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ABSTRACT

Repeated scans of the galactic center region from 1978 September 20 to 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 GX1+4. The 95% confidence contour for this source includes the galactic center but not GX3+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 $\gtrsim 2$ stronger than the upper limit set by Lewin et al. (1971) for the flux from this region in October 1970. It is consistent however, with the 15-40 keV flux detected with the proportional counter on OSO-7 during 1971 to 1974.

High energy X-rays with a softer spectrum were observed from the direction of GX1+4 over the same time interval. The observed counting-rate spectrum of GX1+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 $kT=19\pm4$ keV.

1. 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^{o} of the galactic center (4U1743-29 , commonly referred to as GCX). Cruddace et al. (1978) and Proctor et al. (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, 4U1735-28, about $1\overset{o}{.}5$ 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 et al. (1978) suggesting a high density of such burst sources near the galactic center. No X-ray emission was detected from the compact, non-thermal 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 point-like sources (Epstein et al. 1979). This diffuse emission is centered on the galactic nucleus and extends $\sim 1/2^{o}$ 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 to 10 degrees of the galactic center (Buselli et al. 1968; Lewin et al. 1968; Reigler et al. 1968; Haymes et al. 1969; and 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 GX3+1 was the source of the hard X-ray flux observed using a detector with an 8°-FWHM field of view. Lewin et al. (1971), using a detector with a 1.5 x 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 GX1+4. The results of Buselli et al. (1968) were also consistent with this conclusion. Johnson and Haymes (1973) showed, by observing during a lunar occultation in 1971 November, that GX3+1 was not, at that time, the major contributor to the X-ray flux above $\sim$ 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 GX1+4 has been in doubt since the observation by Lewin et al. (1971) of a source in a $1\frac{1}{2}° \times 13°$ band in the sky containing GX3+1. Ricker et al. (1973) note that confusion of this source with GX1+4 and lack of background data make the spectrum obtained for this source tentative. No flux from GX3+1 was detected during a 1972 balloon flight of a similar instrument (Ricker et al. 1976) but the 2σ 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 GX3+1. Beall (1979) and Dennis et al. (1978a) 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 et al. (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-A4 instrument of several hard X-ray sources in the galactic center region in addition to GX1+4. One of these sources is reported to be within 1° of the galactic center.

In this paper, 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 GX1+4 measured during the same time interval.

2. OBSERVATIONS

The observations of the galactic center region were made from 1978 September 20 to 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 cm^2 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 anti-spin 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 anti-spin axis of the spacecraft was maintained at an angle of approximately 5° from the direction to the galactic center, 5° from GX1+4, and 2° from GX3+1 (see Figure 1). Consequently, each source passed through the detector field of view at a wheel azimuth angle constant to within $\pm 8^\circ$ 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-shaped peaks are indicated for two point sources, one at GX1+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 GX1+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 GX1+4, although the detected flux is lower than that from GX1+4. In the 59 to 114 keV range the maximum in the data is shifted away from the wheel azimuth angle of GX1+4. Thus, the data indicate the presence of at least two sources in this region, one identified as GX1+4 and the other, with a harder spectrum, located closer to the galactic center.

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 $20^{\circ} \times 20^{\circ}$ 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. (1978a) 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 GX1+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 (χ^2_{min}) for the broad energy range from 21 to 114 keV is at right ascension 17^h36^m, declination $-30\overset{\circ}{.}8$ (epoch) 1950). The value of χ^2_{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 χ^2_{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 (χ^2_{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 χ^2_{min} following Avni (1976) and Lampton et al. (1977). 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 (χ^2_{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 anti-spin 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 anti-spin axis.

The counting-rate spectrum of GX1+4 and 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 (χ^2_{min} + 2.3) uncertainties are given in Table 1. The normalization energy, E_c, is included in the functions to make the two fitted parameters, A and α, or B and kT, essentially independent of each other.

3. 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 GX1+4 and GX3+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 reported by Beall (1979) and Dennis et al. (1978).

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 $1^{\circ}.5 \times 13^{\circ}$ field of view (Lewin et al. 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 $\sim$30% of the average rate observed from GX1+4 during the same scans (Ricker 1979, private communication). This corresponds to a 3σ 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 September 1978 than it was in October 1970. The scan across the galactic center during the balloon flight of a similar detector in 1972 April included GX1+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, and suggests that we have detected the same extended source or group of sources to higher energies.

