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DETECTION OF HIGH-ENERGY X-RAYS FROM THE GALACTIC CENTER REGION

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ABSTRACT

Repeated scans of the galactic center region from 1978 September 20–25 with the high-energy X-ray detector on *OSO 8* have located a strong source of high-energy X-rays in the galactic center region in addition to GX 1+4. The 95% confidence contour for this source includes the galactic center but not GX 3+1. A power-law, photon-number spectrum with an index of -2.3 ± 0.3 gives an acceptable representation of the observed counting-rate spectrum in the energy range from 21 to 197 keV. The integrated 18–40 keV flux observed from this source or group of unresolved sources is a factor of ≥ 2 stronger than the upper limit set by Lewin, Ricker, and McClintock for the flux from this region in 1970 October. It is consistent, however, with the 15–40 keV flux detected with the proportional counter on *OSO 7* during 1971–1974. High-energy X-rays with a softer spectrum were observed from the direction of GX 1+4 over the same time interval. The observed counting-rate spectrum of GX 1+4 in the energy range from 21 to 197 keV is acceptably represented by that derived from an incident photon-number spectrum which is either a power-law with a spectral index of -4.1 ± 0.5 or a thermal-bremsstrahlung function with $kT = 19 \pm 4$ keV.

Subject headings: galaxies: Milky Way — galaxies: nuclei — X-rays: sources

I. INTRODUCTION

X-ray observations of the galactic center region in the energy range from 2 to 10 keV have revealed a confused array of sources of many different types. Kellogg *et al.* (1971) discovered an extended source or a group of unresolved point sources within roughly 2° of the galactic center (4U 1743−29, commonly referred to as GCX). Cruddace *et al.* (1978) and Proctor, Skinner, and Willmore (1978) were able to resolve at least four and possibly seven discrete sources in this extended region. Two of these sources are believed to be identified with the transients discovered with *Ariel 5* (Eyles *et al.* 1975; *Ariel 5* Group 1976). Kellogg *et al.* (1971) had earlier detected a third transient, 4U 1735−28, about 1°.5 from the galactic center. Three of the resolved sources may be the steady components of the burst sources discovered in this region by Lewin *et al.* (1976). Three weak bursts were detected from other locations during the 346 s rocket flight of Proctor, Skinner, and Willmore (1978), suggesting a high density of such burst sources near the galactic center. No X-ray emission was detected from the compact, nonthermal radio source in Sgr A West discovered by Balick and Brown (1974). A region of diffuse emission has been detected by the imaging proportional counter on the *Einstein* Observatory in addition to the pointlike sources (Epstein *et al.* 1979). This diffuse emission is centered on the galactic nucleus and extends ~0°.5 along the galactic plane.

At higher X-ray energies, above 20 keV, our knowledge of the emission from the galactic center region is much less refined. The early balloon observations showed a strong flux of X-rays with energies greater than 20 keV from a region within 5°–10° of the galactic center (Buselli *et al.* 1968; Lewin, Clark, and Smith 1968; Riegler *et al.* 1968; Haymes *et al.* 1969; Guo and Webber 1973, 1975). The photon-number spectrum of the X-rays extends to energies in excess of 1 MeV and is well represented by a power law somewhat steeper than $E^{-2.0}$ (Haymes *et al.* 1975).

All of these observations were made using detectors with wide fields of view, typically larger than 8°–10° FWHM. Consequently, identification of individual sources in this region was difficult, and the observations were subject to differing interpretations. Buselli *et al.* (1968) suggested that GX 3+1 was the source of the hard X-ray flux observed using a detector with an 8° FWHM field of view. Lewin, Ricker, and McClintock (1971), using a detector with a 1°.5 × 13° FWHM field of view, were able to resolve three separate sources of high-energy X-rays in the galactic center region and designated the dominant source as GX 1+4. The results of Buselli *et al.* (1968) were also consistent with this conclusion. By observing during a lunar occultation in 1971 November, Johnson and Haymes (1973) showed that GX 3+1 was not, at that time, the major contributor to the X-ray flux above ~40 keV from the galactic center region.

