OBSERVATIONS OF CEN XR–2, SCO XR–1, AND TERRESTRIAL X–RAYS

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Summary

Two identical X-ray experiments were flown on Skylark rockets from Woomera, Australia, during April 1967. Sco XR-1 and Cen XR-2 were observed on both flights. The Cen XR-2 flux was $(1\cdot5\pm0\cdot1)\times10^{-7}$ erg cm^{-2} sec^{-1} (2–8 keV) when first observed but had decreased to $(1\cdot0\pm0\cdot1)\times10^{-7}$ erg cm^{-2} sec^{-1} and had become softer by the second flight. An X-ray flux from the Earth was observed and found to be due to solar X-rays reflected in the atmosphere.

I. Introduction

This paper presents the celestial X-ray results obtained from two identical experiments which were flown on Skylark rockets launched from Woomera, Australia (136°·5 E., 30°·9 S.), at 0032 U.T. on April 4, 1967 (flight I) and 2236 U.T. on April 20, 1967 (flight II). Both flights surveyed essentially the same area of the southern sky including the region around the south celestial pole. The most significant result was the discovery of a strong X-ray source in the constellation Centaurus (Harries *et al.* 1967) referred to as Cen XR-2, which was found to be variable (Chodil *et al.* 1967; Cooke *et al.* 1967; Francey *et al.* 1967).

The X-rays were detected by beryllium-window proportional counters, filled with a 90% xenon and 10% methane mixture at 1 atm pressure and with a depth of 2 in. The individual window thicknesses were measured on the recovered experiments and were found to be typically 14 mg cm^{-2}. The four counters on each rocket were mounted in pairs to form two independent detection systems, each having an effective area of 22 cm^2 and facing in diametrically opposite directions in a plane normal to the spin axis. Slit collimators mounted in front of the proportional counters defined a 10°·5 by 35° full width at half-maximum field of view, with the long axis parallel to the spin axis.

The pulses from a detection system were amplified and fed into a two-channel pulse height analyser, with channels corresponding to 2–5 and 5–8 keV energy deposited in the counter. The count rates observed in these channels will be referred to as S_1 (2–5 keV) and S_2 (5–8 keV) for the first detection system and S_3 (2–5 keV) and S_4 (5–8 keV) for the second system. The channels were calibrated immediately prior to launching using the 5·9 keV X-rays from a ^{55}Fe source.

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The sensitivity of each detection system to a point source of galactic X-rays was dependent on the background count rate, which was due to charged particles and the diffuse celestial X-ray flux. Approximately 75% of the high energy charged particles were rejected by the pulse height analyser because they deposited more than 8 keV in the counter gas. A source with an X-ray flux of approximately 1 photon $cm^{-2}\,sec^{-1}$ in the energy range 2–8 keV would give a response with a significance of three standard deviations for one scan over the source.

The attitudes of the rockets throughout the part of the flight above 60 km altitude were determined from data provided by the standard Skylark sunslits, magnetometers, and rate gyroscopes. Independent attitude solutions were also obtained from the British Aircraft Corporation, Bristol, U.K. The final solutions, used to obtain the position of Cen XR-2, gave correct positions for Sco XR-1 (Gursky *et al.* 1966) and the Sun to an accuracy of better than 2°. The spin period of both rockets was about 11 sec and the spin axis described a slow flat precession cone, with a half-angle of about 64° and period of about 400 sec. This motion was ideal for the survey as it allowed almost the whole sky to be scanned in an orderly manner. Although the parameters of the motion were similar on the two flights, the orientations of the precession cones were very different.

II. Analysis Procedures

A marked increase in the proportional counter count rates was observed as the rocket altitude increased from 70 to 90 km. This increase was caused by the detection of celestial X-rays which can penetrate to this altitude in the atmosphere. Between the altitudes of 40 and 70 km, the count rate was due to energetic charged particles and photons and the detection of secondary particles produced in the rocket. The counts due to these processes were approximately equally distributed between the two energy channels and were present throughout the flight.

