ENERGY SPECTRUM AND THE ABSOLUTE FLUX OF VARIOUS CELESTIAL X-RAY SOURCES

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ABSTRACT

The results on the flux of low energy X-rays in the range 2–18 Kev from Sco-X1, Tau-X1 and Cen-X2 celestial sources observed during two rocket flights, flown from the Thumba Equatorial Rocket Launching Station (TERLS), Trivandrum, India, are presented. The absolute flux and the energy spectrum obtained for these sources are compared with other similar observations. The results indicate a long-term exponential decrease in the energy flux of X-rays from Sco-X1 over the period 1965–1968. The X-ray source Cen-X2, which showed a remarkable outburst of X-rays in April 1967, had ceased to be active after May 1967. We present here the first evidence of the rediscovery of the low energy, X-ray flux from Cen-X2 since May 1967. These short-lived X-ray outbursts may be attributed to a shock wave from the nova outburst expanding into the circumstellar medium.

INTRODUCTION

SINCE the discovery of stellar X-ray source Sco-X1 by Giacconi *et al.*[1] in 1962, a number of experiments have been performed by different groups for determining the absolute flux and the energy spectrum of various galactic as well as extra-galactic X-ray sources. After the optical identification of Sco-X1 by Sandage *et al.*,[2] a large number of photometric observations have been conducted by Hiltner and Mook[3] and others. Such studies have clearly revealed that the optical intensity of Sco-X1 undergoes very rapid variations between 12·2 and 13·2 magnitudes, large flare type enhancements occurring during nearly 50% of the time when Sco-X1 is brighter than 12·6 magnitude. A search by Rao *et al.*[4] for hidden periodicities has shown that besides rapid fluctuations, Sco-X1 optical intensity varies by about a factor of two with a periodicity of about 3 hours. Recent radio observations by Andrew and Purton[5] and Ables[6] have also shown the existence of similar variations in the radio emission from Sco-X1. The possibility of finding correlated changes in X-ray, optical and radio emissions from the same object is truly exciting and will reveal a common origin for the widely different radiations. The observation of X-ray flare from Sco-X1 at balloon altitudes by Lewin *et al.*[7] and the discovery of the highly variable source Cen-X2 by Harries *et al.*[8] have focussed a great attention on the systematic measurements of the absolute flux and the time variation of X-ray luminosity from different celestial sources.

In this paper, we describe the results of the two rocket flights carried out from the Thumba Equatorial Rocket Launching Station (TERLS), Trivandrum (Geogr. Latitude 8° 32′ N; Geogr. Longitude 76° 51′ E), India. Two identical X-ray payloads were launched, one on a Centaure rocket at 0319 UT on November 3, 1968 and the second on a Nike-Alpache rocket at 0305 UT on November 7, 1968 almost vertically (85° elevation) such that the X-ray detector mounted with its axis perpendicular to the spin axis of the rocket scanned the rocket horizon. The launch time was chosen when the Sco-X1, Cen-X2 and Tau-X1 were all in the rocket horizon. The present experiments were conducted with the following objectives:

(*a*) To measure the absolute flux and the energy spectrum of Sco-X1, Tau-X1 and Cen-X2 in the energy range 2–20 Kev.

(*b*) To measure the time variability of the X-ray flux from these sources in the above energy range.

(*c*) To conduct a survey of the southern sky with a view to detect hitherto undiscovered X-ray sources.

INSTRUMENTATION

The X-ray detector consisted of a proportional counter filled with Xenon (90%) and Methane (10%) at one atmospheric pressure and having a 2 mil. thick Berylium entrance window. The counter had an effective path length of 2 inches. The counter resolutions were typically 15% full width half-maximum at 6·0 Kev (Fe^{55}) and 22% full width half maximum at 22 Kev (Cd^{109}). A slat type collimator mounted in front of the proportional counter defined a 8·7° × 17·2° full width half-maximum field of view, with the long axis parallel to the spin axis of the rocket. The effective area of the counter, after taking into account the collimator occultation, was 60·8 cm.^{2}. Figure 1 shows the detector. In Fig. 2 is shown the calculated efficiency of the counter as a function of X-ray quantum energy. The efficiency of the counter $\mathscr{E}(\lambda)$ is calculated using the well-known equation

$$\mathscr{E}(\lambda) = e^{-\mu_\omega x_\omega}(1 - e^{-\mu_g x_g})$$

where μ_ω and μ_g are the absorption coefficients of the window and the gas and X_w and X_g are the respective path lengths.

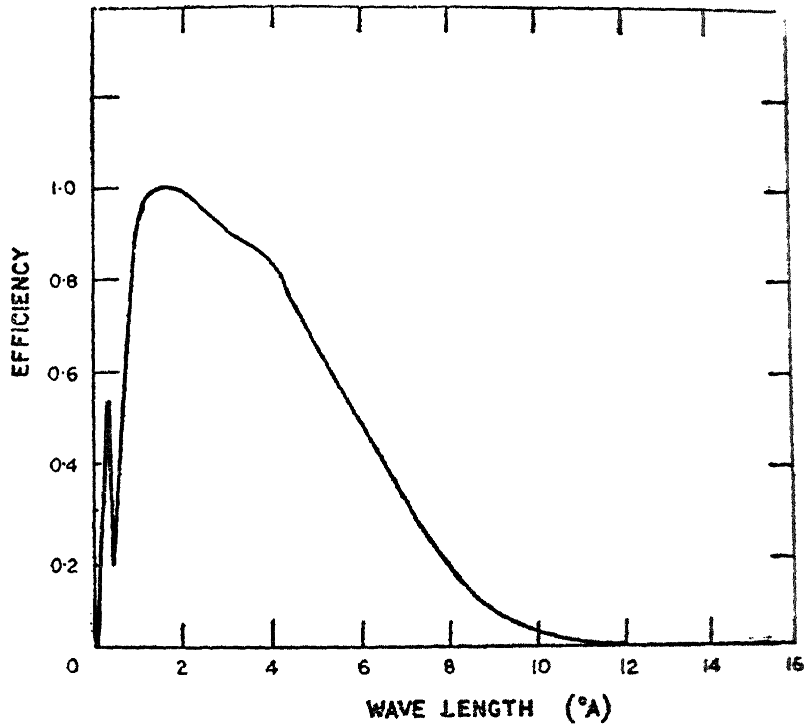

FIG. 2. Efficiency of the proportional counter filled with Xenon (90%) and Methane (10%) at 1 atmospheric pressure and having a 2 mil. thick Berylium window.

