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and K. M. Price

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National Aeronautics and
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Goddard Space Flight Center
Greenbelt, Maryland 20771

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OF SCORPIUS X-1

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May 1979

ABSTRACT

The results from extended high energy X-ray observations of Scorpius XR-1 from the OSO-8 satellite are reported here. The source was observed for a total of 15 days in 1975, 1977 and 1978. Simultaneous 10.7 GHz and 4.75 GHz radio data were obtained during the 1978 observation, and low energy X-ray data during the 1975 and 1978 observations. Detailed studies of the data reveal a lack of any correlation between the high energy X-rays and the other energy ranges. A three standard deviation upper limit of 22% was obtained for any modulation of the high energy flux with the binary period. No high energy tail was observed at any time.

1. INTRODUCTION

Many of the observational characteristics of Scorpius X-1 are well-established but observations of the high energy X-rays have produced apparently conflicting results. Sco X-1 was both the first X-ray source discovered (Giacconi et al. 1962) and the first identified with an optical counterpart, the variable star V818 Sco (Sandage et al. 1966, Johnson and Stephenson 1966). Further optical studies established a photometric modulation ascribed to the binary nature of the source (Gottlieb et al. 1975, Cowley and Crampton 1975) with a period of 0.787313 days. Subsequent detailed X-ray studies, however failed to detect any modulation at this period with an upper limit of 1% set by Holt et al. (1976a) for the energy range 3-6 keV. This lack of geometrical eclipses implies that any binary system has a low inclination value. Similarily, the lack of linear polarization established by Weiskopf et al. (1978), sets an upper limit for the inclination of 64°. A X-ray intensity modulation with the photometric period having an amplitude of $(11 \pm 4)\%$ in the energy range 16-41 keV is reported here, though its exact nature is unclear.

The X-ray spectrum, at least up to 40 keV, is well established as that resulting from thermal bremsstrahlung emission with a variable characteristic temperature in the range 4-10 keV (White et al. 1976). Above 40 keV there has been evidence presented for either a non-thermal or a very high temperature component (for example Peterson and Jacobson, 1966; Haymes et al. 1972; Reigler et al. 1970; Matsuoka et al. 1972 and Greenhill et al. 1979). Others, however, have failed to detect such a feature (Lewin et al. 1970). Evidence presented here from data collected over 15 days will support the latter case.

There have also been several coordinated studies of this source in some or all of the low-energy x-ray, radio and optical regions (see Miyamoto and Matsuoka (1977) for a summary). These studies revealed rapid variations in the 3-10 keV X-ray region while the source was optically bright, and little or no variation while optically faint.

Coordinated studies between specific flare events in these energy ranges showed no evidence for any correlations. Presented in this paper is the first combined radio/hard X-ray coordinated observation. This shows a similar lack of correlation.

The radio source is made up of three separate components separated by $\sim$1.2 arcminutes (Wade and Hjellming, 1971). Presented here is both a measure of the radio spectrum of the central component and a measure of the positions of the three components.

2. THE OBSERVATIONS

The X-ray source Scorpius X-1 was observed with the high energy X-ray spectrometer on OSO-8 during the periods:

1975 September 6-8

1977 August 20-24

1978 August 19-25

The detector consists of an actively shielded CsI(Na) crystal of effective area 27.5 cm^2. It is collimated to a field of view of 5.1^o (FWHM) and has been described in detail by Dennis et al. (1977). During the 1977 and 1978 observations the detector was sensitive to X-ray photons in the energy range 14-280 keV, and in 1975 to the energy range 18-280 keV. The detector axis is offset from the satellite spin axis by 5^o, thereby causing the counting rate from any source also 5^o away from the spin axis to be 100% modulated each spin cycle. The method of data analysis has been described in detail by Dolan et al. (1977).

The radio observations were carried out primarily from the Radio Astronomy Institute, Stanford University (by WG and KMP). This telescope is an East-West array of five 18-meter telescopes operating at 10.7 GHz with an E-W resolution of 17 arc seconds, well able to resolve the three separate radio components. It is described in detail by Bracewell et al. (1973). The remaining radio observations at 4750 GHz were carried out by MJC from the 300' meridian transit telescope at the National Radio Astronomy Observatory* in Greenbank, West Virginia.

*The National Radio Astronomy Observatory is operated by Associated Universities Inc., under contract with the National Science Foundation.

3. PERIODIC MODULATION

Following the work of Holt et al. (1976a) at lower energies (3-6 keV), the OSO-8 data were searched using the photometric period (o.787313 day) and epoch (JD 2440081.13) of Gottlieb et al. (1975). This was done by folding the data modulo the period and adding all three years of data together. The energy range 16-41 keV was chosen because this is the region over which the detector is most sensitive to Sco X-1. The resulting light curve is shown in Figure 1. A harmonic analysis of this light curve was then carried out, giving an amplitude for the first harmoni. of (10.8 ± 3.7)%.

