THEORETICAL REVIEW

Wallace Tucker*
(Cornell University)

First, I will discuss the interaction of the radiation from an X-ray source with the surrounding matter. Then the X-ray emission mechanisms will be considered, and finally, a few of the models which have been proposed will be briefly reviewed.

1. The Interaction of the Radiation from an X-Ray Source with Its Environment

One aspect of X-ray sources which can be studied more or less independently of the origin and detailed physical state of X-ray sources is the extent to which their radiation interacts with any surrounding matter. The X-radiation will ionize and heat this matter, and some of the X-rays will be absorbed.

An investigation of these effects is of practical interest for several reasons. First, emission lines which are characteristic of a cool gas with a temperature of the order of 10^4–10^5 °K have been observed in both the Crab Nebula and Sco X-1. Obviously, an understanding of the excitation conditions produced in the cool gas by the X-ray will improve our understanding of the objects. Secondly, observations of the modifications of the X-ray spectrum which are produced by the absorbing effects of matter between the source and the observer can provide information concerning the interstellar and intergalactic medium. Observational evidence of such absorption has been discussed by Giaconni (1967). Finally, the interaction of the X-rays with the surrounding matter must be taken into account when constructing theories of the origin of the X-ray sources. For example, accretion models encounter severe difficulties, both with respect to the absorption of X-rays and the heating of the accreting gas.

Johnson (1967*a*) has considered the ionizing effects of the X-rays on the cool gas in Sco X-1, Cas A, and Vir A. He concluded that the observed conditions in some cases, but not all, were compatible with those produced by radiative excitation. However, the temperature in this case would be rather low, of the order of 10000°. Then, in the case of Sco X-1, it is very difficult to explain the relative strengths of the N III (4641) and Hβ emissions, which seem to require a temperature of 100000°. The ionization equilibrium would then have to be established by electron collisional ionization and radiative and dielectronic recombination (Tucker, 1967*a*).

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* Present address: Rice University, Houston, Texas.

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Detailed work on the ionization and heating of a gas excited by X-rays has been done by Williams (1967) and Tarter (1967). Williams considered a power law spectrum for the ionizing radiation, Tarter an exponential one. Their general results are the same; (i) each element occupies a number of different stages of ionization at any one time, and (ii) the temperature in the gas heated by X-rays will generally be between 10000 and 20000°, provided that the K shells of ions are still intact. Calculations of this type are very useful because the observation of just one line sets limits on the X-ray source parameters; the radiation cannot be so intense as to ionize the species which is observed. Thus, in the case of Sco X-1, the observation of a N III line implies

$$\frac{L}{NR^2} = \frac{16\pi F}{N\delta^2} \ll 10^{-2}.$$

Here L is the luminosity of Sco X-1, N the electron density in the cool region, R is the radius of the X-ray source, F the flux received at Earth, and δ the angular diameter. Setting $F = 5 \times 10^{-7}$ erg cm^{-2} sec^{-1} yields $\delta \gg 3 \times 10^{-2}/n^{1/2}$. On the other hand, the *upper* limit on the angular diameter appears to be ≈ 1 sec of arc (Johnson, 1967*b*), so $N \gg 4 \times 10^7$ cm^{-3}. In the case of 3C 273, the observed emission lines and the observed X-ray flux (Friedman, 1967) imply that $\delta \gtrsim 1$ sec of arc, considerably greater than the angular diameter of the *radio* source (Cohen *et al.*, 1966).

The X-ray absorption coefficient of a cold gas has been calculated by Felten and Gould (1966). They also discussed the information about the interstellar and intergalactic medium which could be obtained from observations of the absorbing effects. They pointed out that by measuring the spectral discontinuity due to an absorption edge, one could obtain a measurement of the amount of matter in the line of sight which would be independent of the source spectrum. The increase in intensity across an edge should be $e^{\Delta\tau}$ where $\Delta\tau \approx 2 \times 10^{-22} \int N \, \mathrm{d}l$, according to the most recent calculations of the absorption coefficient by Bell and Kingston (1967).

