SOVIET PHYSICS USPEKHI VOLUME 9, NUMBER 4 JANUARY-FEBRUARY 1967

523.85

POWERFUL X-RAY EMISSION OF RADIO GALAXIES

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Usp. Fiz. Nauk 89, 549-562 (August, 1966)

1. INTRODUCTION

A major discovery in the field of x-ray astronomy, and no doubt in astronomy in general, was reported quite recently [1] (March, 1966). We refer to the observation of exceptionally strong x-ray emission from the known galaxies Cygnus A and Virgo A (the Galaxy NGC 4486 ≡ M 87).

The x-ray luminosity (emission power) of Cygnus A is $L_X \cong 3 \times 10^{46}$ erg/sec, which is almost 100 times the radio luminosity ($L_r \sim 4 \times 10^{44}$ erg/sec) of this galaxy, which is one of the most powerful known cosmic radio sources (we note that the optical luminosity of Cygnus A is $L_o \sim 10^{44}$ erg/sec). For Virgo A $L_X \cong 3 \times 10^{43}$ and $L_r \cong 3 \times 10^{41}$ erg/sec.

Thus, Cygnus A and Virgo A, and possibly with no less justification other radio galaxies, too, can be called x-ray galaxies. That we deal here with most unusual objects is evident from a comparison with our own Galaxy. The radio luminosity of our Galaxy is $L_r \sim 3 \times 10^{38}$ erg/sec. Its x-ray luminosity is apparently of the same order, and the optical luminosity is $L_o \sim (3-5) \times 10^{43}$ erg/sec. The (optical) luminosity of the sum is $L_\odot = 3.86 \times 10^{33}$ erg/sec, some 10—11 orders of magnitude higher than the x-ray luminosity of the quiet sun, $L_{\odot,X} \sim 10^{23}$ erg/sec.

So the x-ray luminosity of Cygnus A is 10^{13} times (!) higher than the total luminosity (almost all optical) of the sun, several hundred times higher than the total (optical) luminosity of the Galaxy, and 10^8 times larger than the x-ray and radio luminosities of the Galaxy.

Even prior to this discovery, hypotheses were advanced in the literature concerning the possible existence of powerful x-ray emission of radio galaxies, with concrete reference to Cygnus A (see [2,3]). However, the corresponding estimates could not be sufficiently accurate or convincing. It is the discovery of x-radiation of extragalactic objects (radio galaxies) which heralds a new phase in the development of x-ray astronomy. Of course, we cannot hope to present here a detailed and complete review of the status of x-ray astronomy. We wish, however, to dwell at least briefly both on the history of this question†, on the most important observational results, as well as on the possible mechanisms of cosmic x-ray emission (for more details see the reviews [4-6]).

*Paper at the Scientific Session of the Division of General and Applied Physics, USSR Academy of Sciences, 20 April 1966.

†The first stage of development of x-ray astronomy is described in popular form by H. Friedman (UFN 84, 505 (1964); Scientific American 210 (6), 36 (1964)).

2. START OF X RAY ASTRONOMY

It has been known since 1948 that the sun emits x-rays [1]. Since that time, the study of x-rays from the sun has made much progress [8,9], and by now this method plays an important role in solar physics. In the spectral interval from 1 to 10 Å, the energy flux from the quiet sun to the earth, $F_{\odot,X}$, fluctuates between 10^{-4} and 10^{-5} erg/cm sec, which is 10^{10}—10^{11} times smaller than the total flux of solar radiation $F_\odot = 1.4 \times 10^6$ erg/cm sec (the greater part of this flux is in the visible part of the spectrum). During periods of high solar activity, particularly during flares, the solar x-ray emission increases very strongly, but nonetheless $F_{\odot,X}^{max} \lesssim 10^{-6} F_\odot \sim 1$ erg/cm sec.

The star closest to us is at a distance $R \sim 4 \times 10^{18}$ cm, whereas the astronomic unit (the distance from the earth to the sun) is 1.5×10^{13} cm. It is clear therefore that if the sun were to be placed at the same distance as the closest star, the x-ray emission flux produced on earth even during the most violent activity would be

$$F \sim \left(\frac{1.5 \cdot 10^{13}}{4 \cdot 10^{18}}\right)^2 F_{\odot,X}^{max} \leqslant 10^{-11} \text{ erg/cm}^2\text{sec}.$$

This corresponds to a flux of only 10^{-2} photon/cm^{2}sec even for photons of energy $E_X \sim 10^3$ eV ($\lambda \sim 10$ Å).*

The x-ray emission from stars similar to the sun cannot be observed as yet at the present sensitivity of the apparatus; a few years ago this deduction was even more categoric. Estimates of the x-ray emission from supernova shells, from "exploding" stars, etc. also led to fluxes weaker by many orders of magnitude than for the sun. As a result, the almost universally prevailing opinion was that nonsolar x-ray astronomy has few prospects.

