GAMMA RADIATION FROM THE CELESTIAL X-RAY SOURCE SCO X-1

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ABSTRACT

Gamma radiation from the X-ray sources Sco X-1 due to Compton-synchrotron process is calculated. Comparison with the upper limits set by an experimental survey for sources of gamma-rays with energy greater than 100 MeV has been made and constraints on the size of the source and its magnetic field are discussed. The flux predicted in the energy range $10^{11}-10^{12}$ eV is above the observable lower limit of present-day detectors. An observation of this flux will serve as a test of the synchrotron origin of the X-radiation.

The first and strongest celestial X-ray source discovered is Sco X-1 in the constellation Scorpius. Since the discovery of the source in rocket experiments, it has been identified with an optical object. More recently radio radiation from the source has also been observed. Typical energy flux in each of the above frequency regions is given in Fig. 1. The flux in all energy ranges are found to be variable; thus in the radio region the variation is by as much as a factor of twenty, while in the optical and X-ray regions it is by a factor of two to three only. Synoptic observations of optical and X-ray flux have also been made; but the radio flux has not been measured together with the flux at other frequencies. For this reason, the spectrum given in Fig. 1 may not be the true spectrum at any given time, but is only representative.

The X-ray differential energy spectrum in the region 1–10 KeV is of the form $J(E) = Ke^{-E/E_0}$, where $E$ is the energy of the X-ray photon and $K$ and $E_0$ are constants, suggesting thereby that the X-ray emission is due to thermal bremsstrahlung from a hot gas. It has been suggested that this type of spectrum can also result from synchrotron radiation from high energy electrons with a sharp cut-off at the high energy end. Measurements of hard X-rays ($> 40$ KeV) and the simultaneous observations of optical and
X-ray fluxes, have shown, however, that a simple model of thermal bremsstrahlung from a hot gas with one temperature will not suffice; several volumes of hot gas with different temperatures and opacities have to be invoked. The synchrotron origin also needs a complicated electron spectrum of different volumes of emission to explain the discontinuous nature of the spectrum in the microwave range. A sure test of the thermal bremsstrahlung hypothesis is the observation of lines in the X-ray spectrum. Attempts to observe the Fe line at 6.8 keV have not been successful so far. On the other hand a test of the synchrotron hypothesis is the observation of polarization in the optical and X-ray region. Again observations to date have not led to any conclusion. Another test of the synchrotron hypothesis is the observation of gamma radiation produced

![Graph](image)

**FIG. 1.** The X-ray and gamma-ray spectrum of the object Sco X-1. The experimentally observed points and curves are A. P. Andrew and Purton, A. Ables, C. Chodil et al., N. Neugebauer et al., F. Fritz et al., G. Gorenstein et al. (two observations at different times), B. Agrawal et al. and Buselli et al. In the case of the curves N, the solid line is the observed spectrum and the dotted curve is the spectrum after correction for interstellar absorption. The dashed curve is the synchrotron spectrum used for calculation of the gamma radiation by Compton-synchrotron process. The line, labelled $S_1$, is the upper limit set by a survey of the sky which includes Sco X-1. The line $S_2$ represents the minimum detectable gamma-ray flux by present-day instruments in the $10^{11}-10^{13}$ eV energy region. The full curves are the Compton synchrotron spectra for a magnetic field $H = 1$ gauss and the curve 1 is for $\theta = 10^{-8}$ min. and curve 2 for $\theta = 10^{-6}$ min.
by the Compton scattering of the synchrotron radiation by the parent electrons (Compton-synchrotron process).\textsuperscript{15} In this note we calculate this radiation and discuss the possibilities of its observation.