2. X-Ray Emission Mechanisms

Observations of the X-ray spectra and theoretical arguments have led to the generally accepted conclusion that only synchrotron radiation and bremsstrahlung from a high temperature, low-density gas are feasible mechanisms for producing most of the keV X-rays in the discrete sources. Neutron stars are no longer considered to be a direct source of keV X-rays, in view of their rapid cooling rates (a few years or less for a temperature of 10^7°) and the absence of any observational evidence of a black-body spectrum. Compton scattering and non-thermal bremsstrahlung have been ruled out because of their low efficiency.

In the case of bremsstrahlung, however, an important contribution may arise in the 100 keV range. It can be shown that, if the gas is heated by non-thermal particles with energies of about 100 keV, an observable non-thermal bremsstrahlung flux (three or four orders of magnitude above the 100 keV flux from a 50 million degree gas) is produced in the region 50–100 keV. The 'non-thermal tail' starting around 35 keV, which was observed by Peterson and Jacobson (1966) in Sco X-1, may well be a manifestation of this effect.

A. BREMSSTRAHLUNG FROM A HOT GAS

In attempting to construct a 'hot-gas' model for X-ray sources, a number of formidable problems are encountered. Perhaps the greatest of these is the origin of the hot gas. Although there are evidently a number of ways to heat a plasma under astrophysical conditions, it is by no means obvious how to produce a hot plasma having the high temperature and large energy content necessary to explain X-ray sources. Sartori and Morrison (1967) have argued that a hot gas is produced any time electrons are accelerated, the energy of the hot gas being approximately 100 times that of the relativistic gas. Sturrock (1966) has also mentioned such a possibility in connection with his 'flare' theory of quasars. Ginzburg (1967) has advanced similar ideas but he sets $W_{\mathrm{th}} \approx W_{\mathrm{rel}}$, a much more modest requirement which would not lead to observable fluxes in general.

Another problem is the short cooling time for a compact source ($t_c \approx 6 \times 10^{14}/N_e$ sec for a temperature of 50 million degrees). If $N \sim 10^8$ cm^{-3}, as seems to be required for Sco X-1, then the cooling time is less than 1 year, and a continuous, powerful source of heating is needed. The expansion times are also small for compact sources so the hot gas must be confined by some means.

Because of these difficulties, Ginzburg (1967) has suggested that, whereas the extended sources with long cooling times ($\sim 10^5$ yr) are likely to be hot gases, the compact sources are probably synchrotron emitters. On the other hand, the energy requirements are more severe for extended sources and particles would be thermalized more quickly in the compact sources. For these reasons, I take the opposite viewpoint, *viz.* that sources in which the thermalization mean free-path is less than a certain critical value are hot gases, but in the other extreme the electrons become relativistic and emit X-ray synchrotron radiation.

B. SYNCHROTRON RADIATION

The existence of radio and optical synchrotron sources leads us to believe that this mechanism may also be responsible for the X-rays in some discrete sources. This belief is reinforced by the measurements of the X-ray spectra of the Crab Nebula and Cyg X-1 (Peterson, 1967), which show a power-law dependence of the flux on the frequency. The synchrotron hypothesis has its difficulties, too. Principal among these are (i) the extremely high energy electrons ($\sim 10^{12}$ eV) required to produce the X-rays in magnetic fields of the order of 10^{-3} or 10^{-4} gauss, and (ii) the short radiative lifetimes of the order of a few years ($\tau_s(\propto \nu^{-1/2} H^{-3/2}) \approx 30$ yr for $H = 10^{-4}$ gauss, $\nu = 10^{18}$ c/s). However, the amount of energy required in the form of relativistic electrons is in general about two orders of magnitude less than the energy required by the hot-gas models.

C. DISTINGUISHING BETWEEN HOT GAS AND SYNCHROTRON MODELS

There are several means by which it may be possible to decide between the two possible mechanisms. The detection of the deviations from the bremsstrahlung spectrum which are produced by recombination edges and line emission would establish the hot-gas nature of the source. The jump due to the Ne^{+10} recombination edge should be about 30% at 10^7 °, about 5% at 5×10^7 °, for a gas having the cosmic abundances (Tucker, 1967*b*). The line emission from Mg, Si, S and Fe may also be detectable.

The observation of polarized X-rays would establish the synchrotron nature of the source, but a negative result would not conclusively rule out the synchrotron hypothesis.