The pulses from the proportional counter were amplified, shaped and pulse height analysed in the energy range 2–18 Kev into four consecutive energy windows. A redundant analogue signal giving the actual pulse height of each pulse was also telemetered separately. The entire information was telemetered by FM/FM telemetry system. Monitoring of the 6·0 Kev line from the Fe^{55} radioactive source mounted on the split nosecone provided the inflight calibration upto 70 Km., at which altitude, the source and the nosecone were explosively ejected.

The attitude of the rocket was determined by two suitably mounted geomagnetic aspect sensors, one along the spin axis and another perpendicular to it. The alignment of the detector and the geomagnetic aspect sensors were made to an angular accuracy better than 0·1°. Both the Centaure and Nike-Apache rockets reached an apogee of about 160 Km. Out of the total flight time of about 420 seconds, useful X-ray data above 90 Km. altitude were obtained for about 200 seconds.

ASPECT ANALYSIS

Assuming the rocket to behave like a rigid body, one can estimate the half apex-angle of the precession cone α, using the well-known formula

$$\cos \alpha = \frac{\omega_s}{\omega_p} \frac{I_1}{I_2 - I_1}$$

where ω_s and ω_p are the angular velocities of spin and precession respectively and I_1 and I_2 are the moments of inertia relative to the spin axis and a direction perpendicular to it. The above serves as a crude estimate of the precession cone angle.

After deriving the approximate spin and precession periods from the horizontal and vertical magnetic sensors, a spin precession diagram is drawn showing the time dependence of the phase of the magnetic field in each spin during each precession. Adjustment of the spin period to achieve synchronization of the phase of the magnetic record will yield the right spin and precession periods which can be normally represented as a power series in time t as

$$\omega_s \pm \omega_p = W_0 + At + Bt^2 + \cdots$$

where W_0, A and B are constants. In practice, only the first two terms are of importance.

The peak-to-peak amplitude of the horizontal magnetic sensor (2M) is equal to $2M_{max.} \sin \theta$ where θ is the angle between the spin axis and the magnetic vector. The equation $\sin^{-1} \theta = 2M/2M_{max.}$ is used to determine θ at each maximum of the magnetometer, taking into account the variation of $M_{max.}$ with altitude using the Finch and Leaton expansion of the geomagnetic field. Knowing θ for each spin, one can censtruct the precession circle which is correct to probably within a few degrees. It must be noted that θ will vary between the two limits of $\alpha + \delta$ and $\alpha - \delta$ where α is the half-cone precession angle and δ is the inclination of the precession axis to the vertical. The celestial co-ordinates calculated using the well-known formulas of spherical astronomy at the time of two launches are given in Table I.

A further refinement of the attitude was accomplished by using the successive Sco-X1 sighting. From the spin phase diagram for the passage of X-ray source Sco-X1, the average spin phase difference between Sco-X1 and the magnetic direction which was about 118° and the variation of X-ray intensity in each precession cycle has been employed to refine the precession axis of the rocket to better than 1° using the method described by Wada *et al.*[9]

TABLE I

Celestial Co-ordinates at the Time of Launching

	Flight I		Flight II	
	R.A.	Declination	R.A.	Declination
Sun ...	$14^h 33'$	$-15° \ 1'$	$14^h 49'$	$-16° \ 14'$
Zenith ..	$11^h 18'$	$8° \ 33'$	$11^h 16'$	$8° \ 33'$
Magnetic field ..	$0^h 42'$	$81° \ 54'$	$0^h 40'$	$81° \ 54'$

The spin stabilized Centaure rocket flown on November 3, 1968, with a spin rate of about 8 RPS, had its axis centered at 10^h 18′ Right Ascension and 15·0° N. declination on the celestial sphere. Consequently, the X-ray detector was able to look at Sco-X1 and Cen-X2 sources during the entire duration of the flight (about 200 seconds from 90 Km. altitude to the time of entry into the atmosphere). The Nike-Apache rocket launched on November 7, 1968, however, got into precession after the ejection of the nosecone at 70 Km. and its spin rate which was initially about 9 RPS, changed to about 2·8 RPS. after the nosecone ejection. The precession axis of the rocket, as derived from the attitude sensor analysis described above and Sco-X1 sighting, is 10^h 8′ R.A. and 36° N. declination with the half-cone precession angle being 54°. In the 7 precessions containing 93 spins each, Sco-X1, Tau-X1 and Cen-X2 sources were all scanned for about 8–9 consecutive spins. Figure 3 shows the relevant trajectories of the detector axis in the celestial sphere for both the flights.

The data from all the spins from the Centaure rocket launched on November 3, 1968 have been summed up. Figure 4 shows the observed X-ray counting rates in the energy range 2–6 Kev, as a function of the rocket azimuth. For the flight of November 7, 1968 (Nike-Apache), the data for all consecutive scans during which each source could be observed are summed up and presented in Fig. 5. The relevant scan numbers are also indicated in the figure. In both the figures, the position of Sco-X1, Tau-X1 and

Cen-X 2 sources are marked. The observed data in each scan (spin) was fitted to a theoretical response function of the type A.g. $(t - t_o)$ where A is the absolute strength of the source, t_o is time of maximum response and $g(0) = 1$. The response is obviously a triangular one with a base equal to $17/360 \times \tau_S$ where τ_S is the spin period. A and t_o are chosen for least square fitting, *i.e.*, when

$$E = \sum_i [X(t_i) - A.g.(t_i - t_o)]^2$$

is a minimum. Having obtained the source strength as observed in each scan, the least square method is applied again for consecutive scans, in an identical manner as explained above to obtain the absolute flux of the source.

