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Simultaneous X-Ray and Optical Observations of the Flaring X-Ray Source, Aquila X-1

Principal Investigator: Prof. C. S. Bowyer
Co-Experimenter: Dr. Philip A. Charles

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1. Summary

Under support of NASA contract NSG 5292 we were highly successful in discovering and studying a massive X-ray and optical outburst from the "recurrent transient" Aquila X-1. The outburst lasted for almost 2 months during which time we obtained spectroscopic, photometric, photographic and polarimetric observations of our optical counterpart. The Copernicus observations also demonstrated spectral similarities to Sco X-1 as well as observing a strong flare during the decay phase of the outburst. All our observations were able to show that, contrary to a previous suggestion, this object can be interpreted as a dwarf binary system using the semidetached Roche lobe model.

In addition this grant enabled us to perform simultaneous X-ray and optical observations of the burster MXB 1735-44. These results showed "Sco X-1" type variability, the first instance of such behavior in a burster and which has important consequences for models of X-ray bursts.

2. The Study of the 1978 Outburst from Aquila X-1

After our discovery of the optical counterpart of Aql X-1 in 1977 (Thorstensen, Charles and Bowyer, 1978, Ap. J., 220, L131, hereafter TCB) we set up an international group of optical and X-ray observers in order to detect the next outburst at the earliest possible opportunity. Our efforts were rewarded in June 1978 when the Ariel V All-Sky Monitor detected an X-ray transient in the Aquila-Serpeus region. Copernicus quickly verified, with its smaller field of view, that Aql X-1 was responsible for the emission. We then set our program of observations into motion which yielded the following results:

(a) X-ray Observations

The All-Sky Monitor delineated the overall light curve of the outburst (Figure 1 of attached paper) which was more intense and lasted longer than any previous event. Copernicus and SAS-3 also observed Aql X-1 during the outburst and clearly showed the "Sco X-1" type X-ray temperature-intensity correlation. In addition, Copernicus discovered one very large flare, approximately one month after maximum, that had a risetime of < 10 secs. and decayed within 12 hours to its previous level.

(b) Photometric Observations

Many photographic and photoelectric measurements were made throughout the outburst showing that the optical intensity peaked at $V \simeq 14.8$ where it was distinctly blue ($U-B \sim -0.4$) and then reddened during the decay. A series of long photometric runs at USNO revealed rapid flickering on timescales of ∿1-4 minutes (Figure 8) very similar to the SAS-3 X-ray data. The level of flickering decreased as the outburst decayed. No significant optical polarization was detected.

(c) Spectroscopic Observations

Since Aql X-1 only reached ∿15th magnitude at brightest, we could use only large telescopes to study the object. We were thus fortunate in being able to use our own 120" time at Lick and also arrange for other University of California astronomers to observe the object so as to obtain the maximum amount of coverage. Our summed spectrum (Figure 9) exhibited the classical "X-ray" emission lines of CIII/NIII λ4640-50 and HeII λ4686 as well as NIII λ4103 and Hα. Of considerable interest is the absence of these lines at the start of the outburst, analagous to the X-ray transient A0620-00.

(d) Interpretation

Since these optical observations were the most extensive ever made during an outburst we were able to combine these with the X-ray measurements in order to probe the nature of this system. It had been suggested earlier by Margon et al. (1978, Nature, 271, 633) that the X-ray to optical intensity ratio of this system (L_x/L_{opt}) implied, on the basis of the semidetached Roche lobe model, a mass ratio for the system greater than 100. As this is extremely unlikely they proposed discarding the model in this case, a result of considerable importance. However, Margon et al. could only estimate L_{opt} since simultaneous observations had never been performed throughout an outburst cycle. Our results then made it clear that L_x/L_{opt} was ∿10 times less than Margon et al. had assumed. Consequently, application of the semidetached Roche lobe model, under the assumption of X-ray heating of the normal star in a simple geometry, led to an acceptable mass ratio of ∿3.5.

From the distance estimate of ∿2 kpc (TCB) the X-ray luminosity is $\sim 10^{36} - 10^{37}$ erg s^{-1} and so the compact object could be either a white dwarf or a neutron star. The Sco X-1 type behavior supports the former, although none of these sources have yet been convincingly shown to contain white dwarfs. Certainly the X-ray and optical flickering is similar to Sco X-1 and in contrast to the extraordinarily smooth variations in A0620-00.

3. Secondary Observations: MXB1735-44.

One of the major advantages of our NASA-supported Copernicus guest observations has been our ability to capitalize on targets of opportunity. By informing UCL of our CTIO time in 1978 we were able to study MXB1735-44. This X-ray burster was optically identified by McClintock *et al*. (1978, Ap. J., 223, L75) and, as it is reasonably bright ($\sim 17^m$), we arranged for simultaneous X-ray observations with the Copernicus satellite. Our optical spectroscopy (with the 4m telescope) showed variable Hβ emission, a characteristic of Sco X-1 and further enhancing its similarity to Sco X-1 (already noted when discovered). The X-ray data also showed the well-known correlation of X-ray temperature and intensity in its variability that is a characteristic of the "Sco X-1 class" of sources. This is a particularly important result since the current model for this behavior involves spherical accretion onto a white dwarf while X-ray bursters are explained by thermonuclear flashes on the surface of a neutron star. So far, no model can provide both kinds of behavior. A paper describing these observations has been accepted for publication in Monthly Notices of the R.A.S. (copy attached).

4. Presentations at Scientific Meetings

(a) The 1978 Optical and X-ray Outburst of Aql X-1. Talk presented at High Energy Astrophysics Division of the AAS, September 1978, U.C. San Diego. Abstract published in BAAS, 10, 509, 1978.

(b) Optical Studies of 3 Galactic X-ray Sources. Talk presented at NATO Advanced Study Institute on Galactic X-ray Sources, June 1979, Cape Sounion, Greece. Abstract to be published in the meeting proceedings.

5. Papers Published Under Support of Grant NSG 5292 (copies attached).

(a) The 1978 X-ray and Optical Outburst of Aql X-1 (4U1908+00). P.A. Charles, J.R. Thorstensen, S. Bowyer, G.W. Clark, F.K. Li, J. van Paradijs, R. Remillard, S.S. Holt, L.J. Kaluzienski, V.T. Junkkarinen, R.C. Puetter, H.E. Smith, G.S. Pollard, P.W. Sanford, S. Tapia & F.J. Vrba. Submitted to Ap. J., July 1979.

(b) The Discovery of "Sco X-1 Type" Behavior from the X-ray Burster MXB1735-44. N.E. White, P.W. Sanford, P.A. Charles and J.R. Thorstensen. M.N.R.A.S. (in press) 1979.

THE 1978 X-RAY AND OPTICAL OUTBURST OF Aql X-1 (4U1908+00)

P.A. Charles, J.R. Thorstensen and S. Bowyer
Space Sciences Laboratory and Department of Astronomy
University of California, Berkeley

G.W. Clark, F.K. Li, J. van Paradijs and R. Remillard
Center for Space Research, Massachusetts Institute of Technology

S.S. Holt and L.J. Kaluzienski
NASA/Goddard Space Flight Center

V.T. Junkkarinen, R.C. Puetter and H.E. Smith
Department of Physics, University of California, San Diego

G.S. Pollard and P.W. Sanford
Mullard Space Science Laboratory, University College London

S. Tapia
Lunar and Planetary Laboratory, University of Arizona

F.J. Vrba
U.S. Naval Observatory, Flagstaff Station

Submitted to: The Astrophysical Journal

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Received: ____________________

ABSTRACT

During the summer of 1978 the "recurrent transient" X-ray source, Aquila X-1, underwent its first major outburst in two years. We present the results of extensive observations at X-ray and optical wavelengths throughout this event, which lasted for approximately two months. The peak X-ray luminosity was $\sim$ 1.3 times that of the Crab and exhibited spectral dependent flickering on timescales $\sim$ 5 minutes, which is similar to that of Sco X-1. In addition, one very large flare was observed approximately one month after maximum that also was correlated with spectral changes. This flare had a risetime of < 10s and decayed within 12 hours to its previous level. No regular variability was detected. The previously identified optical counterpart brightened from $V \sim 19$ to a peak of $V = 14.8$, where it was distinctly blue ($U-B \sim -0.4$), and then reddened during the decay. The spectrum exhibited the classical "X-ray" emission lines of CIII/NIII λ4640-50 and HeII λ4686 as well as NIII λ4103 and Hα, although no emission lines were detected at the start of the outburst.

These observations are interpreted in terms of a "standard" accretion disk model with particular emphasis on the similarities to Sco X-1 and other dwarf X-ray systems, although the transient nature of the system remains unexplained. We find that, contrary to an earlier suggestion, Aql X-1 can be described adequately by the semi-detached Roche lobe model and yields a mass ratio of $q \lesssim 3.5$.

Subject headings: stars: variables - x-rays: sources

I. INTRODUCTION

Aquila X-1 is one of the few X-ray sources that may provide a very important link between the transient X-ray sources and the "steady" sources. Its usefulness increased greatly after the recent optical identification (Thorstensen, Charles and Bowyer, 1978, hereafter TCB), which was made on the basis of the archival plate material assembled at Berkeley and an accurate location by SAS-3 (Doxsey et al., 1977). TCB studied the quiescent optical spectrum (which was that of a normal K star) and derived a distance of $\gtrsim$ 1.7 kpc, but it was clear that the source had to be studied during outburst in order to learn more about its nature. Unfortunately, its last major eruption occurred in June 1976 (Kaluzienski et al., 1977), although there was a "mini outburst" in January 1977 (Holt and Kaluzienski, 1977). A tentative 1.3-day binary period with an amplitude of 10% has been reported by Watson (1976) from observations with the Ariel V Sky Survey Instrument during the final decline phase of the 1975 outburst. Models of this source that utilize the time between outbursts (which had been thought to be quasi-regular at 435 ± 40 days, (Kaluzienski et al., 1977) must take into account the presence of the "mini outbursts" which occurred in January 1977 and March 1979 (Holt and Kaluzienski, 1977; 1979).

It was therefore with a view to detecting the next outburst as early as possible that, during the Aql X-1 observing season, we monitored the source both optically and at X-ray wavelengths. This program was rewarded with a very large X-ray outburst that began in mid-June 1978, coupled with a simultaneous optical brightening. We report here the coordinated observations undertaken during this outburst (X-rays in Section II; optical and radio in Sections III and IV) and briefly interpret these data (Section V) in terms of the standard binary X-ray models but with some recently suggested modifications.

II. X-RAY OBSERVATIONS

a) Ariel V All Sky Monitor

As with the previous major outburst of Aql X-1 (Kaluzienski et al., 1977), the start of the 1978 event was detected with the 3-6 keV All Sky Monitor (ASM) on the Ariel V satellite. (For a full description of the ASM, see Holt, 1976.) This was quickly confirmed by the Copernicus X-ray experiment (which, unlike the ASM, does not have any confusion problems with Ser X-1 (4U 1837+04); see Kaluzienski et al.) and reported by Charles, Holt and Sanford (1978). The ASM light curve is given in Figure 1. A comparison with Figure 1 of Kaluzienski et al. immediately demonstrated that this outburst reached a higher peak intensity and lasted longer than either the 1975 or 1976 events. The irregular variability that was present in these events is also evident in the 1978 outburst.

It should be noted that, as in previous ASM observations of Aql X-1 outbursts, there is no evidence for a precursor event such as that seen in several other X-ray transients (e.g., A 0620-00; Elvis et al., 1975), although this could be due to the limited sensitivity of the instrument. Manchanda (1977) presents marginal evidence for a precursor to the 1973 event but his result is crucially dependent on the assumed spectrum which, as we shall discuss below, varies considerably. The Copernicus observations of this outburst also suggest that Aql X-1 was "on" by June 14 at a level $\sim$ 1% of the main peak. However, all such observations must be interpreted cautiously because of potential contamination by Ser X-1 and/or MXB 1905+00. Two orbit ($\sim$ 3 hour) integrations of the data obtained over the decay portion of the flare light curve were searched for the 1.3 day periodicity observed by Ariel V. Utilization of the standard folding technique (variation of χ^2 vs trial period) yielded no statistically significant modulation in the vicinity of this period (fractional sinusoidal amplitude $\lesssim$ 10%). We note that this upper limit is consistent with the level of modulation reported by Watson ($\sim$ 10%) and with the results of earlier searches of the 1975 and 1976 ASM flare data (Kaluzienski et al.).

b) SAS-3

Shortly after the start of the outburst, Aql X-1 was observed with the SAS-3 X-ray observatory, from June 25.0 UT to June 27.5 UT. The source was observed with the Horizontal Tube Detector System (Buff et al., 1977; Lewin et al., 1976), and was continually held within the field of view (1.7° FWHM). We have analyzed count rates recorded in the 1-3, 3-6 and 6-12 keV energy channels. The energy flux density (ergs cm^{-2} sec^{-1}) has been determined using a calibration of the count rate that was obtained from observations of the Crab Nebula. The accuracy of these flux density data is estimated to be $\sim$ 10 - 20%. In Figure 2 the variation of the X-ray flux is shown. The slow variability of the source by a factor $\lesssim$ 2 on a time scale of many hours is probably real, since the strength of the source is correlated with the count rate ratios as observed in the (1.3-3) keV / (3-6) keV and the (6-12) keV / (3-6) keV energy channels (see Figure 3).