This forecast turned to be in error. But at the same time, it becomes clear why galactic x-ray emission was observed somehow by accident. At any rate, the first successful rocket observation of cosmic x-ray emission [10] were made as parts of attempts to observe an entirely different radiation—the x-ray emission that might be produced when the moon is struck by electrons

*Obviously, the wavelength (in Å) is connected with the photon energy E_X (in eV) by the relation

$$\lambda = \frac{hc \cdot 10^8}{1.6 \cdot 10^{-12} E_X \text{ (eV)}} \cong \frac{12\,400}{E_X \text{ (eV)}}.$$

Table I. X-ray sources

Name	Counts/ cm^2sec (data of [15])	Name	Counts/cm^2sec	
			Data of [15]	Data of [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 (Cyg XR-3) (Cygnus A)	—	0.4
Sgr XR-1	1.6	Vir A (M 87, Virgo A)	—	0.2
		Cas A (Cassiopeia A)	—	0.3

of relatively high energy, such as those contained in the solar wind, or under the influence of harder solar x-rays (x-ray fluorescence).

This first successful rocket experiment in the field of extra-solar x-ray astronomy [10] occurred on 12 July 1962 and led to observation of cosmic x-rays with a flux reaching 10 photons/cm^2 sec (we have seen that such a flux is 10^7-10^8 times larger than the flux produced were the quiet sun to be located at the position of the nearest star). The measurements were repeated by two groups in 1963[11,12], after which the existence of powerful cosmic (non-solar) x-ray emission was established without any doubt.

Since that time, a large number of flights (by rockets and balloons rotating about their axes) were made* and notable progress was made in the improvement of the apparatus. This led to a number of important results (see [1,4-6] and the literature cited there). We confine ourselves here to the remark that at present it is possible to identify sources whose x-ray flux is only 0.2—0.3 photon/cm^2 sec. The angular resolution in [1] was about 1.5°, but in some cases much higher resolution was attained. For sufficiently strong sources, a resolution of 1′ is already feasible, or even better when x-ray telescopes, collimators, etc. are used[4,32]. Even better resolution is attained by using the occultation of the source by the moon; this was already realized[13] with respect to the Crab Nebula on 7 July 1964.* Very important measurements of polarization (see below) have not yet been realized, but are perfectly feasible. The most realistic prospects are those of developing polarization apparatus, using the scattering of x-rays in LiH or liquid hydrogen (see [14]).

3. MAIN RESULTS OF X-RAY ASTRONOMY

We turn to the results attained in the field of galactic and extragalactic x-ray astronomy.

The existence of powerful galactic and extragalactic x-ray sources has been established. The brightest of them (when observed on earth) is Sco XR-1 (Scorpion XR-1).* Until recently (more accurately, with publication of [1]), nine more sources were known; these are listed in Table I (data of [15]; see also [6]). The same table lists the data from [1] concerning the two previously known sources Cyg XR-1 and Cyg XR-2, and also three newly discovered sources: Cyg A (Cygnus A), Vir A (M 87, Virgo A), and Cas A (Cassiopeia A). Actually, however, during the flight of the rocket in April 1965 (some results of this flight are given in [1]), a whole number of other new sources was also observed, for example the source Leo XR-1, and apparently not less than ten others, details of which have not yet been reported.

The number of counts indicated in Table I pertains to counters of a definite type, so that the data presented characterize the relative intensity of the sources. We note that one other important discovery was reported in [1] (besides the observation of the x-rays from the radio galaxies), namely the variability of the source Cyg XR-1. Indeed, the data of [15] were obtained in

*Relatively soft x rays ($E_X < 10 - 15$ keV), which are absorbed in air, can be investigated only with the aid of rockets and satellites. Harder cosmic x-rays can be investigated also with high-altitude balloons.