The existence and identification of one or more high-energy X-ray sources closer to the galactic center than GX 1+4 has been in doubt since the observation by Lewin, Ricker, and McClintock (1971) of a source in a 1°.5 × 13° band in the sky containing GX 3+1. Ricker *et al.* (1973) note that confusion of this source with GX 1+4 and lack of background data make the

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spectrum obtained for this source tentative. No flux from GX 3+1 was detected during a 1972 balloon flight of a similar instrument (Ricker *et al.* 1976), but the 2 σ upper limit was above the previously reported flux. Carpenter *et al.* (1975) detected a strong flux of high-energy X-rays during their observations of the galactic center region in 1975 February with the 8° FWHM detector on *Ariel 5*. Their best estimates for the sources of this X-ray flux assigned 60% to a source at the galactic center (GCX) and 40% to GX 3+1. Beall (1979) and Dennis *et al.* (1978*a*) presented evidence for a hard X-ray flux from GCX using data obtained with the high-energy X-ray spectrometer on *OSO 8* during observations in September of the years 1975 and 1976. The photon-number spectrum of the source at the galactic center is well represented by a power law with a spectral index of −3.5 in 1975 and −1.9 in 1976. Johnson, Strickman, and Kurfess (1979) also have detected a hard X-ray source close to the galactic center using a balloon-borne, large-area scintillation phoswich detector flown in 1977. The position of this source was determined to be ~1° from the galactic center, south of the galactic plane. Levine *et al.* (1979) report the detection with the *HEAO* A-4 instrument of several hard X-ray sources in the galactic center region in addition to GX 1+4. One of these sources is reported to be within 1° of the galactic center.

In this *Letter*, we present results from an observation of the galactic center region made with the high-energy X-ray detector on *OSO 8* during five days in 1978 September. A strong, hard X-ray flux was detected during these observations from the vicinity of the galactic center. The spectrum of the flux from this direction is harder than that of GX 1+4 measured during the same time interval.

II. OBSERVATIONS

The observations of the galactic center region were made from 1978 September 20–25 with the high-energy X-ray scintillation spectrometer on *OSO 8*. The detector has been described in detail by Dennis *et al.* (1977). It consists of an actively shielded CsI(Na) scintillator with a sensitive area of 27.5 cm² and a circular field view of 5° FWHM. For these observations, X-rays were recorded in the energy range from 20 to 270 keV. The instrument is mounted in the wheel section of the *OSO 8* spacecraft with its axis offset from the antispin axis by 5°. Once every wheel rotation, or approximately every 10 s, the detector scans across any source located within 10° of the antispin axis. With this scanning technique, the modulated signal from the source can be most efficiently recovered in the presence of the constantly varying detector background observed in the orbital environment.

During the five days of the observation, the antispin axis of the spacecraft was maintained at an angle of approximately 5° from the direction to the galactic center, 5° from GX 1+4, and 2° from GX 3+1 (see Fig. 1). Consequently, each source passed through the detector field of view at a wheel azimuth angle constant

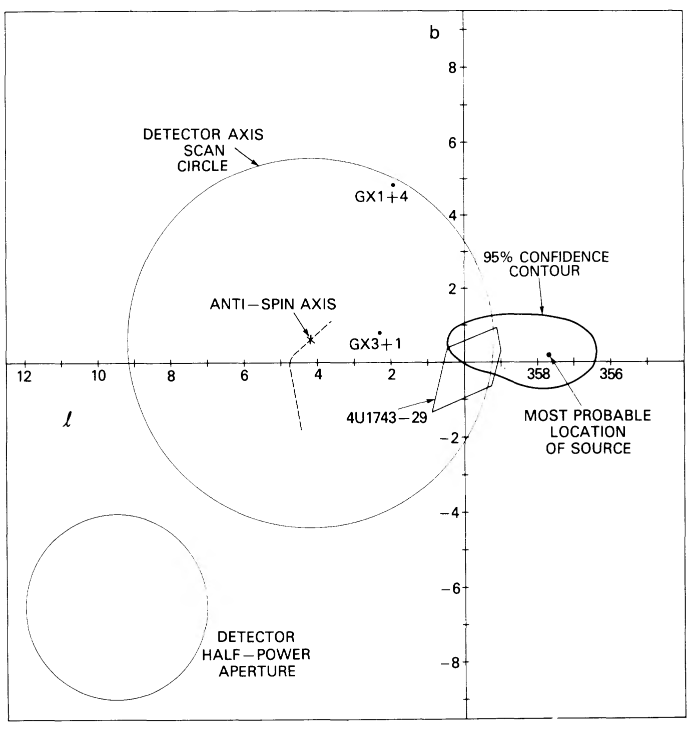

FIG. 1.—Map of the galactic center showing the position of the satellite antispin axis and the detector scan circle in 1978 September 20–25. The (χ^2_{min} + 6) contour, which encloses the "true" source location with a confidence of 95%, is shown for the hard X-ray source observed in the vicinity of the galactic center.