In Figure 4 the raw counting rates of two satellite orbits of data on Aql X-1 are shown. This is illustrative of the irregular flickering on a time scale of 5 to 10 minutes and at a level of ∿ 15% that characterized this observation. The short-term variability in the three energy channels is clearly correlated, with the greatest modulation being at the highest energies.

This correlation is in the same sense as that observed by Mason _et al_. (1976) for Sco X-1 and other sources. The 2.5 day observing period on Aql X-1 is too short to confirm the 1.3 day period proposed by Watson (1976) through Fourier analysis of the data. No evidence for eclipses was found in the data.

c) OAO Copernicus

The Mullard Space Science Laboratory's 3-9 keV X-ray proportional counter onboard _Copernicus_ was used to make several short observations during the outburst. These mean intensities are also plotted in Figure 1. After confirming the start of the outburst, several observations (necessarily short because of satellite viewing constraints) with higher time resolution (4.9 seconds) were made in order to search for rapid variability. This resulted in the discovery of a large flare that occurred on 1978 August 8 at 0029 UT and is displayed in Figure 5a.

The rapid rise (< 10s) is indicated by the individual 4.9s count rates (see Figure 5b), while the overall intensity level did not return to its pre-flare level for ∿ 12 hours. The spectral behavior of this event is also illustrated in Figure 5a as the hardness ratio (ratio of 6-9 keV counts to 3-6 keV counts) and is of particular interest. As the intensity increases so does the hardness ratio, a similar correlation to that seen in the SAS-3 data discussed above, also on a timescale of ∿ hours. We have investigated this phenomenon further by summing all the Aql X-1 Copernicus observations into intensity bins, and then fitting an exponential plus gaunt factor spectrum (with N_x fixed at its average value of 2.10^{22} cm^{-2}) so as to derive a temperature for each bin. The results of this calculation are shown in Figure 6 where a luminosity-temperature* correlation is now well established.

II. OPTICAL OBSERVATIONS

a) Photometry

Photometric observations, both photographic and photoelectric, were made of Aql X-1 throughout the outburst, the results of which are displayed in Figure 7. The photographic work was carried out with the 76 cm reflector of Leuschner Observatory (and announced by Walter et al., 1978) and the 91 cm Crossley reflector at Lick Observatory.

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*Note that the word "temperature" is used here as a way to describe an observed correlation in the data; it should not be taken as implying any information regarding the physical processes occurring in the source since power law spectra provide equally good fits.

The photoelectric observations were carried out with the 100 cm reflector at USNO (Vrba, 1978). A journal of these observations and results is given in Table 1. Note the color changes after the peak brightness. Of particular interest is the result of unfiltered photoelectric photometry that showed significant variability ($\sim$ 0.05-0.2 magnitudes) on timescales of $\sim$ 1-4 minutes. This monitoring of Aql X-1 occurred under photometric conditions on 1978 July 2, 3 and 4 UT for periods of 2.0, 1.5 and 3.0 hours, respectively. Figure 8 represents segments of these observations, smoothed so as to illustrate the longer timescales of variability (the instantaneous signal to noise being $\sim$ 10). On July 2, Aql X-1 showed significant variations over a few minutes and on longer timescales during the course of the monitoring. This is very similar to the X-ray flickering shown in Figures 2 and 4 and the optical and X-ray variability may be related as in Sco X-1 (White et al., 1976). There is some evidence for occasional, marginally significant variations (especially in the third frame) on July 3, whereas by July 4 there is no evidence for any variability during the 3-hour observation. Unfortunately, satellite constraints precluded simultaneous X-ray observations.

All the data presented in Figure 8 was taken with an unfiltered detector. However, at the time of the filter photometry of Aql X-1 on July 2 we also measured the signal unfiltered. On this basis we can estimate the brightness at any point in time during the monitoring, assuming that the ratio of unfiltered to filtered flux remained constant. We therefore estimate that Aql X-1 ranged in brightness on this night from a maximum of $V = 14.6$ to a minimum of $V = 15.1$.

b) Polarization

In addition to the photometric data, polarization measurements were made with the 154 cm telescope of the Lunar and Planetary Laboratory (Tapia, 1978) and yielded a linear polarization for Aql X-1 of 1.3 ± 0.5% (at position angle 71°) during a 5-minute run on July 5 (JD 2443694.84). This is consistent with that expected from interstellar polarization (Hall, 1958) as was evidenced by a similar linear polarization observed in the star HD 177752, which is approximately 1°.3 away from Aql X-1. However, it should also be noted that some marginally significant linear polarization "flickering" was observed on July 5. The run immediately after the one quoted above gave a mean of 2.3 ± 0.5%, but the limited statistics suggest that this result should be treated with caution. In order to search for possible variability, another observation of Aql X-1 on July 13 gave a polarization of 1.5 ± 0.4% (at 75° p.a.). All observations of circular polarization yielded upper limits of 1 ± 0.5%.

c) Spectroscopy

Most of the spectroscopic information reported here was obtained with the Image Tube Scanner (ITS; Robinson and Wampler, 1972) at the Cassegrain focus of the Lick 3m Shane telescope. In addition, some spectra from early in the outburst were obtained with the McGraw-Hill 1.3m reflector and ITS (Shectman and Hiltner, 1976). A journal of these observations and a description of the main spectral features are given in Table 2. It is interesting to note the absence of spectral features during the rise to peak intensity (van Paradijs and Remillard, 1978) followed by the development of the "classical X-ray" emission lines of the CIII-NIII λ4640-50 blend and HeII λ4686 (Puetter and Smith, 1978).

Figure 9 shows the sum of all the Lick spectra taken during July when the source was brightest. Several points should be noted:

(i) the absence of any late type features, such as the Mgb blend (λ5175), that characterize the quiescent spectrum (TCB).

(ii) the absence of any Hβ (emission or absorption), although weak absorption is present on one night's spectrum,

(iii) the strongest emission lines of λ4640 and λ4686 mentioned above,

(iv) the emission line at λ4103 is almost certainly the NIII line produced by the Bowen mechanism (see e.g. McClintock et al., 1975, 1978; Margon and Cohen, 1978); this line can be severely blended with Hδ but the absence of Hβ and Hγ argues against this.

IV. RADIO OBSERVATIONS

Radio observations during the outburst yielded only upper limits. Hjellming (1978, private communication) obtained a 2σ upper limit of 1 mJy in mid-July while Johnson and Thompson (1978, private communication) set a limit of 0.5 mJy to any point source at this location on August 18.

V. DISCUSSION

On the basis of its quiescent spectrum and colors TCB interpreted Aql X-1 as an ∿ 1 $M_\odot$ compact object accreting from a "normal" KOV star. The standard semidetached Roche lobe model was used in these calculations, an assumption which was challenged by Margon et al. (1978) because of the large mass ratio that Margon et al. derived from this model as a result of their high calculated ratio of L_x/L_{opt} ($\sim$ 500-5000). We will now re-examine Aql X-1 in the light of the extensive data obtained during this outburst, the first to have complete optical, as well as X-ray, coverage.

The ASM data show that the peak X-ray intensity was $\sim$ 1.3 times that of the Crab, or 2.2×10^{-8} erg cm^{-2} s^{-1} (in the 2-10 keV band). The brightest optical magnitude (Table 1) is V = 14.8 which, assuming an interstellar extinction correction $A_V \sim 2^m$ and (conservatively) a bolometric correction of -0.2 (for a K0 star; Allen, 1973), implies a peak bolometric optical intensity of 2.3×10^{-10} erg cm^{-2} s^{-1}. Hence the ratio $L_x/L_{opt} \sim 95$, which is approximately one to two orders of magnitude less than the value derived by Margon et al. Since the X-ray intensity was known accurately during previous outbursts, the discrepancy between our result and theirs can be ascribed almost completely to a higher optical intensity than had been seen in any previous archival plate material (TCB) because of poor sampling.

If we take the simple geometrical approach that all the optical emission is due to the heated face of the normal star, then $L_{opt} \sim f\,\phi\,L_x$, where ϕ represents the fractional solid angle presented by the X-ray source to the normal star and f is the X-ray albedo. Now Paczynski (1971) gives $r_1/A = 0.46224\,(1 + q)^{-1/3}$ for mass ratios $q(= M_x/M_{opt}) \gtrsim 1$ in the case of the standard semidetached Roche model, where r_1 is the average Roche lobe radius of the optical star and A is the binary separation. Since we may write $r_1/A = 2\sqrt{\phi}$ then we derive the relation, $q = 0.012\,(fL_x/L_{opt})^{3/2} - 1$. Setting f = 0.5 yields q = 3.5, which is substantially smaller than the Margon _et al._ value of ∿ 100, a difference which is entirely due to the values taken for L_x/L_{opt}.

Additional factors that must be taken into account are:

(a) We have used the simplest form of the semidetached Roche lobe model which assumes isotropic X-ray irradiation. As pointed out by Milgrom (1978) on the basis of geometrical considerations alone there can be substantial shadowing effects when, as seems likely given the observed X-ray flickering, an accretion disk is present. This would act in a manner similar to f (i.e., the normal star would not see the full L_x) and so reduce the implied value of q.

(b) If, as seems likely, the effective temperature is greater than that of a KO star, then the B.C. would be substantially greater and hence increase the value of L_{opt}. Again this would act so as to reduce q.

We therefore prefer to use our data to set an upper limit to q of 3.5, and so we conclude that there are no substantive grounds for discarding the semidetached Roche model for Aql X-1 and that this result is compatible with the dwarf system outlined by TCB. If the 1.3 day periodicity noted by Watson (1976) represents the binary period of this system, and we take 0.5 $M_\odot$ for the mass of the normal star then our upper limit for q implies a binary separation $< 6.6\ R_\odot$ and hence $r_1 < 1.8\ R_\odot$ (a size of this value would imply a distance approximately twice that given by TCB). However, the absence of a repeatable modulation at this period in our data suggests caution in such an interpretation. In addition, we must stress that if there is a disk present in the system which contributes a significant amount of the observed optical radiation during outburst, then our data do not allow us to estimate q.

The development of the optical spectrum of Aql X-1 exhibits considerable similarity to that of the intense X-ray transient A0620-00 (Gull et al., 1976, Oke & Greenstein, 1977), especially in the lack of any spectral features around the time of maximum (some comparisons may also be drawn with Nova Ophiuchi 1977; Griffiths et al., 1978). However, if our distance estimate for Aql X-1 is correct, then A0620-00 was at least ten times brighter than Aql X-1 at their respective peaks at both optical and X-ray wavelengths. Eachus et al. (1976) interpret A0620-00 as a recurrent nova, a model which accounts for one of its most puzzling features, namely the lack of short timescale ($\lesssim$ hours) X-ray variability (Doxsey et al., 1976) which argues against accretion onto a disk as the source of the emission. Aql X-1 does show irregular X-ray variability and moreover, with a luminosity of $\sim 10^{36}$ -10^{37} erg s^{-1}, we may employ either a white dwarf or a neutron star as the compact object. In addition, the flickering and flaring in Aql X-1 shows a luminosity-temperature correlation that is similar to that described by Kylafis and Lamb's (1979) model of spherical accretion onto a white dwarf, and hence, strengthens the relationship of Aql X-1 to Sco X-1. However, we note that an alternative explanation has recently been proposed by Lamb and Sanford (1979) in terms of a Compton scattered thermal bremsstrahlung spectrum, which does not require a white dwarf. These arguments also apply to A0620-00 since neither it nor Aql X-1 shows the absorption spectrum at maximum that is typical of recurrent or slow novae (Payne-Gaposchkin, 1964). If Aql X-1 does contain a white dwarf with a disk structure (line widths $\sim$ 4000 km s^{-1} in A0620-00 are taken by Oke and Greenstein as being due to Keplerian velocities within the disk as opposed to ejecta velocities in an expanding envelope) then it is a system that is very similar to a dwarf nova. The optical outburst range is comparable but the X-ray spectrum of Aql X-1 is much harder than those of known dwarf novae (see e.g. Mason et al., 1978 on U Gem) and their quiescent optical spectra are grossly dissimilar. In spite of the similarities, it is the transient nature of the source that, phenomenologically sets Aql X-1 apart from Sco X-1; the explanation of this behavior is the major remaining problem in understanding these sources.

A potentially sensitive diagnostic tool for further study of Aql X-1 is to search for X-ray emission during quiescent phases; if the recurrent nova model is applicable then there should be continuous accretion of material onto the white dwarf at a level capable of powering the X-ray source at some level (Doxsey et al., 1976). From presently available data, because of confusion problems with Ser X-1 and MXB 1905+00, an upper limit of only $\sim$ 10 UHURU Flux Units, or 1.7×10^{-10} erg cm^{-2} s^{-1} (2-10 keV), can be set for the quiescent X-ray intensity of Aql X-1. TCB give a quiescent V of 19.2 and, with the same assumptions as those above, we derive L_x/L_{opt} (quiescent) < 40. If it is near this upper limit any X-ray emission should still produce an optical emission line spectrum or at least a blue continuum, which is not observed by TCB. An improvement of this limit will require the results of a high spatial resolution observation of this region, such as will be conducted by the HEAO-2 satellite.

