Copernicus Observations of a Number of Galactic X-ray Sources

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INTRODUCTION

The Copernicus satellite was launched on 21 August 1972. The main experiment on board is the University of Princeton UV telescope. In addition a cosmic X-ray package of somewhat modest aperture was provided by the Mullard Space Science Laboratory (MSSL) of University College London. Following a brief description of the instrument, a list of galactic sources observed during the year up to October 1975 is presented. A good deal of the data from these sources has been analysed and much of it will be presented by other speakers at this symposium. Some observations, which will not be discussed in other sessions, will be described in this paper.

Since, in addition to work done by members of the MSSL group, a number of the papers presented at this symposium represent the work of guest investigators, it is important to point out that a continuing guest investigator programme is in progress. Proposals for guest observing time have come from people in many different branches of astronomy and time can still be made available in the course of next year.

Although the X-ray detection aperture is small, as will become clear from the next section, the ability to point the satellite for long periods of time with high accuracy makes Copernicus an ideal vehicle for the study of variable sources. Observing programmes are planned at MSSL two to three months in advance of carrying out the observations. The experiment is operated from the Goddard control centre by a joint team from MSSL and the Appleton Laboratory of the UK Science Research Council.

2. INSTRUMENTATION

The complete MSSL package is illustrated schematically in Figure 1 while the instrument parameters are summarised in table 1. The two grazing incidence X-ray collectors covering the energy range 0.5 to 4.0 keV are unavailable due to the failure, after one year in orbit, of a background shutter. Although the channeltron used in the focal plane of the third reflector suffers from a high background due to a light leak, it is possible to use it for certain observations, (see for example Margon et al (1974) Henry et al (1975)). The collimated proportional counter detector continues to operate reliably and is at present the main X-ray instrument avialable in the package. The usual data integration time is 62.5 sec but this can be reduced to between 1 and 16 sec using the computer on board the spacecraft. The particle background rate is variable but averages about 50 counts per minute. The spacecraft pointing precision is better than one arc second while the jitter is less than a fraction of an arc second when the system is under control of the Princeton fine error sensor. When under gyro control, the spacecraft axis drifts at a rate of 2 arc sec. per hour but the star sensors may be used at any time to update the gyros.

3. OBSERVATIONS OF GALACTIC X-RAY SOURCES - GENERAL SURVEY

The galactic X-ray sources which have been observed in the past year are listed in table II under two headings, galactic variable sources and targets of opportunity. In the first category, Cygnus X-1 has been observed extensively by Paul Murdin, a Copernicus guest investigator, together with a number of MSSL co-workers. X-ray and optical data have been obtained by Sergio Ilovaisky and his colleagues, for the Cygnus X-2 source. Results of both Copernicus and Ariel-5 observations of Cygnus X-3 have been analysed by Keith Mason and his co-workers. The work in these three areas will be presented elsewhere in these proceedings. While Ian Tuohy will report on Ariel-5 observations of Centaurus X-3, studies of the accretion wake associated with this source using Copernicus data have already been published (Tuohy and Cruise, (1975)). Similar studies of the source 3U 0900-40 are reported elsewhere in these proceedings by Phil Charles while results obtained for 3U 1700-37 are described by Keith Mason. The sources at the bottom of the first part of the list (3U 1728-16, 3U 1911-17 and 3U 1813-14) have also been observed and analysis of these data is continuing. I will discuss SCO X-1 and 3U 0352+30 in greater detail below and will also mention briefly some recent observations of Her X-1.

In the category of targets of opportunity, the transient source in Centaurus (A 1118-61) was observed by Copernicus. It was suggested by Fabian (1975), that the transient X-ray emission was 'turned on' at a particular phase of the Mira variable RS Centauri. Copernicus observations have showed that X-ray emission did not recur at the appropriate phase of RS Cen and so the association of this star with A 1118-61 can probably be ruled out. The transient X-ray source (A 1742-28) in the galactic centre has been studied with Copernicus by Graziella Branduardi and her colleagues and I will present some preliminary results of their work later. The X-ray source 3U 1908+00 (Aquilla X-1) was examined by Copernicus and, prior to June 1975, was found to have strength about 2% of that of the Crab Nebula, a value which is six times below the flux reported in the 3U catalogue (Giacconi et al (1974)). During June 1975 the source increased its X-ray output to a level comparable with the Crab Nebula. Studies of this source are continuing. Finally it was possible at very short notice to arrange for Copernicus X-ray observations of Nova Cygni 1975, an optical nova which was discovered in late August. The X-ray observations set an upper limit of approximately 10^{-10} ergs cm^{-2} sec^{-1}

(or 6 Uhuru counts) on the flux in the 2.5 - 7.5 keV band at the time of optical maximum (Sanford et al(1975)).

4. OBSERVATIONS OF GALACTIC X-RAY SOURCES - SPECIFIC OBJECTS

While most of the sources mentioned in the previous sections will be discussed in greater detail by Copernicus guest investigators and MSSL group members in the panel sessions, I would like to present recent results for several objects which will not be reported elsewhere in these proceedings.

a) SCO X-1

A number of Copernicus observations of this source have been carried out in the period October 1972 to June 1975 and a detailed account of this work is in preparation (White et al (1975a)). Broadly speaking the results reported by earlier observers are confirmed in that the X-ray flux exhibits two states, one active and one quiescent. Data representative of an active phase of the source are shown in Figure 2. The observations were made on 10 July 1974. X-ray intensity in counts per 62.5 sec and spectral slope parameter are plotted against time. The spectral parameter is obtained in the following manner. For the purpose of fitting an expression to the data to represent the source photon spectrum we have assumed that the emission is by the free-free process from a hot spherical plasma cloud of radius r(cm) and having uniform temperature and electron density T(^{o}K) and n(cm^{-3}). The source spectrum may then be represented by

$$I(E) = A \exp\left(-\frac{E}{kT}\right) \quad g\,(E,T) \qquad \text{keV keV}^{-1}\ \text{cm}^{-2}\ \text{sec}^{-1} \qquad (1)$$

where the free-free Gaunt factor is approximated by

$$g\,(E,T) = 0.84\left(\frac{kT}{E}\right)^{0.3} \qquad (2)$$

and the normalising constant is given by

$$A = \frac{3.10^{-15}}{(kT)^{0.5}} \qquad \frac{n^2\ r^3}{3d^2} \qquad (3)$$

Here E is photon energy in keV and d is the distance to the source in Cm While values of T obtained from the data are limited in their usefulness because of the simplicity of the above model, and cannot be regarded as a true measure of the plasma temperature, it is of interest to examine the variability of the parameter T under both active and quiet conditions. Values of T and A are obtained from the data by fitting equation (1) using a spectral fitting programme which takes account of detector resolution, quantum efficiency and photon escape effects.

As may be seen in Figure 2, the active state involves the occurrence of bursts of typically 5 to 15 minutes duration and with X-ray flux enhancements of up to a factor two. The temperature parameter varied from a baseline value of about 5.5 keV up to 20 keV or more. The most intense bursts have the longest durations. During active states, in the intervals between flares, the temperature value remains at around 5.5 keV and the flux always returns to a minimum value of 4000 Copernicus counts per minute or 8000 - 9000 Uhuru counts per sec. This minimum value appears stable to within 3% over periods of years at a confidence level of 90%. On one occasion (April, 5th, 1973) a longer lasting flare occurred during which the flux increased by about 25% over a period of approximately one hour.

Data acquired during a typical quiescent period are shown in Figure 3. The X-ray intensity varies by around 20% while the value of the temperature parameter is about 7.5 keV during these intervals. This temperature value is greater during quiescent states than the minimum value reached during the non-flaring portions of the active states.

For the active phase data presented in Figure 2, temperature values have been derived for each 62.5 sec. data sample. These values have been plotted against X-ray counting rates in Figure 4a for the active phase and in Figure 4b for data taken during quiescent phase. In Figure 4c, temperatures have been determined for source intensity intervals of 500 counts. Data from both active and quiescent periods are plotted in this way. The slopes of both plots are similar but it is clear that, for a given source intensity, the quiescent value of the temperature parameter is somewhat higher than the active phase value. Finally the normalising parameter A which represents volume emission measure (see equation (3)) is plotted against temperature in Figure 4d. It is apparent that there is a difference in either plasma density or volume between the two states at a given temperature in agreement with the work of Kitamura et al (1971).