To check for possible spurious modulations in the signal due to passage through the radiation belts or any other effect not related to Sco X-1, data from an almost identical crystal detector on OSO-8 were analyzed in exactly the same manner. The only difference in the two detectors is that one has collimation holes drilled in the shielding crystal and the other is completely closed (Dennis et al. 1977). The result from the closed crystal for the same energy range was a modulation with a significance of only 1.4 standard deviations (compared to 2.9 standard deviations in the open crystal).

To determine whether the period of 18.9 hours was unique to the data, two tests were carried out. First the data were analyzed in a similar manner for a period of 24 hours - the most likely spurious period representing the daily transit of the satellite through the South Atlantic anomaly. This unfortunately, also revealed a significant modulation of amplitude (11.7 ± 3.9)%. Secondly, a Fourier analysis of each year's data was carried out but no significant peak was detected at 18.9 hours, or any other period in the range 14-30 hours. Consequently, the result of this search is most correctly represented by a 3 standard deviation upper limit for any modulation of the X-ray flux in this energy range, 16-41 keV, of 22%.

4. THE X-RAY SPECTRUM

The X-ray spectrum in the 2-20 keV photon energy range has been studied extensively by satellite and rocket instruments. The various authors basically agree that it represent thermal bremsstrahlung emission from a hot plasma of the form:

$$\frac{dN}{dE} - \text{const.} \frac{\exp^{(-E/kt)}}{E^{1.4}}$$

with an electron scattering optical depth of > 10 (Laros and Singer, 1976; Miyamoto and Matsuoka, 1977; White et al. 1976). The observed temperatures lie in the range $2 < kT < 20$ and there exists a correlation between the temperature and intensity (White et al. 1976). The question that remains to be resolved is the existence and nature of the separate higher energy component.

It has been suggested that the existence of this feature is dependent upon the source flaring (Matsuoka et al. 1972), but Lewin et al. (1970) failed to detect any high energy excess during a flare they observed from a balloon in 1969. This hard tail has been interpreted as a hot spot in the system giving rise to thermal bremsstrahlung emission with $kT \sim 100$ keV (Ramaty et al. 1976). This is consistent with the spectrum obtained by Haymes et al. (1972).

The OSO-8 data presented here cover a total of 15 days of observation. The spectrum was determined on timescales as short as 3 hours. At no time during the observation period was any evidence found for a high energy excess over and above a thermal bremsstrahlung spectrum with a temperature of $kT = 5 \pm 2$ keV. The spectrum for the period 1978 Aug. 20-23 is shown in Figure 2 together with a coincident measurement obtained from the Ariel-5 All Sku Monitor (Holt, private communication). A best fit temperature has been found for each year giving:

1975: $kT = 6\pm1$ keV

1977: $kT = 6\pm1$ keV

1978: $kT = 4\pm1$ keV

In order to search for any underlying high energy component all the data for the 15 days were summed. The resulting spectrum is presented in Figure 3. Also shown are the results of Haymes et al. (1972) and the Ariel-5 results of Greenhill et al. (1979). As can be seen, the OSO-8 two standard deviation upper limits do not decisively exclude the existence of a high energy component such as seen by Haymes et al. and Ariel-5. Because, however, the OSO-8 upper limits lie generally below the other measurements, a probability may be calculated that the OSO-8 and the other results are drawn from the same spectral distribution. This is found to be 0.08% for the Haymes and OSO-8 results in the 35-240 keV range, and 1.5% for the Ariel-5 and OSO-8 results in the 35-100 keV range. Thus it seems reasonable to conclude that if this high energy component existed during the 15 days of OSO-8 observations, then it was at least a factor of three beneath that measured by Haymes et al. in 1970. Other observations (e.g. Peterson and Jacobson, 1966; Reigler et al. 1970; Overbeck and Tananbaum, 1968) are, in general, at a higher intensity than those of Haymes et al. and are thus correspondingly even less consistent with the present results.

5. THE RADIO MEASUREMENTS

As explained above (Section 2) the radio observations were carried out primarily from the Stanford RAI telescope at 10.7 GHz (2.8 cm). Supplementary observations were obtained at 4750 MHz (6.3 cm) from the NRAO. The observed daily variations and their relation to the X-ray flux are discussed below in Section 6. In this section two other aspects of the radio observations are described briefly.

Firstly, the shape of the radio spectrum will be considered. The central component of the source never exceeded 80 mJy during any of the observations from either telescope. Consequently it may be assumed that the source was in a dormant or weak state during these periods. Since Wade and Hjellming (1971) estimate that this state exists for $\sim$ 80% of the time, such an assumption is not unreasonable. Thus if an average flux value is obtained for these two frequencies, some rough estimate of the spectral index may be obtained. Assuming a spectral shape of the form

$$I = A\nu^{\alpha}$$

where I is the intensity in mJy, A is a constant and ν is the frequency in GHz, then a value of 0.3 ± 0.4 for the spectral index, α, is obtained. This in in good agreement with the value of 0.5 obtained by Hjellming and Wade (1971) during a similar dormant state of the source. Indeed, if an estimate is made from their published data of the average flux value and its standard deviation during the quiet source times at 2695 MHz (11.1 cms), then this is found to agree with an extrapolation of the above spectral shape (see Figure 4). Furthermore, if an average value for the flux at 1415 MHz (21.2 cm) is obtained from the published data of Braes and Miley (1971) then this also agrees quite well with the same extrapolation.