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REFERENCES

Allen, C.W., 1973. Astrophysical Quantities 3rd Edition, Athlone Press, London.

Buff, J. et al., 1977. Ap. J., 212, 768.

Charles, P., Holt, S.S., and Sanford, P., 1978. IAUC 3235.

Doxsey, R. et al., 1976. Ap. J., 203, L9.

Doxsey, R.E., Apparao, K.M.V., Bradt, H.V., Dower, R.G., and Jernigan, J.G., 1977. Nature, 269, 112.

Eachus, L., Wright, E. & Liller, W., 1976. Ap. J., 203, L17.

Griffiths, R.E. et al., 1978. Ap. J. (Letters), 221, L63.

Gull, T.R., York, D.G., Snow, T.P., and Henize, K.G., 1976. Ap. J., 206, 260.

Hall, J.S., 1958. Publ. U.S. Naval Obs. 2nd series, 7, 275.

Herbig, G.H., 1975. Ap. J., 196, 129.

Holt, S.S., 1976. Ap. Sp. Sci., 42, 123.

Holt, S.S., and Kaluzienski, L.J., 1977. IAUC 3031.

________________________________, 1979. IAUC 3342.

Kaluzienski, L.J., Holt, S.S., Boldt, E.A., and Serlemitsos, P.J., 1977. Nature, 265, 606.

Kylafis, N.D., and Lamb, D.Q., 1979. Ap. J. (Letters), 228, L105.

Lewin, W.H.G. et al., 1976. Ap. J., 207, L95.

Manchanda, R.K., 1977. Ap. Sp. Sci., 51, 501.

Margon, B. and Cohen, J., 1978. Ap. J., 222, L33.

Margon, B., Katz, J.I., and Petro, L.D., 1978. Nature, 271, 633.

Mason, K.O., Charles, P.A., White, N.E., Culhane, J.L., Sanford, P.W., and Strong, K.T., 1978. M.N.R.A.S., 177, 513.

Mason, K.O., Lampton, M., Charles, P., and Bowyer, S., 1978. Ap. J. (Letters), 226, L129.

References Cont.

McClintock, J.E., Canizares, C.R. and Backman, D.E., 1978. Ap. J., 223, L75.

McClintock, J.E., Canizares, C.R., and Tarter, C.B., 1975. Ap. J., 198, 641.

Milgrom, M., 1978. Astr. Astrophys., 67, L25.

Oke, J.B., and Greenstein, J.L., 1977. Ap. J., 211, 872.

Paczynski, B., 1971. Ann. Rev. Astr. Ap., 9, 183.

Payne-Gaposchkin, C., 1964. The Galactic Novae (New York: Dover).

Puetter, R.C., and Smith, H.E., 1978. IAUC 3243.

Robinson, L.B., Wampler, E.J., 1972. Publ. A.S.P., 84, 161.

Shectman, S. and Hiltner, W.A., 1976. Publ. A.S.P., 88, 960.

Smith, H.E., 1975. Ap. J., 199, 591.

Tapia, S., 1978. IAUC 3243.

Thorstensen, J.R., Charles, P.A., and Bowyer, S., 1978. Ap. J. (Letters) 220, L131 (TCB).

van Paradijs, J., and Remillard, R., 1978. IAUC 3243.

Vrba, F.J., 1978. IAUC 3243.

Walter, F., Charles, P., Thorstensen, J., and Bowyer, S., 1978. IAUC 3243.

Watson, M.G., 1976. M.N.R.A.S., 176, 19P.

White, N.E., Mason, K.O., Sanford, P.W., Ilovaisky, S.A. and Chevalier, C., 1976. M.N.R.A.S., 176, 91.

TABLE 1: Photometry of Aql X-1 at USNO

Julian Date	V	B-V	U-B
2443691.82	14.82	+1.47	-
2443692.82	15.69	+0.89	-
2443693.81	15.70	+0.73	-
2443695.77	16.08	+0.45	-0.41
2443696.84	16.13	+0.58	-0.38
2443702.81	16.01	+0.55	-0.11

TABLE 2: Spectroscopic Observations

		E.W. of Features (Å)$^{+}$				
Date 1978 UT	Obs.*	4640/50	4686	$H\beta$	$H\alpha$	Notes
June 25	vPR	<1.5	<1.5	<1.5	-	
June 26	vPR	<1.3	<1.3	<1.3	-	
June 30 & July 1	SP	2.6	1.5	<0.3	<2	
July 3	M	<2	<1.5	<1.5	-	
July 4	M	2.7	1.2	<0.6	-	
July 10	BJ	1.3	0.9	-0.7	-	
July 11	BJ	1.9	1.9	0.5	-	
July 12	BCT	1.8	1.2	<0.3	-	
July 14	BCT	2.2	1.0	<0.3	-	
July 15	BCT	2.8	2.8	<0.9	2.9	(1)
Aug 2	S	<0.6	0.9	<0.6	-	(2)
Aug 7	BCT	<1	<1	<1	-	

(1) λ4640 & 4686 features confirmed at this level by McCall and Uomoto (1978, private communication) using McDonald 2.1m on July 15.

(2) Observations by Mook and Kurtz (1978, private communication) on July 29 gave upper limits to the emission lines consistent with these observations.

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*BCT = Bowyer, Charles & Thorstensen (Lick 3m.)
BJ = Burbidge & Junkkarinen (Lick 3m.)
vPR = van Paradijs & Remillard (McGraw-Hill)
M = Miller (Lick 3m.)
SP = Smith and Puetter (Lick 3m.)
S = Spinrad (Lick 3m.)

$^{+}$positive = emission
negative = absorption

FIGURE CAPTIONS

Fig. 1: The overall X-ray light curve of Aql X-1 during the 1978 outburst as recorded by the Ariel V All-Sky Monitor in the 3-6 keV energy range. Data points represent ∿ ½-day integrations in the instrument; coarse (filled circles), and fine (open circles) spatial resolution modes with corresponding 1σ statistical uncertainties. The crosses indicate the intensity during the Copernicus observations. The flare (dotted line) occurred on Aug 8 just after 0^h UT.

Fig. 2: The irregular X-ray variability of Aql X-1 is clearly demonstrated during this 2-day observation with the SAS-3 Horizontal Tube Detector. Each dot is an average over one satellite orbit (1.5 hours). The fluxes were computed by scaling with respect to the Crab Nebula and hence are accurate to ∿ 10-20%. Relative errors due to counting statistics are smaller than the size of the dots.

Fig. 3: (a) The X-ray spectral variability in Aql X-1 is here shown with the two hardness ratios HA/HB and HC/HB plotted against each other. The bands are defined by 1.3-3 keV (HA), 3-6 keV (HB) and 6-12 keV (HC). Each point is again derived from an average over one satellite orbit.

(b) The variation of the overall flux level with these spectral changes is evident in this plot of intensity against the hardness ratios as defined above. The plot of F against HC/HB should be compared to similar displays for the Sco X-1 type sources (Mason _et al._, 1976).

Figure Captions Cont.

Fig. 4: Two orbits of the raw SAS-3 counting rates during the observation of Aql X-1 early in the outburst. These data were taken with the 3-energy channel slat collimators and indicate the energy dependence of the irregular variability of Aql X-1 on timescales of ∿ 5-10 minutes. The line at ∿ 80 counts/13.3 s for the 6-12 keV data indicates the background rate. The background for the other channels is negligible on these scales.

Fig. 5: (a) Copernicus observations of a 3-9 keV flare from Aql X-1 approximately 6 weeks after the peak of the outburst. The spectral hardness ratio (see text) is shown plotted above the observed count rate and both are integrated in 20 min. intervals. The spectral change during the flare is evident.

(b) The very rapid commencement of the flare is here shown in a plot of the data using the highest time resolution (4.9 s). The risetime is less than 10 s.

Fig. 6: All the Copernicus X-ray observations of Aql X-1 during the outburst have been summed into this display of implied X-ray temperature against intensity (cf. Figure 3(b)). The column density was held fixed at 2.10^{22} cm^{-2}. The luminosity-temperature correlation is again clearly evident.

Fig. 7: Photometric magnitudes and colors of Aql X-1 obtained both photographically (Leuschner and Lick Observatories) and photoelectrically (USNO). Note the dramatic reddening of the source around the time of peak brightness.

Figure Captions Cont.

Fig. 8: Smoothed samples of unfiltered photoelectric monitoring of Aql X-1 at USNO selected from observations on 1978 July 2, 3 and 4 UT indicate the progressive reduction in activity during this period. The noise level is well represented by the July 4 data and emphasizes the considerable variability 2 days previously.

Fig. 9: Sum of all spectra taken of Aql X-1 with the Lick 3m ITS during July. All identifiable features are indicated. N/S refers to poorly subtracted night sky emission lines. The arrow at λ5400 points to a break in the spectrum that is not real. It is due to the red and blue portions of the spectrum being observed at different times when the source had varied in intensity.

AUTHORS' ADDRESSES

S. Bowyer, P.A. Charles & J.R. Thorstensen
Space Sciences Laboratory
University of California, Berkeley, CA 94720

G.W. Clark, F.K. Li, J. van Paradijs and R. Remillard
Center for Space Research
MIT
Cambridge, MA 02139

S.S. Holt
Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

L.J.Kaluzienski
Code SC-7, NASA Headquarters
Washington, D.C. 20546

G.S. Pollard & P.W. Sanford
Mullard Space Science Laboratory
Holmbury St. Mary, Dorking, Surrey
England

V.T. Junkkarinen, R.C. Puetter & H.E. Smith
Department of Physics, C-011
University of California, San Diego
La Jolla, CA 92093

S. Tapia
Lunar & Planetary Laboratory, University of Arizona
Tucson, AZ 85721

F.J. Vrba
U.S. Naval Observatory, Flagstaff Station
P.O. Box 1149
Flagstaff, AZ 86002