It is unlikely that GX3+1 contributes significantly to the observed counting rate, except possibly at the lowest energies observed. The location of GX3+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 GX3+1 in the energy range from 21-59 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 GX1+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 $kT = 19\pm4$ 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 GX1+4 was in a high intensity state compared to the level reported by Lewin et al. (1971) during 1970 October. Doty et al. (1978) reported that the HEAO-A4 observations of GX1+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 result, 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 $\sim 2\times10^{37}$ 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 or sources 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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TABLE 1

SOURCE	GX1+4	Second source at most probable location
Galactic Latitude, b^{o}	4.8	0.2
Galactic Longitude, l^{o}	1.5	357.7
Degrees of Freedom	11	11
Energy Range (keV)	21-197	21-197
E_o (keV)	30	50
<u>Power-Law Fit</u>		
A (photons cm^{-2} s^{-1} kev^{-1})	$(3.5\pm0.3)x10^{-3}$	$(6.3\pm0.9)x10^{-4}$
α	4.1 ± 0.5	2.3 ± 0.3
χ^2/degrees of freedom	1.93	1.23
Probability (%)	3.1	26
<u>Thermal Bremsstrahlung Fit</u>		
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/degree of freedom	1.11	1.37
Probability (%)	34.8	17.9

Notes to Table 1

All spectral fits were obtained assuming a source at the location of GX1+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

$$I(E) = A(E/E_o)^{-\alpha} \quad \text{photons/(cm}^2\text{ s keV)}$$

and for a thermal bremsstrahlung spectrum of the form

$$I(E) = B\ E^{-1.4} \quad \exp\left[\frac{-(E - E_o)}{kT}\right] \quad \text{photons/(cm}^2\text{ s keV)}.$$

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.

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FIGURE CAPTIONS

Figure 1 Map of the galactic center showing the position of the satellite antispin axis and the detector scan circle in 1978 September 20 to 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.

Figure 2 The detector counting rate measured in 1978 September 20 to 25 as a function of the wheel azimuth angle of the detector axis. Also shown are the triangular-shaped responses to fluxes from GX1+4 and from a source at the location giving the minimum value of χ^2.

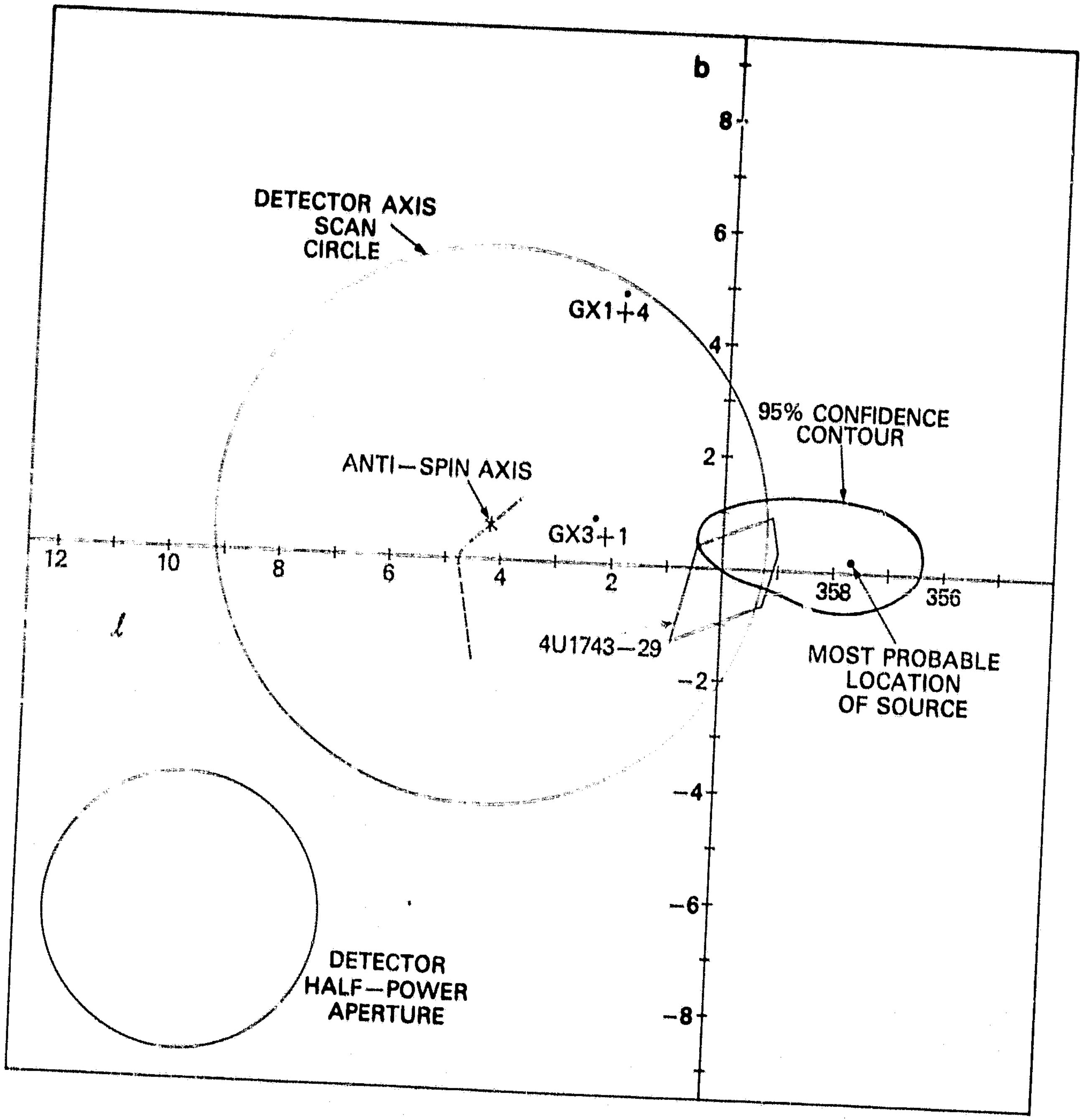
b
8
6
4
2
-2
-4
-6
-8
12
10
8
6
4
2
358
356
l
DETECTOR AXIS
SCAN
CIRCLE
GX1+4
95% CONFIDENCE
CONTOUR
ANTI-SPIN AXIS
GX3+1
4U1743-29
MOST PROBABLE
LOCATION
OF SOURCE
DETECTOR
HALF-POWER
APERTURE