The long term behaviour of the source may therefore be summarised as follows.

During the quiescent phases the flux from SCO X-1 varies by up to 50%, which may be correlated with an associated temperature variability from 5.5 to 8.0 keV. The transition into its active state is heralded by a decline in flux to a minimum level, with a reduction in temperature to 5.5 keV. From this level it then flates with temperatures ranging from 5.5 keV. to above 20 keV that are well correlated with the intensity level. Between flares the flux always returns to the same minimum level. When the active phase terminates the source resumes its quiescent variability and moves away from the base level flux and temperature.

The stability of the underlying flux introduces the problem of how this situation can arise in such an otherwise variable source. The emission may include two components with one component emitting constantly with a temperature of 5.5 keV while a second, more active component, is responsible for the variability seen in both quiescent and active phses. Our data are consistent with a single component spectrum ; however the energy range and the limited number of channels of the detectors do not enable us to resolve a second component. Continuous monitoring over a large energy range will clarify this point.

At present the models for the SCO X-1 system can be divided into two groups ; Close Binary Systems (e.g. Basko and Sunyaev, 1973) and Rotating Degenerate Stars (e.g. Davidson et al, 1971). The 0.7874 day optical periodicity seen in both the light curve (Gottlieb et al (1975) and the radial velocity observation of Cowley and Crampton (1975)), makes it almost certain that the system is a binary. Here the energy source for the X-ray emission is mass accretion from a normal star onto a compact secondary. However among the other X-ray sources known to be contained in binary systems, none exhibit the stable X-ray base level of SCO X-1. Because the initiation of a SCO X-1 binary system must be of the order of 90^{0} the situation is somewhat unique in that we are observing disc or radial accretion 'end on'. The properties reported for this source could well result from this, and may give an indication of which accretion mechanism is operating.

b) <u>3U 0352 + 30</u>

A considerable ammount of Copernicus observing time has been devoted to the study of this source. Positional data from the work of Hawkins, Mason and Sanford (1975) are given in Figure 5. The area of overlap of the Copernicus and Uhuru position boxes is approximately 7 square arc min. Two candidate objects are shown in this region of overlap, one of which is the star X Persei, a peculiar 6th magnitude Be object.

The X-ray source and the star have been studied simultaneously by the Princeton UV telescope and the MSSL X-ray detectors on Copernicus in order to estimate the column density of interstellar material in front of both the star and the X-ray source (Mason et al (1975)). Table III summarises the results of observations with the Princeton instrument. Values of atomic,molecular and total Hydrogen column densities are presented in the table. The high value of the molecular hydrogen column is of particular interest.

The results of X-ray determinations of the gas column density are summarised in table IV. Copernicus data for the energy range 0.5 to 7.5 keV were employed. While the numbers listed are in equivalent Hydrogen atoms, the absorption is primarily due to elements such as oxygen and neon and the values of N_H determined from X-ray data depend very largely on the element abundances assumed for the interstellar material. Because of this, values of N_H have been deduced from the X-ray data for a number of different models of the interstellar absorption cross sections of Brown and Gould and those of Fireman (1974) which include the effect of grains of different sizes. The result of assuming the Princeton value of the molecular hydrogen column with a consequent increase in the column densities of a number of the heavier elements is also quoted in the table. The range of N_H values derived from the X-ray data (2.6 to $4.0.10^{21}$ atoms cm^{-2} column) illustrates the importance of employing an adequately representative model of the interstellar medium. However the UV based column density does lie within the range of values permitted by the X-ray observations and hence the identity of 3U0352 + 30 with the star X Per is not excluded.

Studies of Copernicus X-ray data for the interval October 1972 to January 1975 have lead to the discovery of a 13.9 minute periodicity. Period determinations made at various times during this interval are listed in table V. Data obtained in December 1972 show periods measured for the three Copernicus energy ranges. All other measurements refer to the 2.5 to 7.5 keV band. All the periods determined agree within the errors and so a mean period of 13.9325 + 0.0047 minutes has been derived. The column headed mean source count per minute indicates the 2.5 - 7.5 keV flux from the sourc changed by 30% in the interval Feb 1974, to January 1975. Peak to mean amplitude values for the periodic flux are presented in the last column of the table and the 2.5 - 7.5 keV values of this parameter do not appear to vary significantly. Data folded modulo the 13.9325 minute period are presented in Figure 6. Two complete cycles are shown. The observations made in February 1974 were used to generate this light curve. Although only 13 bins can be displayed in each cycle due to the time resolution os the instrument, the light curve is quasi-sinusoidal in shape and does not suggest the sharp cut off that would be associated with binary eclipse. Sharply pulsed emission, such as might arise due to beamed radiation from a neutron star, would also appear to be excluded. A very close binary system has been suggested by Pringle and Webbink involving a pair of compact objects and having the quasi-sinusoidal light curve established by an orbital variation in the electron scattering optical depth could explain the observations using a model similar to that proposed for Cygnus X-3 by Pringle (1974) and Davidson and Ostriker (1974). However six other sources including 0900-40 (Rappaport and McClintock (1975)), two transient sources (Ives et al (1975)), Rosenberg et al (1975)) and three galactic sources (White et al (1975)) have now been found to exhibit periodic behaviour with periods in the range 1.73 to 31.9 minutes and so the possible existence of a class of slow rotators should also be considered. In particular, Fabian (1975) has drawn attention to mechanisms which could lead to the slowing down of a neutron star's rotation and give rise to periods in the range 1 - 100 minutes.

In addition to the pronounced 13.9325 minute periodicity, there is evidence for X-ray modulation at a period of either 11 or 22 hours for at least some of the time during which Copernicus has been observing the source. The general nature of larger term X-ray variability is illustrated by the three samples of data shown in Figure 7. Each data point represents an average taken over 5 integration periods. The data suggest a longer term variability but its nature is not immediately obvious from an inspection of Figure 7. The nature of the data, which includes many time gaps, makes it impossible to use straight forward Fourier analysis techniques. A rather different approach has been developed by Murdin and co-workers for application to data of this kind. A detailed discussion of this work has been submitted to MNRAS by White et al (1975b). The results of this work are summarised in table VI. While no evidence for a 22 hour variation emerges from the power spectral analysis, the 12 hour gaps in some of the data make it possible that a 22 hour period would not have been detected at a level of modulation of as much as 20%. There is further evidence for a 22 hour period in data obtained recently with the MSSL proportional counter on Ariel 5 (Figure 8) but this observation has not yet been subjected to a power spectral analysis.

Thus the X-ray source poses a number of questions particularly if we attempt to establish its association with the star X Per. The positional evidence and the permitted agreement between X-ray and UV column densities are suggestive of an association but not conclusive. Efforts to establish the existance of simultaneous X-ray and optical variability have not yet been successful (see Margon, these proceedings) although further work of this kind will be undertaken in the near future. Hutchings et al (1975) have obtained evidence for periodic radial velocity variations which suggest a 580 day binary period. These authors present evidence for the accretion rate being a factor 2.10^3 lower than that in other X-ray emitting binary systems and it is interesting to note that the X-ray luminosity of 3U0352+30 is lower than that of other systems by a similar factor.

Because of the presently confused situation further studies of X Per and 3U0352 + 30 are urgently required. While a better position determination for the X-ray source could solve a number of problems, an adequate position will probably not become available until after the launch of HEAO-B. In the meantime, a continued search for simultaneous X-ray and optical variability could prove fruitfull.

Although a good deal of Copernicus time has been spent in observations of Her X-1, analysis of the data is still in progress. However a particularly sharp exit from binary eclipse is illustrated in Figure 9 (Davison (1975)). The time taken to emerge from occultation is less than one Copernicus integration period or 62.5 seconds. A consideration of the orbital parameters of the Her X-1 system suggests that the size of the X-ray emitting region must be less than 5000 Km.

Reference is made in table II to several observations of 'targets of opportunity'. One of these was the transient X-ray source (A1742-28) which was first detected in the region of the galactic centre by the rotation modulation collimator instrument on Ariel 5 (Eyles et al (1975)). The light curve of this object is shown in Figure 10. Data from a number of satellites including Ariel 5 (Branduardi et al (1975), ANS (Brinkman (1975) and Copernicus, are plotted. The Copernicus observations in particular provide source intensities at between 50 and 200 days after the peak of the light curve. These points suggest that the rate of decay of the X-ray flux is becoming less steep with time.