to within $\pm 8°$ for the entire five days. The resulting distribution of counting rate as a function of the wheel azimuth angle measured from the solar vector is shown in Figure 2 for four broad energy bins. The expected triangular peaks are indicated for two point sources, one at GX 1+4 and a second at the location which gives the best fit to the data. A strong peak in the data, reaching a maximum at the wheel azimuth angle of GX 1+4, can be seen at energies below 59 keV. The asymmetry of this peak indicates the detection of X-rays from at least one other source besides GX 1+4, although the detected flux is lower than that from GX 1+4. In the 59–114 keV range the maximum in the data is shifted away from the wheel azimuth angle of GX 1+4. Thus the data indicate the presence of at least two sources in this region, one identified as GX 1+4 and the other, with a harder spectrum, located closer to the galactic center.

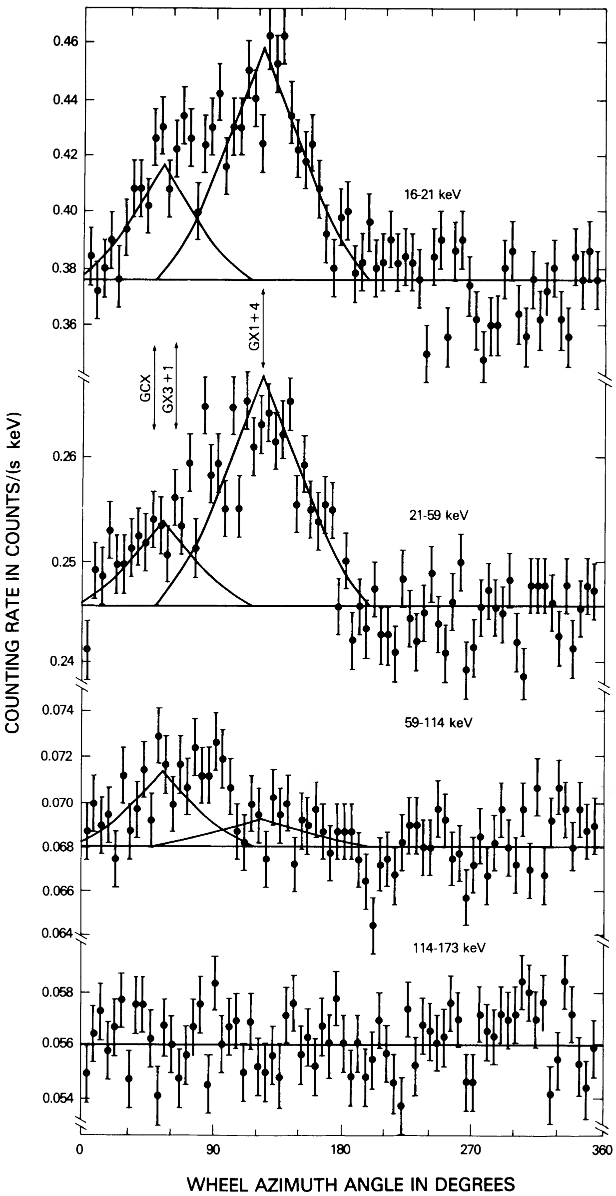

Fig. 2.—The detector counting rate measured in 1978 September 20–25 as a function of the wheel azimuth angle of the detector axis. Also shown are the triangular responses to fluxes from GX 1+4 and from a source at the location giving the minimum value of χ^2.

In order to determine the most probable source locations and the counting-rate spectra of the different sources, the data were analyzed using a modified form of the sky-mapping program described by Beall (1979). Maps of the detector counting rate above background were obtained for 20 energy bins in a $20° \times 20°$ area on the celestial sphere. Prior to the accumulation of the data in these maps, the effects of the $<1\%$ variations in photomultiplier gain discussed by Dennis *et al.* (1978*b*) were removed by correcting pulse amplitudes of each event using a factor dependent on the strength and orientation of the Earth's magnetic field. The effects of variations in detector background rate were removed by subtracting an average background rate for each orbit. The locations of sources and their counting-rate spectra were determined from these maps by a least-squares fitting technique in which the right ascension and declination of up to three sources, the counting rates from the sources, and the residual background rate in each energy bin could be treated as free parameters.