Although a low energy electron flux could contribute to the count-rate increase between 70 and 90 km, this was considered unlikely owing to the lack of a pitch angle distribution about the geomagnetic field and to the distribution of the increase between the two energy channels. Electrons of about 80 keV could penetrate the window, but they would produce about twice as many counts in the higher energy channel. The observed increase was four times greater in the low energy channel than in the high energy channel.

Above 90 km the count rate due to discrete X-ray sources was superimposed on a diffuse celestial X-ray flux and a constant energetic charged-particle background. The main discrete X-ray sources observed were the Sun, Sco XR-1, and Cen XR-2. X-rays were also observed from the sources near the galactic centre with intensities consistent with the results of Friedman, Byram, and Chubb (1967), but the angular resolution and small detector area precluded any detailed analysis. Although the X-ray count rate observed from the Sun saturated the system, an estimate of the solar flux was obtained by considering the X-rays reflected from the atmosphere. This albedo flux is discussed in Section V.

X-rays from Sco XR-1 or Cen XR-2 were detected on at least seven consecutive scans by each detection system on both flights and so an accurate position and flux could be obtained which were not subject to errors in the correction for collimator response. For each individual scan of the source a triangular collimator response, whose base was related directly to the spin period, was fitted to the observed count rate by the least-squares technique. This gave the position of maximum response along the scan and the corresponding count rate due to the source. The response curve from scan to scan, i.e. across the long axis of the collimator, depended on the attitude solution but it was found that for source positions within 5° of each other the shapes of the response curves were almost identical. Hence, using a preliminary source position a theoretical response curve was obtained and fitted to the count rates from the different scans, again by the least-squares method. This gave the position of the source relative to the scan paths and also the count rate corresponding to normal incidence.

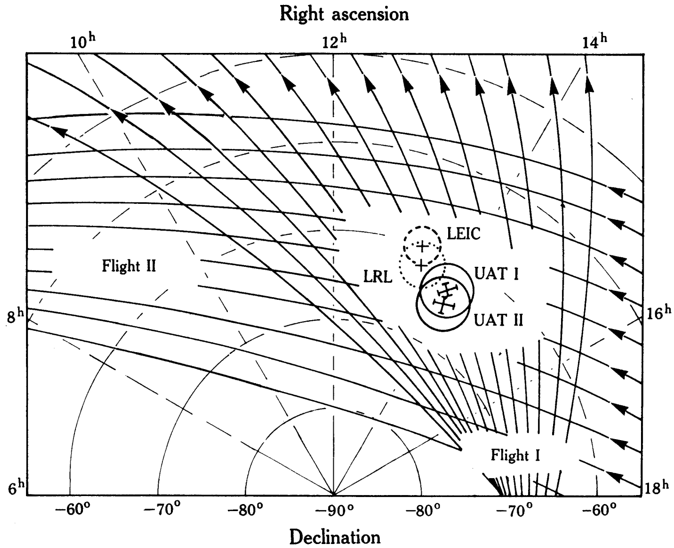

Fig. 1.—Scan paths on flight I and flight II during which Cen XR-2 was detected. The resultant UAT positions are indicated (mean position R.A. $13^{h}\cdot9$, Dec. $-64°$); error bars show the statistical uncertainty in the maximum of the count rate data while the circles combine the statistical error with the 2° accuracy of the attitude solutions. The LRL (Chodil *et al.* 1967) and LEIC (Cooke *et al.* 1967) positions are also shown, together with their claimed accuracies.

