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LONG TERM TEMPORAL VARIATIONS
OF THE HARD X-RAY FLUX
FROM THE CENTAURUS REGION

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ABSTRACT

The University of California at San Diego (UCSD) X-ray telescope
aboard the third Orbiting Solar Observatory (OSO-III) observed the
Centaurus region daily from 1967 October to 1968 February, and also
for five days in 1968 June. For this period, we derive a stable
minimum flux of 0.33 ± 0.03 photons $(cm^2 sec)^{-1}$ between 7.7 and 38 keV
from a source around $\ell = 305°$. Several single days show enhanced fluxes,
and two extensive flaring episodes, one with a soft and the other a very
hard spectrum, last at least ten days.

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I. <u>INTRODUCTION</u>

The OSO-III X-ray telescope observed the Centaurus region almost daily for four months between October 1967 and February 1968, and during five days in June 1968. Assuming one single source at $\ell = 305°$, $b = 1.5°$, as measured from balloons by Lewin, Clark, and Smith (1968b) on 1967 October 15 and 24, our counting rates during October 1967 are consistent with the average strength and spectrum (extrapolated to 10 keV) of those balloon measurements. The single source at this position also explains much of our counting rate over the entire period of observation, and we find this source to have a generally constant flux when averaged over one day. We also see two periods of flaring on at least a 10 day time scale, and several single days of enhanced fluxes. We cannot directly determine the origin of these flares. They quite possibly arise from any of several known variable sources (Lewin, et al. 1971; McClintock et al. 1971; Cooke & Pounds 1971; Giacconi et al. 1971; Margon et al. 1971) within 15° of the above position. We have spectral measurements of both the steady and flaring emission spanning the energy range observable from rockets to that observable from balloons.

The source observed by the MIT balloon survey (Lewin, Clark and Smith 1968a) was originally identified with Cen XR-2, a source which flared up in Spring 1967 by a factor of > 50 in the 2-8 keV range and then decayed with about a 25-day e-folding time. The several original rocket results gave the position of this source as $\ell = 307°$ to $310°$, with typical error circles of 3° (Chodil et al. 1967; Francey et al. 1967; Cooke et al. 1967). A recent reanalysis of one of the April 1967

rocket flights gives a galactic longitude 310.2 ± 1.0° (Francey 1971),

incompatible with the balloon position. We will use the revised desig-

nation GX 304-1 (McClintock et al. 1971) for the basic source which

we observe.

II. EXPERIMENTAL DETAILS

The UCSD X-ray telescope (Hicks, Reid, and Peterson 1965) aboard

OSO-III consists of a 9.6 cm^2 NaI(Tl) scintillator actively collimated

by a concentric CsI(Tl) cylindrical shell to a 50% response radius of

11.5°. The satellite telemeters 5 useful channels of pulse height analysis,

logarithmically spaced between 7.7 and 113 keV. The basic data consist

of arrival directions of individual photons in each energy channel; these

are reduced to true count rates averaged over bins 6° along the scan

circle, as described by Schwartz, Hudson, and Peterson (1970). The one

difference is that the data here are averaged over only 1 day, which

represents a negligible precession of only 1° on the sky perpendicular

to the scan circle. From the aspect solution and the satellite spin

rate, we calculate the total effective response in (cm^{2}sec) for each

bin along the scan circle, to any _given_ position of a cosmic X-ray source.

Because of our large aperture and the uncertainty arising from digitizing

the arrival direction, we make no attempt to _derive_ positions of X-ray

sources from our data alone.

An error of 3° in the adopted source position would change our de-

rived fluxes by 1 to 20% during certain periods of observation, but would

not change our general conclusions. In particular, the observed flaring

episodes cannot be attributed to aspect errors or sudden changes in the

satellite spin axis. We use only data which contain less than about 10%

contamination from other nearby known sources, based on previous surveys

of this region (Lewin, Clark, and Smith 1968a; Cooke and Pounds 1971) and

assuming the other sources do not vary. The breakdown of this assumption

may explain the observed flares. The existence of a constant minimum flux,

reported below, indicates that most of our counts do come from the vicinity

of GX 304-1.

