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THE EVOLUTION OF THE 1984 OUTBURST OF THE TRANSIENT X-RAY SOURCE 4U 1630−47

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ABSTRACT

We present the results of a series of *EXOSAT* observations of the X-ray transient 4U 1630−47 during an outburst in 1984. The source decayed over an interval of ~100 days from a maximum 1–50 keV luminosity of $\sim 2.8 \times 10^{38}$ to $\sim 4 \times 10^{36}$ ergs s^{-1} (for an assumed distance of 10 kpc). The 1–50 keV spectrum was best represented by a soft Wien-like spectrum with a temperature ~1 keV and a high-energy power-law tail. The relative contribution of the soft component to that of the high-energy power law decreased by at least a factor of ~2 as the overall luminosity decreased. When the source was at its maximum observed luminosity, short time scale 7% intensity variations (1–7 keV) were seen with a characteristic time scale of ~20 s. The shortest time scale variability detected was ~50 ms. A 10″ position obtained using an imaging telescope excludes a previously suggested optical counterpart. The spectral properties of 4U 1630−47 are reminiscent of those of the black hole candidate Cyg X-1 when it evolves from a high to a low state.

Subject headings: X-rays: sources — X-rays: spectra

I. INTRODUCTION

Transient X-ray sources are caused by a large surge in the mass accretion rate onto a compact object in a binary system. Increases in luminosity in excess of 1000 are typically seen, which allows a much larger dynamic range of mass accretion rate to be sampled than normally occurs in the more persistent sources. Because of this, these objects provide a useful test for the luminosity dependence of models for the emission region in binary X-ray sources.

4U 1630−47 is a recurrent X-ray transient located in the general direction of the Galactic center that has undergone a number of outbursts since its discovery in 1972 (Jones *et al.* 1976). The outbursts probably occur quasi-periodically every 1.66 yr (Priedhorsky 1985; Jones *et al.* 1976; Kuluzienski and Holt 1977). The peak flux during each outburst is typically 500 μJy with an *e*-folding decay time of ~50 days, although some outbursts last much longer (Kaluzienski *et al.* 1978; Sims and Watson 1978). The X-ray spectrum of 4U 1630−47 is absorbed by $\sim 10^{22}$ H cm^{-2} (Jones 1977), consistent with that expected if it lies in the vicinity of the Galactic center. This transient is one of several that show unusually soft 2–10 keV spectra compared to the majority of Galactic accretion-driven X-ray sources (White and Marshall 1984; White, Kaluzienski, and Swank 1984). Such soft spectra are a characteristic of the black hole candidate Cyg X-1 (in a high state) and LMC X-3.

In 1984 April the *Tenma* X-ray astronomy team reported 4U 1630−47 to be once again active with a flux of 500 μJy on April 1 and 7 (Tanaka *et al.* 1984), close to the peak values previously seen. This paper reports the results of a series of four observations of 4U 1630−47 made by the European Space Agency's X-ray observatory *EXOSAT* (Taylor *et al.* 1981) with the objective of investigating in detail the evolution of the X-ray properties of 4U 1630−47 as the flux decayed.

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II. THE SPECTRUM

The first *EXOSAT* observation of 4U 1630−47 was made on 1984 April 11 and lasted for 7 hr. The medium energy proportional counter array (ME; Turner, Smith, and Zimmermann 1981) was operated in a coaligned configuration and gave a background-subtracted count rate of 1200 counts s^{-1} (1–15 keV) in the argon detectors. For most of this observation, 256 channel pulse height analyzer spectra covering the range 1–15 keV (argon detectors) and 5–55 keV (xenon detectors) were obtained every 10 s.

Single-component power-law, thermal bremsstrahlung, and blackbody spectra were convolved through the detector response, but all gave large values (>100) of reduced χ^2. A two-component photon spectrum consisting of a function of the form $E^{\Gamma_S} \exp(-E/kT)$, with $\Gamma_S = -1.85$ and $kT = 1.15$ keV, plus a power law with a photon index Γ_H of 2.5, came closest to providing a formally acceptable fit, giving a χ^2 of 247 for 101 degrees of freedom (dof) (see Table 1). A 1% systematic uncertainty was included in the spectral fitting to account for uncertainties in the ME calibration. The uncertainty in each parameter has been estimated by the variation leading to an increase in χ^2 of 2.7 (90% confidence for a single parameter of interest) allowing the other parameters to vary. Since the fit is formally unacceptable, this will tend to underestimate the uncertainty. In order to provide a conservative estimate of the uncertainties, the χ^2 was renormalized to give a reduced χ^2 of one. The best-fitting value of Γ_S is consistent, within the uncertainties (± 0.4), with the form of a Wien spectrum ($\Gamma_S = -2.0$). Low-energy absorption in the line of sight equivalent to $6.55 \pm 0.25 \times 10^{22}$ H cm^{-2} was required.