*X-ray sources are customarily denoted by indicating the constellation and the letters X or XR (X-rays); in any one constellation, the sources are numbered in decreasing order of brightness. Thus, Sco XR-1 is the brightest x-ray source in the Scorpion constellation,

Table II. Identified x-ray sources

Name	Flux on earth in the 1-10 Å region, in 10^{-8} erg/cm^{2}sec	Distance, light years	Luminosity, erg/sec		
			X-ray	Radio	Optical
Cygnus A (Cyg XR-3)	0.5	$660 \cdot 10^6$	$3 \cdot 10^{46}$	$4.4 \cdot 10^{44}$	$\sim 10^{44}$
Virgo A (M 87≡NGC 4486, Vir XR-1)	0.2	$33 \cdot 10^6$	$3 \cdot 10^{43}$	$3 \cdot 10^{41}$	$\sim 10^{44}$ *)
(Taurus A, Tau XR-1)	3.2	$3.3 \cdot 10^3$	$4{,}5 \cdot 10^{36}$	$8 \cdot 10^{33}$	$10^{36} \div 10^{37}$**)
Cassiopeia A (Cas XR-1)	0.4	$10 \cdot 10^3$	$5 \cdot 10^{36}$	$2.6 \cdot 10^{35}$	$10^{35} \div 10^{36}$

*The fraction of cyclotron radiation is $10^{42} - 10^{43}$.
**Essentially cyclotron radiation.

June 1964, at which time Cyg XR-1 produced 3.6 counts/cm^2 sec. In April 1965 the same source gave only 0.9 count/cm^2 sec. Incidentally, it is only this circumstance which made it possible to observe a source in Cygnus A (Cyg XR-3) which is very close (in direction) to the source Cyg XR-1 and which could not be resolved earlier, when the latter source was much brighter.

The first optically-identified x-ray source was the Crab nebula (radio source Taurus Z), which, as is well known, is the shell of the supernova of 1054 (this supernova is either of type I or a very rare supernova of a unique type). By now x-ray emission has been observed[1] also from the brightest radio source, Cassiopeia A, which is the shell of a supernova of type II that burst in the Galaxy about 250 years ago. There is no doubt that most other observed x-ray sources lie also within the confines of the Galaxy. This is clear from Fig. 1, which shows the position of the first 10 sources of Table I. The sources are distinctly concentrated near the galactic equator, i.e., in the region of the galactic disc. Extragalactic sources, to the contrary, should have a more or less uniform distribution.

A most significant fact is that so far no optical or radio source had been observed at the location of the brightest x-ray source Sco XR-1 (the angular dimension of Sco XR-1 in a direction parallel to the galactic equator is smaller than 7′, and according to the latest data it is smaller than 20″; see the note added in proof at the end of the article.

In the case of the Crab Nebula, it was established (by the lunar occultation method[13]) that the x-ray source Tau XR-1 lies within the limits of the nebula and has an approximate dimension 1′, amounting to approximately $\frac{1}{5}$ of the optical and radio dimensions of the Crab (for more details see [16]). The position of the x-ray source is marked in Fig. 2 by a circle. Since the Crab is 3300 light years = 3.3×10^{21} cm away, the diameter of the x-ray source mounts to about 1 light year ≈ 10^{18} cm ≅ 10^5 a.u. For three other sources identified with known objects (Cassiopeia A, Cygnus A, and Virgo A), nothing is known concerning the dimensions and positions of the x-ray sources. Assuming, however, that the identification itself is reliable (this,

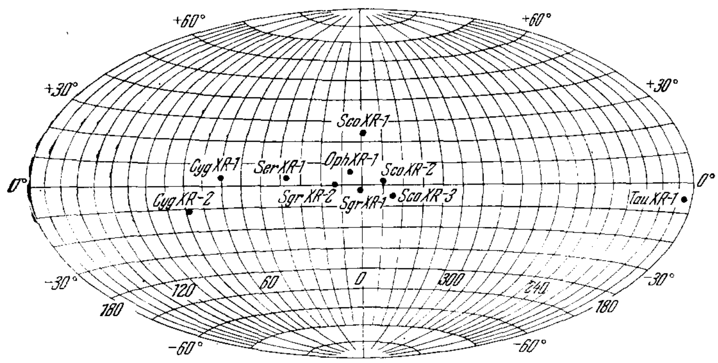

FIG. 1. Position of X-ray sources (only the first 10 sources of Table I are indicated) on the celestial sphere (the line 0° – 0° corresponds to the galactic equator).

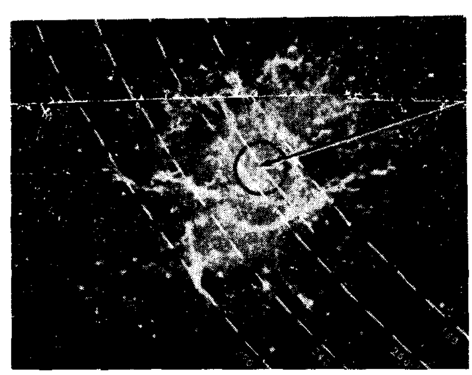

FIG. 2. Crab nebula (optical photograph taken in the rays of one of the spectral lines). The circle shows the position of the x-ray source. The dashed lines show the position of the lunar edge (the numbers indicate the time in seconds elapsed since the launching of the rocket).