From the raw true count rate we separately subtract corrections for

background induced by radioactivity and by cosmic rays, and then subtract

a correction due to the previously determined diffuse component of cosmic

X-rays. The more straightforward procedure of estimating background from

the same scan with the telescope pointing off the source is not applicable

because different parts of this circle receive sky exposure during differ-

ent parts of the orbit, and because when several sources are simultaneously

on the scan circle we do not accumulate sufficient off-source background

statistics. The danger of contamination of the counting rates by geo-

magnetically trapped particles made it necessary to reject a large fraction

of the raw data. By studying the background over the 16 months of satellite

operation, we estimate that these corrections are known to better than 10%

(Schwartz 1969). The background rate summed over the 3 lowest channels

equals about 7.7 counts per second, of which 6.5 sec^{-1} arise from the diffuse

cosmic x-rays. We measure additional rates of 3 to 10 counts per second

from Centaurus. Because of this large signal to background ratio the present

data have about the same statistical significance that previous observers

have obtained at the same energies, even though our telemetry limits us to

about 100 to 200 $(cm\ sec)^{-1}$ effective daily exposure per energy channel.

III. <u>OBSERVATIONS</u>

Figure 1 presents data from our coverage of Centaurus. The bottom points represent the one-day averages of the integral flux from GX 304-1, with background subtracted, from our three lowest channels in units of counts $(cm^2 sec)^{-1}$ between 7.7 and 38 keV. The error bars shown are based solely on counting statistics and are not connected for a few points of less than 2 σ significance. We also show the integrated fractional exposure per spin revolution to GX 304-1, which we calculated by taking account of the declination of the source from the scan circle. The error bars show the change in exposure resulting from a $\pm$ 2° error in the aspect solution. Such an aspect error would represent about a 2 σ deviation from the average solutions determined independently by the MIT group (Clark 1968) and at UCSD. A given percentage error in the true exposure would produce the same percentage error in the integral flux; note that such errors are not symmetric about the mean.

The OSO scan circle on the celestial sphere is inclined by about 60° to the equator, and automatically precesses about 1° per day in right ascension to follow the apparent solar motion. It is the chance declination of GX 304-1 at about -60° which allows it to stay within our scan so long (see Fig. 9 of Peterson 1970). For comparison, we have data on the Crab nebula for 20 days between 1967 December 3, and December 29. It appears to have a constant flux of 1.41 photons $(cm^2 sec)^{-1}$ between 7.7 and 38 keV. The root-mean-square deviation for a single day is 8.5% and the maximum deviation of 18% occurs on the day when the Crab is calculated to be the furthest from the scan circle, and thus most susceptible to aspect errors.

Figure 1 shows two definite, extended episodes of flaring; 1967

October 31 to November 14 and 1968 January 23 to February 2. Individual

days, such as 1967 November 19, 21 and 23, December 30, and 1968 Jan. 4

and 24 show fluxes of 2.5 to 5 σ above surrounding days. For such enhance-

ments, we do not have other evidence, such as the systematic decline of

counting rate for the extended flares, to rule out possible charged

particle contamination of the X-ray telescope. Actually, our daily

average does not represent a uniform sample throughout the day, but

rather contains all the data during each day that happened to occur at

times consistent with background selection criteria. Thus these single

day enhancements could have occurred on the same time scales, ten minutes

to a few hours, as flares observed from Sco X-1 (Hudson, Peterson, and

Schwartz 1970; Lewin et al. 1970) and from a source at $\ell \sim 301°$. (Lewin

et al. 1971; McClintock et al. 1971).

Ignoring 3 σ deficits on October 25 and 30 and a 3 σ increase on

February 11, the flux during each interval denoted by a bar at the bottom

of Figure 1 is statistically consistent with an assumed constant source.

Also, the average flux over each of these intervals is barely consistent

(to 4% confidence by a χ^2 test) with a constant received "base-line" flux

from GX 304-1 of 0.33 $\pm$ 0.03 photons $(cm^2 sec)^{-1}$ (corrected for detector

response) between 7.7 and 38 keV. Satellite observations allow analysis

for periodic variations of the order of a few days, such as might arise

from eclipsing binaries. During the constant intervals we derive an

upper limit of 5% for a fraction of the emission associated with a

sine wave with a period between 4 and 20 days.