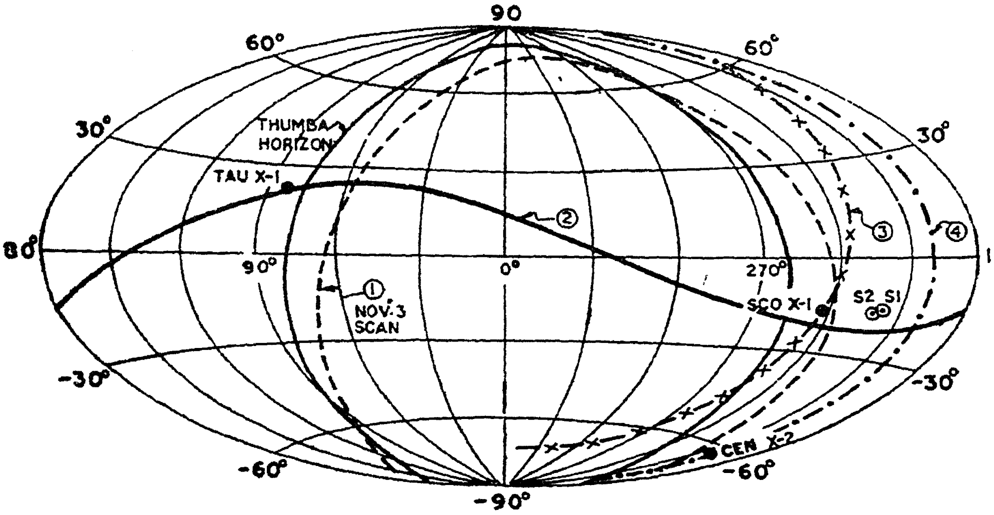

FIG. 3. Trajectories of sky scans for the two flights of November 3, 1968 (Number 1) and November 7, 1968 (Numbers 2, 3 and 4). The Thumba horizon at the time of launching is also indicated. S1, S2 indicate positions of sun on November 3 and November 7 respectively.

ABSOLUTE FLUX OF TAU-X1 SOURCE

Figure 6 shows the energy spectrum of Tau-X1 in the range 2–18 Kev. The observations by Chodil *et al.*[10] and Boldt *et al.*[11] are also plotted in the same figure. Our results show an excellent agreement with the observations made by other workers and are consistent with a power law energy spectrum of the type

$$f(E) = 8 \cdot 0 \, E^{-0 \cdot 9 \pm 0 \cdot 2} \, dE$$

The flux in the energy range 2–5 Kev is found to be $(1 \cdot 6 \pm 0 \cdot 3) \times 10^{-8}$ ergs/cm.^{2} sec.

The recent discovery of an X-ray pulsa by Fritz *et al.*[12] in the general direction of the crab nebula and its tentative identification with the optical

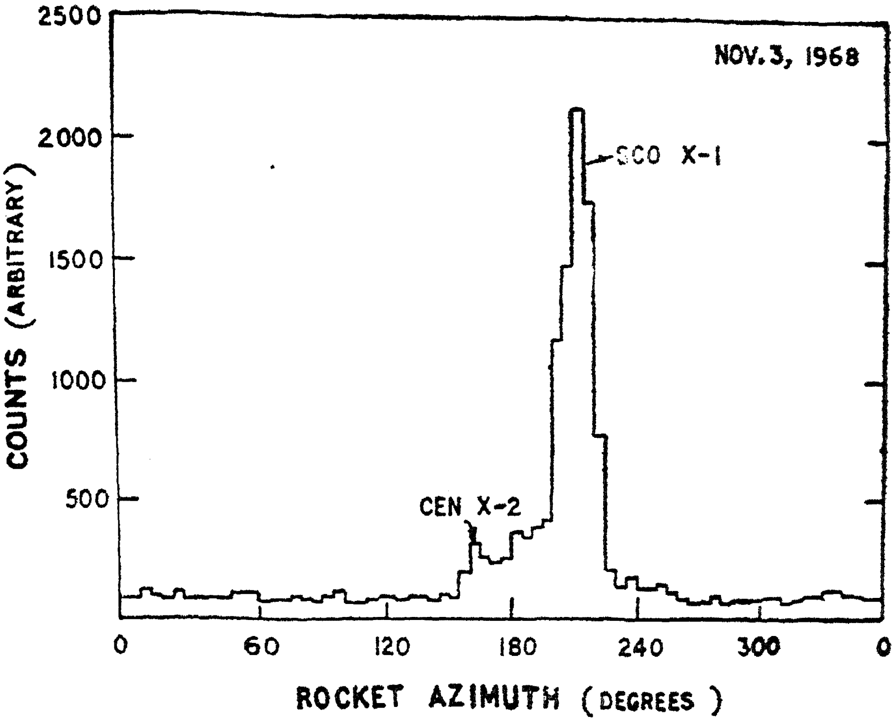

FIG. 4. Observed X-ray counting rates in the energy range 2–6 Kev as a function of rocket azimuth for the flight of November 3, 1968.