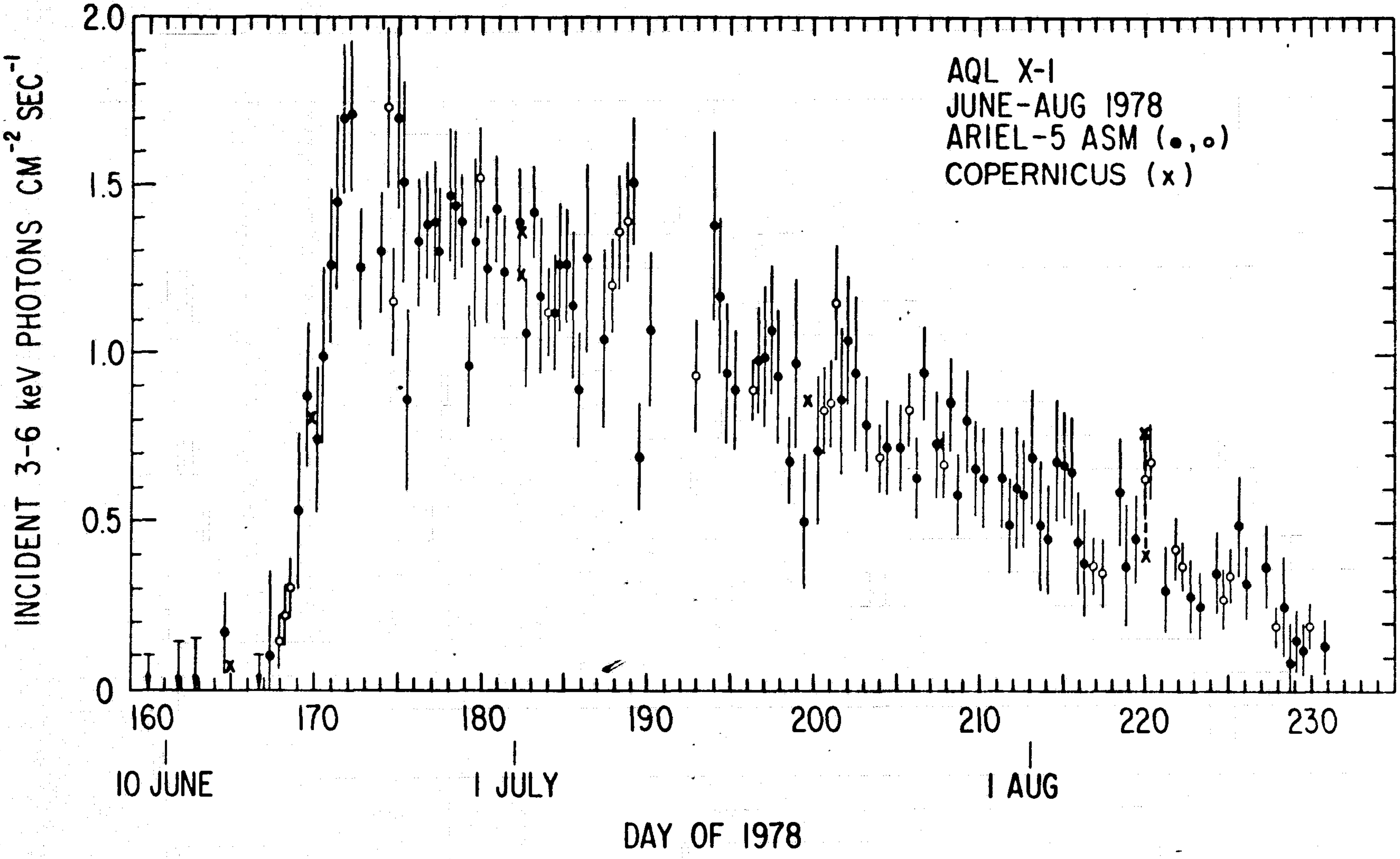
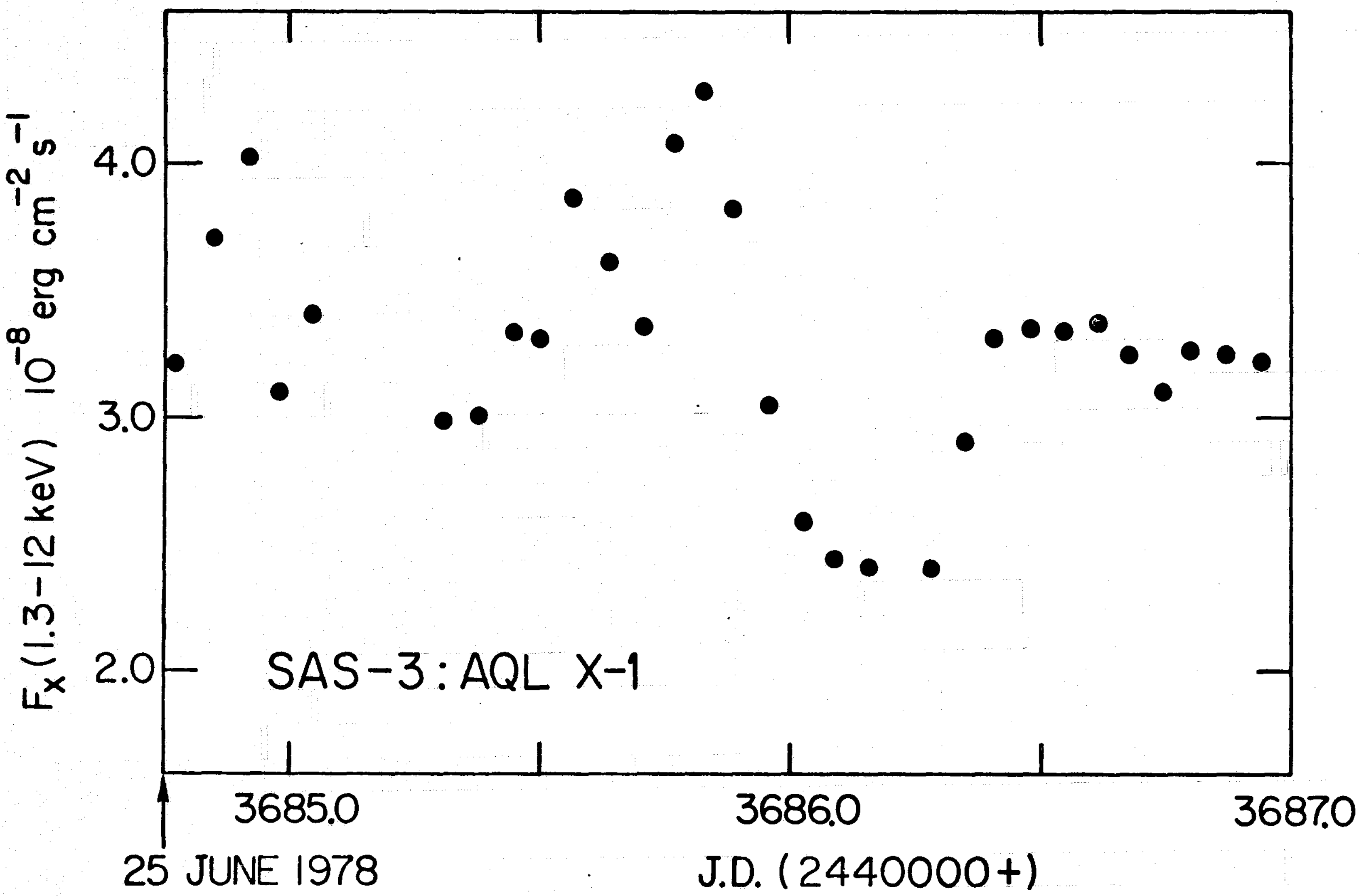

AQL X-1
JUNE-AUG 1978
ARIEL-5 ASM (●,○)
COPERNICUS (x)
INCIDENT 3-6 keV PHOTONS CM^{-2} SEC^{-1}
2.0
1.5
1.0
0.5
0
160
170
180
190
200
210
220
230
10 JUNE
1 JULY
1 AUG
DAY OF 1978

FIGURE 1



4.0
3.0
2.0
F_x (1.3–12 keV) 10^{-8} erg cm^{-2} s^{-1}
SAS-3 : AQL X-1
3685.0
3686.0
3687.0
25 JUNE 1978
J.D. (2440000+)

FIGURE 2

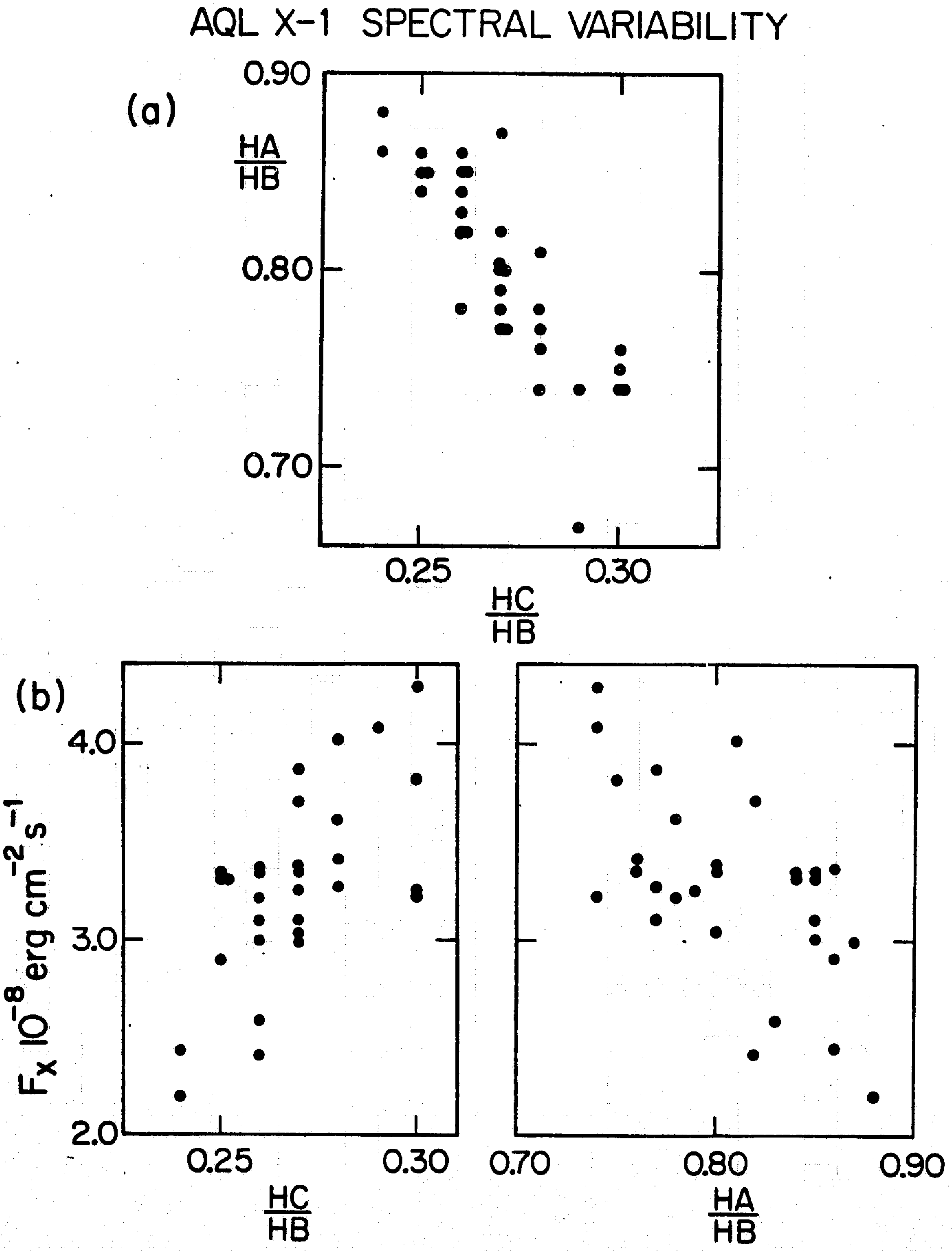

AQL X-1 SPECTRAL VARIABILITY
(a)
0.90
0.80
0.70
HA/HB
0.25
0.30
HC/HB
(b)
4.0
3.0
2.0
F_x 10^{-8} erg cm^{-2} s^{-1}
0.25
0.30
HC/HB
0.70
0.80
0.90
HA/HB

FIGURE 3

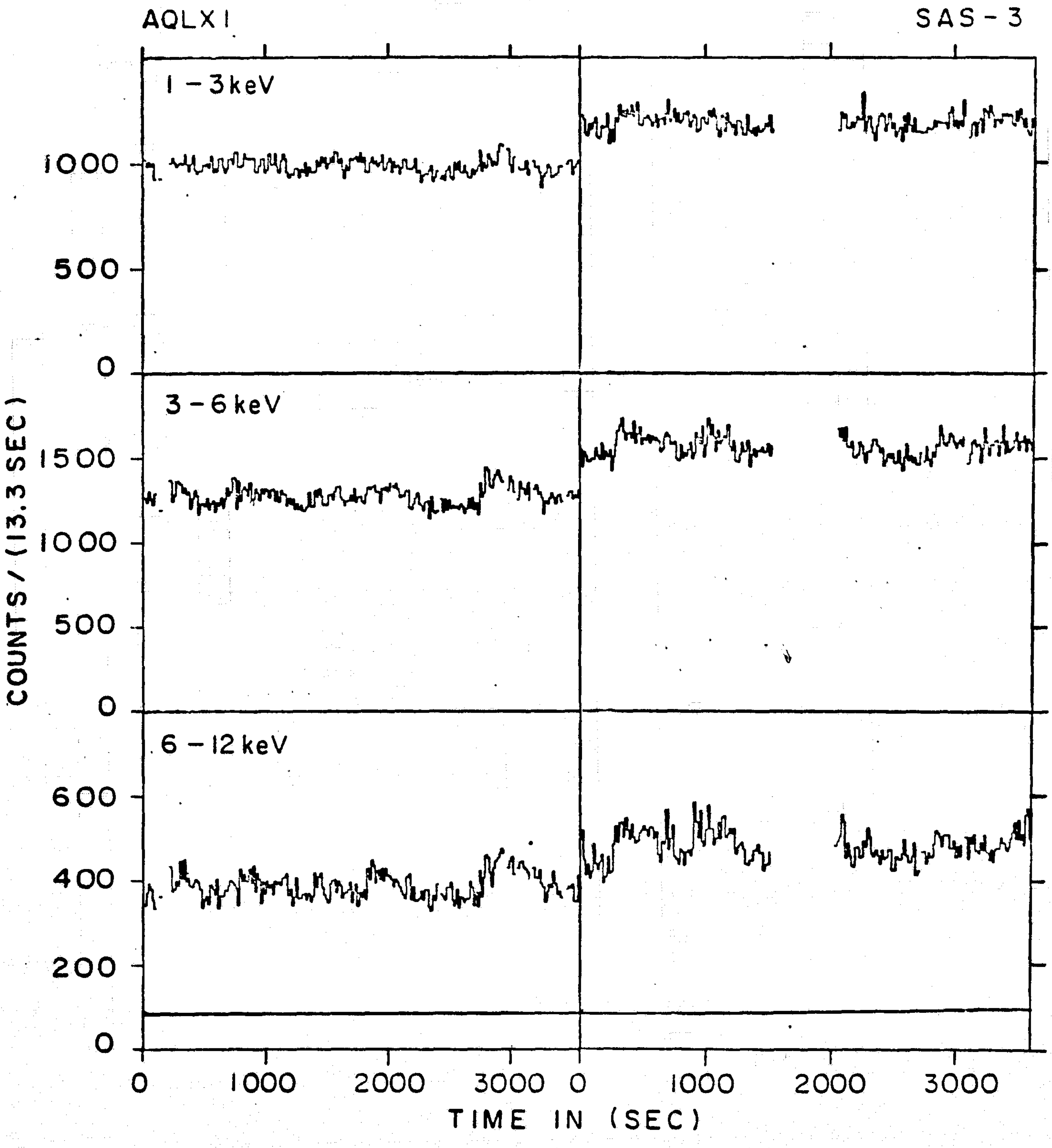
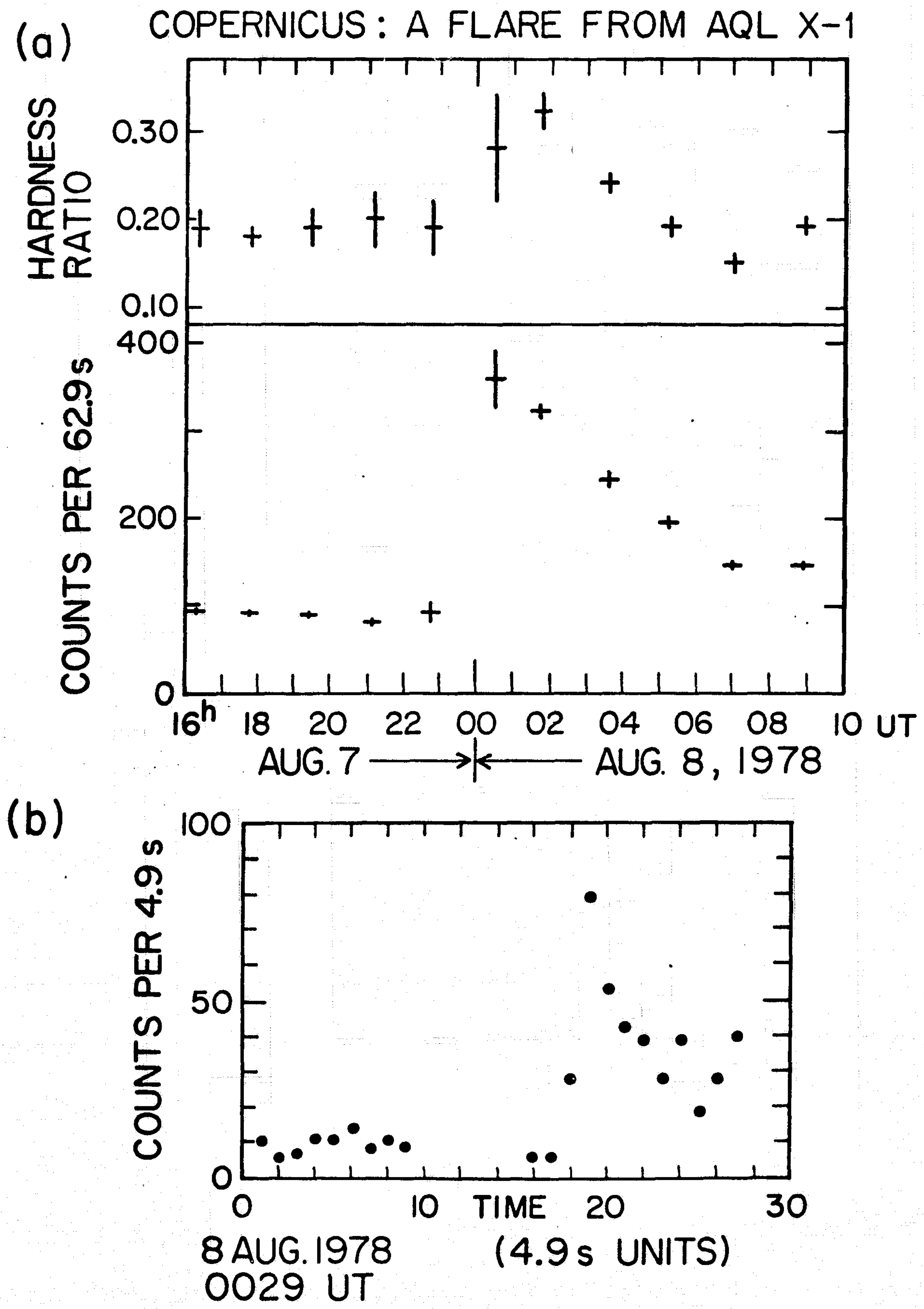