of course, still requires confirmation), we obtain directly the distances to these sources (Table II).* As to the x-ray fluxes on earth and the x-ray luminosities L_X of the sources, the result depends on the emission spectrum, with respect to which the available data are highly approximate. In general they do not contradict the assumption that the x-ray spectrum (in the range 1—10 Å) coincides with the spectrum of a transparent (optically thin) layer of gas with temperature $T \geq 5 \times 10^7$ °K ≅ 5 keV. The values indicated in Table I correspond to such a thermal radiation with $T = 5 \times 10^7$ °K. If it is assumed that this is synchrotron radiation with spectral index $\alpha = 1$ (the intensity is $I \sim \nu^{-\alpha}$, where ν is the frequency), then the flux changes insignificantly (for example, for Cygnus A $L_X = 2 \times 10^{46}$ in this case; see [1]).

The question of the x-ray source spectrum is of prime importance when it comes to establishing the mechanism responsible for the emission. Unfortunately, no measurements with monochromators have been made to date, and some information on the spectrum was obtained only through the use of various filters, and also scintillation and proportional counters (see [4,6,18]). Because of the insufficient data, the customary procedure is to compare the observational data with three theoretical spectra. Namely, for a black body the intensity assumed is

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

for bremmstrahlung 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 synchrotron radiation of electrons with spectrum $K_e = KE^{-\gamma}$ the x-ray spectrum is

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

(see [17,18]).

For the Crab Nebula (Tau XR-1) the data are apparently compatible with both the synchrotron radiation and the bremsstrahlung spectra ($I_{sr,\nu}$ and $I_{b,\nu}$), but in both cases the index α or the temperature T must be modified somewhat for different sections of the spectrum (such a situation might arise for an inhomogeneous source). In the case of Sco XR-1, the latest data offer evidence against the black-body spectrum and are fully compatible with the bremsstrahlung spectrum for $T = 5.8 \times 10^7$ °K. The radiation flux from Sco XR-1 on earth, in the photon-energy interval 2—20 keV, is 74.6 photons/cm² sec, or 4.8×10^{-7} erg/cm² sec (see [19]). According to [4] the flux from Sco XR-1 is somewhat smaller, $F_X = (1.6 \pm 0.4) \times 10^{-7}$ erg/cm² sec in the interval $1 < E_X < 10$ keV (according to the same data $F_X = 2 \times 10^{-8}$ for the Crab Nebula). If Sco XR-1 is 10^3 light years away from us, then its luminosity is $L_X = 4\pi R^2 F_X \sim 3 \times 10^{36}$ erg/sec.

We note, finally, that a diffuse cosmic x-ray background was also observed besides the discrete x-ray sources. In the interval $2 Å \leq \lambda \leq 8 Å$, the background intensity is $I_{bg} \cong 10$ photons/cm² sec-sr. According to [4] there is still no full assurance that the observed background is of cosmic origin, although this is highly probable. Since the background is isotropic, it should be of extragalactic origin (provided, of course, the background is cosmic, i.e., extraterrestrial), It is possible that the background is a superposition of galactic x-rays that are not resolved by the apparatus (see [1]). The background could also be, however, the result of bremsstrahlung of hot intergalactic gas, or the x-radiation produced when thermal photons are scattered by relativistic electrons. Related to the question of the x-ray background, and also to the absorption of x-rays in intergalactic space, are important problems which we shall not stop to discuss here (see [5,6,20-25]).

4. NATURE OF COSMIC X RADIATION

The most important question raised by the observation is how to explain the character of the sources and of the nature of the cosmic x-rays emitted by them. An essential factor here is that we are dealing with very powerful radiation, which competes with optic and radio emission. It is this aspect of the situation which is unexpected, since weak cosmic x-radiation could be expected, of course, even on the basis of the data on solar x-rays. It is interesting that an exactly analogous situation arose 15—20 years ago, when the powerful radio emission from supernova shells and radio galaxies was discovered.

We have already made mention of the character of the sources and the nature of their x-radiation. We must define more precisely what we have in mind.

With respect to the character of the sources, a distinction must first be made between "compact" and "extended" ones. A classical example of a compact source is a star; when dealing with the x-ray band, particular interest attaches to neutron stars. The point is that "ordinary" stars are in general relatively weak x-ray emitters. Neutron stars, on the other hand, can be so hot ($T \gtrsim 10^7$ °K) that in spite of their small size (radius $r \sim 10$ km) they are powerful x-ray sources (see the reviews [5,26] and the literature cited there). Another possible example of a compact x-ray source is the magnetosphere of a quasar core and similar formations (see [5,26,27,28]).