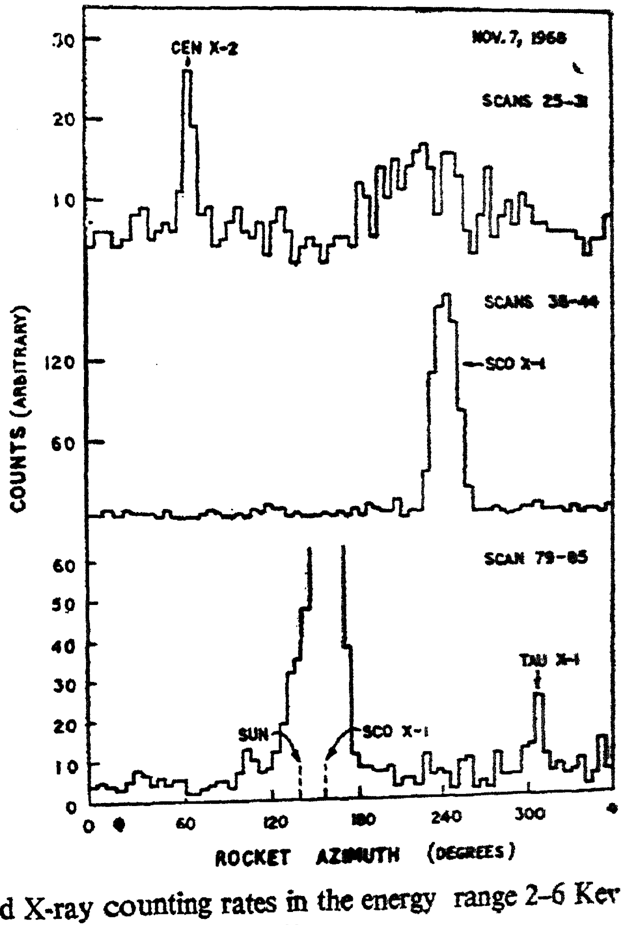

FIG. 5. Observed X-ray counting rates in the energy range 2–6 Kev as a function of rocket azimuth for the flight of November 7, 1968.

pulsar NP 0532 has increased the importance of the study of this X-ray source. The frequency of the X-ray pulsations in the crab nebula is in close agreement with the frequency of radio and optical pulsations. However, since only 5 per cent of the total X-ray power of the nebula appears in the pulsed component, the absolute flux of X-ray from Tau-X1 is practically constant which is also borne out from our observations which are in close agreement with other observations made at different times.

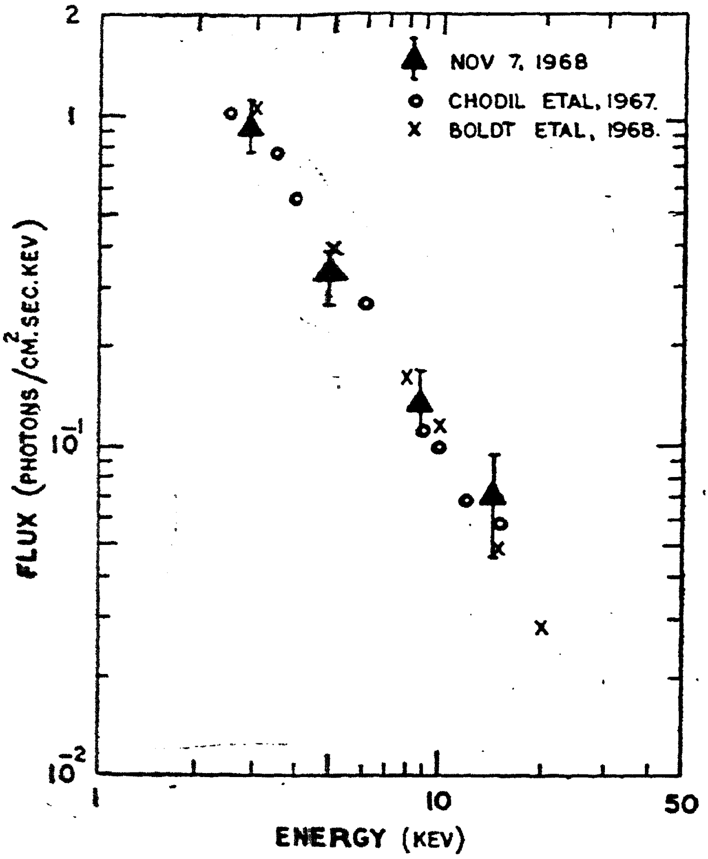

FIG. 6. Energy spectrum of Tau-X1 X-ray source in the range 2-18 Kev.

ABSOLUTE FLUX AND TIME VARIATION OF SCO-X1

Figure 7 shows the observed counting rate as a function of the rocket azimuth for different energy windows of nominal value 2–4 Kev; 4–6 Kev; 6–12 Kev and 12–18 Kev for both flights of November 3, 1968 and November 7, 1968 respectively. The data have been fitted to an energy spectrum of the type

$$f(E) = K \exp^{-E/E_0} dE$$

The value of E_0 for both the flights has been found to be $4 \cdot 4 \pm 0 \cdot 2$ Kev corresponding to a temperature of a hot thin plasma of $5 \cdot 1 \times 10^7$ °K. The energy spectrum beyond 12 Kev, however, is consistent with only $E_0 \approx 18$ Kev in agreement with the observations of Busseli *et al.*[13] The flattening of the spectrum at higher energies has been explained in terms of the multilayer complex model for Sco-X1 proposed by Shklovsky,[14] the higher energies being emitted from the higher temperature plasma in the core of the object.

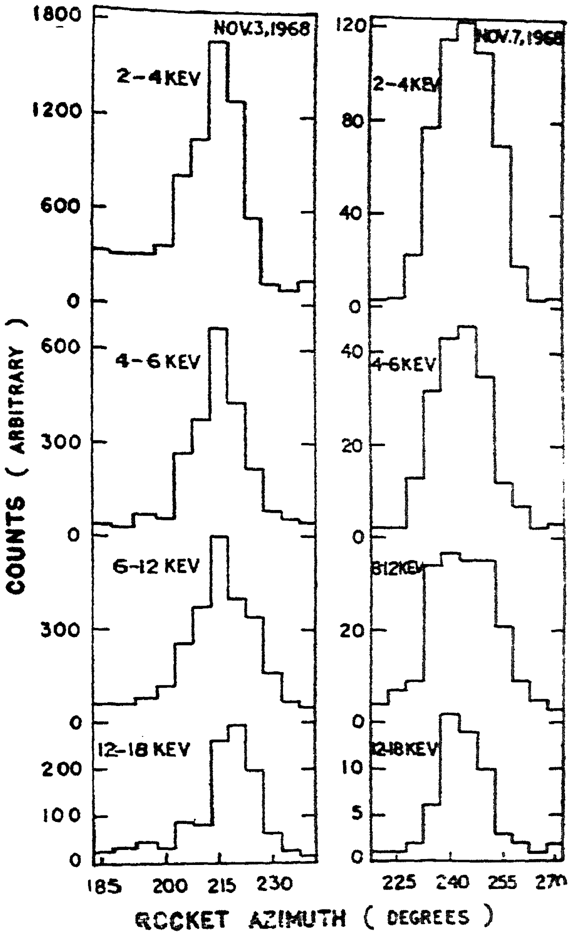

FIG. 7. X-ray count rate of Sco-X1 source for different differential energy windows.