X-ray spectra of A1742-28 have been obtained with Ariel 5 and Copernicus and are shown in Figure 11. The spectrum of the galactic centre X-ray source (GCX) is plotted for comparison. While the spectral shapes measured in February 1975 by Ariel 5 and March, 1975 by Copernicus are consistent and the Copernicus spectrum for May, 1975 shows a significant hardening. A more detailed account of these observations is in preparation (Branduardi, et al (1975)).

Many other observations have been carried out by Copernicus in the year up to October 1975 as will be apparent from the list presented in table II. It is expected that Copernicus will continue to observe galactic X-ray sources in the course of next year.

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Table I : Copernicus X-ray Instrument Parameters

Detector	Energy Range (keV)	Field of view
Collimated Proportional Counter	2.5 - 7.5	3.5^{o} x 3^{o} (FWHM)
Paraboloidal X-ray reflector and Proportional Counter	1.4 - 4.2	10', 3' and 1'
" " " " " " " "	0.5 - 1.5	10', 6' and 2'
Paraboloidal X-ray reflector and Channel Multiplier	0.1 - 0.6	10'

Table II : Copernicus Observations 1974 - 75

1) GALACTIC SOURCES

CYGNUS X-1	VELA X-1
CYGNUS X-2	3U1700 - 37
CYGNUS X-3	X PERSEI (3U0352 + 30)
CENTAURUS X-3	3U1728 - 16
SCORPIO X-1	3U1811 - 17
HERCULES X-1	3U1813 - 14

2) TARGETS OF OPPORTUNITY

CENTAURUS X-5

GALACTIC CENTRE TRANSIENT

3U1908 + 00

NOVA CYGNI 1975

Table III

X-PERSEUS (3U0352 + 30)

COPERNICUS UV HYDROGEN COLUMN

1) HYDROGEN Ly-α $N_1 = 2.0 \pm 0.5.10^{20}$ ATOMS CM^{-2}

2) MOLECULAR HYDROGEN $N_2 = 1.1 \pm 0.3.10^{21}$ ATOMS CM^{-2}

3) TOTAL HYDROGEN $N_T = N_1 + 2N_2$

$= 2.4 \pm 0.4.10^{21}$ ATOMS CM^{-2}

4) MOLECULAR FRACTION $f = \frac{2N_2}{N_T} = 0.92 \pm 0.04$

Table IV

X-PERSEUS (3U0352 + 30)

COPERNICUS X-RAY HYDROGEN COLUMN

1) BROWN + GOULD (1970) ISM - ALL H ATOMIC

$$N_X = 4.0 {}^{+0.2}_{-0.4} \cdot 10^{21} \quad \text{ATOMIC CM}^{-2}$$

2) FIREMAN (1974) ISM - ALL H ATOMIC

a) NO GRAINS $N_X = 3.3 \pm 0.3 . 10^{21}$ ATOMS CM^{-2}

b) 0.15 μ GRAINS

$N_X = 3.8 \pm 0.1 . 10^{21}$ ATOMS CM^{-2}

3) FIREMAN (1974) ISM - MOLECULAR FRACTION AS FROM UV DATA - BROWN + GOULD (1970) MOLECULAR CROSS SECTION

a) NO GRAINS $N_X = 2.6 \pm 0.3 . 10^{21}$ ATOMS CM^{-2}

b) 0.15 μ GRAINS

$N_X = 2.8 \pm 0.2 . 10^{21}$ ATOMS CM^{-2}

Table V

COPERNICUS - PERIODS OF 3U0352 + 30 (X PER)

Date	Period	Duration of observation (DAYS)	No. of 62.5 sec integration periods	Mean source count per min. MEAN CT	Peak to mean Aplitude
Oct 72	13.940 ± 0.010	3.35	908	6.28*	44%*
Dec 72					
2.5 to 7.5 keV	13.927 ± 0.018	1.88	480	10.31	30%
1.0 to 3.1 keV	13.933 ± 0.020	1.88	300	3.04	37%
0.6 to 1.4 keV	13.939 ± 0.024	1.88	300	3.55	21%
Mean	13.993 ± 0.012				
Feb 74	13.934 ± 0.010	3.47	912	12.63	33%
Jan 75	13.9228 ± 0.0021	10.77	1788	7.33	34%

Mean = 13.9325 ± 0.0047

Mean 2.5 - 7.5 keV Amplitude = 37%

Sample standard deviation = ± 0.023

* 34% Reduction in flux due to source being offset in collimator.

Table VI

POWER SPECTRA OF 1 - 3Å INTENSITIES

Date	No. of data	Mean intensity (counts)	Duration of data stream (d)	Regular oscilations : Period (h)	Amplitude (counts)	Relative Amplitude
Oct 72	912	7.7*	3.3		0.9*	11
Dec 72	471	14.0	1.9		0.9	6
Feb 74	1050	12.2	5.3	11.2±0.2	2.3	18
Jan 75 (First 3 days (First 3 days)	1000	6.1	2.2		0.8	12
Jan 75 (Last 8 days)	792	7.0	8.5	11.4±0.15	1.4	19
Jan 75 (background)	720	-2.5	3.4	26 ± 7	0.8	-

This data was taken with the source off-axis. Multiply by 1.5 to correct for response function of the detector beam.

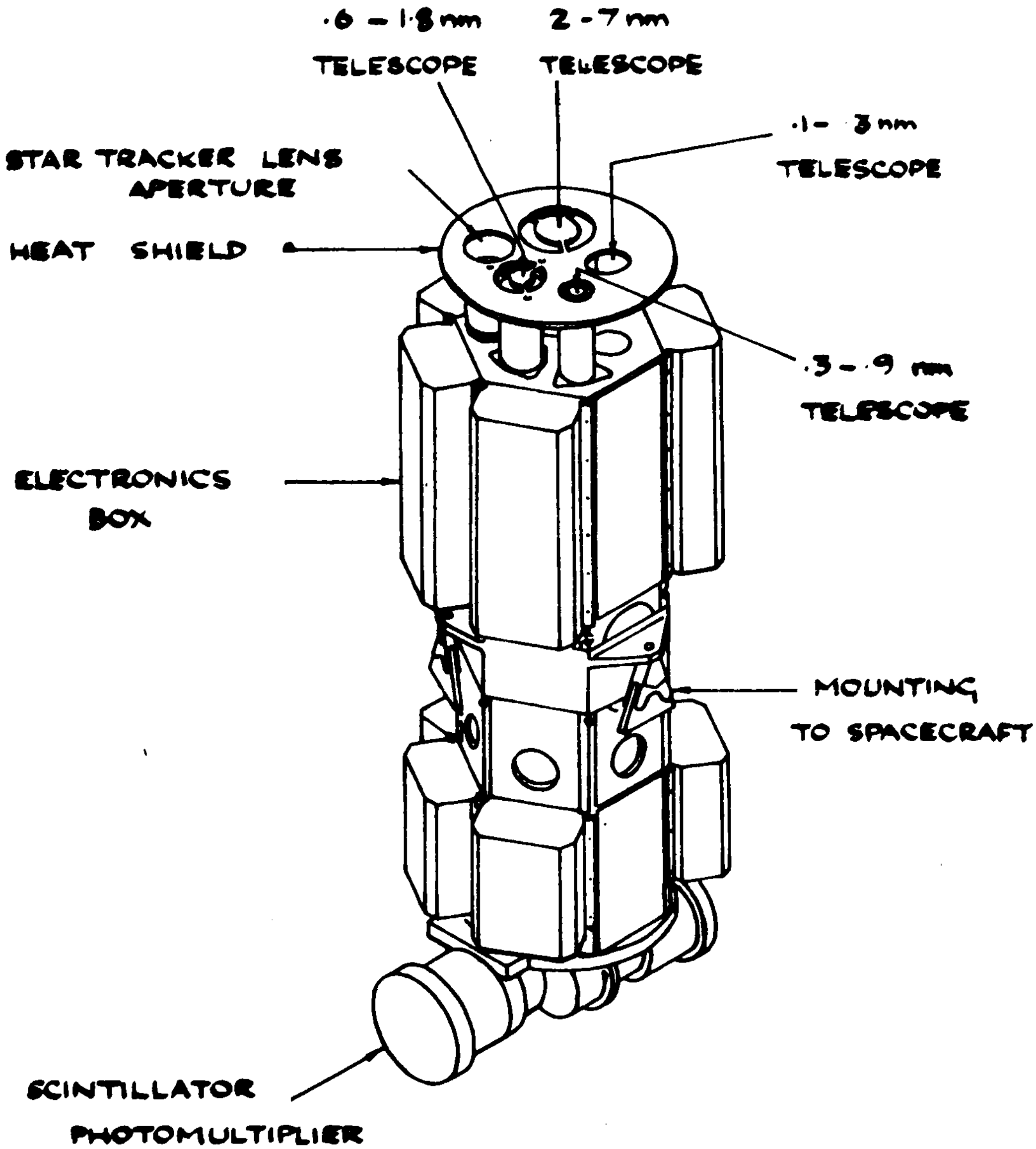

Figure 1 The MSSL X-ray telescope system on Copernicus. Openings in the heat shield permit the three X-ray telescopes, the collimated proportional counter and the instrument star tracker to view the celestial sphere. Detectors and aperture changing mechanisms are located at the base of the package.

