THEORETICAL IDEAS CONCERNING X-RAY SOURCES*

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Dr. Rossi has given an account of the present status of observational x-ray astronomy. As you are all aware a considerable number of discrete x-ray sources have been discovered in the last three or four years. In addition to this a background flux of x-rays and γ-rays has been detected. It appears that this latter flux is extragalactic in origin, arising either from a large number of external galaxies, or by the inverse Compton process involving high energy electrons scattering on low energy photons in the intergalactic medium, and I shall not discuss it here since we are restricting this symposium to the galaxy. For the same reasons I shall not be discussing the possible identification of discrete sources with extragalactic objects.

There have been a number of reviews describing the physical mechanisms which may give rise to hard photons in the Universe. Fairly complete discussions have been given by Ginzburg and Syrovatsky, by Hayakawa and his collaborators, and by Gould and myself. I shall not discuss all of these physical mechanisms, but shall restrict myself to four which have been frequently discussed, namely, black body radiation, the inverse Compton process, synchrotron radiation, and thermal bremsstrahlung from optically thin gas. I shall consider these mechanisms in relation to the galactic sources only.

The idea that a very hot black body could be the source of the discrete x-ray sources was advanced very strongly by Friedman and his associates, together with a number of theoreticians, when the Crab Nebula was first identified as an x-ray source. The idea was that the black body was a neutron star which had been formed in the supernova explosion. The objections to this hypothesis are now well known. The source in the Crab has an energy spectrum which is certainly not that of a black body; the source is known to have a finite angular size, and the rate of cooling of a hot neutron star through neutrino emission is so high that its lifetime at a temperature $> 10^6$-10^7 degrees will be exceedingly short, much shorter than the life of the Crab. Most people have concluded therefore that neutron stars acting as black bodies are not likely to be able to account for the galactic x-rays sources. However, there are some who still believe that the ultimate energy sources which give rise to x-ray sources are the internal energies contained in neutron stars. It is argued that this energy is transformed ultimately to x-rays through one of the other mechanisms mentioned above.

The inverse Compton process requires the existence of regions of high radiation density in which high energy electrons are present. Such regions would be exceedingly bright in optical frequencies, and the known energy densities of radiation in the regions where discrete x-ray sources are seen are not high enough to give appreciable fluxes of x-rays. Only in the quasi-stellar objects, which are certainly extragalactic, is there the strong possibility that the inverse Compton process is effective.

Thus we are left with synchrotron radiation and thermal bremsstrahlung. Let us consider these briefly in connection with the x-rays sources in the galaxy which have been identified with optical objects.

The Crab Nebula was the first optical object identified with an x-ray source. Measurements of the x-ray flux have been made in the range 1 - 100 kev as has been mentioned by Dr. Rossi. It is known that the radio emission and the optical emission from this object are emitted by the synchrotron process, and the form of the spectrum plotted throughout the whole spectrum range

($P(\nu) \propto \nu^{-\alpha}$) , with α increasing at the high frequency end) suggests that the synchrotron process may be responsible for the x-ray flux also. This question has been discussed by Burbidge, Gould, and Tucker, by Ginzburg, and by Shklovsky. A detailed discussion of the possible models has recently been made by Tucker at La Jolla in a Ph.D. thesis, to be published. In order to obtain hard radiation by the synchrotron process high energy electrons or strong magnetic fields, or both are required. For example, in a magnetic field $H = 10^{-4}$ gauss, electrons with energies $\sim 5 \times 10^{13}$ eV are required to radiate photons of 10 kev. Such electrons have half-lives $\sim$ 25 years. Thus the synchrotron process requires the continuous acceleration or injection of very high energy electrons. Some workers are still inclined to the view that the bremsstrahlung process is responsible for the hard radiation from the Crab, but in order to explain the observed flux of x-rays in this way, it is necessary to invoke very high temperatures to explain the high energy tail of the x-ray spectrum, or else non-thermal bremsstrahlung, which leads to other difficulties. At the present time I think that the synchrotron process is the most natural explanation of the hard photons from the Crab.