On 1978 August 20 the brightest measurement of the intensity of the central component was obtained. This was 65$\pm$15 mJy at 10.7 GHz. A two standard deviation upper limit of 55 mJy was obtained at 4750 MHz. These two measurements are also shown in Figure 4. As can be seen there is no reason to require any spectral change during this brighter than average state.

Secondly, a map of the region was obtained from the Stanford data. The three components were all resolved, but the positions were shifted by 10 arcseconds to the east of the map published by Wade and Hjellming (1971). This is, however, within two standard deviations of their positions.

6. TIME VARIATIONS

No previous long term studies of the variations in the high energy flux of Sco X-1 have been carried out. Detailed studies at energies < 10 keV, however, by Holt et al. (1976b), Bradt et al. (1975) and Canizares et al. (1975) have been published. Holt et al. determined that the variations they saw (generally less than a factor of two) could be explained by assuming $\sim$ 200 flares per day occurring each with a duration of $\sim$ 0.3 days. Bradt et al. in a 21-day coordinated X-ray, optical and radio study, found the X-ray activity to be highest ($\sim$ factor of 2 change in intensity) during optically active periods and almost zero ($\sim$ 5%) during optically quiet times. No correlation with any radio behaviour was observed. Similar results were obtained by Canizares et al.(1975) in a 10-day coordinated X-ray, radio and optical study.

Observations above 10 keV have nearly all been carried out from balloons and are consequently of only a few hours duration. They nonetheless reveal larger variations than these obtained by lower energies. Agrawal et al. (1969) observed a change by a factor of 4 in one hour in the energy range of 30-52 keV, while Lewin et al. (1970) observed a change of > 5 in the intensity of 18-39 keV X-rays during a 3-hour period.

The 15 days of OSO-8 data were analyzed in time bins corresponding to 0.1 of the binary period (1.9 hours). Four energy channels were used: 16-21 keV, 21-26 keV, 26-33 keV and 33-50 keV. No significant fluxes were measured above 50 keV. The results, summed over differing multiples of 1.9 hours, are presented for all three years' observations in Figure 5. Also shown in this figure are 3-6 keV data from the All Sky Monitor on Ariel 5 when available (Holt, private communication) and daily measurements during the 1978 observations of the radio flux at 10.7 GHz (2.8 cm). These radio measurements of the central component lasting several hours each, were carried out from the telescope at the Radio Astronomy Institute, Stanford University. The source was only positively detected in the radio at greater than the 3 standard deviation level of significance on 2 out of the 7 days. This corresponds to a flux of $>$ 45 mJy. This is confirmed by simultaneous observations carried out each day from the 300' dish at the National Radio Astronomy Observatory, Greenbank, West Virginia. These latter measurements were made at 4750 MHz (6.3 cm) but, because this telescope is a transit device, they lasted only a few minutes and failed to detect Sco X-1 on any singly occasion. Nonetheless, the daily three standard deviation upper limit of 80 mJy is consistent with the Stanford results.

The X-ray data show behaviour similar to that previously reported. The high energy fluctuations in intensity are less than a factor of four and are on timescales down to the shortest resolvable ($\sim$ 1.9 hours). On one occasion, 1975 September 7, a rise in the 3-6 keV X-rays correlated with rises in the higher energy X-rays, but on other occasions (e.g. 1978 August 20) no such correlation was evident. These two events may be intrinsically different because the 1975 rise occurred while the source was at a lower intensity level (in the 3-6 keV range), and lasted for a longer duration, than the 1978 flare. There is also evidence in the OSO-8 data for the "apparent coherence" observed by Holt et al. (1976b), i.e. the number of counts in any one time bin seems to be related to the number in the previous bin, a behaviour characteristic of shot-noise. A daily estimate of the spectral temperature was obtained from the OSO-8 data alone using an emission spectrum of the form detailed in Section 4. The result is also presented in Figure 5. As can be seen, there are no significant deviations from a temperature of 4 ± 2 keV.

To assess any correlation between the X-ray behaviour and the radio emission, a linear correlation coefficient was calculated between the radio and each of the X-ray energy ranges 3-6 keV, 16-21 keV, 21-36 keV and 26-33 KeV. This revealed no support for any related behaviour, the probability of correlation varying between 30% and 60%.