In Fig. 8 are plotted the observational data on the intensity of low energy X-ray flux in different windows observed during the two flights. The observations of Chodil *et al.*,[15] Hill *et al.*[16] and Overbeck *et al.*[17] are also plotted in the same figure. Our observations are in quite a good agreement with the observations by other workers.

Investigation of the time variation of the absolute flux of Sco-X1 is of great importance in understanding the nature of the source. The large number of observations in the visible, in the near ultraviolet by Hiltner and Mook and by Stepien,[18] in the near infrared by Neugebauer *et al.*[19] and in the radio region by Andrew and Purton have all pointed out to the large variability of Sco-X1. Simultaneous optical and X-ray measurements by Chodil *et al.*[15] has shown that the brighter optical intensity is accompanied by a lower temperature and a bluer emission spectrum. The measurements seem to be consistent with the model of both the X-ray and optical continuum being produced by thermal bremsstrahlung from the same hot thin plasma. Observations of X-ray flares from Sco-X1 at balloon altitudes by Lewin *et al.* and Agarwal *et al.*[20] seem to add strength to the above hypothesis, even though a large number of simultaneous optical and X-ray observations of Sco-X1 are needed to make any positive conclusion regarding the nature of the source.

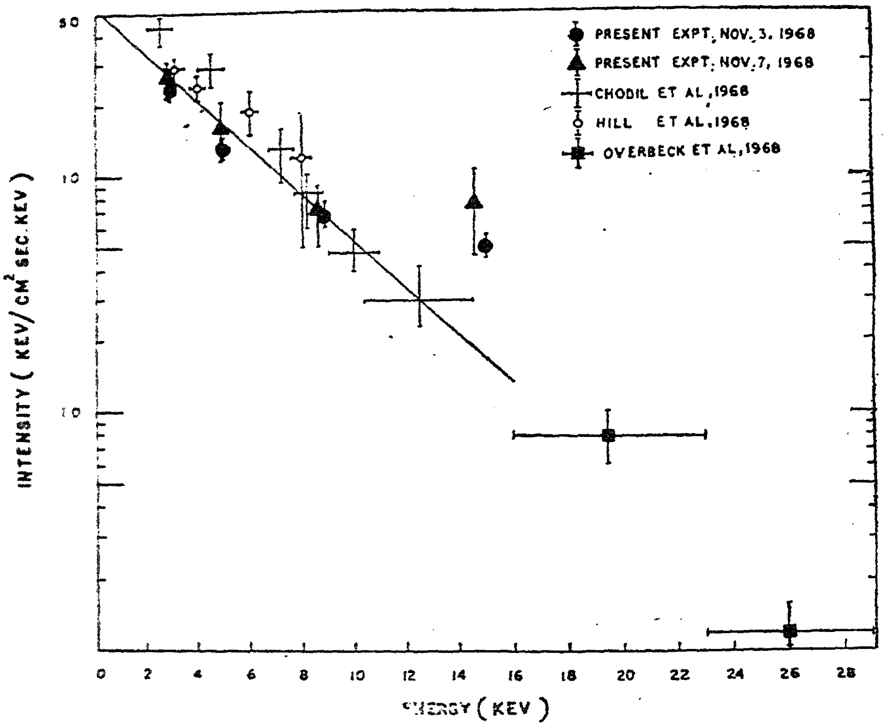

FIG. 8. Energy spectrum of Sco-X1 X-ray source in the energy window 2–18 Kev.

Taking reasonable numbers for the distance of Sco-X1 and the total energy flux as 1000 light-years and 6×10^{36} ergs/sec. respectively, the radius of Sco-X1 has been estimated to be between 3×10^{10} and 10^{13} cm. In order to keep the X-ray source going, the cooling time of the cloud, which is variously estimated between 10 and 10^5 seconds, should be of the same order as the heating time. This would indicate the possible existence of time variations in the X-ray flux from Sco-X1, having a time scale of 10 to 10^5 seconds. We do not observe any statistically significant variation between the absolute flux of Sco-X1 measured on November 3, 1968 and November 7, 1968. Addition over shorter periods of time have also been intercompared to make sure that statistically significant variations of Sco-X1 flux over periods of about 4 minutes do not exist. We may, however, point out that Overbeck *et al.* have reported significant time variations over time scales of about a month for X-rays in the energy range 16–30 Kev at balloon altitudes. Even though such large variations in the high energy flux can result from very small changes in temperature, nevertheless, the evidence together with the flare-like increases of X-ray flux strongly indicate the time variability of Sco-X1 X-ray source.