AQLX1
SAS-3
1 - 3 keV
3 - 6 keV
6 - 12 keV
1000
500
0
1500
1000
500
0
600
400
200
0
COUNTS / (13.3 SEC)
0
1000
2000
3000
0
1000
2000
3000
TIME IN (SEC)

FIGURE 4



COPERNICUS: A FLARE FROM AQL X-1

FIGURE 5

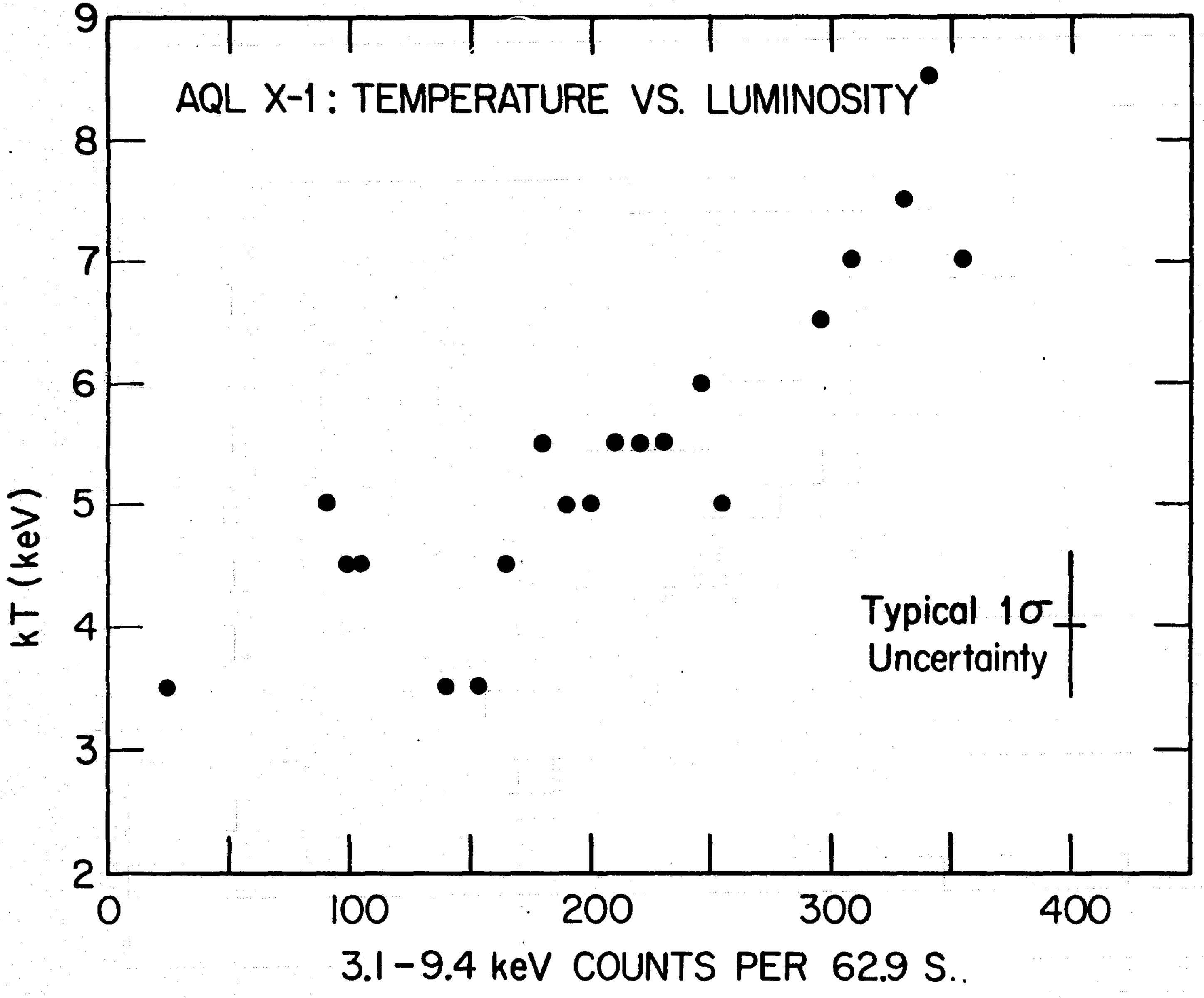
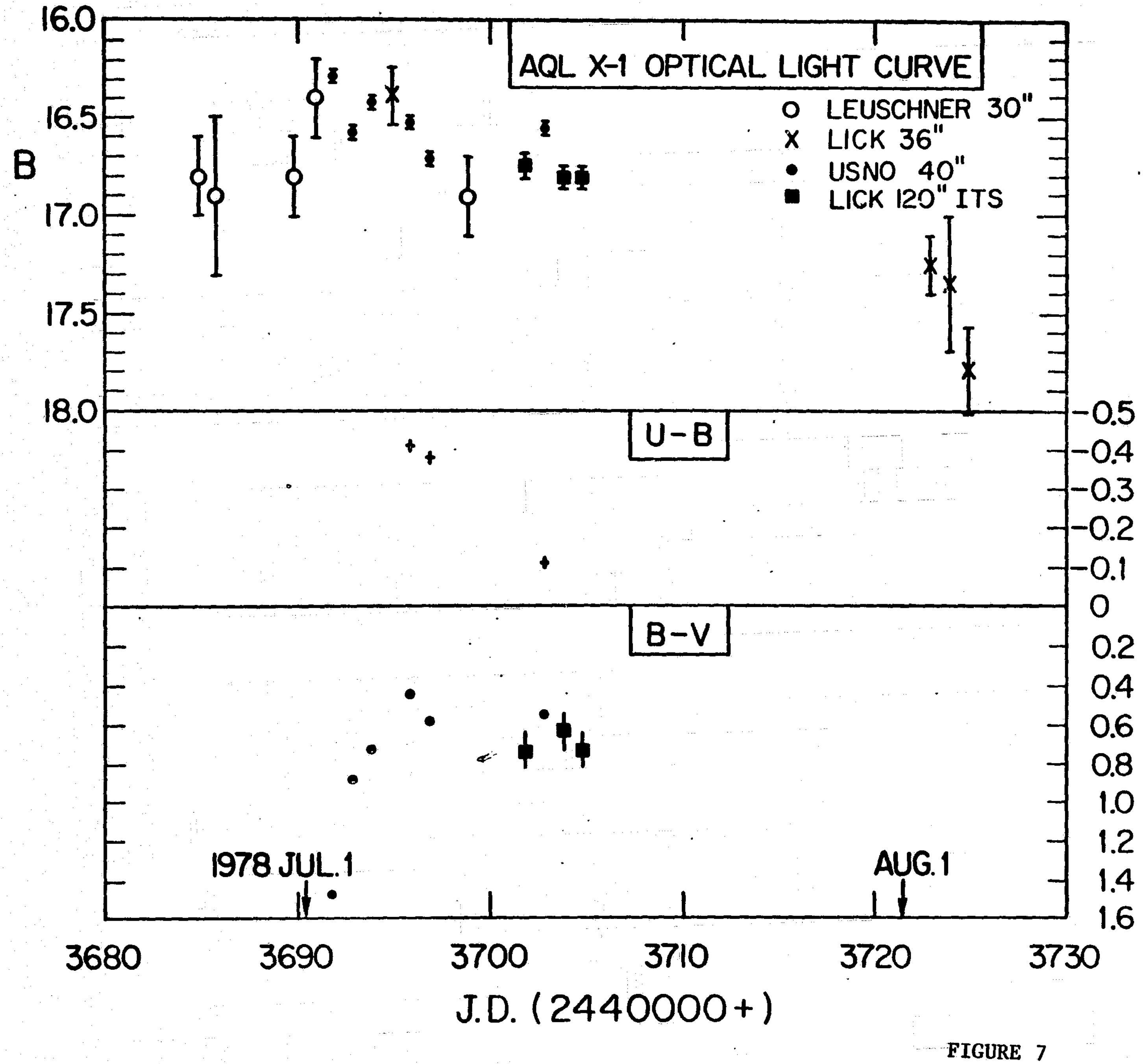

AQL X-1: TEMPERATURE VS. LUMINOSITY
kT (keV)
9
8
7
6
5
4
3
2
0
100
200
300
400
3.1-9.4 keV COUNTS PER 62.9 S.
Typical 1σ Uncertainty

FIGURE 6



AQL X-1 OPTICAL LIGHT CURVE
○ LEUSCHNER 30"
X LICK 36"
● USNO 40"
■ LICK 120" ITS
B
16.0
16.5
17.0
17.5
18.0
U−B
−0.5
−0.4
−0.3
−0.2
−0.1
0
B−V
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1978 JUL. 1
AUG. 1
3680
3690
3700
3710
3720
3730
J.D. (2440000+)