The resultant position for Cen XR-2 is shown in Figure 1, together with the scans on which it was observed. The crossed error bars represent the statistical errors given by the fitting process, while the error circles include an estimated 2° uncertainty due to systematic errors in the attitude solution. The positions for Sco XR-1 and the Sun obtained by the same method were accurate to within 2°. The position of Cen XR-2 from this analysis was $13\cdot9\pm0\cdot4$ hr right ascension and $-64°\pm3°$ declination ($l^{\mathrm{II}} = -2°\pm3°$, $b^{\mathrm{II}} = 310°\pm3°$). An optical search of most of the region about this position for Cen XR-2 by Dr. G. Lynga and Dr. L. Searle of Mt. Stromlo Observatory (personal communication) found about 80 violet stars down to 16th magnitude. A search for nova-like characteristics in both optical and radio emissions is being undertaken.

III. Spectra

In order to obtain the incident X-ray spectra corresponding to the observed counting rates of the two-channel pulse height analyser it was necessary to understand the manner in which the detection system would modify the X-ray spectrum.

Initially the incoming X-rays were assumed to have the exponential spectrum

$$\mathrm{d}N/\mathrm{d}E = J_0 E^{-1} \exp(-E/T) \quad \text{photons cm}^{-2}\,\text{sec}^{-1}\,\text{keV}^{-1}. \tag{1}$$

This type of spectrum is consistent with bremsstrahlung radiation from a thin hot plasma of temperature T.

The above spectrum was corrected for the proportional counter efficiency using the measured beryllium-window thickness and the mass absorption coefficients of Victoreen (1949). The spectrum of photons absorbed in the counter gas was then modified to allow for the finite resolution of the counter. The resolution of most of the counters was considerably worse than that of an ideal counter. For calculation, the resolution (full width at half maximum expressed as a percentage of the mean pulse height) was assumed to consist of ideal resolution plus an energy-independent factor to bring it up to the observed resolution at 5·9 keV. Corrections were made for the end effects of the counters of flight II which affected approximately 30% of the window area. Field-forming electrodes in the counters of flight I eliminated this problem; however, corrections had to be made to S_3 and S_4 of this flight for a gain decrease observed and measured prior to launching. These calculations gave the spectrum of output pulses corresponding to an incident X-ray spectrum.

Taking into account the effective window area of the detector, the count rates expected in each channel of the pulse height analyser were obtained. The ratio of the count rates in the two channels (that is, S_2/S_1 or S_4/S_3) was then a function of T, and for a given T the total number of counts (S_1+S_2 or S_3+S_4) was a function of J_0.

As discussed below, the Sco XR-1 spectrum observed on flight II was in close agreement with that of the other groups. In flight I, although the total number of counts from Sco XR-1 was in agreement with the flight II result, the ratio was inconsistent with the predicted value. Furthermore, it was found that the ratios for the other known sources were inconsistent with the predicted values and that the ratio for the energetic charged-particle background differed from unity. These factors could be explained only by assuming that the centre bias level of the pulse height analyser had changed during launching. Measurements on the recovered round predicted that for flight I the channels should be 2–4·5 and 4·5–8 keV, and these were also the channels necessary for the Sco XR-1 spectra to agree on both flights.

The incident X-ray spectra from Sco XR-1 observed by the two UAT flights (Universities of Adelaide and Tasmania) agreed with the results of Gorenstein, Giacconi, and Gursky (1967) in October 1966, Cooke *et al.* (1967) (the University of Leicester (LEIC) group) in April 1967, and Chodil *et al.* (1967) (the Lawrence Radiation Laboratory (LRL) group) in May 1967. These spectra were a factor of two less than some early proportional counter measurements (Chodil *et al.* 1965; Grader *et al.* 1966; Hayakawa, Matsuoka, and Yamashita 1966) but were consistent with the less accurate flux measurements made by other early experimenters (Bowyer *et al.* 1964; Giacconi, Gursky, and Waters 1965). Manley (1967) has suggested that the discrepancy was instrumental in origin and did not represent a real variation. Even if such a variation did occur the agreement between the Sco XR-1 spectra during April–May 1967 could be used as a common reference for the comparison of the different measurements of Cen XR-2.