7. DISCUSSION

The X-ray source Scorpius X-1 represents in many ways an excellent target for high energy X-ray instruments. The X-ray spectrum, represented by a thermal continuum, is extremely intense only falling below the spectrum of the Crab Nebula at energies > 30 keV. It is therefore feasible to do meaningful studies of its short-term fluctuations - a very powerful tool for establishing constraints on source models. There is also evidence that on at least some occasions it has a high energy tail, which is clearly not an extension of the low energy continuum and may well represent emission from a much hotter part of system. Such a feature in the accretion disk has already been suggested by the He II emission line studies of Cowley and Crampton (1975) who found evidence for a hot spot following behind the compact object. If this is the source of the high energy tail, then studies of its emission will tell us more about the basic behaviour of the system than studies of the diffuse lower energy X-rays. Furthermore, exhaustive studies of the radio and the low energy X-ray emission have failed to discover any relation between the secular changes in these two spectral regions. The possibility exists, however, that there may be some correlation between the behaviour pattern of the radio and the hard X-ray emission. The results presented here represent an attempt to address some of these problems.

The source was studied for a total of 15 days in three separate observations representing the first long term study of Sco X-1 at high energies. For the last 7 days a concurrent measurement of the radio flux at 10.7 GHz was obtained for several hours each day. This is the first time such coincident observations have been carried out.

The results are consistent with larger variations in the higher energy flux than the low energy emission. Since Holt <u>et al</u>. (1976b) have put forward a model involving $\sim$ 200 flares per day emitting in the 3-6 keV energy range, then one possible interpretation of the increasing variability with energy may be a decreasing frequency of higher temperature flares.

On the question of the existence of a high energy tail, the results presented here show that it is not likely to be a permanent feature - at least not at the intensities previously reported. Consequently, it is probably a variable feature related to the activity of the source in some way. These new results indicate that it did not exist at the intensity seen by Haymes <u>et al</u>. (1972) for more than $\sim$ 30% of the present observation period.

The existence of a high energy component in the spectrum suggests emission from a different part of the system than that emitting the lower energy X-rays, consequently such emission is worth examining for evidence of any modulation with the binary period. The result of this work is inconclusive, probably because 15 days worth of data is insufficient to establish the existence of any such modulation in view of the "apparent coherence" lasting several hours shown originally by Holt <u>et al</u>. (1976b). Long term observations of the high energy component when it is at the level reported by Haymes <u>et al</u>. (1972) may be able to unambiguously reveal a true binary modulation. If the light curve in Figure 1 is subsequently confirmed as a real modulation, then it represents two levels of emission from Sco X-1, the brighter state occurring while the compact object is moving away from us. This would take place during that part of the binary cycle when our view of the hot spot suggested by Cowley and Crampton (1975) is unobstructed by the compact object.

Thus, in conclusion, we have a picture of a binary system whose continuum X-ray emission arises from a series of flares, the frequency of which decreases with increasing temperature. Superimposed on that continuum we have a variable hard X-ray component possibly modulated with the binary period arising from a hot spot in the accretion disk.

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FIGURE CAPTIONS

Figure 1: Data in the energy range 16.2-40.6 keV from 1975 Sept., 1977 Aug. and 1978 Aug. folded modulo the period of 0.787313 days and with the epoch JD 2440081.13 proposed by Gottlieb et al. 1975.

Figure 2: The spectrum of Sco X-1 measured over the period 1978 Aug. 20-23 inclusive. The concurrent 3-6 keV point is from the All Sky Monitor experiment on Ariel-5 (Holt, private communcation). Upper limits are shown at the 2 standard deviation level.

Figure 3: A comparison of the total of the OSO-8 data (1975 + 1977 + 1978) with previous reported high energy X-ray measurements. All upper limits are shown at the 2 standard deviation level.

Figure 4: Measurements of the radio spectrum of Sco X-1. The points labelled NRAO and RAI were obtained from the 300-foot telescope at the National Radio Astronomy Observatory and the array at the Radio Astronomy Institute, Stanford University, respectively. The point labelled HW-71 comes from Hjellming and Wade (1971) and that labelled BM-71 from Braes and Miley (1971). The solid NRAO and RAI points are the average flux values obtained from measurements carried out during the period 1978 Aug. 20-25. The open NRAO and RAI points come from observations on 1978 Aug. 20 only. The upper limit is shown at the 2 standard deviation level.

Figure 5: The summary of X-ray and radio observations carried out in 1975, 1977 and 1978. The 3-6 keV data come from the All Sky Monitor experiment on Ariel-5 (Holt, private communication). The data in the range 16-50 keV come from the present OSO-8 experiment, and the radio measurements from the Radio Astronomy Institute, Stanford University.