FIGURE 7

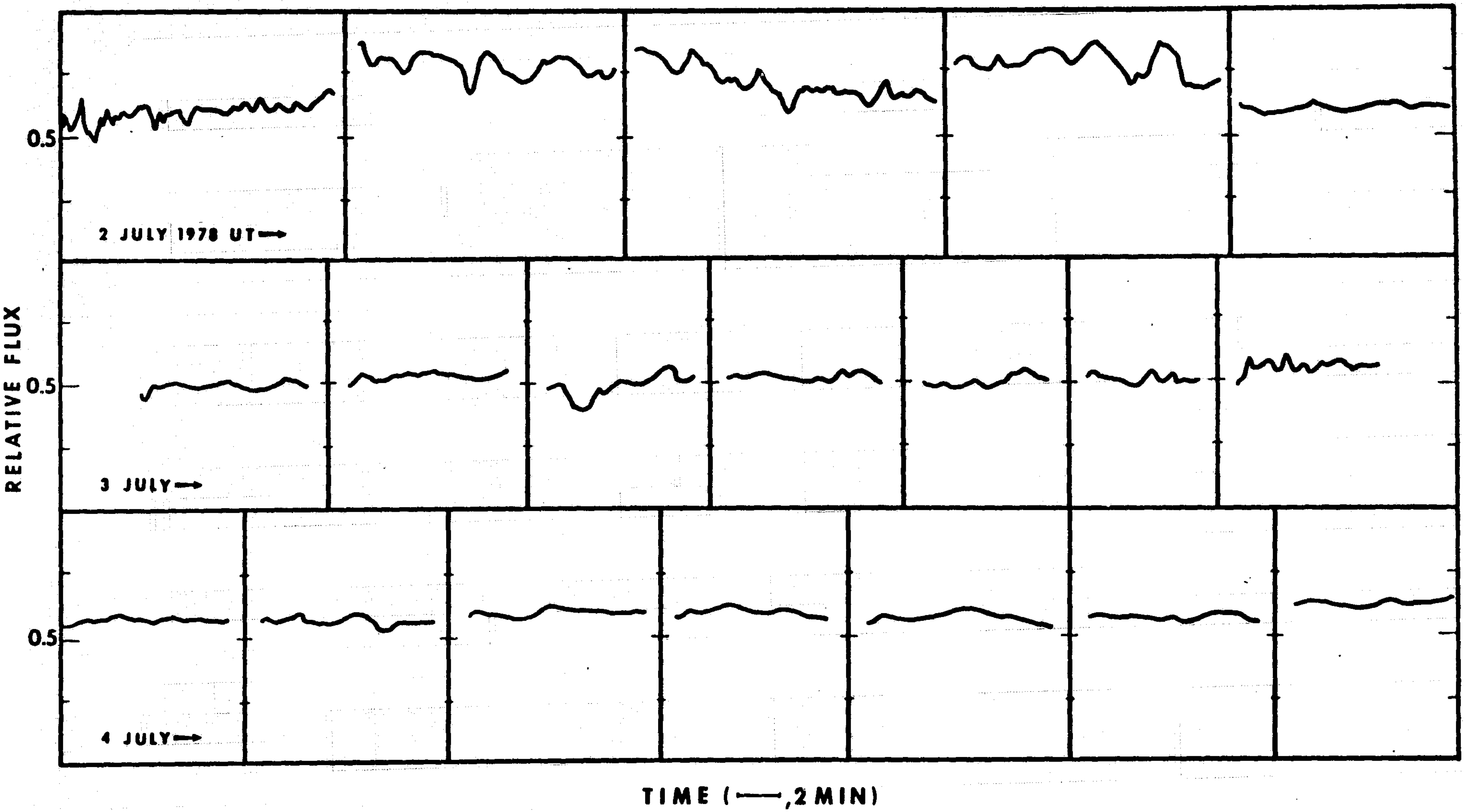


FIGURE 8

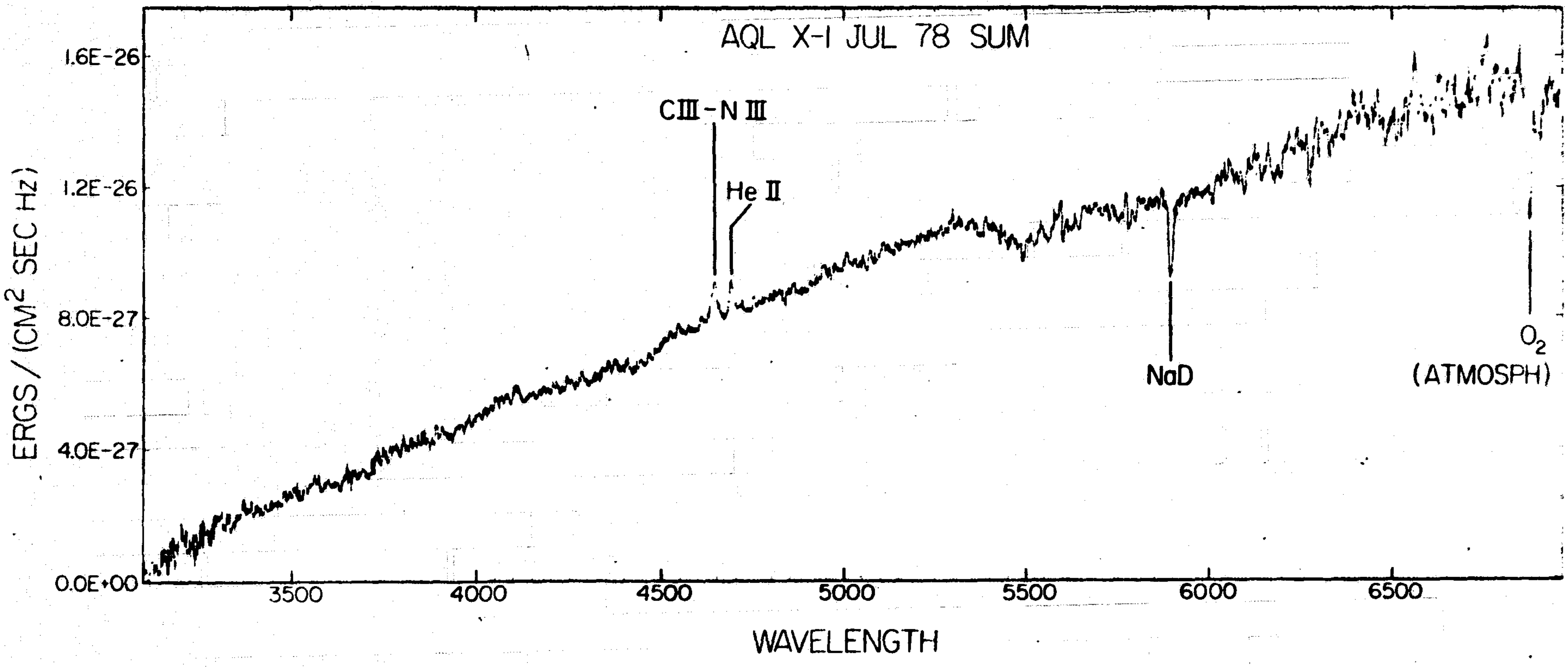

AQL X-I JUL 78 SUM
CIII - N III
He II
NaD
O_2
(ATMOSPH)
ERGS / (CM^2 SEC Hz)
1.6E-26
1.2E-26
8.0E-27
4.0E-27
0.0E+00
3500
4000
4500
5000
5500
6000
6500
WAVELENGTH

FIGURE 9

THE DISCOVERY OF "SCO X-1 TYPE" BEHAVIOR FROM THE X-RAY BURSTER 4U1735-44

N.E. White* and P.W. Sanford
Mullard Space Science Laboratory
University College London
Holmbury St. Mary, Dorking, Surrey
England

and

P.A. Charles[+o] and J.R. Thorstensen[+xo]
Space Sciences Laboratory[+]
and
Department of Astronomy[x]
University of California, Berkeley,
California 94720, U.S.A.

*Present address:
Code 661
Goddard Space Flight Center
Greenbelt, Maryland 20770, U.S.A.

[o] Visiting astronomers, Cerro Tololo Interamerican Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

SUMMARY

A series of Copernicus, Ariel V and optical observations of the X-ray burst source 4U1735-44 (= MXB 1735-44) revealed properties very similar to those of the "Sco X-1 like" sources. During one run, the non-burst X-ray flux varied by a factor of 2 on a timescale of hours and this was associated with a general hardening of the spectrum. The source was relatively constant throughout the remaining observations. An Ariel V spectrum obtained during a quiescent interval deviated from a simple thermal model in that it showed both a high energy deficiency and a low energy excess. Near simultaneous spectroscopy of the optical counterpart confirmed the general features reported by McClintock _et al_. Spectra taken on successive nights revealed the Hβ emission to be variable.

1. Introduction

The X-ray burster 4U1735-44 (=MXB 1735-44) has recently been optically identified by McClintock *et al*. (1978, hereafter MCB) with a faint (V = 17.5) blue star that exhibits spectral features and colors similar to those of V818 Sco, the optical counterpart of Sco X-1. The X-ray emission from Sco X-1 and several other similar sources is characterized by flaring intervals during which the X-ray temperature is found to be correlated with the intensity (White *et al*., 1976; Mason *et al*., 1976; White *et al*., 1978). Beyond the factor two variability reported by UHURU (Forman *et al*., 1978) and the X-ray bursts (Lewin *et al*., 1977), little is known about the spectral or temporal signature of 4U1735-44. We report here a series of X-ray observations of 4U1735-44 made in 1978 March and April wherein this source was found to exhibit similar features to those observed from other "Sco X-1 type" sources. Near simultaneous spectroscopic observations from CTIO of the optical counterpart are also presented.

2. X-Ray Observations

a. OAO-Copernicus

The 3.1-9.4 keV collimated proportional counter onboard Copernicus (Bowles *et al*., 1974) observed 4U1735-44 on two occasions in May 1978. The first observation on May 1 is presented in figure 1 with the data averaged over 15 minute intervals. The source flux varied by about a factor two on a timescale of hours. The spectral hardness ratio is also plotted in figure 1; this ratio is obtained from the 6 channels of pulse height analyser (PHA) information and is the ratio of the 6.3-9.5 keV intensity to the 3.0-6.3 keV intensity. It is clear that the flux changes are correlated with variations in the hardness ratio, there being an overall increase at approx. 12^h UT. We fitted the PHA data with a simple exponential plus gaunt factor spectrum and the resulting temperatures as a function of the observed intensity are shown in figure 2. For a factor two increase in flux the temperature increased from ∿ 7 keV to greater than 10 keV.

The second observation of 1 1/2 days duration started on May 11. The flux remained approximately constant at about the minimum seen on May 1. The X-ray temperature was ∿ 9 keV and also did not vary significantly. A typical temperature measured within one 12 hour interval is also plotted in figure 2 along with the range of flux variability seen throughout the whole observation.

b. Ariel V

The Ariel V proportional counter spectrometer (PCS) observed 4U1735-44 for three days in April 1978. The experiment was operated in two modes. Firstly, in spectral mode, 32 channels of PHA data were accumulated for ∿ 30% of each 100 min. orbit. Secondly, in pulsar mode we obtained 18 minutes of 0.5 s time resolution data every satellite orbit. No spectral information was available in this latter mode.

The mean 2-12 keV spectrum for the 2 days of spectral observations summed into 12 logarithmic energy channels is shown in figure 3. Neither a thermal plus gaunt factor or a power law model gave an acceptable fit to the data. In figure 3, the best fit thermal model is shown and two points are notable:

(i) there is a substantial low energy excess below 3 keV;

(ii) there is a high energy deficiency above 9 keV.

We have fitted the data in the 3-9 keV interval (the Copernicus energy range) and obtain an acceptable fit with a temperature of 8.5 ± 0.7 keV. The overall flux level during this observation was comparable with the minimum seen by Copernicus. There were no significant variations in intensity or spectrum throughout the Ariel V spectral observations.

The high time resolution observations lasted for one day, during which time one X-ray burst was detected (figure 4). The center of the 3°5 FWHM field of view is offset from the spin axis during these observations and it was thus 100% spin modulated with a period of ∿ 5 s. This can be clearly seen in figure 4. The overall modulation envelope shows some evidence that the steady flux from 4U1735-44 was about 50% lower prior to the burst, relative to that recorded after. The burst was at least 1/3 Crab in intensity and lasted no longer than ∿ 10 s. This is consistent with the events reported by Grindlay <u>et al</u>. (1978a). If a similar burst had been present in the Copernicus data, it would not have been detected.

c. Optical Observations

Spectroscopic observations of the MCB counterpart of 4U1735-44 were performed with the CTIO 4 m telescope and Ritchey-Chrétien spectrograph, digital readout being accomplished with a silicon intensified target (SIT) vidicon detector (see Osmer and Smith, 1976). The spectral resolution of this system was 20 Å over a wavelength range of ∿ 3500-6000 Å. Spectra were taken starting at 0909 UT May 2 (for 30 min.) and 0550 UT May 3 (for 60 min.), flux calibration being achieved (approximately) through observations of L 745-46A and L 930-80 (Oke, 1974). These spectra are displayed in figure 5. Unfortunately, conditions were not photometric on either night (there was some cirrus) and so we cannot comment on any night to night photometric variability or differences with the MCB total intensity. However, we do see spectral differences between the 2 nights and the MCB spectrum.

The relevant features are marked on figure 4 and, although the first night spectrum is at a poorer signal to noise ratio, the variability of the Hβ emission is noticeable. In addition, the CIII - NIII λ4640-50 blend appears weaker on the first night.

3. Discussion

The existence of a class of X-ray sources that exhibit behavior similar to that observed from Sco X-1 is now well established (Mason et al., 1976; White et al., 1978). MCB have pointed out the marked similarity in the spectra of the optical counterparts of 4U1735-44 and Sco X-1, although the apparent absence of Balmer emission has been considered possibly significant by Grindlay et al. (1978b). It is clear from our data that Balmer emission is not always absent; the reason for its variability remains unknown. If the Balmer emission strength is inversely correlated with the X-ray intensity (Mook et al., 1972), the resemblance between this object and Sco X-1 will be strengthened.