Over the 1–50 keV energy band, the ratio of the luminosity in the hard to that in the soft, L_H/L_S, was 1.2 ± 0.3. The best-fitting spectrum is shown in Figure 1 with a dashed histogram indicating the contribution of the soft component. The formally unacceptable χ^2 indicates that the true incident spectrum deviates from the simple models used. Increasing the number of component spectra did not give any significant improve-

TABLE 1

SPECTRAL RESULTS

OBSERVATION START (1984)	DURATION (hr)	SPECTRAL PARAMETERS					1–50 keV LUMINOSITY[a] (ergs s^{-1})	L_H/L_S (1–50 keV)
		Γ_S	kT (keV)	N_H (10^{22} atoms cm^{-2})	Γ_H	χ^2/dof		
Apr 11.3	7.0	-1.8 ± 0.40	1.15 ± 0.08	6.55 ± 0.25	2.48 ± 0.09	247/101	2.8×10^{38}	1.2 ± 0.3
May 10.1	5.1	-2.9 ± 0.8	0.78 ± 0.10	4.5 ± 0.4	1.74 ± 0.10	138/52	9.2×10^{37}	2.1 ± 0.3
Jul 1.4	3.4	-2.0[b]	$0.50^{+0.30}_{-0.10}$	$3.0^{+2.5}_{-1.2}$	$1.0^{+0.8}_{-1.0}$	12/16	1.5×10^{36}	1–6
		...	...	1.3 ± 0.8	1.8 ± 0.3	25/19	...	...
Jul 29.7	4.4	-2.0[b]	0.60 ± 0.20	$1.1^{+3.4}_{-1.1}$	0.6 ± 0.6	27/13	1.0×10^{36}	2.5–25
		...	...	$02.^{+0.8}_{-0.2}$	1.2 ± 0.2	38/16	...	...

NOTE.—All uncertainties are 90% confidence.

[a] Assuming a distance of 10 kpc and that the observed low-energy absorption is interstellar.

[b] Held constant.

ment in the fit. For example, the sum of a blackbody, a thermal, and a power law spectrum gave a χ^2 of 230 for 100 dof.

The spectrum obtained from the gas scintillation proportional counter (Peacock *et al.* 1981), gave similar results to those obtained from the ME. No obvious iron K line was present in the spectrum between 6 and 7 keV with a 90% confidence upper limit to a 1 keV full width half-maximum feature of 30 eV.

A second observation of 4U 1630−47 was made on 1984 May 10. On this occasion a count rate from the source of 400 counts s^{-1} was recorded in the argon detectors, a factor of 3 lower than that seen one month earlier. The spectrum was still reasonably well represented by a Wien-like spectrum plus a high-energy tail with $kT = 0.8$ keV and $\Gamma_H = 1.7$. The ratio L_H/L_S had increased by almost a factor of 2 to 2.1 ± 0.3.

4U 1630−47 was observed during the *EXOSAT* Galactic plane scan (Turner *et al.* 1985) on 1984 June 29 (Watson 1985). The effective exposure time was ~ 1 minute, during which a 2–10 keV count rate was detected of ~ 5 counts s^{-1}, a factor of ~ 100 lower than that seen during the first pointed observation. A further pointed observation was made on 1984 July 1, when a count rate of 6.5 counts s^{-1} was detected. Another observation on 1984 July 29 gave a comparable count rate of 5.1 counts s^{-1}. Because the source was now relatively weak, the ME was on these two occasions operated with half the detector array offset to optimize the background subtraction. Spectra from both observations can be represented by a single power law with Γ_H of 1.8 ± 0.3 ($\chi^2 = 25$ for 19 dof) and 1.2 ± 0.2 ($\chi^2 = 38$ for 16 dof) for July 1 and 29 respectively. Including a soft Wien-like component gave some improvement with χ^2 of 12 for 16 dof and 27 for 13 dof with $kT \approx 0.5$ in both cases.