There is now also a tentative identification of a source of x-rays in the 2 - 8 A region with the radio source Cassiopeia A. This is the strongest non-thermal radio source in the sky and is a supernova remnant. Dr. Gould has recently informed me that if we plot the radio spectrum and extrapolate it with the same slope to the x-ray region the x-ray flux detected from this source lies on this extrapolated curve. This may indicate that the x-rays from this source are produced by the synchrotron process, though the lifetimes of the x-ray electrons will be shorter by a factor $\geq 10^4$ than those giving rise to the radio emission.

The most recent optical identification is that of Sco X-1 which has just been described by Dr. Rossi. You have heard that the optical object which has been identified is a light blue star-like object. There appears to be a high probability that the identification is correct. Preliminary spectroscopic and color measurements suggest that the object has the optical characteristics of an ex-nova. It is thus of some interest to discuss the kind of model which may be constructed from the data as we understand it at present. The ideas that I shall describe in what follows arose in a joint discussion with Dr. Rossi involving Drs. Ginzburg, Shklovsky, Woltjer, and myself, together with some others, which was held in Noordwijk a few days ago.

The x-ray spectrum of Sco X-1 is thought to show that it is a thermal bremsstrahlung source, since an exponential law is indicated, in which case a temperature of about 5×10^7 degrees is required. The total flux which is emitted by this source is uncertain because the distance remains uncertain*,

*At the time that this talk was given we were not familiar with the work of Friedman who has argued from his detection of a flux of much softer x-rays that the object must be comparatively nearby, since if it were at a distance ≥ 100 pc the absorption of these x-rays by the interstellar gas would be very large. This point remains unclear at the time of writing. It has been realized that it is possible to obtain an estimate of the amount of interstellar matter lying between Sc X-1 and the solar system directly, and independently of the distance assumed for the source, from the strengths of the interstellar lines due to Ca^+ which are present in the optical spectrum of this source. This rough estimate suggests that $\tau \geq 5$. Thus the difficulty is severe and the possible ways out are (a) that an immense flux of soft x-rays is generated by this source, much larger than that generated by a 5×10^7 degree plasma, (b) that the observation of soft x-rays associated with Sco X-1 is spurious, (c) that the optical identification is incorrect.

but we shall, in what follows, assume that the total energy emitted by the source is 10^{36} erg/sec; this is the flux calculated by supposing that the distance is 250 pc. On this basis, assuming a temperature of 50 x 10^6 degrees, we can easily compute the dimensions of the hot cloud, its energy content, and cooling time (energy content times 10^{-36} secs) as a function of the electron density N_e (assuming a uniform cloud). Some values are given in Table 1. Since the x-ray source is known to have a size < 20", the dimension R must be less than 7.5 x 10^{16} cm. If we suppose that the hot gas cloud also gives rise to the optical object, an assumption which was made as one of the steps leading to the optical identification, then since it is star-like we must assume an angular size < 1", or R < 4 x 10^{15} cm.

In the paper by Sandage et al. it was pointed out that the spectrum of the optical object is reminiscent of that of an old nova. While it is possible to argue that the object is a new type of astronomical object which in its spectral characteristics is superficially similar to an ex-nova, it is natural to suppose that the object is indeed an old nova. This is the assumption that we shall make in the following discussion.

It has been known for some years that a number of the ex-novae are close binary systems, and Kraft has given plausible arguments for supposing that the nova phenomenon is closely tied to the binary nature of the system, and that all old novae are binaries. In the systems which have been studied in detail it has been shown that the two stars are exceedingly close together and are moving with relative velocities ~ 500 km/sec. The periods are very short, of the order of hours in some cases. One of the stars is a highly evolved object which is contributing little to the optical luminosity. In order to explain the x-ray properties of such an object we have to consider two questions.

(1) What is the source of the energy for the hot cloud, and in what way is it related to the binary system?

(2) Where does the line spectrum originate?