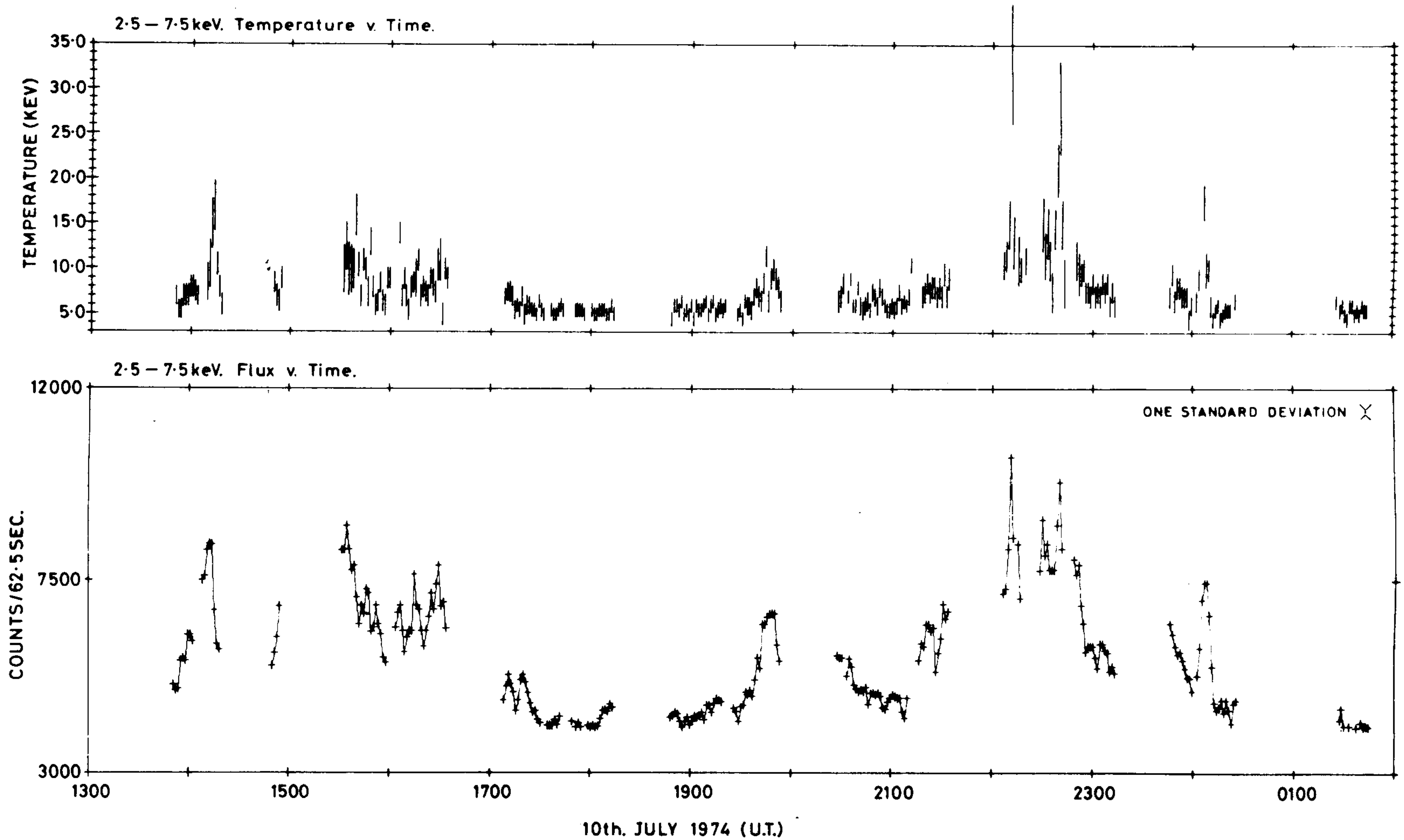

Figure 2 Plots of spectral parameter (temperature) and source intensity against time on July 10th, 1974. Data were obtained during an active phase of SCO X-1.

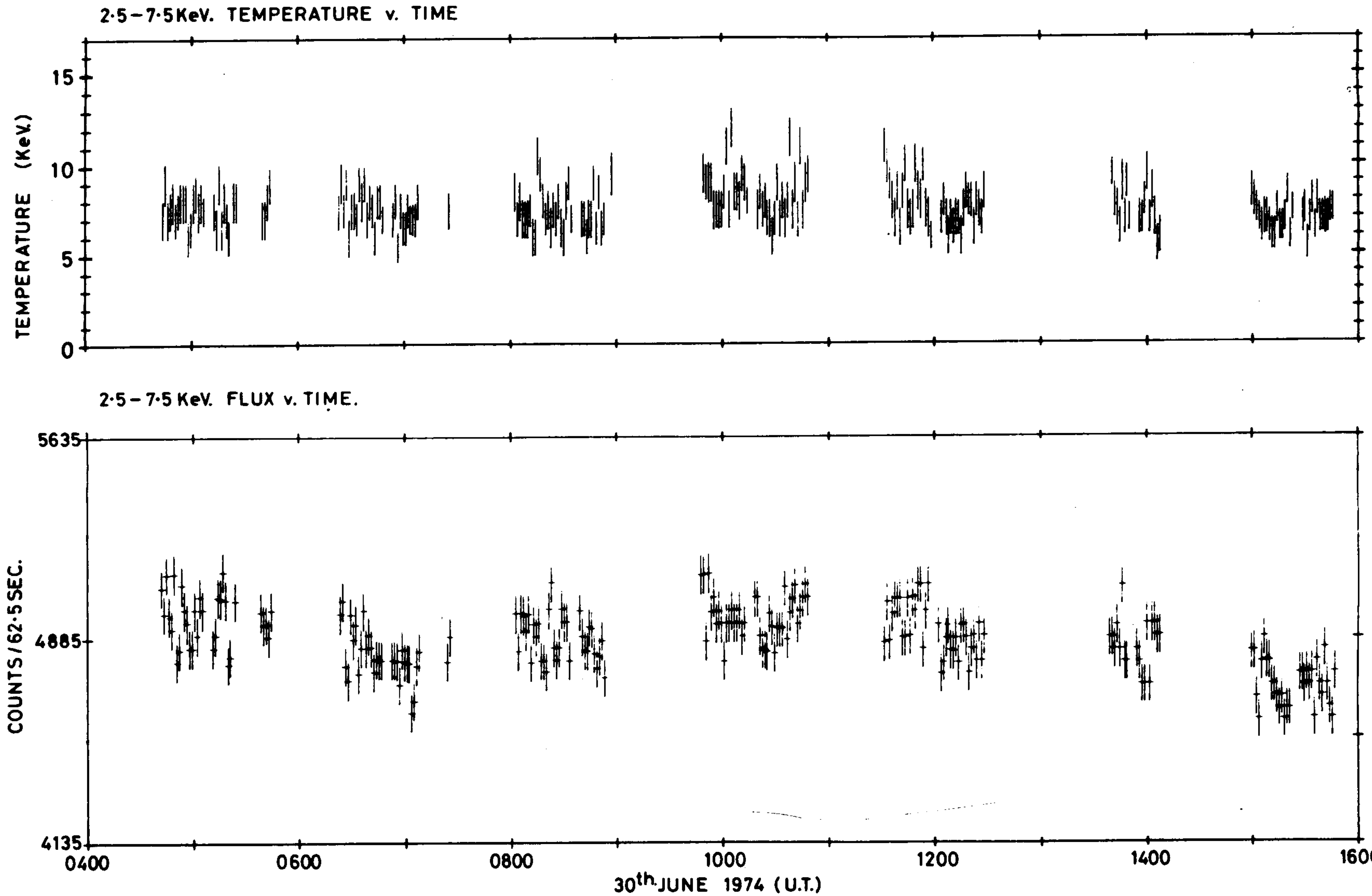

Figure 3 Spectral parameter and source intensity for SCO X-1 plotted against time during a quiescent phase. The intensity scale is expanded by a factor 18 with respect to Figure 2 in order to better illustrate the nature of quiescent variability.