Initially, two point sources were assumed to exist in this region, one source fixed at GX 1+4 and a second source for which the coordinates were considered as free parameters in the fitting routine. The location of the second source which gives the minimum value of χ^2 ($\chi^2_{\rm min}$) for the broad energy range from 21 to 114 keV is at right ascension $17^{\rm h}36^{\rm m}$, declination $-30\overset{\circ}{.}8$ (epoch 1950). The value of $\chi^2_{\rm min}$ was 107 for 105 degrees of freedom, indicating a very good fit to the data. The counting rates at energies below 21 keV showed larger background fluctuations than expected from statistics, probably because of charged-particle contamination, and hence were not used in any of the data analysis. The value of $\chi^2_{\rm min}$ was not reduced significantly either by adding a third source in the region or by allowing the second source to be extended. The best-fit value obtained for the radius of a circular extended source was $1\overset{\circ}{.}7$ with ($\chi^2_{\rm min} + 1$) uncertainties of $+1\overset{\circ}{.}6$ and $-1\overset{\circ}{.}7$.

The uncertainty in the location of the second source was determined from plots of the contours of constant χ^2 around the position of $\chi^2_{\rm min}$ following Avni (1976) and Lampton, Margon, and Bowyer (1976). For a linear fitting function and the two "interesting parameters" used to determine the source location (i.e., the two coordinates), the contour which encloses the "true" location of the source with a confidence of 95% is the ($\chi^2_{\rm min} + 6$) contour. This is the contour shown in Figure 1. The elongation of this contour with its long axis on a line from the direction of the satellite antispin axis reflects the ability of the observations to locate a source in azimuth angle about the antispin axis more accurately than in angular separation from the antispin axis.

The counting-rate spectrum of GX 1+4 and that of the second point source at the position giving the minimum value of χ^2 were obtained from least-squares fits to the data in narrower energy bins. Assumed source spectra were folded through the detector response function and the results compared with the observed counting-rate spectrum for each source. Acceptable least-squares representations of the data were obtained with power-law or thermal-bremsstrahlung spectra for both sources. The functional forms used and the values of the fitted parameters with their ($\chi^2_{\rm min}$ + 2.3) uncertainties are given in Table 1. The normalization energy E_0 is included in the functions to make the two fitted parameters, A and α, or B and kT, essentially independent of each other.

III. CONCLUSIONS

The observations show the existence in 1978 September of a strong flux of high-energy X-rays from within an error box containing the galactic center but excluding GX 1+4 and GX 3+1. The photon-number spectrum of this flux is very hard and can be acceptably represented in the energy range from 21 to 197 keV by a power law with a spectral index of -2.3 ± 0.3. These results are essentially in agreement with the results of similar *OSO 8* observations made in September of 1975 and 1976 and reported by Beall (1979) and Dennis *et al.* (1978*a*).

Comparisons with the high-energy X-ray fluxes observed from sources in this region by other workers are important in any search for evidence of long-term variability. Significant comparisons are generally very difficult, however, because of the large field of view of the instruments used and the resulting source confusion. An upper limit can be obtained on the strength of a source at our χ^2-minimum position from the balloon flight in 1970 October of a detector with a 1°.5 × 13° field of view (Lewin, Ricker, and McClintock 1971). Examination of the counting rate data from this flight for scans 5 and 7 across the galactic center region shows the counting rate from a source at our χ^2-minimum position could not have been greater than ~30% of the average rate observed from GX 1+4 during the same scans (Ricker 1979, private communication). This corresponds to a 3 σ upper limit on the energy flux in the range from 18 to 40 keV of 0.7 keV cm^{-1} s^{-1}, and is to be compared to a flux of 1.5 (+0.5, −0.4) keV cm^{-2} s^{-1} determined from our best-fit power-law spectrum over the same energy range. Thus the flux from this region must have been a factor of $\gtrsim$2 stronger in 1978 September than it was in 1970 October. The scan across the galactic center during the balloon flight of a similar detector in April 1972 included GX 1+4 in the field of view at the same time as a source at our χ^2-minimum position, thus preventing any significant upper limit from being obtained (Ricker *et al.* 1976).