The statistics during one day do not suffice to give spectral information, so we average over each of the intervals shown in Figure 1. The resulting data appear in Table 1. Figure 2 shows spectral measurements from this region. OSO-III "quiet" data are the average of lines 1, 6, 8, 11 and 12 in the Table. We also show the lower energy measurements from Cen XR-2, which have generally been interpreted as thermal bremsstrahlung radiation because of the exponential energy spectrum observed in the original source flareup (Chodil, et al. 1967). The present data fit such spectra very well, although power law spectra of number index 2.2 $\pm$ 0.3 could fit the data as well from at least 7.7 to 40 keV. In our highest energy channel we sometimes see an excess such as that reported by Lewin et al. (1968a). This excess varies independently of the 7 to 40 keV flux, decreasing between October 1967 and January 1968 and then increasing to a maximum in February 1968. Note the sharp cutoff in channel five of the "hard flare" spectrum (Table 1, line 9).

IV. DISCUSSION

Figure 3 shows X-ray sources in the Centaurus region, along with the OSO-III scan circles at different times. The source symbols generally represent a 1 σ position uncertainty, except Cen A and Cen X-3 have been measured by UHURU to greater precision than shown (Kellogg et al. 1971; Giacconi et al. 1971). Although our 50% response circle is quite large, for a constant source to give a steady derived flux, to better than 30% as we scan the region over many different paths, it must locate within

about 4° of our assumed position of GX 304-1. The sources GX 301-2 and
Cen XR-2 would be candidates for the source of the steady emission,
except for their absence in 1967 October (Lewin, Clark and Smith 1968a).
The flares might be due to Cen X-3, Cen X-5, GX 301-2, or Cen XR-2, all
of which are known to be highly time variable. The exact flare magnitude
would then depend on the relative exposure factor of GX 304-1 and the
actual flare-source position.

The November flare has a much lower temperature than the steady
emission, and thus is presumably not connected with it. Subtracting the
steady component gives an effective temperature of about 7 or 8 keV.
This flare spectrum, extrapolated below 10 keV, gives a flux somewhat
in excess of the measurements attributed to Cen XR-2 by Rao et al. (1969)
on 1968 November 3 and November 7. MacGregor et al. (1970) report that
Cen XR-2 was not detectable just 15 hours after the first flight of
Rao et al. We see no inconsistency between these two observations in
view of the rapid variations we find, for example, in the interval
1967 November 16 and 24. Note that these authors were actually assuming a
source position of $\ell = 305°$ to $307°$.

The e-folding decay times for the two flares we observe are on the
order of ten days, probably consistent with the 25 day decay time of
the lower energy X-rays in Spring of 1967. The rise times may also all
be about 1 day. (Although the 2-8 keV outburst was not directly
observed for Cen XR-2, Conner, Evans, and Belian (1969) found a rise time of
a few days for the similar burst from Cen XR-4). In spite of the rough
similarities of their time profiles, the various outbursts from this
region had appreciably different amplitudes and spectral behavior!

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FIGURE CAPTIONS

FIGURE 1: OSO-III observations of Centaurus. Top points: calculated
fractional exposure to GX304-1, with error bars correspond-
ing to a 2° aspect error. Bottom points: total flux summed
over 7.7 to 38 keV range and averaged over each day. Bottom
bars: periods of time-averaging to obtain spectral informa-
tion.

FIGURE 2: Spectral data from Centaurus. OSO-III "quiet" refers to the
intervals indicated in Figure 1. The "soft" and "hard" flares
represent the November and January flareups, respectively.
MIT 1967 data are averaged over their 15 and 24 October balloon
flights.

FIGURE 3: OSO-III scans of the Centaurus region, together with known
X-ray sources. The ellipses and diamonds are variable sources
observed by the MIT balloon group. We identify the "steady"
source of OSO-III observations with the MIT source around
$\ell = 304°$. Cen X-3, Cen X-5, Cen XR-2, Cen XR-4, and Lup XR-1
are also known to be variable sources.