FIGURE 1

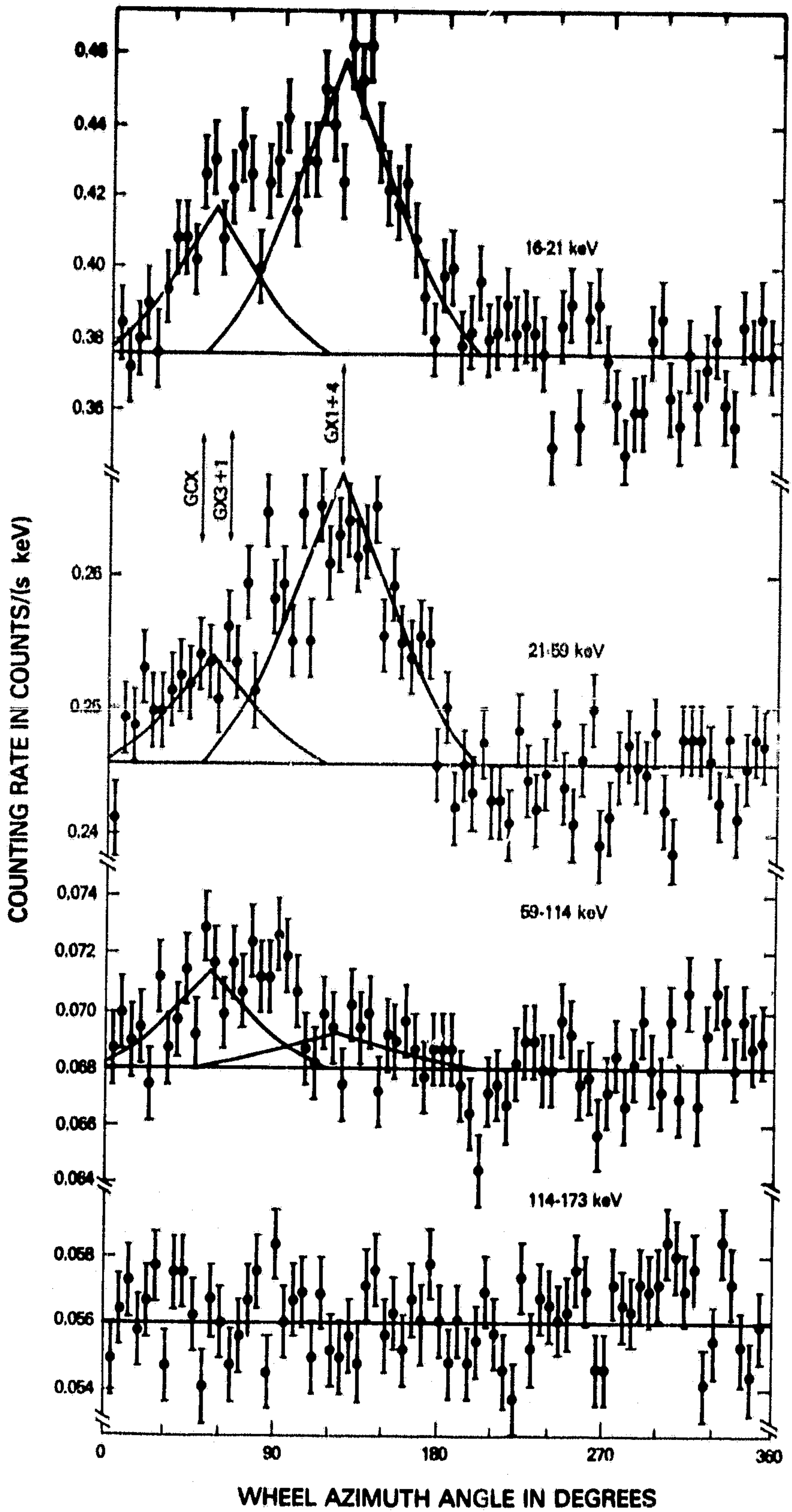
COUNTING RATE IN COUNTS/(s keV)
WHEEL AZIMUTH ANGLE IN DEGREES
16-21 keV
21-59 keV
59-114 keV
114-173 keV
GCX
GX3+1
GX1+4
0
90
180
270
360
0.46
0.44
0.42
0.40
0.38
0.36
0.26
0.25
0.24
0.074
0.072
0.070
0.068
0.066
0.064
0.058
0.056
0.054

FIGURE 2