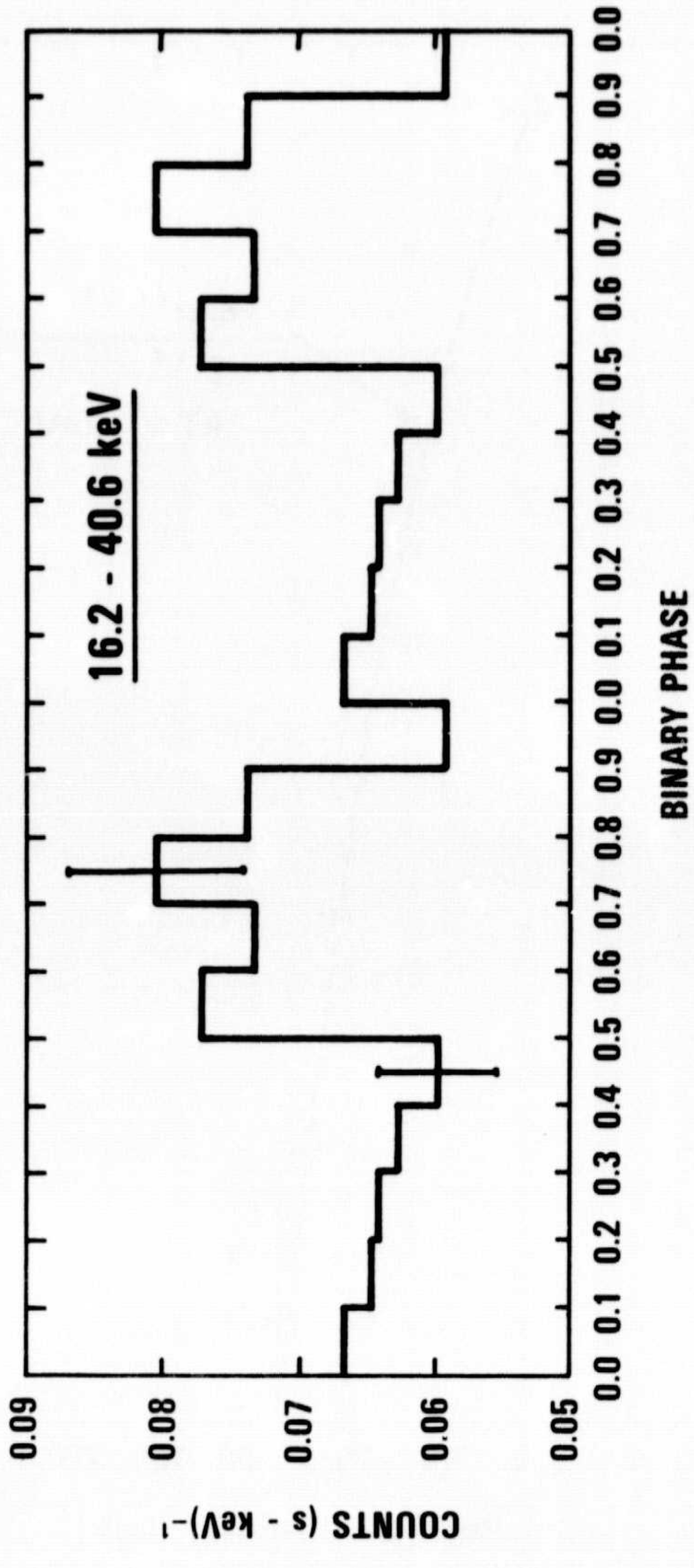
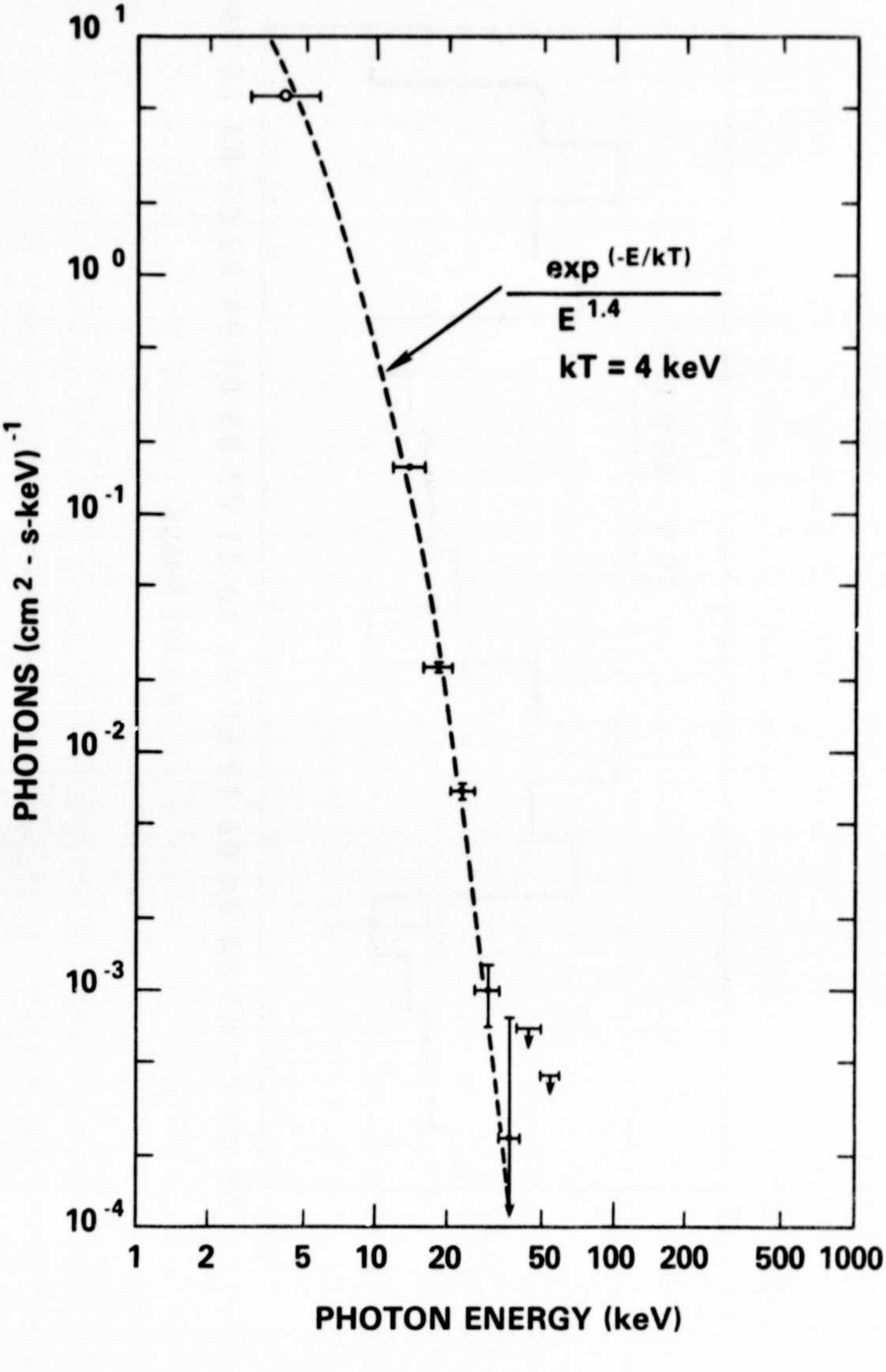