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TABLE 1

HARD X-RAY FLUXES FROM CENTAURUS

LINE	DATES OF OBSERVATION	7.7--12.5 keV EXP.*	FLUX†	12.5--22 keV EXP.	FLUX†	ENERGY RANGE 22-38 keV EXP.	FLUX#	38--65 keV EXP.	FLUX#	65--113 keV EXP.	FLUX#	EFFECTIVE TEMP. (keV)	EMISSION MEASURE (10^{15} d^2 cm^{-3})
1	15-30 Oct. 67	849	.13 ±.05	2257	.12 ±.02	3136	5.5 ±1.4	4291	1.2 ±.9	4080	1.3 ±.8	18.6 ±2.2	9.7 ±1.8
2	31 Oct.-4 Nov.	283	.39 ±.09	692	.25 ±.04	1064	7.8 ±2.4	1265	2.2 ±1.7	1468	< 3.3	9.4 ±0.6	33 ±5
3	5-10 Nov.	266	.31 ±.10	553	.21 ±.04	656	6.9 ±3.3	1052	< 2.8	921	< 3.1	10.3 ±0.5	26 ±5
4	12-18 Nov.	256	.15 ±.09	771	.13 ±.03	1315	6.4 ±2.2	2691	< 1.9	2171	< 2.5	18.5 ±1.5	10.6 ±3.2
5	19-23 Nov.	385	.21 ±.08	825	.18 ±.03	1882	6.6 ±1.8	2373	1.9 ±1.2	2425	1.7 ±1.1	14.8 ±2.7	15.8 ±3.5
6	24 Nov.-9 Dec.	594	.13 ±.06	1357	.15 ±.02	2830	7.0 ±1.4	4406	2.6 ±.85	4344	1.3 ±.8	21.2 ±2.1	10.8 ±1.5
7	21 Dec.-3 Jan.	414	.24 ±.07	1105	.18 ±.03	1805	7.6 ±1.8	2465	3.1 ±1.1	2197	1.8 ±1.1	15.2 ±2.6	14.7 ±3.2
8	9-22 Jan. 68	1026	.13 ±.04	2641	.16 ±.02	3776	4.5 ±1.2	5301	2.6 ±.8	5405	< 1.5	16.1 ±5.1	12.2 ±3.1
9	23-28 Jan.	454	.22 ±.08	1008	.23 ±.03	992	16.±3.	1477	2.7 ±1.7	1457	< 3.6	46 ±12	17.4 ±4.2
10	29 Jan.-2 Feb.	342	.14 ±.08	739	.15 ±.04	731	11.±3.	1016	< 4.5	1011	< 4.4	36 ±8	11.6 ±3.6
11	3-16 Feb. 68	1046	.11 ±.04	2163	.11 ±.02	2285	7.0 ±1.6	3062	3.3 ±1.0	2871	2.2 ±1.0	32 ±3	8.3 ±2.0
12	23-27 June 68	217	.13 ±.09	350	.15 ±.05	393	< 8.	1130	< 2.1	1101	< 2.0	12 ±4	14.2 ±8.1

*Exposure in (cm^2--sec)
†Flux in counts (cm^2--sec)$^{-1}$. Fluxes shown with error bars are more than 2 σ above background.
#Flux in 10^{-2} counts (cm^2--sec)$^{-1}$

Figure showing galactic coordinate plot with X-ray sources. Y-axis: GALACTIC LATITUDE (+30°, +20°, +10°, 0°, -10°, -20°, -30°). X-axis: GALACTIC LONGITUDE (340°, 330°, 320°, 310°, 300°, 290°, 280°, 270°, 260°).

Labeled sources: CEN XR-4, CEN A, LUP XR-1, CEN XR-1, CEN X-5, CEN X-3, NOR XR-1, NOR XR-2, CEN XR-2.

Scan line dates: 15 FEB 1968, 25 JUNE 1968, 5 DEC 1967, 15 OCT 1967.

OSO-III 50% RESPONSE APERTURE (circle at lower left).