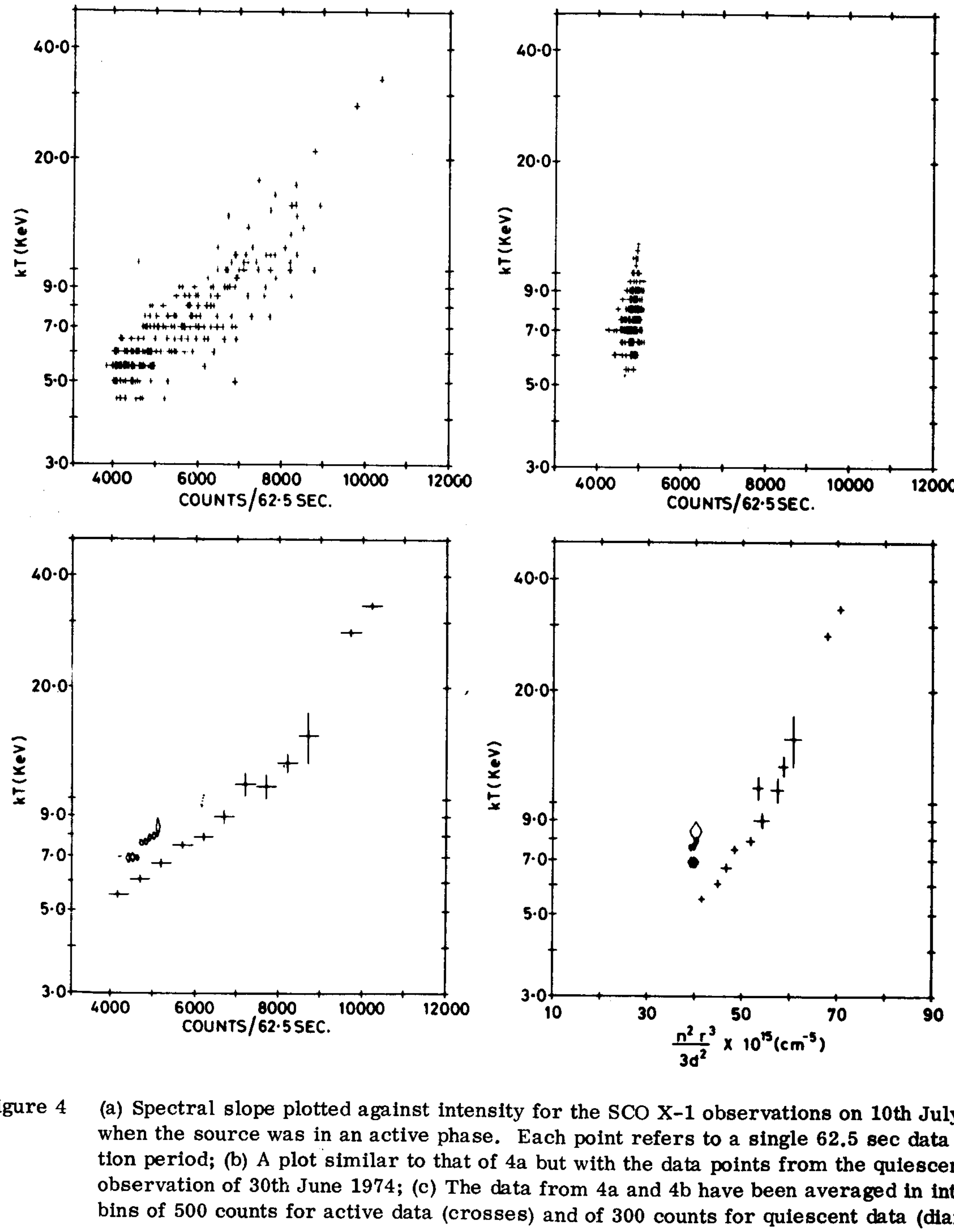

Figure 4 (a) Spectral slope plotted against intensity for the SCO X-1 observations on 10th July, 1974 when the source was in an active phase. Each point refers to a single 62.5 sec data integration period; (b) A plot similar to that of 4a but with the data points from the quiescent phase observation of 30th June 1974; (c) The data from 4a and 4b have been averaged in intensity bins of 500 counts for active data (crosses) and of 300 counts for quiescent data (diamonds).

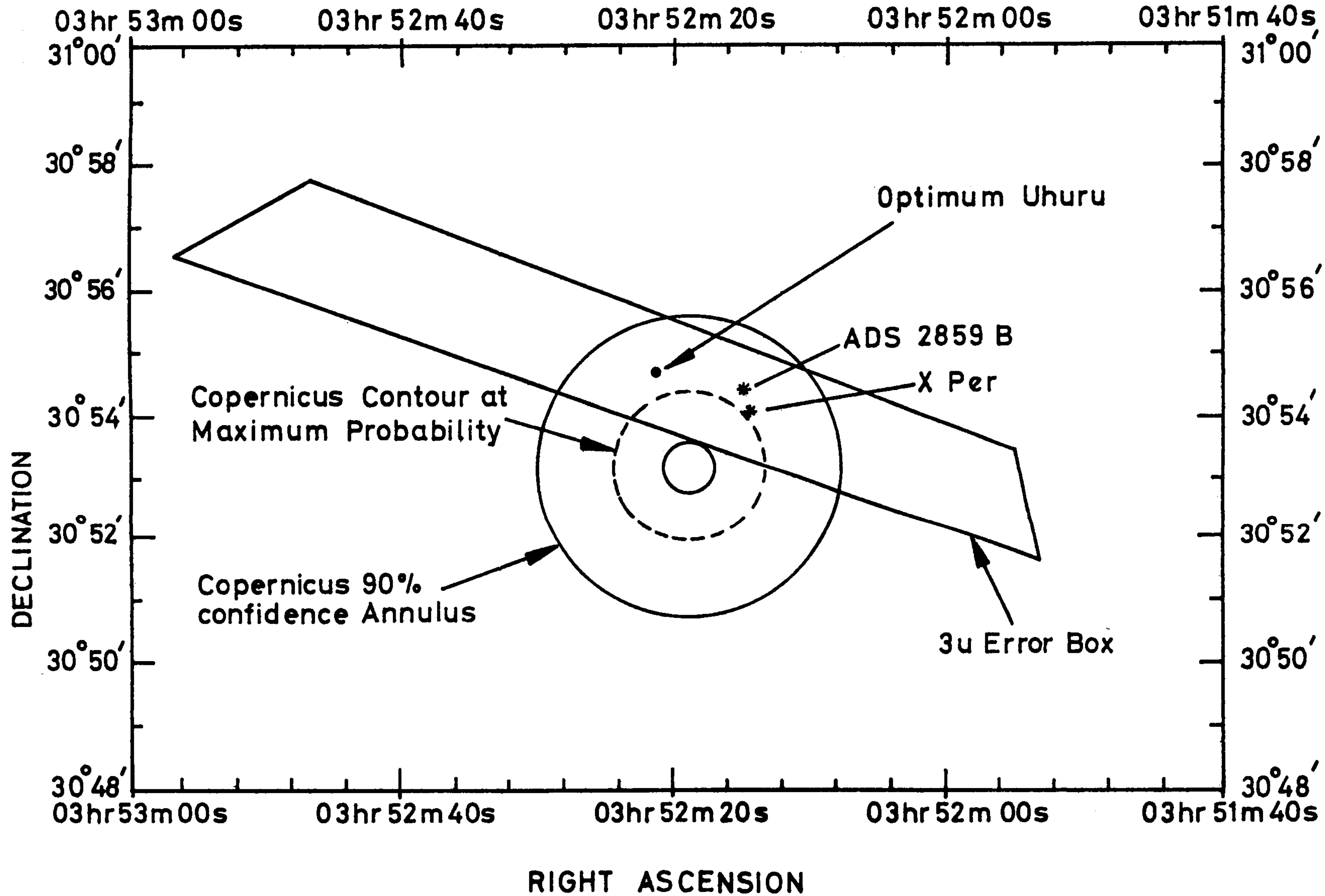

Figure 5 The Copernicus 90% confidence annulus for the source 3U0352 + 30. The error box from the 3U catalogue is also shown. The area of overlap is approximately 7 square arc min.