A study of the time variations of the X-ray emission could also provide information concerning the emission mechanism, The spectrum of a composite hot-gas model would become flatter, a synchron spectrum steeper, as a result of radiation losses. Also, for extended sources the cooling time for a hot gas is so long that no time variations would be expected, as is possible with the synchrotron mechanism.

3. Theoretical Models for X-Ray Sources

A. SCO X-1

The strongest X-ray source in the sky, Sco X-1 has an exponential spectrum characteristic of a hot gas with a temperature of 50 million degrees. It has been identified optically with a flickering, blue, star-like object. Optical observations show that its optical continuum radiation is consistent with the extrapolation of a bremsstrahlung spectrum from X-ray to optical frequencies (Johnson, 1967*b*).

Šklovskij (1967) has proposed a model of Sco X-1 according to which it is a binary system composed of a neutron star accreting matter from an unstable companion. The difficulty with this and the other binary star models which have been put forth is that very high densities ($\sim 10^{16}$ particles/cm^3) are needed to get the required energy-conversion rate. Then the cool gas in front of the shock wave will quickly absorb the X-rays, so that it is very difficult to construct a realistic binary star model.

Another possibility is that a hot gas is produced by the dissipation of magnetic energy. Assume that the X-ray emission from Sco X-1 is due to an optically thin hot plasma having the cosmic abundances, and that the plasma is confined by a magnetic field which is anchored to a central object. Then it can be shown (Tucker, 1967) that the radius of the X-ray source is between about 10^{12} and 10^{15} cm and the electron density is between about 10^6 and 10^{10} particles per cm^3. If the distance is greater than 500 pc as suggested by Wallerstein (1967), then $R_x \sim 5 \times 10^{14}$, $N_x \sim 10^7\ \mathrm{cm}^{-3}$, and the radius of the central object must be $\sim 10^{14}$ cm, in order to have both confinement of the hot gas and stability of the central object. All this suggests that Sco X-1 may be a protostar in the process of shedding its magnetic field, as originally suggested by Manley (1966). In this model the energy of the magnetic field is degraded into thermal energy by means of flare-like events. Since the source is much more extensive and massive than the solar corona, most of the non-thermal energy normally associated with flares would be transformed into thermal energy by means of ionization, generation of plasma waves, etc. An observable amount of optical synchrotron radiation and high energy non-thermal bremsstrahlung ($\gtrsim 100$ keV) could quite possibly be produced.

Synchrotron models of Sco X-1 have been proposed by Ginzburg (1967), and Manley (1966). The difficulty with such models is that a flat spectrum ($N(E)\,\mathrm{d}E = K\,\mathrm{d}E$) is needed to explain the absence of strong optical synchrotron emission. In addition, no optical polarization has been observed.

B. THE CRAB NEBULA

The first radio source and the first X-ray source to be optically identified, the Crab Nebula is known to be a synchrotron emitter at radio and optical frequencies. The shape of the optical spectrum is disputed and the X-ray spectrum is still uncertain. Nevertheless, one is tempted to join the optical and X-ray spectrum and say that the spectral index between about 10^{14} c/s and 10^{18} c/s is constant and equal to about $-1{\cdot}1$. The radio spectral index is $-0{\cdot}27$, so the change in spectral index is about $-0{\cdot}83$, which can be understood in terms of continuous injection varying with time as $(t - t_0)^{2/3}$, where t_0 is the present age of the nebula. Šklovskij (1966) has contended that the spectral index in the optical is $-0{\cdot}8$, and results from continuous injection at a constant rate. The UV flux is then very large, and the spectral index must change again before X-ray frequencies. Two difficulties with this model are the large UV flux which would produce too much ionization in the filaments (Williams, 1967), and the lack of an explanation for the shape of the X-ray spectrum.

Another possibility is that there are two distributions of electrons in the nebula. Then a number of models can be constructed which fit the observational data (Tucker, 1967). However, special conditions must prevail, such as a flat electron spectrum and Fermi acceleration, or a low energy cutoff around 10^{12} eV. The latter case is interesting since a continuous input of energy is not needed to explain the X-ray emission.

Hot-gas for the Crab Nebula has been proposed by Sartori and Morrison (1967), and by Hayakawa *et al.* (1966). However, in light of the observations, which indicate that the power-law spectrum holds at energies up to 200 keV (Peterson, 1967), such an explanation is very unlikely.

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