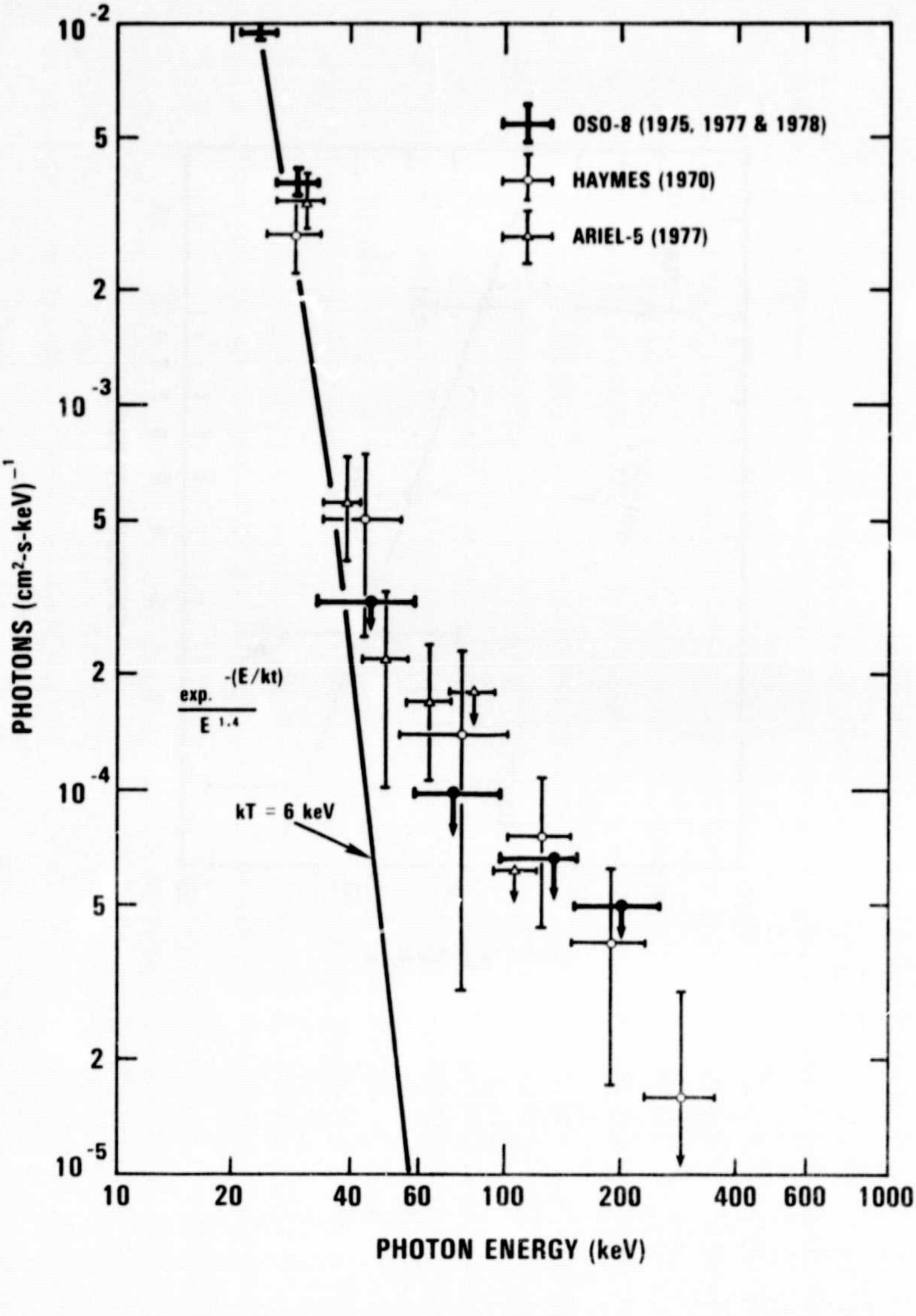

