities is realized, and if so, which one. The first of them appears to us as being the somewhat more natural and probable. However, we are confronted in any case with a situation that is entirely new in astrophysics: up until now no indications of any sort were available that would point to the presence in radiogalaxies of enormous masses of hot gas, just as no sound foundations existed in favor of hypothesis on X-ray quasars "sitting" in radiogalaxies.

5. CONCLUDING REMARKS

Any further progress in the field of X-ray astronomy is impossible without improving the apparatus. Oriented satellites must be available, inasmuch as the observations with the aid of rockets are quite short-lived. Meanwhile, prolonged observations are necessary, particularly for ascertaining the variability of the sources. Such a variability is interesting not only in itself, but because it allows us to estimate the source's maximum dimensions (it is clear that a source with dimensions r can not change their brightness particularly strongly in a time $t < \frac{r}{c}$). Obviously, the variability of sources may be made apparent also as a result of repeated rocket launchings, as this already took place in regard to Cyg XR-1.

Another path for the determination of sources' dimensions evidently consists in the increase of the angular resolution. A high angular resolution (angular seconds) may be achieved in the simplest way of all by merely utilizing the eclipse of the source by the Moon. Incidently, fairly large possibilities exist also in the area of improvement of various-type X-ray "telescopes" (including the quasi-optical systems). The increase of X-ray telescopes' light-gathering power (or the area) will undoubtly allow us to move forward in regard to the study of the spectrum of sources. Finally, polarization measurements are entirely indispensable, inasmuch as they allow us to make apparent in the best way possible the presence of magnetic bremmstrahlung radiation of X-rays. It is true, however, that the absence of notable polarization still does not conceal the magnetic bremmstrahlung mechanism; however, its presence practically demonstrates the magnetic bremmstrahlung nature of the source*.

The development of X-ray astronomy is in remarkable way resemblant to that of radioastronomy, as we had the opportunity to underscore earlier.

Cosmic radioemission was sought after as late as at the end of the 19th century. Its existence could not have been subject to doubt (if we have in mind, in particular, the thermal radioemission of the Sun). It could have been assumed, however, that this emission is weak and, say for the Sun, it responds to the emission of a blackbody with temperature $T \cong 6000\ ^\circ$. But in reality it was found that even the "quiet" Sun is a source of radioemission with temperature $T \sim 10^6$, whereas the sporadic solar radioemission is at times even by several orders stronger. Such a situation takes also place in the X-ray region.

The discovery of powerful radioemission of supernova shells and radiogalaxies was unexpected, and it introduced in the field of astronomy contributions of permanent significance. The same may be said about the discovery of powerful X-ray emission of galactic sources and radiogalaxies (incidently, Cyg A was the first revealed discrete source of cosmic radioemission). By the same token it is now quite clear that the X-ray astronomy is not simply of promising direction over which something new can be found. The something new has already been found, and it surpassed by its significance all the expectations. We thus are no longer led to question the fact that in the years to come the X-ray astronomy will be given exceptional attention, and that by its specific weight in astronomy it will promptly occupy a place alongside with optical and radio astronomy. By the same token the presently going astronomical revolution will be basically completed in its traget to transform astronomy from optical to the "all-wave".

*** THE END ***

Institute of Physics in the name of
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of the USSR Academy of Sciences

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* It is obvious that optical observations are very important for ascertaining the nature of X-ray sources (for example, the optical emission of hot gas, endowed with a continuous spectrum [29, 31]). The detection of linear X-ray spectrum would doubtless play an essential role (here atoms of highly-ionized iron would offer particular interest from that viewpoint; see [30, 31]).

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ADDENDUM DURING CORRECTION

According to the latest data [32], the angular dimension of the source Sco XR-1 is less than 20". This case makes little probable the assumption that Sco XR-1 is an extended object of the supernova shell type. It is most likely that here we are confronted with a hot neutron star or with a contracting magnetic star [27, 33], emitting magnetic bremmstrahlung X-rays. Because of the scarcity of data on the spectrum and on its distortion on account of processes in the neutron star shell, the objections against identifying Sco XR-1 with a hot neutron star based upon the fact that the spectrum of this source is not a spectrum of blackbody is not yet convincing. At the same time, the hypothesis on the quasistellar magnetobremmstrahlung X-ray source [27, 33] appears to us as no less probable. Communication has also been obtained [34] about the discovery of a discrete source of γ-rays in the Cygnus constellation. If it is referred here to Cyg A, γ-radiation may have emerged as a result of scattering of relativistic electrons on X-ray photons emitted by the very same source Cyg A XR-3 (see [29]).

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