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HIGH ENERGY X-RAY AND RADIO STUDIES OF SCORPIUS X-1

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ABSTRACT

The results from extended high energy X-ray observations of Scorpius X-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 3 σ 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.

Subject headings: radio sources: general — X-rays: binaries

I. 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, Wright, and Liller 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.* (1976*a*) for the energy range 3–6 keV. This lack of geometrical eclipses implies that any binary system has a low inclination value. Similarly, the upper limits set on the X-ray linear polarization by Long *et al.* (1979) restrict the inclination angle to less than 44°. The optical data presented by Perrenod (1976) set a limit of 30° on the inclination angle with a most likely value of 10°.

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 nonthermal or a very high temperature component (for example, Peterson and Jacobson 1966; Haymes *et al.* 1972; Reigler, Boldt, and Serlemitsos 1970; Matsuoka *et al.* 1972; and Greenhill *et al.* 1979). This hard component has not always been detected (Lewin *et al.* 1970), and the results presented here indicate that it was not present at the previously observed level during a total of 15 days in 1975, 1977, and 1978.

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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 are results from the first coordinated radio and hard X-ray observation. They show a similar lack of correlation.

The radio source is made up of three separate components separated by $\sim 1\rlap{.}'2$ (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.

II. 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, and 1978 August 19–25.

The detector consists of an actively shielded Cs I(Na) crystal of effective area 27.5 cm^2. It is collimated to a field of view of $5\rlap{.}^\circ1$ (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°, thereby causing the counting rate from any source also 5° 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 (RAI), Stanford

University by W. G. and K. M. P. This telescope is an east-west array of five 18 m telescopes operating at 10.7 GHz with an east-west resolution of 17″, well able to resolve the three separate radio components. It is described in detail by Bracewell *et al.* (1973). The remaining radio observations at 4.75 GHz were carried out by M. J. C. from the 300′ meridian transit telescope at the National Radio Astronomy Observatory[2] (NRAO) in Greenbank, West Virginia.

III. PERIODIC MODULATION

Following the work of Holt *et al.* (1976*a*) at lower energies (3–6 keV), the *OSO 8* data were searched using the photometric period (0.787313 day) and epoch (JD 2,440,081.13) of Gottlieb, Wright, and Liller (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, where the indicated uncertainties are the internal errors based on the observed scatter of the individual counting rates used in the computation of the average rate in each phase bin. The observed scatter of the rate in any one phase bin is a factor of approximately 2 larger than that expected on the basis of the uncertainties in rates observed in 1.9 hour intervals. This reflects the asynchronous variation of the source flux discussed in § VI. A Fourier analysis of the light curve shown in Figure 1 gave an amplitude of the first harmonic of $10.8 \pm 3.7\%$, i.e., evidence for modulation with the photometric period at the 2.9 σ level of significance.

Several tests on the data were carried out to check for possible spurious modulations. Data from the second, completely shielded scintillator on *OSO 8* were analyzed in exactly the same way for a modulation with the photometric period. The only difference between the two detectors is that one is exposed to the source through collimation holes drilled in the shield scintillator and the other is completely shielded (Dennis *et al.* 1977). The result from the completely shielded crystal for the same energy range was a modulation with a significance of only 1.4 σ, considerably smaller than that observed from the crystal exposed to the source. However, reanalysis of the data from the open crystal for a modulation with a period of 24 hours—the most likely spurious period since it represents the period of the transits of the satellite through the South Atlantic Anomaly—revealed a significant modulation with an amplitude of $11.7 \pm 3.9\%$. Furthermore, a Fourier analysis of the data for each year showed no significant peak in the power spectrum at the photometric period or at any other period in the range from 14 to 30 hours.

The conclusion to be reached from this discussion of the data is that the observed modulations probably result from asynchronous variations of Sco X-1, and that any modulation with the photometric period must be less than a 3 σ upper limit of 22% in the energy range from 16 to 41 keV.