The observed change in spectrum is consistent with a pro-

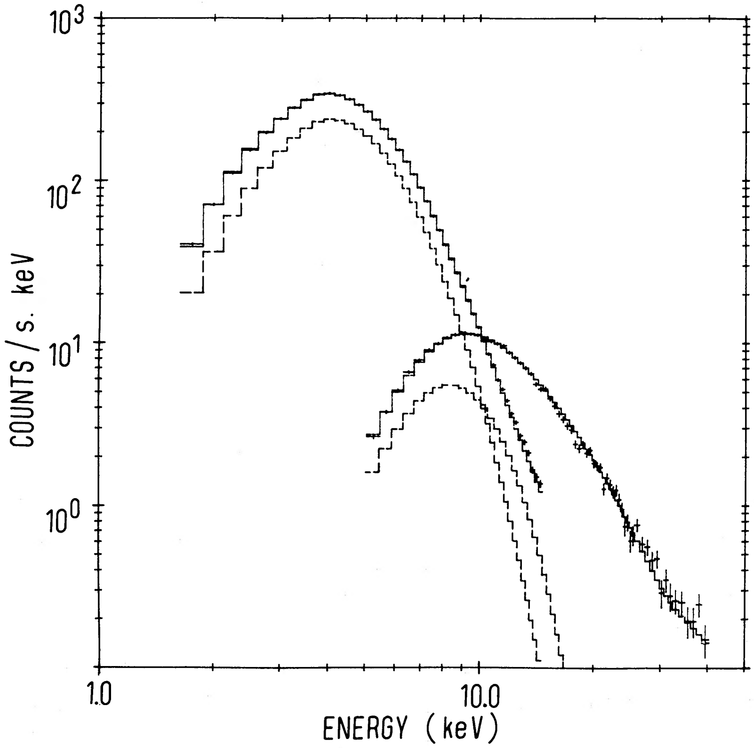

FIG. 1.—The observed ME argon (1–15 keV) and xenon (6–40 keV) spectra for the 1984 April 11 observation (*plusses*). The histograms show the best-fit model described in the text. The dashed lines show the contribution of the Wien component.

gressive flattening of the power-law tail as the source decayed. Since the spectrum above 10 keV was in these cases not determined, any statement on the value of L_H/L_S is sensitive to how the power law is extrapolated to higher energies. The two limiting cases are where the power law either cuts off abruptly at 10 keV or continues on to higher energies with the same slope. This gives a range of L_H/L_S between 1 and 6 on July 1, and 2.5 and 25 on July 29. Between the first two observations, L_H/L_S increased by a factor of ~ 2 with no evidence for a spectral break at energies below 40 keV in either case. During the last two observations, the tendency for the power-law tail to flatten and the low-energy absorption to decrease continued. Given that it it is very unlikely that both spectra end abruptly at 10 keV, it seems likely that between the first and the last observations this trend for L_H/L_S to increase as the source decayed also continued. The tendency for the low-energy absorption to decrease as the source intensity declined (see Table 1) is most likely caused by inadequate modeling of the spectral shape at low energies.