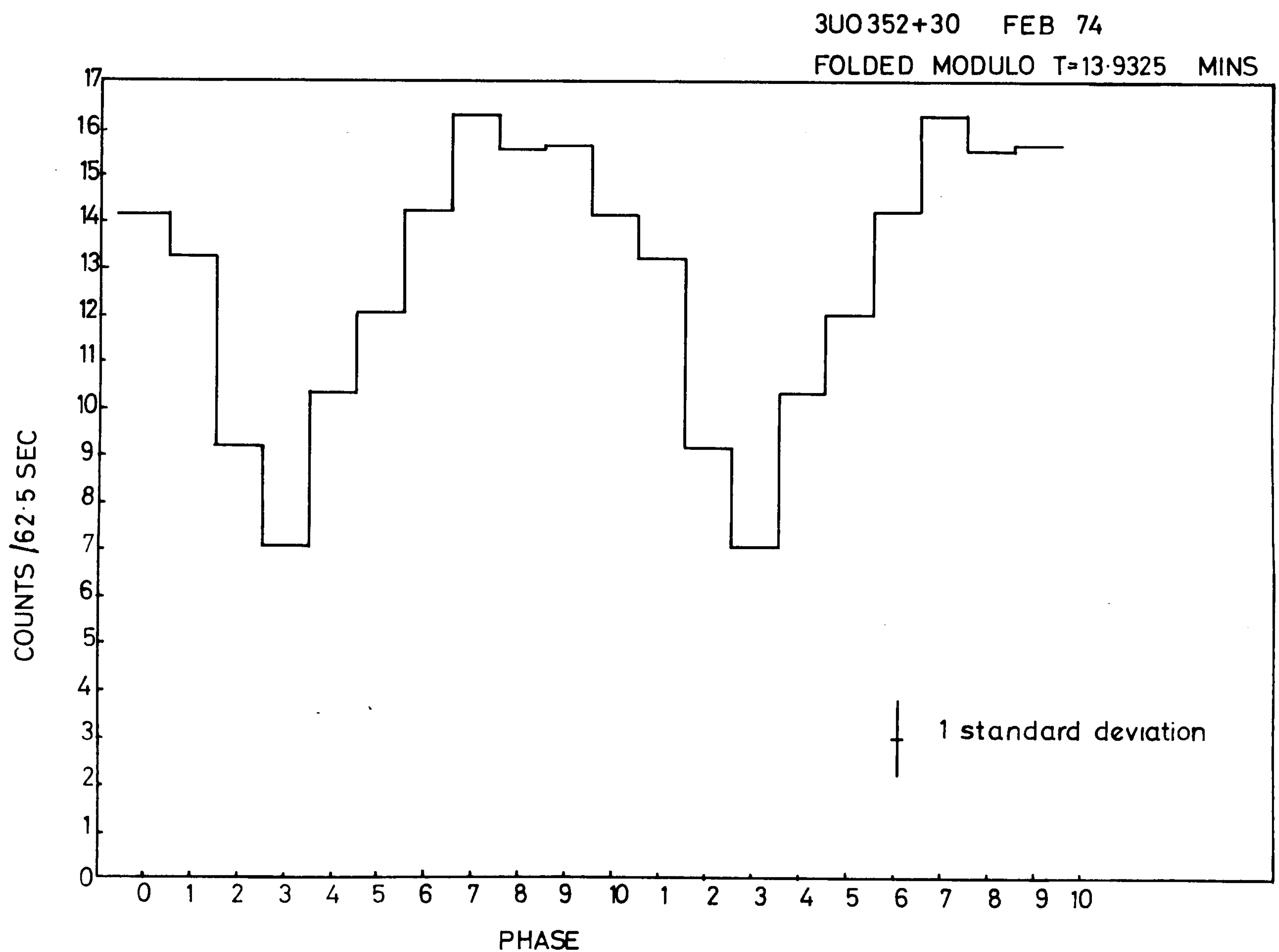

Figure 6 Data from a 2.5 – 7.5 keV Copernicus observation of 3U0352 + 30 folded modulo the period 13.9325 minutes. Two complete

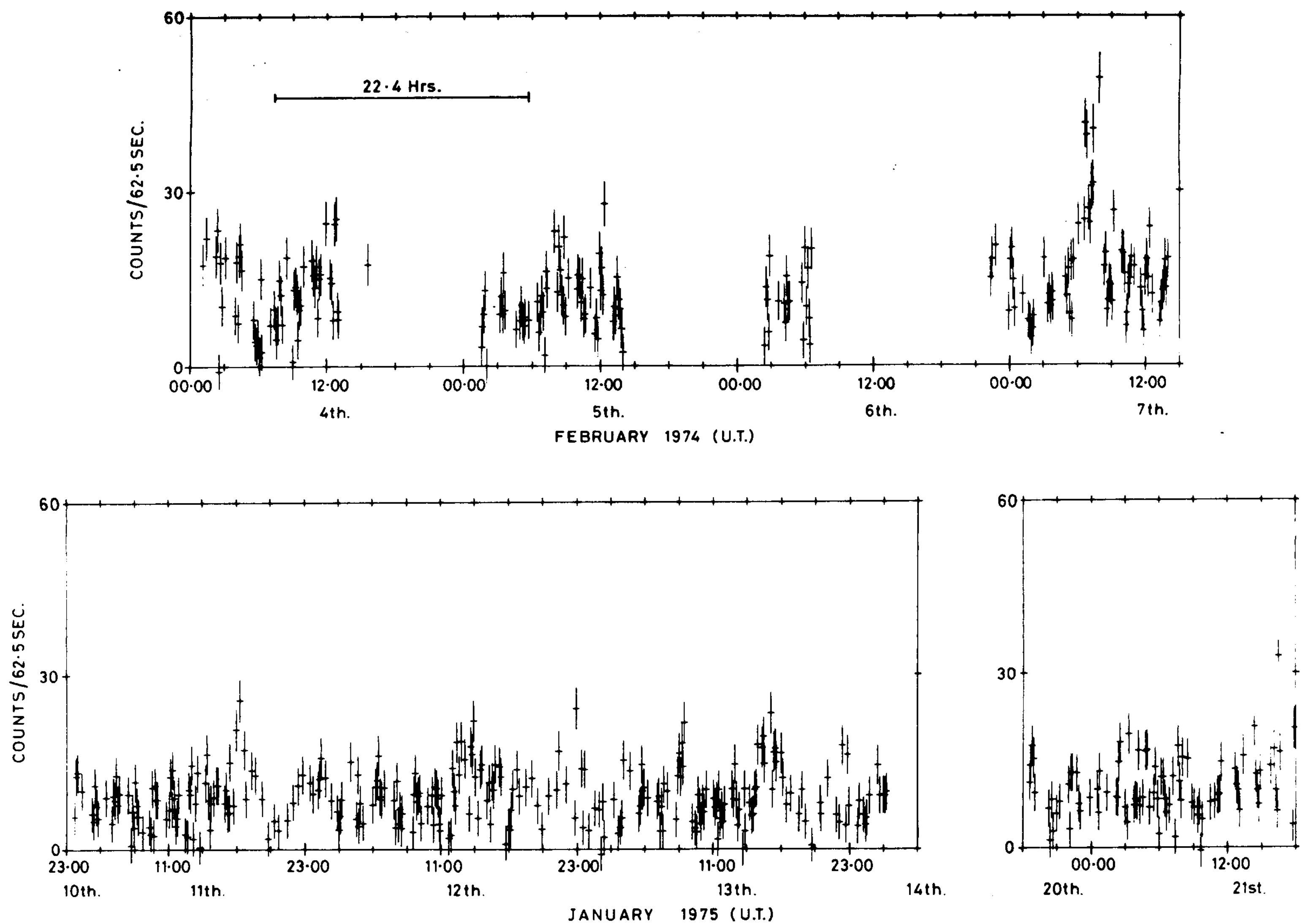

Figure 7 Copernicus counting rates for the 2.5 - 7.5 keV band observed from 3U0352 + 30 during February 1974 and January 1975. Each data point represents the count per 62.5 sec frame averaged over five frames.