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

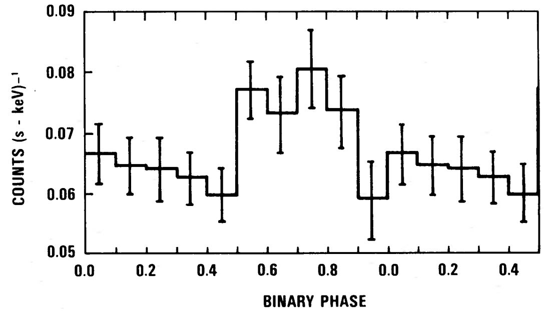

FIG. 1.—Data in the energy range 16.2–40.6 keV from 1975 September, 1977 August, and 1978 August folded modulo the period of 0.787313 days and with the epoch JD 2,440,081.13 proposed by Gottlieb *et al.* (1975). The indicated error bars represent the internal uncertainties based on the observed scatter of the individual data points used to compute the rate in each phase bin.

IV. 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 represents 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 existence and nature of the separate higher energy component remain open to question. 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 $kT \approx 100$ keV (Ramaty, Cheng, and Tsuruta 1974). 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 time scales 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 August 20–23 is shown in Figure 2 together with a coincident measurement obtained from the *Ariel 5* All Sky Monitor (Holt, private communication). A best fit temperature has been found for each year, giving $kT(1975) = 6 \pm 1$ keV, $kT(1977) = 6 \pm 1$ keV, and $kT(1978) = 4 \pm 1$ 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,

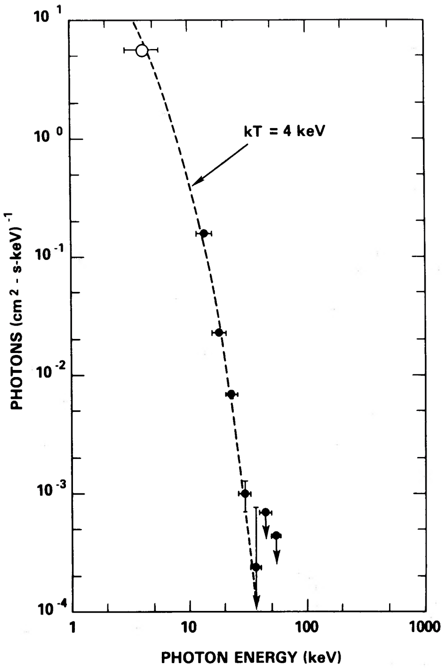

FIG. 2.—The photon spectrum of Sco X-1 measured over the period 1978 August 20–23 inclusive, the concurrent 3–6 keV point is from the All Sky Monitor experiment on *Ariel 5* (Holt, private communication). Upper limits are shown at the 2 σ level.

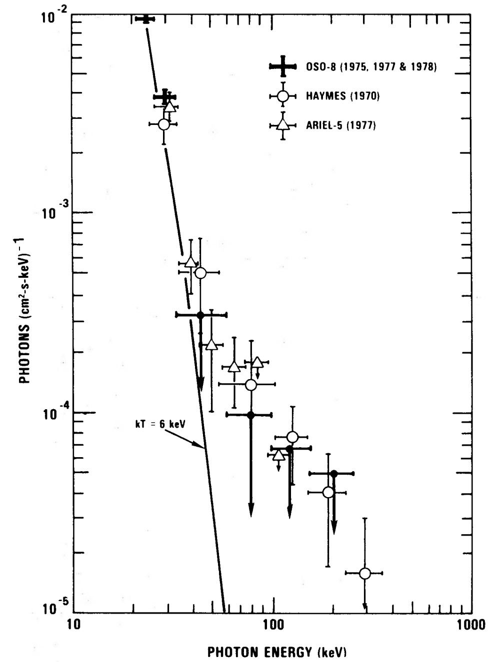

FIG. 3.—A comparison of the photon spectrum of Sco X-1 measured with *OSO 8* (1975 + 1977 + 1978) with previously reported high energy X-ray measurements. All upper limits are shown at the 2 σ level.

the *OSO 8* 2 σ upper limits do not decisively exclude the existence of a high energy component such as that seen by Haymes *et al.* (1972) 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 3 beneath that measured by Haymes *et al.* in 1972. Other observations (e.g., Peterson and Jacobson 1966; Reigler, Boldt, and Serlemitsos *et al.* 1970; Overbeck and Tananbaum 1968) are, in general, at a higher intensity than those of Haymes *et al.* (1972) and are thus correspondingly even less consistent with the present results.