As far as (1) is concerned we were naturally led first to the idea that the hot gas cloud forms a hot corona about the binary system. An attractive possibility here is that this gas cloud is gravitationally contained by the binary system and that its energy source is the gravitational potential energy of the binary system. Thus we must suppose that the gas cloud has dimensions no greater than the separation between the stars, i.e. about 10^{11} cm, so that $N_e \simeq 10^{13}$ cm^{-3}. If the gas occupied a larger volume it would escape. The mechanism of heating in this case would then be the stirring of the corona by the stars moving in it, and the maximum temperatures that could be generated would be given approximately by $(m_p v^2/k) \sim 25 \times 10^6$ degrees for $v \sim 500$ km/sec. The snag associated with this mechanism was pointed out by Dr. Prendergast. It is simply that such a heating process may be effective as long as the corona is effectively at rest with respect to the rotating binary system. However, if the corona begins to co-rotate with the stars it will do longer work. One alternative possibility then, suggested by Dr. Ginzburg is that the energy is derived from a stellar wind - gas must be ejected from one or both of the stars at velocities $\sim 10^3$ km/sec. It is important to realize that these two suggestions concerning the mechanism of the heating of the gas involve two quite different energy sources. In the first case we are utilizing the gravitational energy of the binary system. In the second we must suppose that the energy is derived from the internal energy of one or the other of the stars. Conventional thermo-nuclear or graviatational energy sources might be invoked. Alternatively it might be supposed that the highly evolved component of the binary system is a neutron star and that the internal energy of this star is being slowly released in the form of high velocity gas.

Finally, we must consider the problem of the place of origin of the optical line spectrum. The emission lines which are seen include the Balmer lines, He II $\lambda 4686$, and high excitation lines due to C^{++}, N^{++}, and O^{+}. Such lines are produced in a stellar atmosphere with a temperature $\sim 25000^{\circ}$-50000°, and while this is a very hot stellar atmosphere it is a very cool region as compared with the plasma giving rise to the x-ray flux. It is therefore necessary to consider ways in which such a cool region can exist in conjunction with an exceedingly hot plasma. This problem has not been solved, though it is clear that since the hard radiation emitted by the hot plasma will ionize the outer atmospheres of both stars, we must suppose that the line formation takes place in conditions of high density where the ionizing effect is significantly reduced. Very severe limits are probably placed on the model by this condition.

Novae explode in our Galaxy at the rate of about 30 per year; after they explode they still contain appreciable energy sources - many are recurrent - and they remain optically detectable after the explosion. Thus many millions should be present in our Galaxy. However, it is clear that only a small fraction of these are emitting significant fluxes of x-rays. It may very well be that the majority of the known x-ray sources are ex-novae, though present evidence shows that some supernova remnants are also x-ray sources. Why should only a small fraction of the ex-novae be x-ray sources? On the basis of the ideas developed here there are many possible explanations. It may be that only in rare cases, or for a short time, is it possible for gas to be heated by the two stars. Alternatively it might be supposed that only in a few cases is the gas heated to temperatures in excess of 10^{7} degrees and that in most ex-novae the gas is cooler and fluxes of much softer x-rays are emitted.

These ideas have been developed very hurriedly following the optical identification of Scorpius X-1. Much more work is required to produce a detailed model and it may be found that some of the views expressed will not survive detailed investigation.

Table 1

PROPERTIES OF UNIFORM CLOUDS WITH T = 50 x 10^6 DEGREES

REQUIRED TO GIVE X-RAY FLUX FROM Sco X-1

N_e (cm^{-3})	R (cm)	Energy Content E (ergs)	Cooling Time 10^{-36} E (secs)
$10^{4.5}$	3×10^{16}	2×10^{46}	2×10^{10}
10^{6}	3×10^{15}	6×10^{44}	6×10^{8}
$10^{7.5}$	3×10^{14}	2×10^{43}	2×10^{7}
10^{9}	3×10^{13}	6×10^{41}	6×10^{5}
$10^{10.5}$	3×10^{12}	2×10^{40}	2×10^{4}
10^{12}	3×10^{11}	6×10^{38}	600
$10^{13.5}$	3×10^{10}	2×10^{37}	20
10^{15}	3×10^{9}	6×10^{35}	0.6