In Fig. 9 is shown the measurements of absolute flux of X-rays from Sco-X1 since 1965. Since many of the observations in the past did not have their sensor and attitude well calibrated, only those measurements from which reasonably accurate measurements can be derived are plotted in the figure. Table II gives the flux at 4·0 Kev, 6·0 Kev and the energy in the range 2–5 Kev as well as the temperature. It is evident from the figure as well as the table that the absolute flux of Sco-X1 has undergone significant time variations. The most conspicuous result from Fig. 9 is that the flux and the energy of Sco-X1 has steadily decreased over the period 1965–1968. Sporadic short time variations are superimposed upon

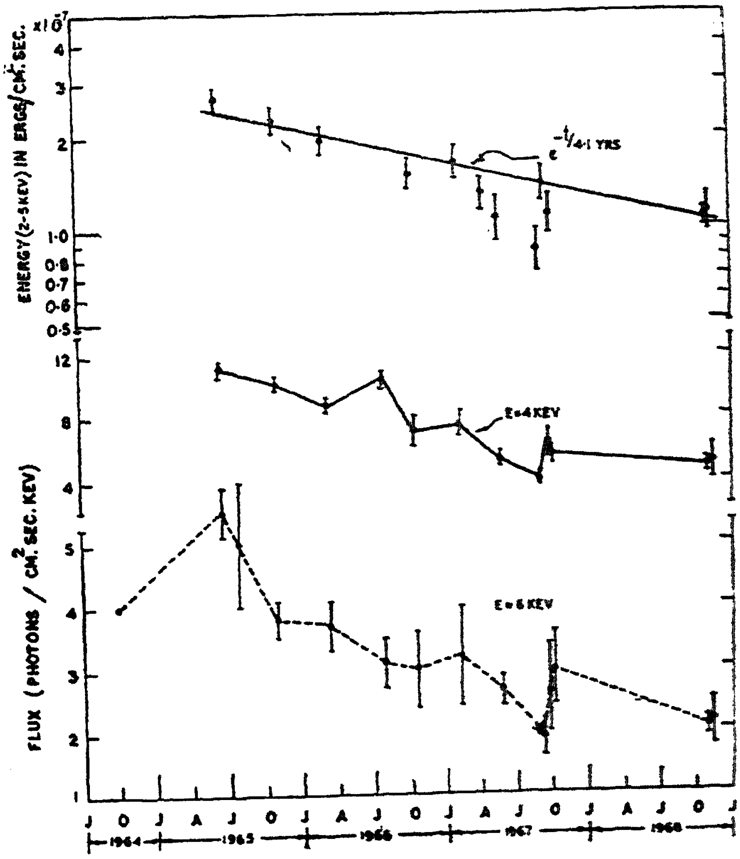

FIG. 9. Time variation of the flux and energy spectrum of Sco-X1 X-ray source during 1964–1968.

this general decrease in flux. The observations indicate that the general pattern of the time variation of Sco-X1 is consistent with an exponential decay of X-ray luminosity with a time constant of about 4·1 years which would mean that the flux of Sco-X1 would decrease by two orders of magnitude in a period of about 20 years.

TABLE II

Time variation of Sco-X1

Experimenter		Flight date	Flux of 4 Kev photons/cm.^{2} sec. Kev	Flux of 6 Kev photons/cm.^{2} sec. Kev	Energy (2–5 Kev range) $\times 10^{-7}$ ergs/cm.^{2} sec.	Temperature $\times 10^7$ °K
Fisher *et al.*[21]	..	1 October 1964	..	4·0	..	1·6
Chodil *et al.*[22]	..	12 June 1965	11·25 ± 0·6	5·5 ± 0·4	2·65 ± 0·23	4·8
Hayakawa *et al.*[23]	..	26 July 1965	..	5·0 ± 1·0	..	3·8
Grader *et al.*[24]	..	28 October 1965	10·3 ± 0·4	3·8 ± 0·3	2·28 ± 0·22	4·6
Gursky *et al.*[25]	..	8 March 1966	8·8 ± 0·5	3·7 ± 0·4	1·93 ± 0·21	5·0
Chodil *et al.*[26]	..	28 July 1966	10·5 ± 0·5	3·1 ± 0·4	..	5·8
Gursky *et al.*[27]	..	11 October 1966	7·1 ± 0·9	3·0 ± 0·6	1·49 ± 0·17	4·8
Matsuoka *et al.*[28]	..	6 February 1967	7·6 ± 0·8	3·2 ± 0·8	1·64 ± 0·20	5·0
Cocke *et al.*[29]	..	10 April 1967	..	..	1·30 ± 0·15	..
Chodil *et al.*[15]	..	18 May 1967	5·2 ± 0·4	2·6 ± 0·2	1·08 ± 0·18	8·1
Fritz *et al.*[30]	..	8 September 1967	4·0 ± 0·4	1·9 ± 0·3	0·85 ± 0·11	10·4
Chodil *et al.*[15]	..	29 September 1967	6·3 ± 0·8	2·6 ± 0·6	1·41 ± 0·17	4·6
Hill *et al.*[16]	..	2 October 1967	5·4 ± 0·6	2·9 ± 0·6	1·12 ± 0·16	10·4
Rao *et al.* (present experiment)		3 November 1968	4·9 ± 0·3	2·1 ± 0·2	1·07 ± 0·15	5·1
,,		7 November 1968	5·2 ± 0·7	2·2 ± 0·3	1·12 ± 0·16	5·1

Different theoretical models give different estimates ranging from 10–50 years for the lifetime of Sco-X1. For example, if we consider Manley's[31] model of a protostar shedding its magnetic field, where the high energy electrons are produced through the utilisation of magnetic energy, which upon interaction with the same field, can produce X-rays an estimated lifetime of about 30 years is obtained for an extar like Sco-X1. Such an estimate is obtained from considerations of energy for the magnetic field required to supply energy to electrons. The experimental observation of about 20 years for the lifetime of Sco-X1 obtained from the long-term variation of the absolute X-ray flux of Sco-X1 is consistent with the theoretical models.