V. THE RADIO MEASUREMENTS

As explained in § II 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 § VI. In this section two other aspects of the radio observations are described briefly.

First, 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 $\pm$ 0.4 for the spectral index, α, is obtained. This is 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 cm), then this is found to agree with an extrapolation of the above spectral shape (see Fig. 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 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 2 σ 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.

Second, a map of the region was obtained from the Stanford data. The three components were all resolved, but the positions were shifted by 10″ to the east of the

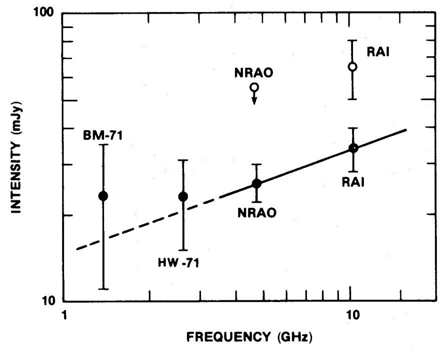

FIG. 4.—Measurements of the radio spectrum of Sco X-1. The points labelled NRAO and RAI were obtained from the 300 foot (91 m) telescope at the National Radio Astronomy Observatory and the array at the Radio Astronomy Institute, Stanford University, respectively. The point labeled HW-71 comes from Hjellming 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 August 20–25. The open NRAO and RAI points come from observations on 1978 August 20 only. The upper limit is shown at the 2 σ level.

map published by Wade and Hjellming (1971). This is, however, within 2 σ of their positions.

VI. 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.* (1976*b*), 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 2) could be explained by assuming ~ 200 flares per day occurring each with a duration of ~ 0.3 days. Bradt *et al.* (1975), in a 21 day coordinated X-ray, optical, and radio study, found the X-ray activity to be highest (factor of ~ 2 changes 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 those obtained at lower energies. Agrawal *et al.* (1969) observed a change by a factor of 4 in 1 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 RAI telescope. The source was only positively detected in the radio at greater than the 3 σ level of significance on 2 out of 7 days. This corresponds to a flux of >45 mJy. This is confirmed by simultaneous observations carried out each day from the 300 foot (91 m) dish at the NRAO. 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 single occasion. Nonetheless, the daily 3 σ upper limit of 80 mJy is consistent with the Stanford results.

The X-ray data show behavior similar to that previously reported. The fluctuations in the measured high energy flux are as large as a factor of 4 on time scales as short as 1.9 hours. The low energy data (3–6 keV) show no variability greater than a factor of 2. Because of the size of the uncertainties on the high energy data, however, we cannot state unequivocally that there are larger fluctuations of the source flux in that energy range than at the lower energies as previously suggested by Agrawal *et al.* (1969). Our results are, however, consistent with such a hypothesis. 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.* (1976*b*); i.e., the number of counts in any one time bin seems to be related to the number in the previous bin, a behavior 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 § IV. 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 behavior 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 behavior, the probability of correlation varying between 30% and 60%.

VII. DISCUSSION

The X-ray source Scorpius X-1 is 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