These Ariel V and Copernicus observations show that 4U1735-44 is also characterized by the two types of spectral and intensity behavior seen in the Sco X-1 type sources. Namely, (i) an active state which exhibits the characteristic X-ray temperature-intensity correlation, (ii) a quiescent state during which the temperature varies on a timescale of many hours to days over a comparable range to that seen in the active state but with little, if any, related change in intensity (White et al., 1978).

The X-ray variability of 4U1735-44 recorded by Copernicus on May 1 clearly falls into the former category. The other two observations were probably made during quiescent periods. The two unusual features of the X-ray spectrum have also been noted in other "Sco X-1 like" objects. A high energy deficiency when fitting a thermal model is a feature of all the "Sco X-1 like" sources for which Ariel V measurements have been made (a total of four). This phenomenon has been qualitatively interpreted either as the result of a very broad iron line emission at ∿ 7 keV (cf. Swank, 1977; Parsignault and Grindlay, 1978) or as the result of comptonization of an underlying thermal spectrum (cf. Felten and Rees, 1972; Illarianov and Sunyaev, 1972; Kylafis and Lamb, 1978). Low energy excesses have also been seen in two other "Sco X-1 like" sources: 4U0614+09 and Cyg X-2 (K.O. Mason, private communication; Branduardi, 1977).

Swank (1977) reported that the sources 4U1820-30, 4U1636-53 and 4U1837+04 (Ser X-1), all of which are associated with X-ray bursters, all display the correlation between X-ray temperature and intensity. Furthermore, Swank et al. (1978) observed one burst from the vicinity of 4U0614+09. The fact that 4U1735-44 is also a burster now provides further evidence for a link between these two enigmatic classes of X-ray sources: bursters and "Sco X-1 like" objects. Recent theoretical work (Kylafis and Lamb, 1978) suggests that many of the features of "Sco X-1 like" objects, in particular the observed temperature-luminosity correlation and the low energy excess, can be well accounted for by variable spherical accretion onto a white dwarf. However, current models for burst sources (type 1, cf. Lewin, 1978) involve thermonuclear flashes on the surface of a neutron star. At this time, these models appear fundamentally incompatible for explaining the "Sco X-1 like" bursters and we must await further theoretical developments.

Acknowledgements

We are grateful to Keith Mason and Jean Swank for useful discussions. The optical work reported here was supported by the National Science Foundation under grant AST78-06873.

References

Bowles, J. A., Patrick, T. J., Sheather, P. H., and Eiband, A. M., 1974, J. Phys. E. Sci. Inst. 7, 183.

Branduardi, G., 1977, Ph.D. thesis, University of London.

Felten, J. E. and Rees, M. J., 1972, Astr. Ap. 17, 226.

Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., and Giacconi, R., 1978, submitted to Ap. J. Suppl. Series (4U catalog).

Grindlay, J., McClintock, J., Canizares, C., and van Paradijs, J., 1978a, IAUC 3230.

Grindlay, J. E., Canizares, C., and McClintock, J.E., 1978b. B.A.A.S. 10, 515.

Illarianov, A. F. and Sunyaev, R. A., 1972, Soviet Astr. - A. J. 16, 45.

Kylafis, N. and Lamb, D., 1978, preprint.

Lewin, W.H.G., 1978, Invited talk at IAU/COSPAR Symposium on X-ray Astronomy, Innsbruck, Austria.

Lewin, W. H.G., Hoffman, J. A., Doty, J., Li, F. K. and McClintock, J. E., 1977 IAUC 3075.

Mason, K. O., Charles, P. A., White, N. E., Culhane, J. L., Sanford, P. W., and Strong, K T., 1976, MNRAS 177, 513.

McClintock, J. E., Canizares, C. R., and Backman, D. E., 1978, Ap. J. 223, L75.

Mook, D. E., Edwards, S. and Hiltner, W. A., 1972, Ap. J. 177, L63.

Oke, J. B., 1974, Ap. J. Suppl., 27, 21 (No. 236).

Osmer, P. O. and Smith, M. G., 1976, Ap..J. 210, 267.

Parsignault, D. R. and Grindlay, J. E., 1978, Ap. J. (in press).

Swank, J. H., 1977. Bulletin of the American Physical Soc., 22, 588.

Swank, J. H., Becker, R. H., Boldt, E. A., Holt, S. S., and Serlemitsos, P. J., 1978 MNRAS 182, 349.

White, N. E., Mason, K. O., Sanford, P. W., Ilovaisky, S. and Chevalier, C., 1976, MNRAS 176, 91.

White, N. E., Mason, K. O., Sanford, P. W., Johnson, H., Catura, R. C., 1978, Ap. J., 220, 600.

Figure Captions

Figure 1: (Lower) The 3-9 keV flux per 63 s recorded by Copernicus from 4U1735-44 and accumulated in time intervals of 15 min. (Upper) The spectral hardness ratio (defined in the text) during the same interval.

Figure 2: The 4U1735-44 X-ray temperature is plotted as a function of count rate, the error bars indicated are 2σ in total length. For the May 1-2 data the hydrogen column density was fixed at the mean value for the whole observation of $4 \times 10^{22} \mathrm{cm}^{-2}$ and was treated as an uninteresting parameter. For the May 11-13 measurement we used one typical temperature derived during an interval of 12 hours. The variation in count rate over the entire observation is shown by the width of the "diamond".

Figure 3: The X-ray spectrum of 4U1735-44 as measured by the Ariel V PCS. Note the low energy excess and apparent "break" at ∿ 8 keV.

Figure 4: Approximately 5 minutes of "pulsar" data from Ariel V on 1978 April during which an X-ray burst was detected from 4U1735-44. The continuous 5 s modulation of the data is due to the spin period of the spacecraft.

Figure 5: Spectra of the MCB counterpart of 4U1735-44 taken with the CTIO 4 m telescope on 1978 May 2 (upper curve) and May 3 (lower curve). Resolution is approximately 20 Å. Note the variation of Hβ, the possible variation of CIII-NIII λ4640-50 and HeII λ4103 compared to MCB. The feature labelled N/S is incomplete subtraction of the night sky emission line of oxygen at λ5577.

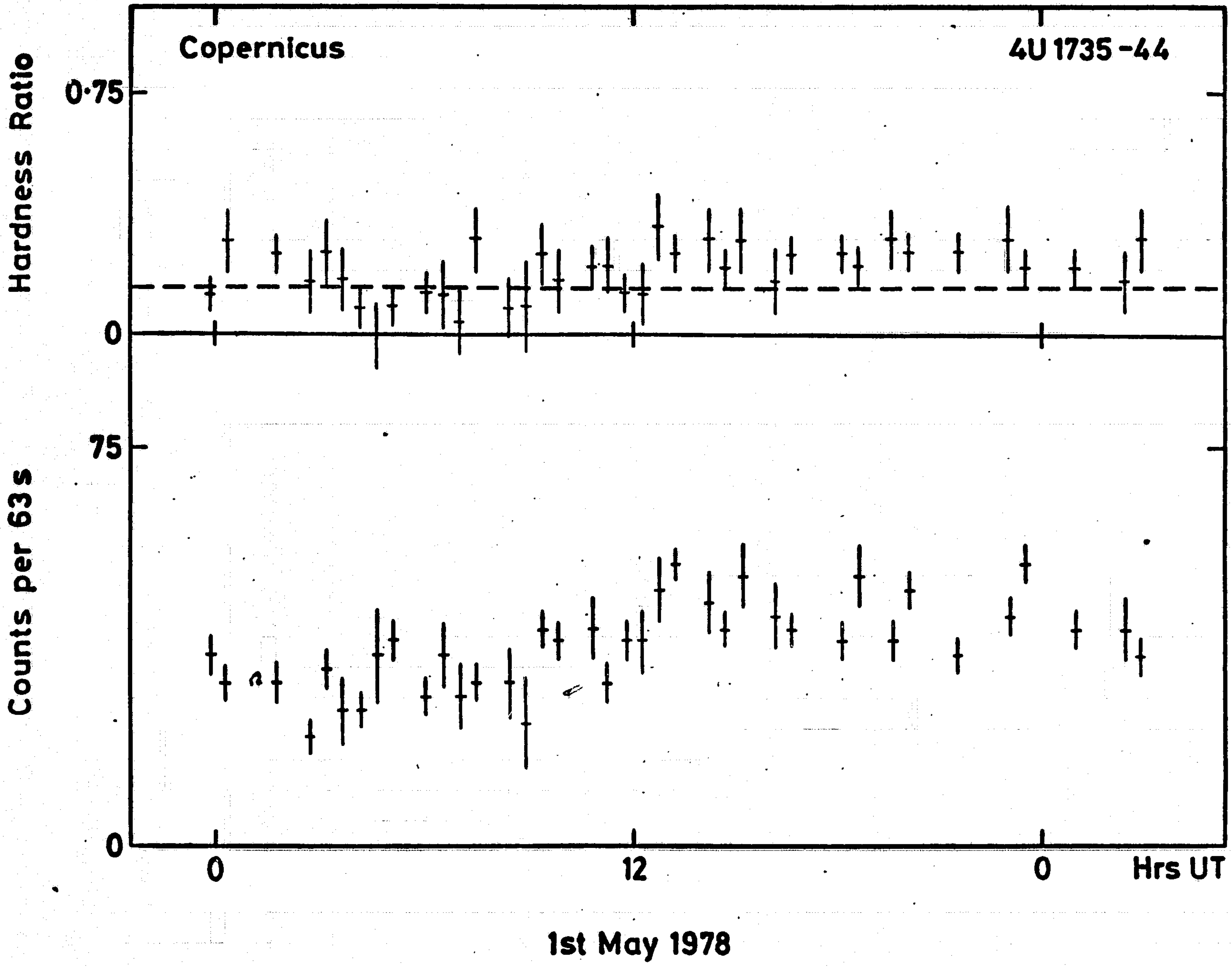

Copernicus
4U 1735-44
Hardness Ratio
0·75
0
Counts per 63 s
75
0
0
12
0
Hrs UT
1st May 1978