ABSOLUTE FLUX AND TIME VARIATION OF CEN-X2

The rediscovery of low energy X-ray flux in the range 2–18 Kev from Cen-X2 source is the most important result of these flights. The presence of low energy flux from Cen-X2 is unambiguously proved in both the flights as may be seen from Figs. 4 and 5. The level of detection of Cen-X2 on November 3, 1968 flight is more than 10 standard deviation level and on November 7, 1968 flight at about 6 standard deviation level. The best estimate of the position of Cen-X2 as determined from our experiment is $201 \pm 2^\circ$ R.A. and $-62\cdot5 \pm 2^\circ$ declination, which is consistent with the position of Cen-X2 observed by Harries *et al.* and Chodil *et al.*

In Fig. 10 is plotted the energy spectrum of the X-ray intensity from Cen-X2 observed during both the flights. Even though the data from both the flights can be adequately represented by an exponential spectrum with a characteristic temperature of about 5·4 Kev ($T = 6\cdot3 \times 10^{7\circ}$ K), a power law spectrum fits the data better. The X-ray flux on November 3, 1968 can be represented by the spectrum

$$f(E) = 5\cdot8\, E^{-1\cdot2\pm0\cdot2}\, dE$$

and that on November 7, 1968 by the spectrum

$$f(E) = 5\cdot1\, E^{-0\cdot9\pm0\cdot2}\, dE.$$

We conclude that the energy spectrum of the X-ray flux measured on November 3, 1968 and November 7, 1968 are same within the statistical error. In the same figure, the observations of high energy flux observed at balloon altitudes by Lewin *et al.*[32] on October 15, 1967 are also plotted. The low and high energy observations taken one year apart seem to fit a single power law spectrum with an exponent of 1·2.

Figure 11 summarizes the remarkable time variation of the X-ray flux from Cen-X2, the numerical data being given in Table III. It was not detected in October 1965, was observed as a time-varying object in April–May 1967 and again could not be detected in September 1967. The decreases in the X-ray flux during the period April–May 1967 was found to be exponential, with a time constant of 23·4 days. This decrease was also accompanied by a softening of the spectrum. Even though Cen-X2 was again sighted in the high energy range in October 1967, no low energy flux from the same source was detected in June 1968, by Pounds *et al.* They provide an upper limit of 0·15 photons/cm.^{2} sec. for the flux in the energy range 2–5 Kev, which is more than an order of magnitude below the low energy flux that has been detected in our experiments in November 1968. Our observations are the first evidence for the existence of the low energy X-ray flux from Cen-X2 in the range 2–20 Kev since May 1967.

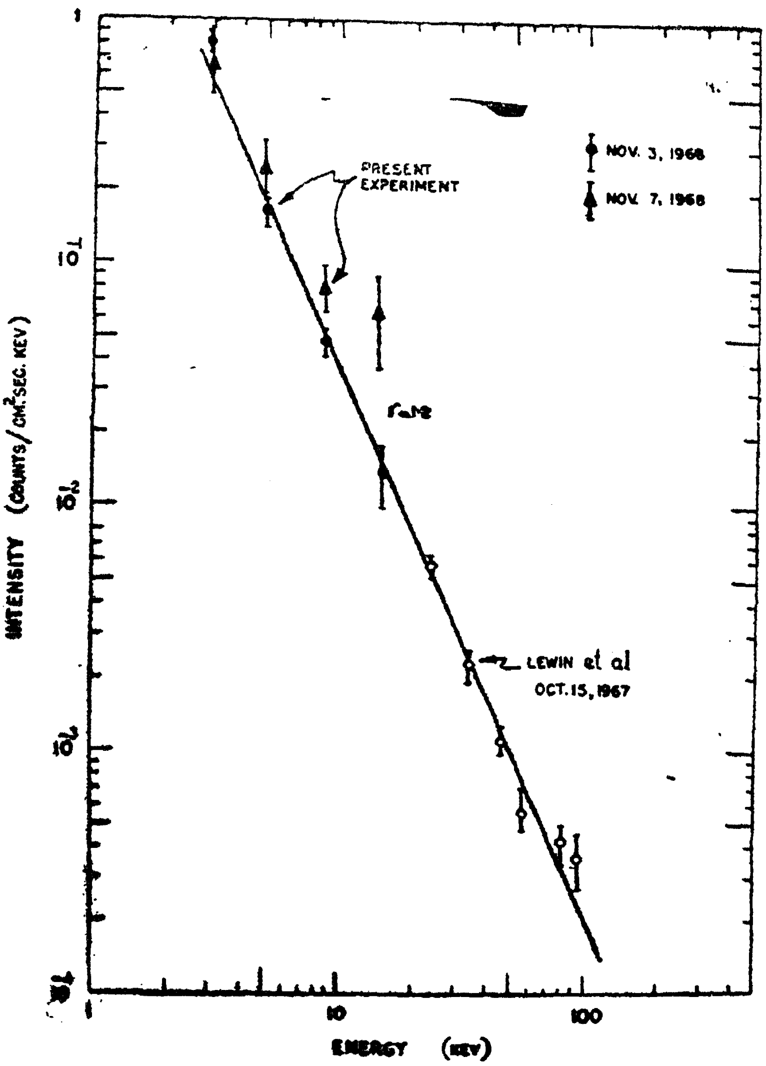

FIG. 10. Energy spectrum of Cen-X2 X-ray source in the range 2–18 Kev.

The remarkable time variability of Cen-X2 makes this extar a unique object of interest. The spectacular outburst in April–May 1967 was followed by the outbursts in October 1967 as observed by Lewin *et al.*, and in November 1968 as observed in the two rocket flights conducted by us from India. The totality of observations made so far clearly indicate that Cen-X2 is a nova-like source giving rise to recurring X-ray outbursts, each

TABLE III

Time variation of X-ray Intensity from Cen-X2

Experimenter	Flight date	Energy flux in 2-5 keV range 10^{-8} ergs cm^{-2} s^{-1}
Grader *et al.*[24]	28 October 1965	< 0·25
Harries *et al.*[8]	4 April 1967	11·0 ± 1·[illegible]
Cooke *et al.*[29]	10 April 1967	16·9 ± 1·0
Francey *et al.*[33]	20 April 1967	7·5 ± 1·0
Chodil *et al.*[34]	18 May 1967	2·6 ± 0·4
Chodil *et al.*[15]	28 September 1967	< 0·3
Lewin *et al.*[32]	15 October 1967	0·62 extrapolated
Pounds *et al.*[35]	12 June 1968	< 0·1
Rao *et al.* (present experiment) ..	3 November 1968	0·68 ± 0·[illegible]
,, ..	7 November 1968	0·33 ± 0·14

outburst lasting probably a short period of time. In order to explain this behaviour, Manley proposed an expanding constant mass plasma model for the source, according to which a dense plasma cloud of radius ~ 10^{14} cm. was heated at constant volume to nearly 2 × 10^{7} °K which then proceeded to expand isothermally and cool off. The recurring short-lived outbursts like the one observed by Lewin *et al.* and more recently our low energy observations can be attributed to a shock wave from the nova