16.2 - 40.6 keV
COUNTS (s - keV)-1
0.09
0.08
0.07
0.06
0.05
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 0.0
BINARY PHASE

FIG.1



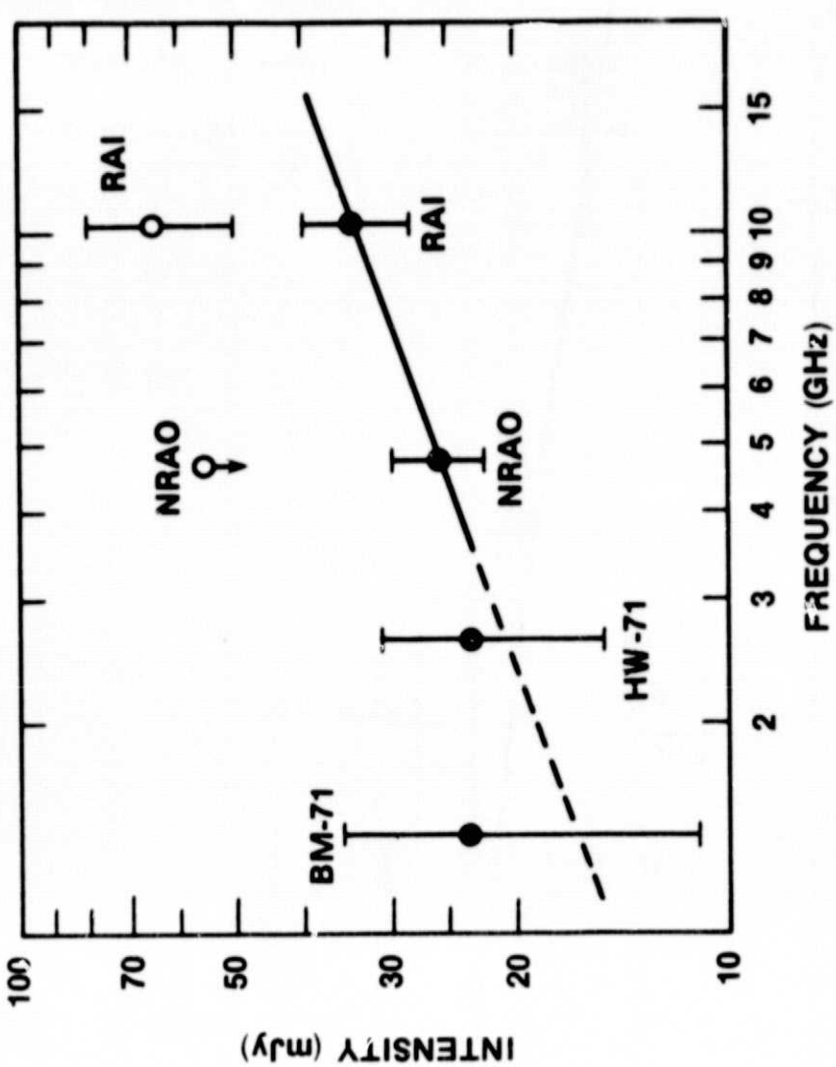
PHOTONS (cm 2 - s-keV) -1
10 1
10 0
10 -1
10 -2
10 -3
10 -4
exp (-E/kT)
E 1.4
kT = 4 keV
1 2 5 10 20 50 100 200 500 1000
PHOTON ENERGY (keV)