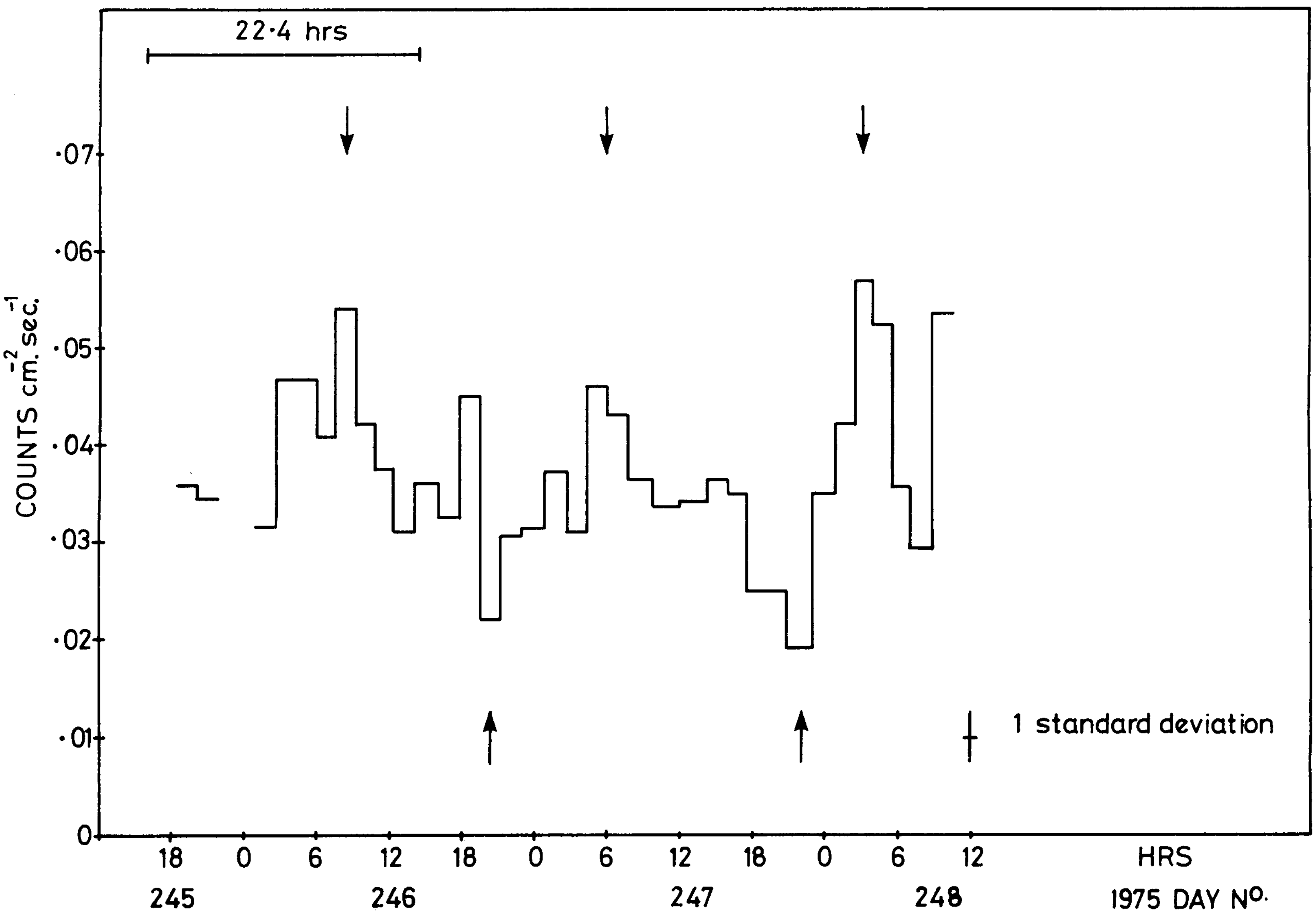

Figure 8 Preliminary data from the MSSL proportional counter on the Ariel 5 spacecraft. The 3U0352 + 30 counting rate is averaged over two orbit intervals and plotted against time. Variability on a 22 hour time scale appears to be present.

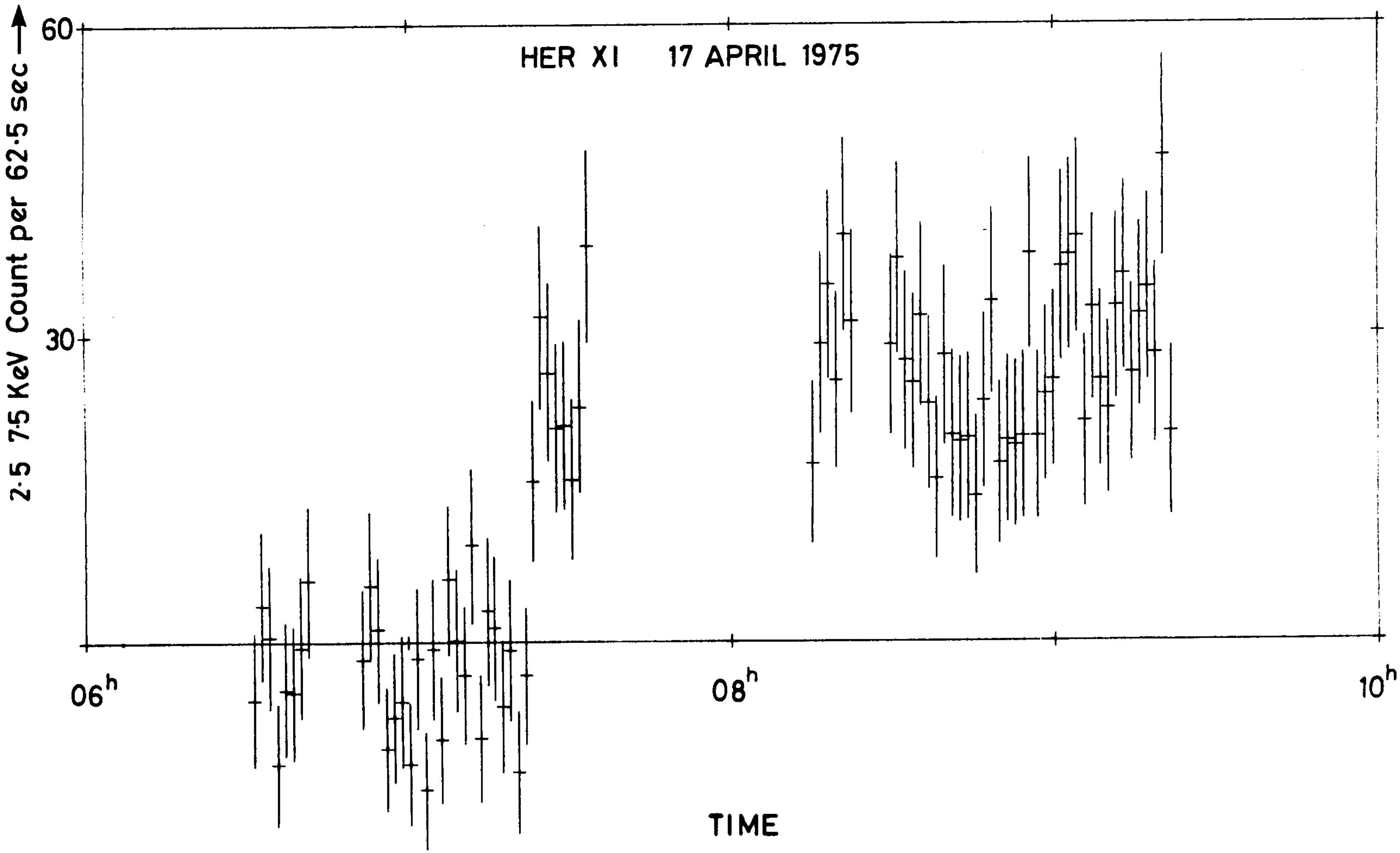

Figure 9 Copernicus data for Her X-1 (2.5 - 7.5 keV) plotted against time during the emergence from a source occultation. The source "turns on" in less than 62.5 seconds.