The spectra of Cen XR-2, calculated on the assumption of an exponential spectrum, are given in Figure 2 and show the effects observed in the raw data, namely, the source was decreasing in intensity and becoming softer with time.

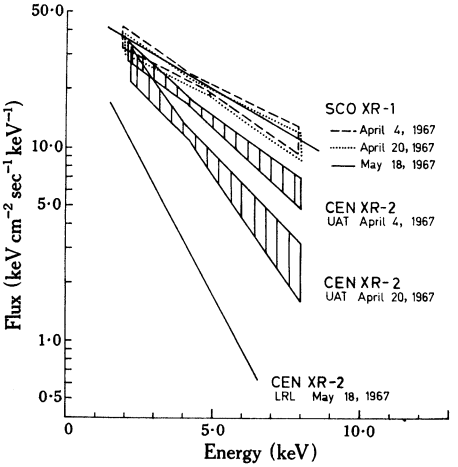

Fig. 2.—Variations in the Cen XR-2 spectra as observed on the present flights and the LRL flight (Chodil *et al.* 1967). The good agreement obtained for Sco XR-1 serves as a reference between the different experiments.

The bremsstrahlung from a thin hot plasma as represented by equation (1) is only one of three likely mechanisms for the generation of celestial X-rays. A black body would give a Planck distribution,

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{AE^2}{\exp(E/T_\mathrm{b})-1} \quad \text{photons cm}^{-2}\,\text{sec}^{-1}\,\text{keV}^{-1}, \tag{2}$$

while a synchrotron (magnetic bremsstrahlung) emitter would give

$$\mathrm{d}N/\mathrm{d}E = AE^{-\alpha} \quad \text{photons cm}^{-2}\,\text{sec}^{-1}\,\text{keV}^{-1}. \tag{3}$$

Clearly, two-channel pulse height analysis cannot distinguish between these various two-parameter spectra, and so spectra of Cen XR-2 were also calculated on the assumption of both the black-body and the power law spectra using the same method as for the exponential spectrum. The results for the three types of spectra are shown in Table 1. The total 2–8 keV flux for the UAT experiments is the same for all three types of spectra within the errors shown. The April 10 flux was obtained by the University of Leicester (Cooke *et al.* 1967) in the range 2–5 keV; nevertheless their flux is greater than the flux measured over the larger range 2–8 keV on April 4 or April 20 and suggests that Cen XR-2 might have passed through a maximum.

All three types of spectra could be fitted to the Cen XR-2 results of the LRL group. The black-body temperature was obtained on the assumption of a body of constant dimensions as determined by the UAT flights. Chodil *et al.* (1968), from a flight on September 28, 1967, found that Cen XR-2 was too weak to be observed. The results for all these flights are given in Table 1.

The count rates observed when the counters were not looking at any discrete X-ray sources or at the atmosphere were analysed to obtain the diffuse celestial X-ray flux. The count rate was corrected for the high energy charged-particle background by subtracting the count rate observed below an altitude of 70 km. A power law spectrum (equation (3)) was assumed and the background spectrum calculated from the count rates using the method previously discussed for the exponential spectrum. The incident diffuse flux was found to be $2\cdot8\pm0\cdot6$ photons $\mathrm{cm^{-2}\,sec^{-1}\,sr^{-1}\,keV^{-1}}$ at 3 keV and $0\cdot8\pm0\cdot5$ photons $\mathrm{cm^{-2}\,sec^{-1}\,sr^{-1}\,keV^{-1}}$ at 6 keV.