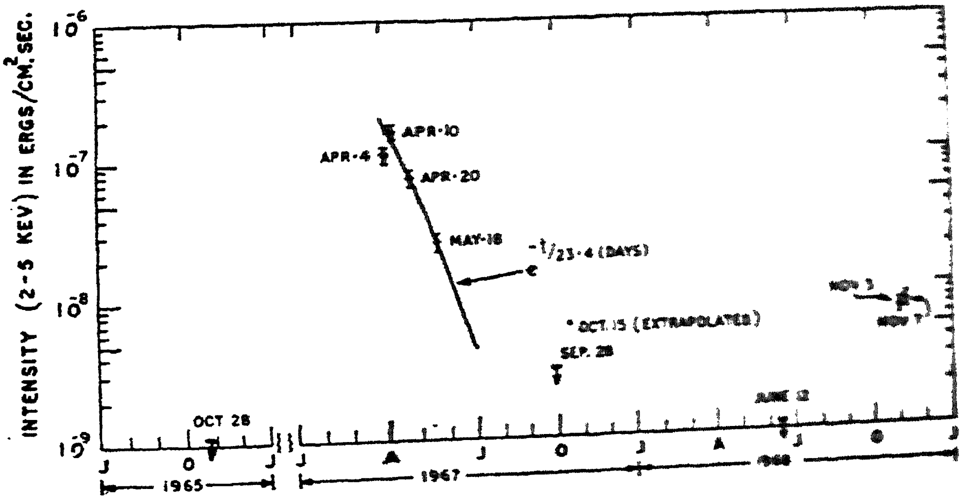

FIG. 11. Time variation of the X-ray flux from Cen-X2 source

outburst expanding into the circumstellar medium. Such a shock could accelerate and heat the gas to a high temperature as it propagates into a medium of decreasing density.

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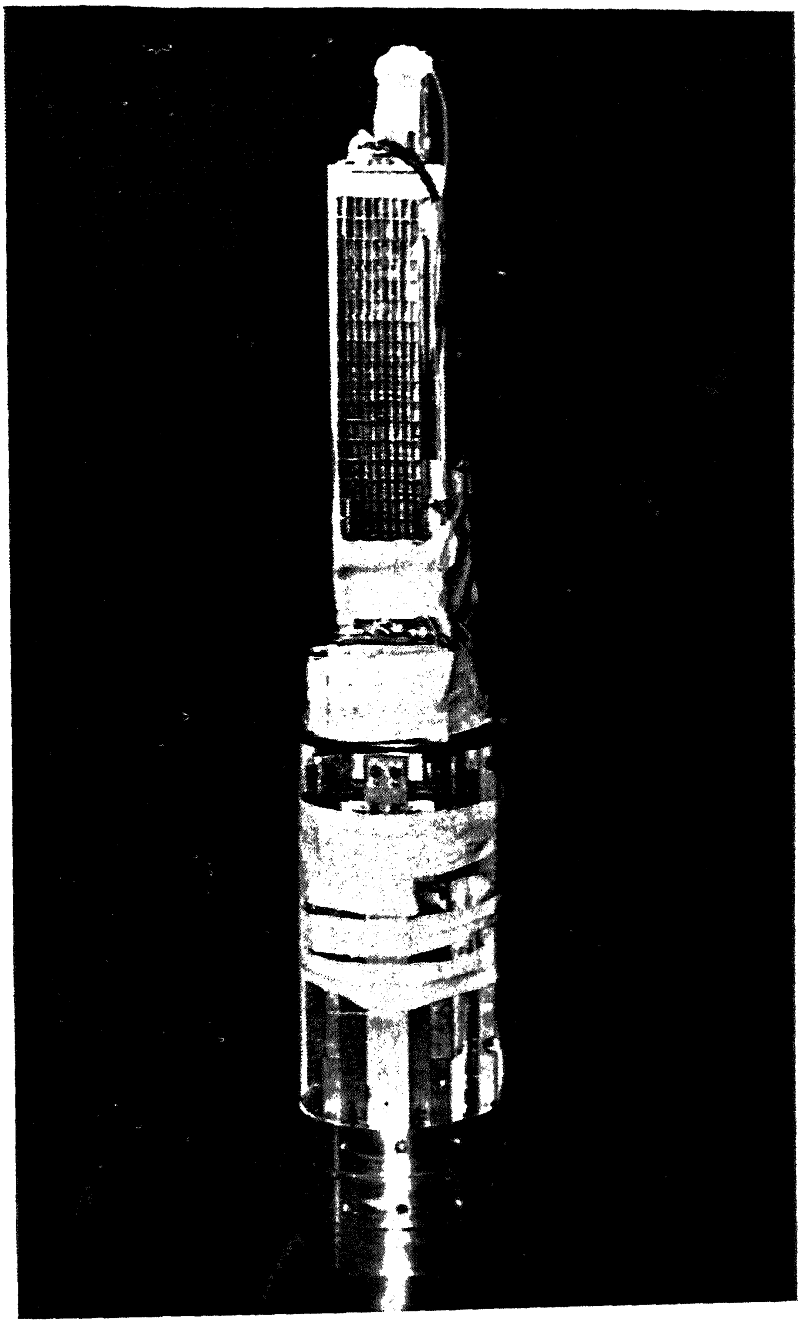

FIG. 1. Rocket-borne X-ray payload to measure extra-terrestrial X-rays