FIG.2



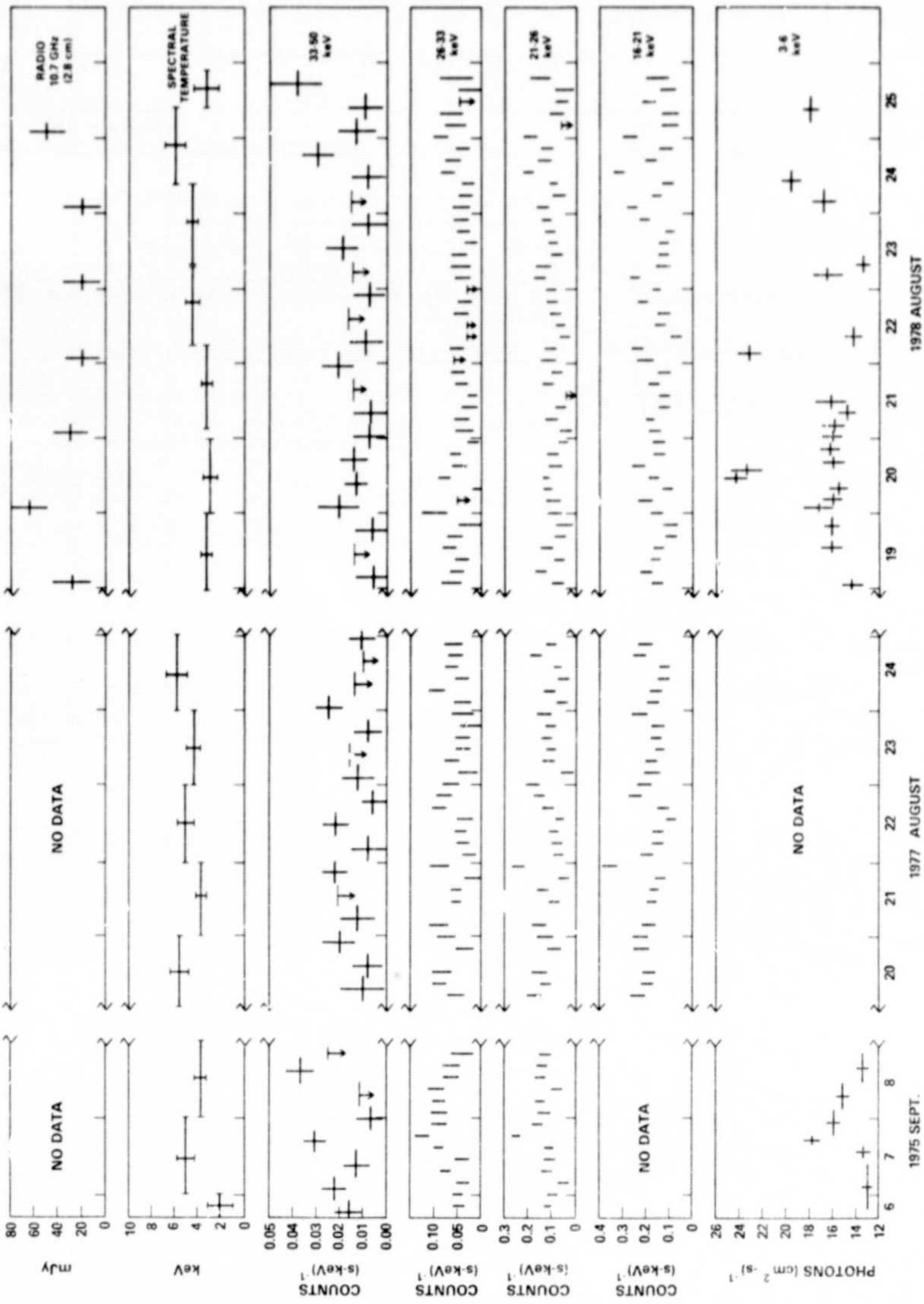
OSO-8 (1975, 1977 & 1978)
HAYMES (1970)
ARIEL-5 (1977)
PHOTONS (cm²-s-keV)⁻¹
exp. -(E/kt)
E 1.4
kT = 6 keV
10 -2
5
2
10 -3
5
2
10 -4
5
2
10 -5
10
20
40
60
100
200
400
600
1000
PHOTON ENERGY (keV)

FIG.3



INTENSITY (mJy)
100
70
50
30
20
10
FREQUENCY (GHz)
2
3
4
5
6
7
8
9
10
15
RAI
NRAO
BM-71
HW-71

FIG.4



RADIO 10.7 GHz (2.8 cm)
SPECTRAL TEMPERATURE
33-50 keV
26-33 keV
21-26 keV
16-21 keV
3-6 keV
NO DATA
NO DATA
NO DATA
NO DATA
mJy
keV
COUNTS (s-keV)-1
PHOTONS (cm 2 -s)-1
1975 SEPT.
1977 AUGUST
1978 AUGUST

FIG.5

BIBLIOGRAPHIC DATA SHEET

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
High Energy X-Ray and Radio Studies of
Scropius X-1

5. Report Date
May 1979

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16. Abstract
The results from extended high energy X-ray observations of Scorpius XR-1 from the OSO-8 satellite are reported here. The source was observed for a total of 15 days in 1975, 1977 and 1978. Simultaneous 10.7 GHz and 4.75 GHz radio data were obtained during the 1978 observation, and low energy X-ray data during the 1975 and 1978 observations. Detailed studies of the data reveal a lack of any correlation between the high energy X-rays and the other energy ranges. A three standard deviation upper limit of 22% was obtained for any modulation of the high energy flux with the binary period. No high energy tail was observed at any time.

17. Key Words (Selected by Author(s))
X-Ray, Radio, Scorpius X-1, Binary Systems

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