The formulation for the calculation is given by Gould\textsuperscript{15} and is used in the present calculation. The parameters needed are the distance of the source D, its angular width $\theta$ and the relevant magnetic field B. The distance of Sco X-1 has been estimated from optical observations and from measurements of soft X-rays, to be about 500 pc. The angular size can be deduced using the distance given above and the estimated radius R of the source. An upper limit on the radius R is obtained from the limit on the visual size of Sco X-1 and is of the order of $10^{15}$ cm. Westphal \textit{et al.}\textsuperscript{16} however suggest a dimension in the range $10^{11}$ to $10^{12}$ cm. Neugebauer \textit{et al.}\textsuperscript{8} interpret the dip in the infrared spectrum as due to synchrotron self-absorption and derive $R \approx 10^9$ cm. The estimates from X-ray observations\textsuperscript{8} yield R ranging from $10^9$ to $10^{15}$ cm. On the other hand, the time scale of variation of radio and optical fluxes is of the order of 10 minutes suggesting $R \ll 10^{13}$ cm. Thus the angular size $\theta$ is in the range $10^{-10}$ to $10^{-4}$ minutes. The magnetic field in the emission region is unknown. Riegler and Ramaty\textsuperscript{17} using the hypothesis that the radio emission is due to gyro-synchrotron process derive $B \approx 1$ gauss. In our calculation, we use $B = 1$ gauss and various values of $\theta$ in the range given above. We then discuss the effect of changing B.

In performing the calculations, we have used the synchrotron spectrum shown by the dashed line in Fig. 1 which has been smoothed through the experimental points to facilitate calculations. The experimental observations in the infrared region ($10^{14}$ Hz) suggest a sharp drop of radiation energy flux; if this is true, then the synchrotron spectrum used should be cut off at about $10^{14}$ Hz. The calculated Compton-synchrotron curves for two different values of $\theta$ are shown in Fig. 1 as curves 1 and 2. If a cut-off for the synchrotron spectrum at about $10^{14}$ Hz is used, the Compton-synchrotron curves will have a cut-off around $10^{20}$ Hz.

In Fig. 1 is also shown the upper limits (S 1) on the gamma-ray emission from Sco X-1 with energy greater than 100 MeV ($3 \times 10^{22}$ Hz). This upper limit is implied by the survey made by instruments in the satellite OSO III, where no sources are detected in this region\textsuperscript{18} of the sky. Also shown in Fig. 1 is the minimum detectable flux by present-day detectors in the $10^{11}$--$10^{13}$ eV gamma-ray region. Using the upper limit in the 100 MeV energy region, it is seen from the figure that for $B = 1$, $\theta = 10^{-8}$
min. If B is increased, the intensity is suppressed for a given $\theta$, approximately proportional to B. In this case the upper limit from the survey implies a larger $\theta$. Thus the gamma ray upper limit from the survey implies that $B \theta^2 \approx 10^{17}$ gauss min.\(^2\). The values of B and $\theta$ derived by Riegler and Ramaty\(^1\) in their model are consistent with the above limit.

In the energy region $10^{11}$–$10^{13}$ eV the minimum detectable flux by instruments detecting gamma-rays,\(^9\) using air-shower Cerenkov technique is shown as line S 2 of Fig. I. The calculated gamma-ray flux corresponding to the limit given above for $B \theta^2$ lie considerably above the minimum detectable level. The flux corresponding to the limit is about $10^{-8}$ photons/cm.\(^2\) sec. sterad at an energy $10^{11}$ eV. It seems then that it is possible that a gamma-ray flux, with the photon energy greater than $10^{11}$ eV, can be detected from Sco X-1. A detection of such flux will show that the process of emission of radio, optical and X-ray flux is of synchrotron nature.

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Note.—After this paper is submitted for publication Dr. G. G. Fazio has communicated to me their observations * on high energy gamma-ray flux from Sco X-1. He quotes an upper limit of $9 \times 10^{-11}$ photons cm.$^{-2}$ sec$^{-1}$ at an effective energy $6 \times 10^{11}$ eV, which is approximately the limit shown as S 2 in the figure. This limit implies that $B \theta^2 \geq 10^{-13}$ gauss min$^2$. This means, for the magnetic field of the order of 1 gauss, the size of the source must be greater than $\sim 1$ Astronomical Unit.

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REFERENCES


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