*We note that the distance most frequently assumed of late for the Crab is 5×10^3 light years. The distance to Cygnus is determined from the red shift and is equal to 6.6×10^8 light years (220 Mpsec), if it is assumed that Hubble's constant is H = 75 km/sec-Mpsec. It is presently assumed that H = 100 km/sec-Mpsec is a more probable value, leading to a distance of 165 Mpsec to Cygnus A. Since such refinements are immaterial from the point of view of this article, Table II is based on the values given in [1], and only the optical luminosity based on data supplied to us by I. S. Shklovskiĭ, is indicated. The data given in [17] for the radio luminosities are close to these.

Extended sources are large clouds of hot gas and, say, a cluster of relativistic electrons contained in some extended region. Radio galaxies and supernova shells are just such extended sources of radio emission. When speaking of the nature of the source, we have in mind the mechanisms and processes responsible for its x-ray emission. Obviously, compact and extended sources can have entirely different natures. Indeed, x-rays can be produced by a whole number of processes, the most important of which are:

1. Bremsstrahlung produced when electrons collide with nuclei. In astrophysical (and at the same time quantum) language, we are dealing here with free-free transitions, i.e., transitions of an electron from level to level in a continuous spectrum, followed by emission of a photon.

2. The characteristic x-ray emission produced by transitons in atoms from one discrete level to another discrete level (bound-bound transitions); this includes recombination radiation (free-bound transitions). Of course, the x-ray region proper contains only the lines of elements not lighter than nitrogen or oxygen (for a hydrogenlike ion with charge Z, the ionization potential from the ground state is $13.6\,Z^2$ volts; for the ion C VI this corresponds to about 500 V or to a wavelength $\lambda \cong 25\,\text{Å}$).

3. Synchrotron radiation of relativistic electrons, produced when the latter move in magnetic field.

4. Compton (frequently called inverse Compton) x-radiation generated when relativistic electrons are scattered by optical or radio photons.

We cannot discuss these mechanisms in detail here, and confine ourselves only to a few remarks concerning processes 1, 2, and 3 (for details see [5,6]; the characteristic radiation is discussed in [6] and in references indicated there).

The bremsstrahlung spectrum of an electron of energy E has a maximum at a frequency*

$$\nu_{sr} = 0.07\frac{eH_\perp}{mc}\left(\frac{E}{mc^2}\right)^2 = 1.2\cdot 10^6 H_\perp\left(\frac{E}{mc^2}\right)^2 = 4.6\cdot 10^{-6} H_\perp [E(\text{eV})]^2 \ \text{Hz}, \tag{1}$$

where $H_\perp$ is the projection of the magnetic field perpendicular to the line of sight.

In the shells of supernovas and in radio galaxies, disregarding small regions, the field is $H \lesssim 10^{-3}$ Oe; therefore synchrotron x-rays with $\nu \sim 10^{18}$ ($\lambda = c/\nu \sim 3\,\text{Å}$, $E_X = h\nu \sim 4$ keV) can be essentially the result of electrons with energy $E \gtrsim 10^{13}$ eV.

The characteristic time of the synchrotron-radiation losses (the time in which the electron energy is reduced by one-half) is

$$T_{sr} = \frac{5{,}1\cdot 10^8}{H_\perp^2}\frac{mc^2}{E}\ \text{sec}. \tag{2}$$

When $H_\perp \sim 10^{-3}$ Oe and $E \gtrsim 10^{13}$ eV, the time is $T_{sr} \lesssim 3\times 10^7$ sec $\cong$ 1 year. Yet the age of the Crab Nebula (the shell of the supernova of 1054) is more than 900 years, and the active phase for radio galaxies is on the order of 10^6 years and more. It is therefore clear that the x-rays from the supernova shells and the radio galaxies can have a synchrotron nature only if electrons with very high energy are continuously "pumped in." For the Crab and Virgo A, where optical synchrotron radiation is undoubtedly observed, the question of the energy pumping arises in any case. Therefore the synchrotron-radiation nature of the x-rays from these sources (especially the Crab) is possible. The most convincing proof of this hypothesis would be observation of as much as 15% polarization of the x-rays from the Crab. No other emission mechanism can produce such a polarization at all, if we deal with real conditions.