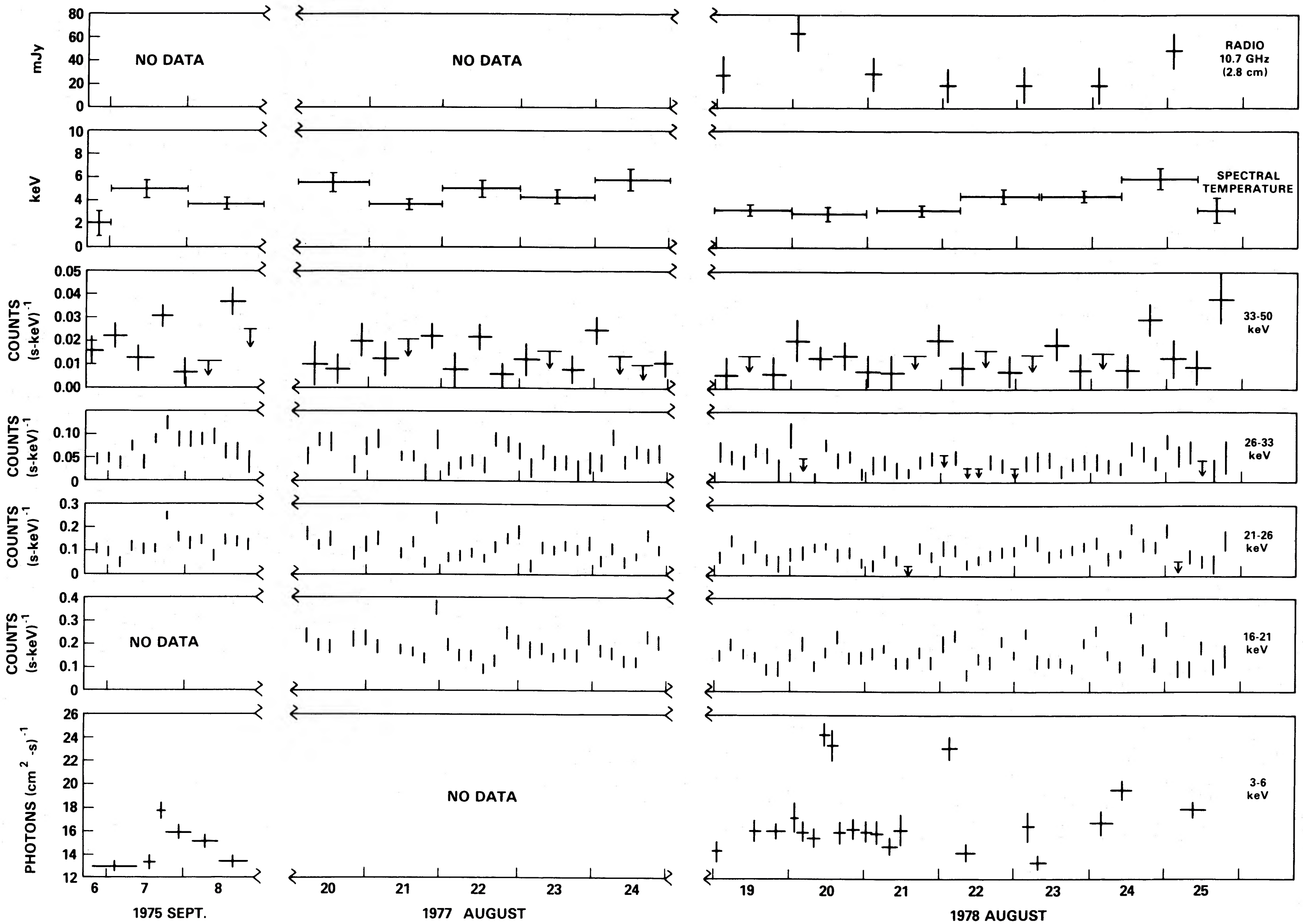

FIG. 5.—The summary of X-ray and radio observations carried out in 1975, 1977, and 1978. The 3–6 keV data come from the All Sky Monitor experiment on *Ariel 5* (Holt, private communication). The data in the range 16–50 keV come from the present *OSO 8* experiment, and the radio measurements from the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

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 behavior 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 behavior 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.

While the large uncertainties in the observed rate from Sco X-1 limit measurements of source variability, the results are consistent with larger variations in the higher energy flux than in the low energy emission. Holt *et al.* (1976*b*) have put forward a model involving 200 flares per day emitting in the 3–6 keV energy range. One possible interpretation of the increasing variability with energy may be a decreasing frequency of higher temperature flares.

The results presented here show that the high energy tail on the Sco X-1 spectrum is not likely to be a permanent feature, at least not at the intensities previously reported. Such a hard tail to the spectrum did not exist at the intensity measured by Haymes *et al.* (1972) for more than 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 data from 15 days of observation are insufficient to establish the existence of any such modulation in view of the asynchronous variability of the flux and the "apparent coherence" lasting several hours shown originally by Holt *et al.* (1976*b*). Long-term observations of the high energy component when it is at the level reported by Haymes *et al.* (1972) may 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. Superposed on that continuum we have a variable hard X-ray component, possibly modulated with the binary period, and arising from a hot spot in the accretion disk.

We are grateful to Dr. Steve Holt for providing data from the All Sky Monitor experiment on *Ariel 5* prior to publication.

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