Table 1

VARIATIONS OF THE CEN XR-2 SPECTRUM

Group	Date	Exponential Temperature (keV)	Black-body Temperature (keV)	Synchrotron Index α	Flux ($\mathrm{erg\,cm^{-2}\,sec^{-1}}$)	
LRL	Oct. 28, 1965				$<2\times10^{-9}$	(2–8 keV)
UAT	Apr. 4, 1967	$3\cdot6\pm0\cdot5$	$1\cdot21\pm0\cdot07$	$2\cdot15\pm0\cdot15$	$(1\cdot5\pm0\cdot1)\times10^{-7}$	(2–8 keV)
LEIC	Apr. 10, 1967				$1\cdot6\times10^{-7}$	(2–5 keV)
UAT	Apr. 20, 1967	$2\cdot4\pm0\cdot4$	$1\cdot10\pm0\cdot07$	$2\cdot75\pm0\cdot25$	$(1\cdot0\pm0\cdot1)\times10^{-7}$	(2–8 keV)
LRL	May 18, 1967	$1\cdot5$	$0\cdot73$	$3\cdot8$	$2\cdot8\times10^{-8}$	(2–8 keV)
LRL	Sept. 28, 1967				$<3\times10^{-9}$	(2–5 keV)

IV. Albedo X-rays from the Earth

A flux of X-rays was observed from the direction of the Earth in the 2–5 keV energy interval, which was comparable to the celestial diffuse X-ray flux. The albedo flux in the 5–8 keV channel was at least an order of magnitude less than that in the 2–5 keV channel, indicating a very soft spectrum.

The solar X-ray flux, observed directly, saturated the telemetry system and a lower limit of only 2000 photons $\mathrm{cm^{-2}\,sec^{-1}}$ greater than 2 keV could be obtained. In fact, the solar flux would be expected to be considerably higher and to have a soft spectrum (Mandelstam 1965). Although most of these photons will be absorbed at about 80 km altitude in the atmosphere by the photoelectric effect, some of them will be scattered by the electrons in the gas molecules of the atmosphere. The calculation of the scattering differential cross section for oxygen, nitrogen, and argon takes into account the coherent scattering of a photon by all of the electrons in the molecule using the method of Compton and Allison (1935). This was an important effect as it caused the cross section to increase rapidly at small scattering angles producing the peak in the albedo flux at the X-ray horizon nearest the Sun (Fig. 3).

When corrections are made for the attenuation of the incident and scattered X-rays in the atmosphere and for the geometric factor of the collimator, the flux $\mathrm{d}N_{\mathrm{S}}/\mathrm{d}E$ of X-rays entering the counter window is

$$\frac{\mathrm{d}N_{\mathrm{S}}}{\mathrm{d}E} = 2\cdot 08\times 10^{22}\frac{\omega}{\mu(E)\,(1+\cos\psi/\cos\theta)}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(E,\phi)\frac{\mathrm{d}N_0}{\mathrm{d}E}\quad \text{photons cm}^{-2}\,\text{sec}^{-1}\,\text{keV}^{-1}, \qquad (4)$$

where $\mathrm{d}N_0/\mathrm{d}E$ is the differential solar X-ray flux, $\mu(E)$ is the atmospheric attenuation at energy E keV (Victoreen 1949), $\mathrm{d}\sigma/\mathrm{d}\Omega$ is the scattering differential cross section at angle ϕ, θ and ψ are the Sun and rocket zenith angles measured from the scattering volume, and ω is the collimator solid angle.

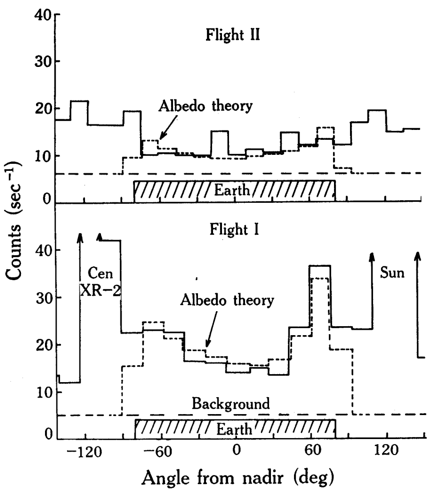

Fig. 3.—Averages of five (flight II) and four (flight I) scans through the nadir showing the X-rays observed from the Earth. The flight II scans are normal to the Sun zenith line while the flight I scans pass through the Sun and show the peak albedo flux at the horizon closest to the Sun. The horizontal dashed lines indicate the charged-particle background.