For the brightest source Sco XR-1, and also for all galactic sources other than the Crab, the synchrotron radiation hypothesis is very improbable. Suffice it to say that these sources produce no noticeable optical synchrotron radiation, with the exception of Cassiopeia A, nor any noticeable radio emission. Under such conditions we can assume that the x-rays are due to synchrotron radiation only by making far-fetched additional assumptions.*

When electrons of energy

$$E \ll \frac{mc^2}{\varepsilon} mc^2 \tag{3}$$

are scattered by photons of energy ϵ, photons are produced with energy

$$E_X = h\nu \sim \varepsilon\left(\frac{E}{mc^2}\right)^2. \tag{4}$$

For thermal optical photons ($\epsilon \sim 1$ eV) condition (3) takes the form $E \ll 3\times 10^{11}$ eV and $E_X \sim 10^3$–10^4 eV for $E \sim (2$–$5)\times 10^7$ eV. For relict metagalactic photons (see [21]) $\epsilon \sim 10^{-3}$ eV ($T \cong 3°$K) and $E_X \sim 10^3$–10^4 eV for $E \sim 5\times 10^8 - 2\times 10^9$ eV. In the region of (3), the Compton losses differ from the synchrotron-radiation losses in an isotropic field of intensity H in that $H^2/8\pi$ is replaced by w_{ph}, which is the energy density of the thermal (scattering) photons (this result has a simple physical meaning; see [4,17]).

For extended sources $w_{ph} \le 5\times 10^{-12}$ erg/cm^3 (we have in mind the density of thermal radiation in the optical and radio regions; the energy density of black-body radiation with $T = 3°$K is $w_{ph} \cong 0.6\times 10^{-12}$ erg/cm^3). Thus, the Compton losses are smaller than the synchrotron-radiation losses so long as $w_{ph} \lesssim 5\times 10^{-12} < H^2/8\pi$ or $H > 10^{-5}$ Oe. In radio galaxies and in supernova shells this inequality is usually satisfied; it is clear even from this that the Compton x-rays are in general weaker than the total synchrotron radiation from the source. By using similar reasoning, we can

*All formulas concerning synchrotron radiation can be found, for example, in [18].

*We have assumed here that we deal with extended sources. The situation is different in the case of compact sources (see the Note added in proof).

see that both the Compton and the synchrotron radiation mechanisms have very low probability of causing the x-rays from Cassiopeia A, Cygnus A, or many other x-ray sources, if the latter are extended.

Worthy of serious consideration in the case of extended sources is the bremsstrahlung mechanism, more accurately bremsstrahlung from a quasi-equilibrium hot plasma, i.e., a plasma in which the electron velocity distribution is Maxwellian or close to it.

An electron of energy E produces bremsstrahlung that lies in the entire frequency interval below $\nu_{max} = E/h$. The plasma bremsstrahlung spectrum depends in addition not only on the emission spectrum of one electron, but also on the electron velocity distribution function. If this distribution is Maxwellian with temperature T, then the energy emitted from a unit volume of a fully ionized hydrogen plasma per unit time is

$$\varepsilon = \frac{64\sqrt{2\pi}e^6n^2}{3mc^3h}\left(\frac{kT}{m}\right)^{1/2} \cong 1.6\cdot 10^{-27}n^2\sqrt{T}\ \text{erg/cm}^3\,\text{sec}, \qquad (5)$$

where n is the electron (and proton) concentration, and the temperature T in the last expression, as well as in all that follow, is measured in absolute degrees. Were the gas to consist of ions with charge Z (more accurately, eZ), then n^2 in (5) would have to be replaced by $nn_ZZ^2 = n^2Z$, where n is the electron density, and the ion density is $n_Z = n/Z$ by virtue of the quasineutrality. Formula (5) is valid in the Born approximation when $e^2Z/\hbar v \ll 1$; for a hydrogen plasma this means an electron velocity $v \gg 3 \times 10^8$ cm/sec or

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

In the frequency region $h\nu/kT \gtrsim 1$ the spectral density of the bremsstrahlung is given by

$$\varepsilon_\nu \cong \varepsilon\frac{h}{kT}e^{-h\nu/kT} = 7.7\cdot 10^{-38}\frac{n^2}{\sqrt{T}}e^{-h\nu/kT}\ \text{erg/cm}^3\text{sec}\cdot\text{Hz} \qquad (7)$$

where ϵ is given by (5). If we integrate (7) over the spectrum $\int_0^\infty \epsilon_\nu d\nu$, then the result coincides with (5), although formula (7) is approximate. The point is that formula (5) is also approximate. This approximation is good because the region of low frequencies $h\nu/kT \ll 1$ makes only a small contribution to ϵ (in this region ϵ_ν satisfies Eq. (7) multiplied by $(\sqrt{3}/\pi) \times \ln[4kT/1.781\,h\nu]$). Expressions (5) and (7) were obtained without taking reabsorption into account, i.e., they pertain to an optically thin (transparent) layer of gas. When allowance is made for absorption (reabsorption), the radiation is decreased and becomes black-body for a thick layer. By virtue of Kirchhoff's theorem $\epsilon_\nu = \epsilon_{0,\nu}\mu_\nu$, where μ_ν is the radiation absorption coefficient and $\epsilon_{0,\nu}$ is the spectral density of the black-body radiation:

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

We therefore obtain from (5), (7), and (8)

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

The layer can be regarded as thin so long as the optical thickness is $\tau_\nu = \int_0^L \mu_\nu dl \ll 1$, or, in the case of a homogeneous layer of thickness L, so long as $\mu_\nu L \ll 1$. The flux radiated by a unit black-body surface (in particular, by the surface of an optically thick layer of an equilibrium plasma) is

$$F = \sigma T^4, \quad \sigma = \frac{\pi^2k^2}{60\hbar^3c^2} = 5.67\cdot 10^{-5}\ \text{erg/cm}^2\text{sec-deg}^4$$

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

A cloud of equilibrium plasma with volume V has by virtue of the foregoing a luminosity

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

the plasma being assumed homogeneous (we shall proceed in the same manner, for concreteness, later on when we obtain the average gas concentration by putting $n \sim \sqrt{\overline{n^2}}$); The subscript X denotes that we are interested in the case $h\nu \sim kT \gtrsim 10^3$ eV ($T \gtrsim 10^7$ °K) and the bulk of the radiation lies in the x-ray region of the spectrum.

It is clear from (6) that if we knowing the luminosity L_X and the temperature T we can express n^2, the mass of the gas M, and its internal energy W_T in terms of V:

$$n^2 = \frac{L_X}{1.6\cdot 10^{-27}\sqrt{T}V}, \quad M \sim 2\cdot 10^{-24}\sqrt{\overline{n^2}}V \sim \frac{(L_XV)^{1/2}}{2\cdot 10^{10}T^{1/4}}\ \text{g},$$
$$W_T \sim \sqrt{\overline{n^2}}kTV \sim 3\cdot 10^{-3}(L_XV)^{1/2}T^{3/4}\ \text{erg}. \qquad (11)$$

In the case of the Crab $L_X \sim 5 \times 10^{36}$ erg, and the volume V is known and amounts approximately to $V \sim 4\pi r^3/3 \sim 5 \times 10^{53}$ cm^3. For $T \sim 10^8$ we thus have $n^2 \sim 10^6$, $M \lesssim M_\odot$, and $W_T \sim 5 \times 10^{48}$ erg. As far as we can judge, such a possibility, which has been discussed many times in the literature, cannot be excluded (see, e.g., [6]). The internal energy of the gas is $W_T \sim W_{cr}$, where W_{cr} is the energy of the cosmic rays in the source. Such a ratio is not only not contradictory, but is even natural (see [20,22,29]). A possible objection against the assumed existence of a large amount of hot gas in the Crab is that strong depolarization of the centimeter and decimeter synchrotron radiation from the Crab should be observed as a result. This objection, however, does not seem convincing to us, since the volume of the x-ray source in the Crab is smaller by one order of magnitude than the source responsible for the polarized optical and radio emission (see [16,29]).

By virtue of the foregoing, the question of the nature of the x-ray emission from the Crab is presently still open. Both the synchrotron-radiation and the bremsstrahlung mechanisms are possible for this source, although synchrotron radiation is apparently somewhat more probable. Only polarization measurements can provide a decisive answer.

In the case of Virgo A, the bremsstrahlung and synchrotron-radiation mechanisms are likewise the main contenders, but the situation is more complicated, since the size of the x-ray source is unknown. The larger this source, the more probable the bremsstrahlung nature of the source. This hypothesis meets with difficulties connected essentially with the need for having a large reserve of hot gas (see [29,30]).

For Cassiopeia A and Cygnus A it seems to us that the bremsstrahlung mechanism is more probable. An alternate assumption would be that the corresponding x-ray sources, unlike the radio sources, are very small (compact). Although there are no indications whatever that such compact sources exist in Cygnus A and in Cassiopeia A, such a possibility is nevertheless not excluded. If we assume that the x-rays from Cygnus A are due to bremsstrahlung with $T \cong 5 \times 10^7$ °K, then we get from (11)

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

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

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

Even in the second variant, let alone the first, the gas mass is large. On the other hand, even for the first variant we have for the energy $W_T \sim W_{cr}$ —the cosmic-ray energy in Cygnus A (see [17]); therefore assumption of a bremsstrahlung mechanism for the powerful x-radiation from Cygnus A leads to no additional difficulties with respect to the energy (see [29]).

It seems to us, therefore, that only two possibilities are presently probable in the case of Cygnus A:

a) the presence of a large amount of hot gas, leading to formation of bremsstrahlung x-rays;

b). the existence in Cygnus A of some compact x-ray source, not revealed by radio or optical observations (an active galactic core, an x-ray quasar, etc); such a source could emit x-rays by a number of mechanisms.