Figure 1

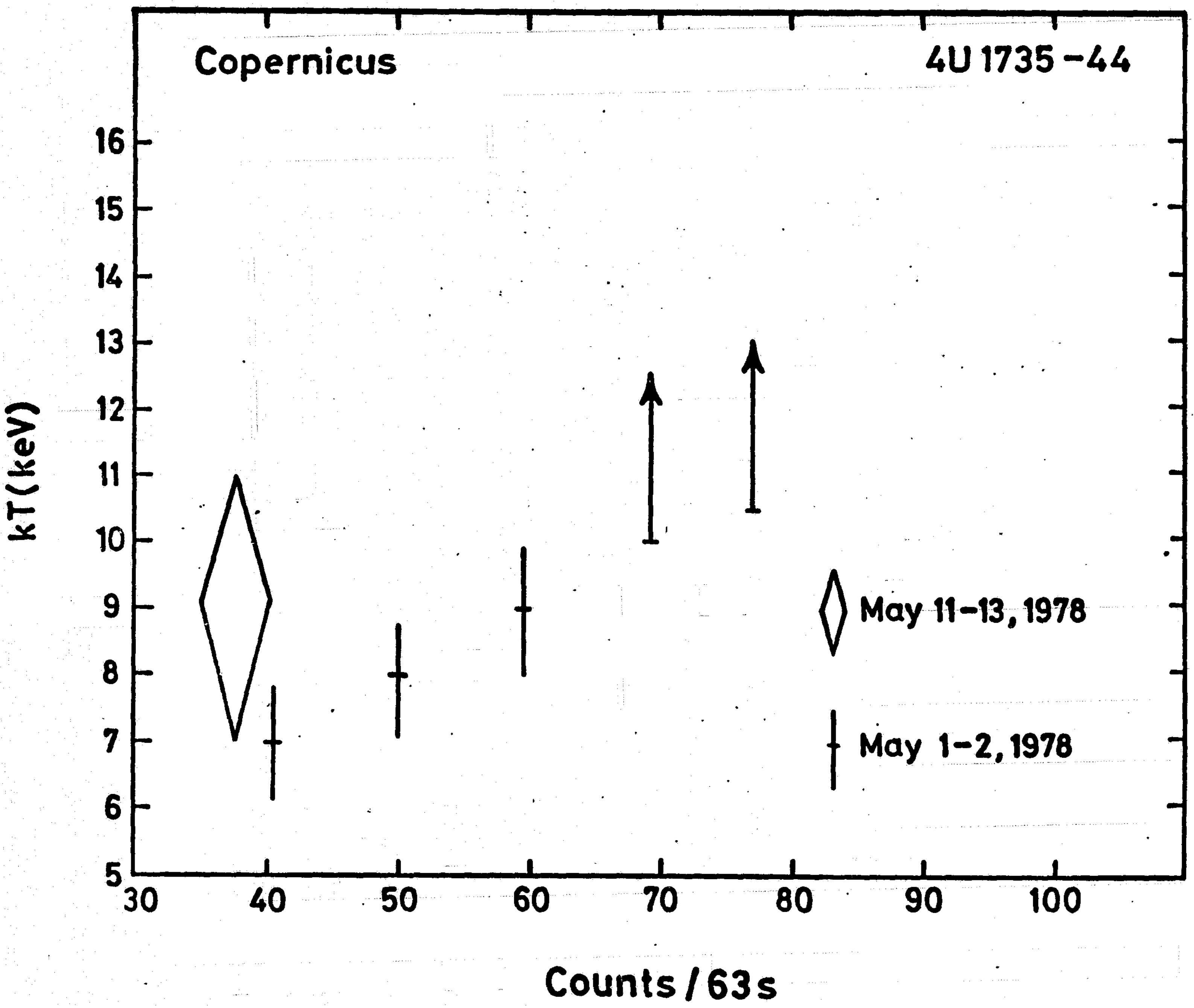
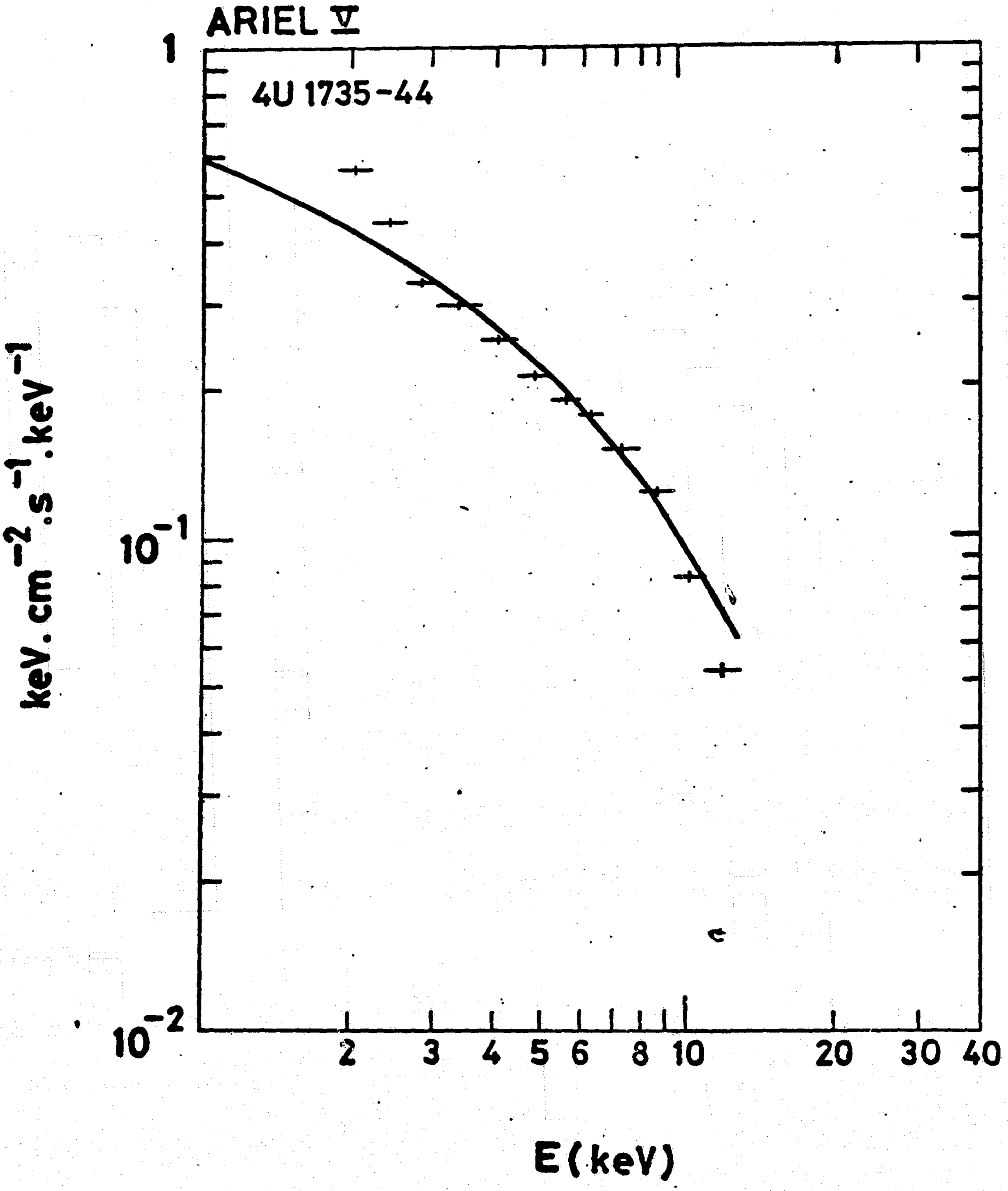

Copernicus
4U 1735-44
kT(keV)
16
15
14
13
12
11
10
9
8
7
6
5
30
40
50
60
70
80
90
100
Counts / 63s
May 11-13, 1978
May 1-2, 1978

Figure 2


ARIEL V
4U 1735-44
1
10^{-1}
10^{-2}
keV. cm^{-2}.s^{-1}.keV^{-1}
2
3
4
5
6
8
10
20
30
40
E (keV)

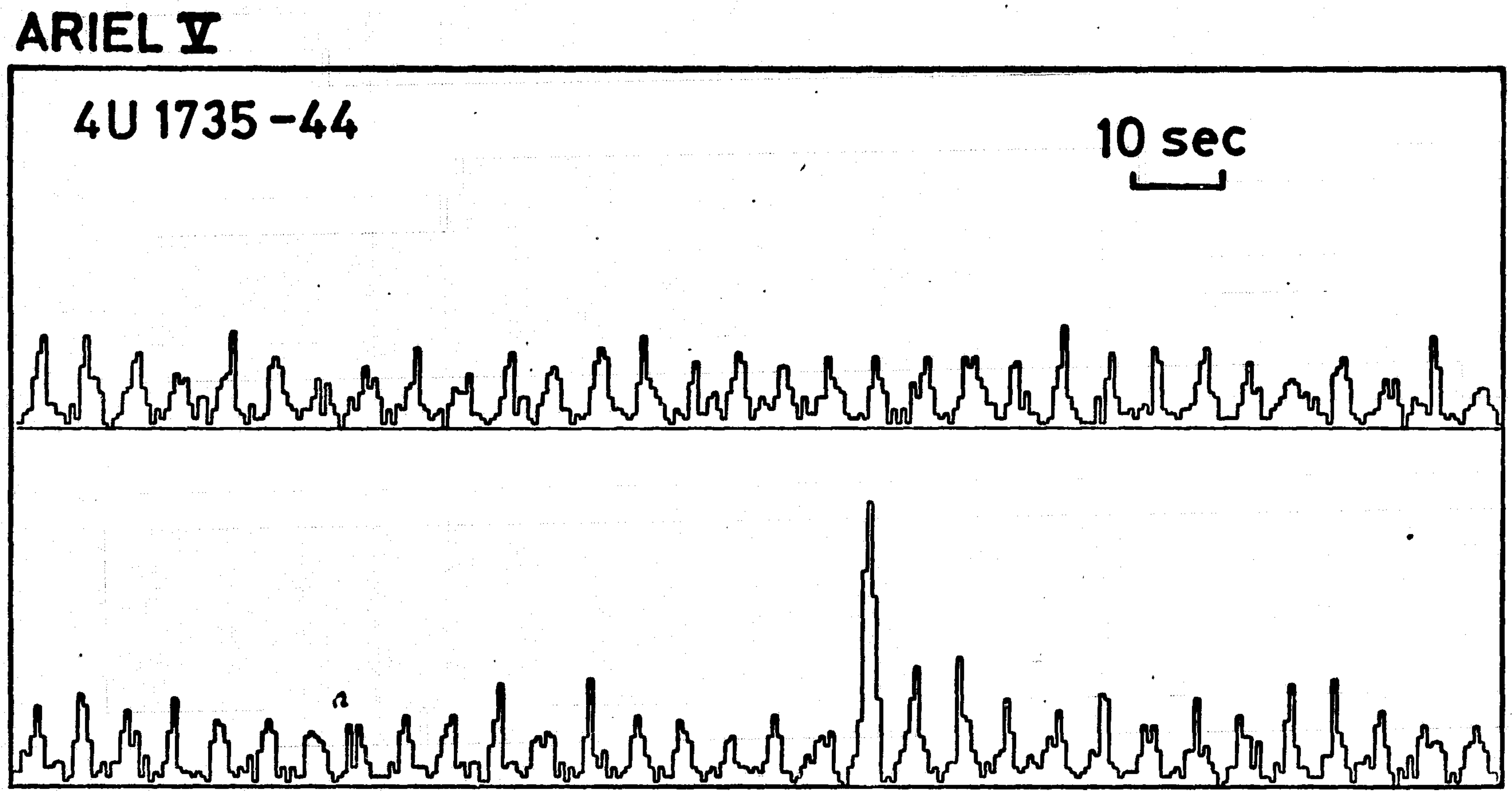


Figure 4

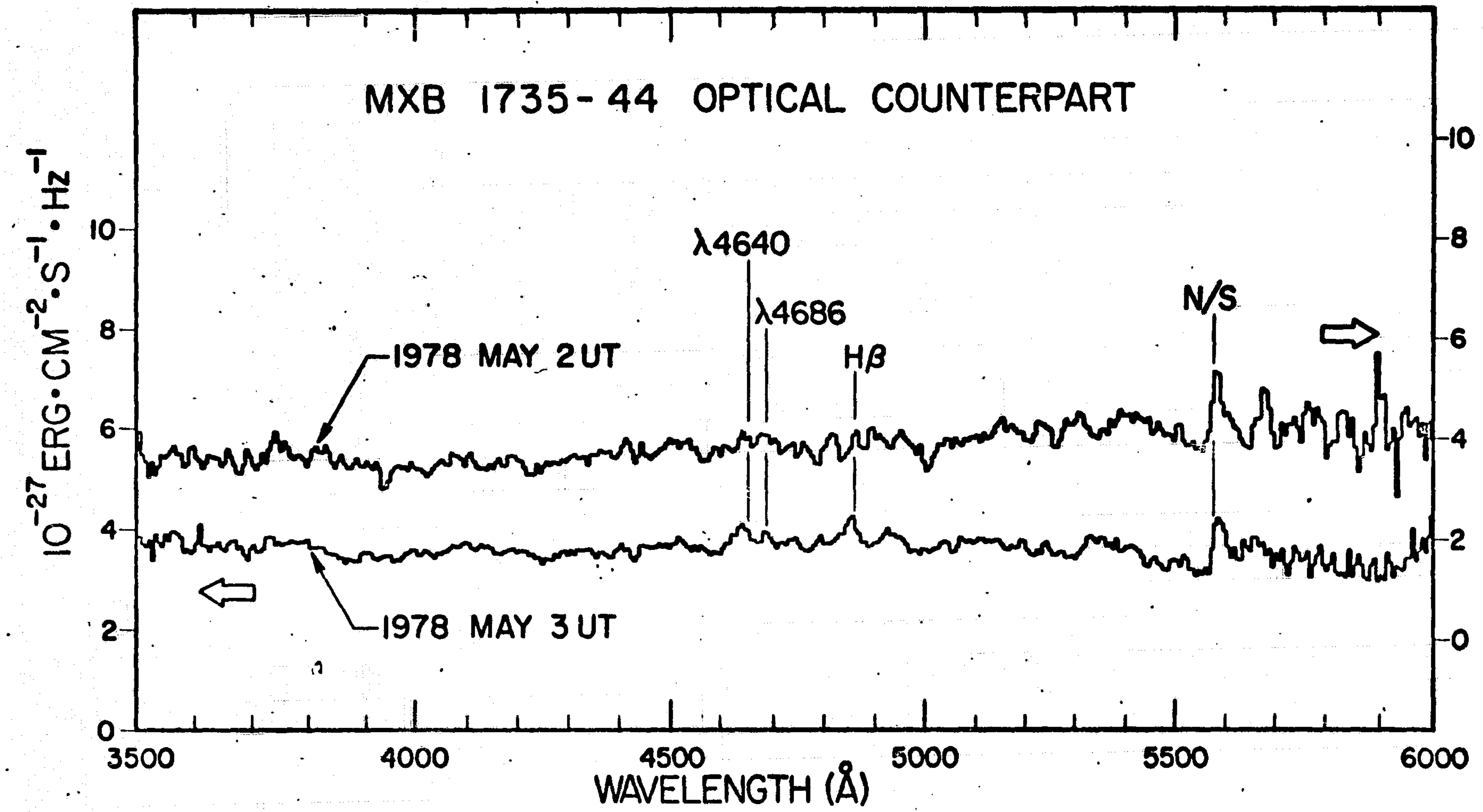
MXB 1735-44 OPTICAL COUNTERPART
10^{-27} ERG•CM^{-2}•S^{-1}•Hz^{-1}
0
2
4
6
8
10
0
2
4
6
8
10
λ4640
λ4686
Hβ
N/S
1978 MAY 2 UT
1978 MAY 3 UT
3500
4000
4500
5000
5500
6000
WAVELENGTH (Å)

Figure 5