Another small fraction of the incident solar X-ray flux will undergo photoelectric absorption in argon. Photons with energies greater than $3\cdot 2$ keV can eject a K electron, which will be followed in 12% of the cases (Fink *et al.* 1966) by the emission of a K X-ray of energy $2\cdot 94$ keV. These X-rays will be emitted in all directions and those reaching the rocket will be detected in the lower energy channel. When corrections are made for the absorption of the fluorescent X-rays in the atmosphere, the flux reaching the detector window is found to be

$$N_{\mathrm{F}}(2\cdot 94\,\mathrm{keV}) = 1\cdot 14\times 10^{-3}\int_{3\cdot 2}^{\infty}\frac{\omega}{\mu(2\cdot 94)/\mu(E)+\cos\psi/\cos\theta}\frac{\mathrm{d}N_0}{\mathrm{d}E}\,\mathrm{d}E\quad \text{photons cm}^{-2}\,\text{sec}^{-1}.$$

Since the scattered and fluorescent components constitute only a small proportion of the incident solar flux, the total albedo flux is the sum of the two effects. The solar X-ray spectrum was assumed to be exponential (equation (1)) and to be absorbed in a thin layer at 80 km altitude. The angles θ, ψ, and ϕ could then be determined from the direction of arrival of the X-rays at the rocket and the altitude of the rocket.

The albedo flux was calculated for various values of the effective plasma temperature T, and the expected count rate of the pulse height analyser channels was obtained. The variation of the albedo flux with the nadir angle was found to be almost independent of plasma temperature in the range $0 \cdot 2$–$0 \cdot 5$ keV. The value of J_0 was varied by the least-squares method to fit the observed data. The theoretical albedo is shown in Figure 2 for a solar spectrum with an effective plasma temperature of $0 \cdot 4$ keV ($4 \cdot 6 \times 10^6$ °K) for some averaged scans from both flights. The solar flux required to give these fits was about 9×10^4 photons cm^{-2} sec^{-1} above 2 keV, and was very similar (within 20%) on both flights. The difference in the magnitude of the albedo between the flights was mainly caused by the difference in the Sun zenith angle, which was 49° for flight I and 74° for flight II. These fluxes were in very good agreement with the satellite measurements at the time (Solar Geophysical Data 1967).

V. Conclusions

The observed variability of Cen XR-2 makes it important to determine if the other known sources are varying to any extent. Several models of Cen XR-2 have been proposed (Manley 1967; Edwards 1968; Edwards and Harries 1968; Prendergast and Burbidge 1968) and would indicate that the rapid variation is perhaps only a transient stage in the life of an X-ray object.

The existence of the albedo flux raises doubts about the measurement of the diffuse X-ray flux by the difference between the count rates when the counter looks up and when it looks down. Fortunately, to date, most experiments with results on the diffuse flux have been made at night-time, or have only measured the flux above about 5 keV (Hayakawa, Matsuoka, and Yamashita 1966; Cooke *et al.* 1967; Seward *et al.* 1967). However, any daytime measurement at energies less than 10 keV must be suspect unless it can be shown that there was no X-ray activity on the Sun at that time.

Note added in proof. Lewin, Clark, and Smith (1868*a*, 1968*b*) have observed X-rays above 20 keV on October 15 and 24, 1967 from a source in the vicinity of Cen XR-2 and whose intensity decreased by 35 ± 17% between the two flights. If this source is Cen XR-2 then its observable life is much longer than is suggested by a simple extrapolation of the 2–8 keV observations discussed in the present paper.

VI. Acknowledgments

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