Only observations can decide which of these possibilities is realized, if any. Nonetheless, we regard the first as somewhat more natural and more probable. However, we encounter in any case a situation which is entirely new in astrophysics: there have hitherto been no indications that tremendous masses of hot gas exist in radio galaxies, there being no weighty grounds favoring the hypothesis of x-ray quasars "sitting" in radiogalaxies.

5. CONCLUDING REMARKS

Further progress in x-ray astronomy is impossible without better apparatus. We must have oriented satellites, since rocket observations are too brief. Prolonged observations are needed, in particular, to reveal the variability of the sources. This variability is not only of interest in itself, but allows us to estimate the maximum source dimensions (it is clear that an x-ray source with dimension r cannot strongly change in brightness within a time $t < r/c$). Of course, the variability of the sources can be revealed also by repeated rocket launchings, as was done for the source Cyg XR-1.

Another way of determining the source dimensions is, of course, to increase the angular resolution. High angular resolution (seconds of an angle) is simplest to attain by using the occultation of the source by the moon. Incidentally, sizable improvements in various types of x-ray "telescopes" are also possible (including quasi-optical ones). An increase in the transmission (area) of x-ray "telescopes" will undoubtedly result in progress in the study of the spectra of the sources. Finally, polarization measurements are indispensable, since they can reveal in the best manner the presence of synchrotron x-radiation. To be sure, the absence of noticeable polarization still does not negate the synchrotron-radiation mechanism; its presence, however, proves in practice that the source has a synchrotron-radiation nature.*

The development of x-ray astronomy, as was already emphasized, is strikingly similar to the development of radio astronomy.

Searches for cosmic radio emission were started already in the 19th century. There could be no doubt of its existence (if we bear in mind, for example, the thermal radio emission from the sun). It could be assumed, however, that this radiation is weak and, say for the sun, corresponds to black-body radiation with $T \cong 6000°$. Actually, however, it turned out that even the "quiet" sun is a source of radio emission with temperature $T \sim 10^6$, and the sporadic solar radio emission is stronger by many orders of magnitude. A similar situation obtains in the x-ray region.

The discovery of powerful radio emission from supernova shells and galaxies (particularly radio galaxies) was unexpected and made a permanent contribution to astronomy. The same can be said of the observation of powerful x-radiation from galactic sources and radio galaxies (incidentally, A-Cygni was the first observed discrete source of cosmic radio

*Of course, to ascertain the nature of the x-ray sources it is very important to have optical observations, too (we refer, for example, to hot-gas radiation in the optical spectrum [29,31]). A major role would also be played by observation of an x-ray line spectrum (of special interest in this respect are atoms of highly ionized iron; see [30,31]).

emission). It has become clear by the same token that x-ray astronomy is not merely a promising path towards new discoveries. The new discovery was already made and its significance exceeded all expectations.* There is therefore no doubt that x-ray astronomy will be studied with exceptional scrutiny in the nearest years and its role in astronomy will soon be comparable with that of optical or radio astronomy. This will complete the present astronomic revolution, wherein optical astronomy is giving way to "all-wave" astronomy.

Note added in proof. According to the latest data [32] the angular dimension of the Sco XR-1 source is smaller than 20". This makes it little likely that Sco XR-1 is an extended object such as a supernova shell. We are more likely to deal here with either a hot neutron star or with a contracting magnetic star [27,33] emitting cyclotron x-rays. The objection to identifying Sco XR-1 with a hot neutron star, based on the fact that the spectrum of this source is not a black-body spectrum, is as yet unconvincing in view of the insufficient data on the spectrum and on the possible distortion of this spectrum by processes occurring in the shell of the neutron star. At the same time, the hypothesis of a quasistellar cyclotron-radiation source [27,33] seems no less probable. Observation of a discrete γ-ray source in the Cygnus constellation has also been reported [34]. If this pertains to Cygnus A, then the γ radiation may be the result of scattering of relativistic electrons by x-ray photons emitted by the same source Cyg XR3 in Cygnus A (see [29]).

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*The role of the "simply promising" trend which may turn out to be quite fruitful (but, in principle, may also not), is left to gamma astronomy. Of course, gamma astronomy is directly related to x-ray astronomy, but differs from it in frequency range (we can arbitrarily set the γ-photon limit at $E_\gamma > 10^5$ eV), and to a certain degree in the radiation sources. If powerful γ radiation from quasars [28] and ratio galaxies [29] is ever observed, then, of course, gamma astronomy will become the *center of attention* (see Note Added in Proof at the end of the article).

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