A comparison can also be made with the extended high-energy X-ray source or group of unresolved sources detected at the galactic center by Markert *et al.* (1977) using the proportional counters with a 1° field of view on *OSO 7* between 1971 and 1974. The counting rates from this region in the argon-filled and in the krypton-filled proportional counters, which cover the energy range from 3 to 10 keV and 15 to 40 keV, respectively, were approximately 25% of the rates measured with the Crab nebula in the field of view. This is approximately the same fraction of the Crab counting rate that we observed from this region,

TABLE 1

Parameter	GX 1+4	Second Source at Most Probable Location
Galactic latitude (b°)	4.8	0.2
Galactic longitude (l°)	1.9	357.7
Degrees of freedom	11	11
Energy range (keV)	21–197	21–197
E_0 (keV)	30	50
Power-Law Fit:		
A (photons cm^{-2} s^{-1} keV^{-1})	$(3.5 \pm 0.3) \times 10^{-3}$	$(6.3 \pm 0.9) \times 10^{-4}$
α	4.1 ± 0.5	2.3 ± 0.3
χ^2/degrees of freedom	1.93	1.23
Probability (%)	3.1	26
Thermal Bremsstrahlung Fit:		
B(photons cm^{-2} s^{-1} keV^{-1})	0.44 ± 0.04	0.15 ± 0.03
kT (keV)	19 ± 4	88 (+55, −28)
χ^2/degrees of freedom	1.11	1.37
Probability (%)	34.8	17.9

NOTE.—All spectral fits were obtained assuming a source at the location of GX 1+4 and a second point source at the most probable location. The best-fit spectral parameters were obtained for a power-law spectrum of the form $I(E) = A(E/E_0)^{-\alpha}$ photons/(cm^2 s keV) and for a thermal bremsstrahlung spectrum of the form $I(E) = BE^{-1.4} \exp[-(E - E_0)/kT]$ photons cm^{-2} s^{-1} keV^{-1}. The values of the probability in the last line of the table for each spectral fit are the percentage probabilities that a value of χ^2 equal to or exceeding the measured values would be obtained as a result of random fluctuations in the counting rates about the rates expected on the basis of the best-fit spectral function.

and suggests that we have detected the same extended source or group of sources to higher energies.

It is unlikely that GX 3+1 contributes significantly to the observed counting rate, except possibly at the lowest energies observed. The location of GX 3+1 lies well outside the 95% confidence contour and is only 2° from the antispin axis, resulting in a relatively low exposure to this source. A 3σ upper limit can be placed on the flux from GX 3+1 in the energy range from 21 to 59 keV of 2×10^{-3} photons cm^{-2} s^{-1} keV^{-1}, consistent with the fluxes reported by Ricker *et al.* (1973) and Johnson and Haymes (1973).

The photon-number spectrum obtained for GX 1+4 is considerably softer than the spectrum of the second source in this region. It can be acceptably represented over the energy range from 21 to 197 keV by a power law with a spectral index of -4.1 ± 0.5 or by a thermal bremsstrahlung spectrum with $kT = 19 \pm 4$ keV. This spectrum is in good agreement in intensity and form with that reported by Ricker *et al.* (1976) from a balloon flight in 1972 April when GX 1+4 was in a high-intensity state compared to the level reported by Lewin, Ricker, and McClintock (1971) during 1970 October. Doty *et al.* (1978) reported that the *HEAO* A-4 observations of GX 1+4 can be well represented by a thermal spectrum with a kT value of 24 keV but that a power-law spectrum does not give an acceptable fit to the data. While our results give a lower value of χ^2 for a thermal spectrum with a kT value in agreement with the *HEAO* results, we cannot rule out a power-law spectrum on the basis of our data alone (see Table 1).

If the high-energy X-rays which we have detected are from a source at the galactic center, then the X-ray luminosity calculated from either the power-law or the thermal-bremsstrahlung spectral fit is $\sim 2 \times 10^{37}$ ergs s^{-1} in the energy range from 20 to 100 keV. This must represent a significant fraction of the bolometric luminosity of a source at the galactic center. It is therefore of great importance to locate more precisely the high-energy X-ray source in this region. A comprehensive analysis of the complete set of *OSO 8* data from the three scans through this region in 1975, 1976, and 1978 is being carried out and the results will be presented in a later paper.

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