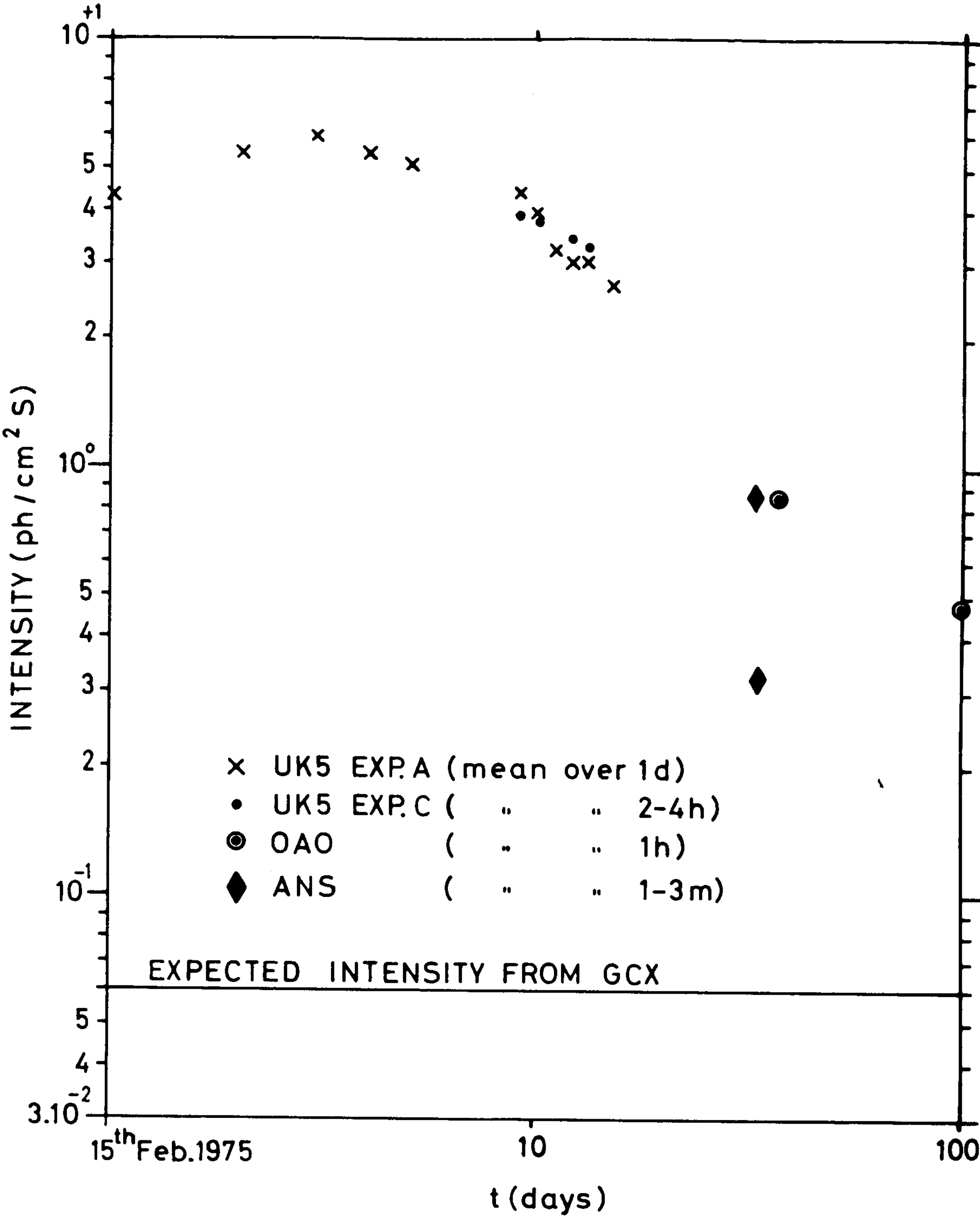

Figure 10 The X-ray light curve of the transient source A1742 - 28 located in the region of the galactic centre. Data were obtained from a number of spacecraft as shown in the figure and discussed in the text. The expected intensity from the source G CX is shown for comparison.

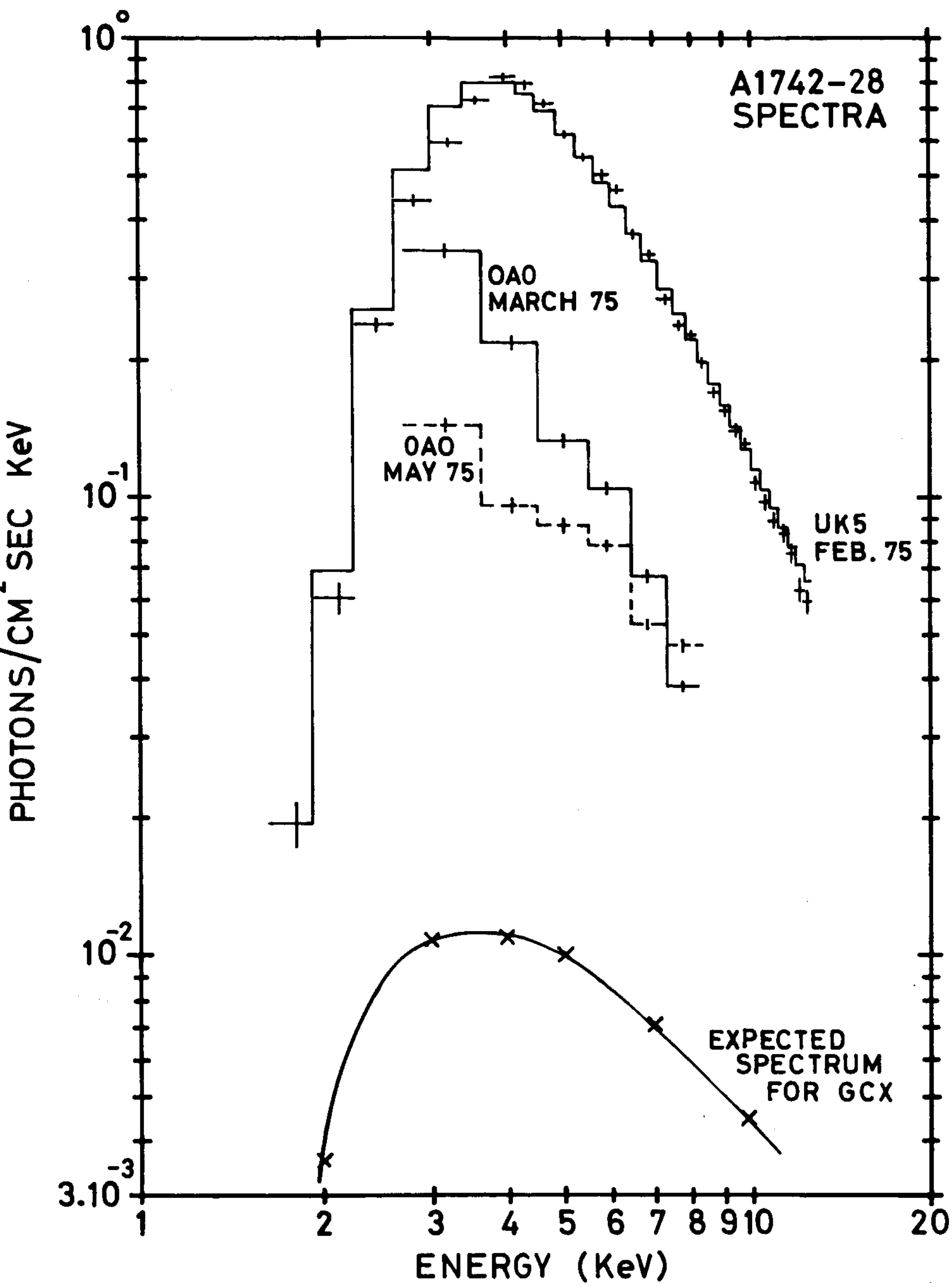

Figure 11 X-ray spectra of A1742 - 28 obtained with the MSSL proportional counter on Ariel 5 and with the 2.5 - 7.5 keV Copernicus detector. The spectrum of GCX is shown for comparison.