In Figure 2 the incident spectra deconvolved from the detec-

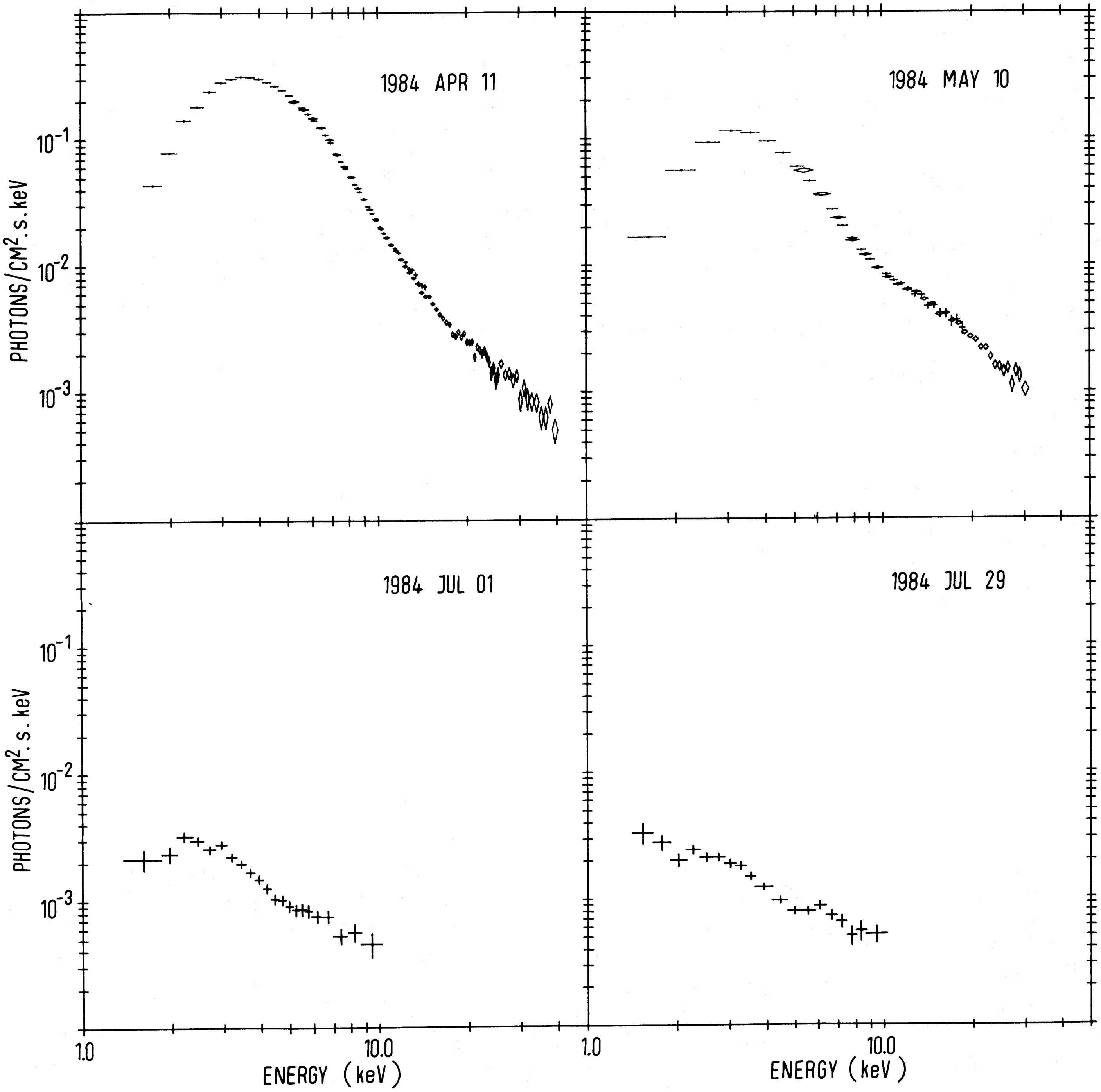

FIG. 2.—The incident ME spectra for each of the observations deconvolved using the model and parameters described in the text. The plusses represent the argon detector data and the diamonds the xenon detector data.

tor response are shown for each of the four observations. The tendency for the luminosity of the soft component relative to that of the power-law tail to decrease as the overall luminosity declined is evident.

III. TIME VARIABILITY

Timing data were obtained with a variety of accumulation times. For the first observation, in addition to the 10 s energy histogram data, high time resolution 8 ms data summed over the entire bandpass of the argon detectors (1–15 keV) was obtained. For 90 minutes the 128 channel energy histogram was replaced by eight-channel energy histograms every 125 ms.

Figure 3 shows two 3–7 keV light curves obtained from the first two observations. The time resolution is 10 s, and the plots have been scaled so that in both cases the ordinate extrema represent $\pm 25\%$ variations in source intensity. During the 1984 April 11 observation, the source was extremely variable. The rms excess variability ϵ, corrected for sampling effects and counting statistics, can be defined as $(\sigma_{\rm obs}^2 - \sigma_c^2)^{0.5}/X$, where $\sigma_{\rm obs}^2$ is the observed variance, σ_c^2 the variance expected from a constant source, and X the mean source count rate. This parameter has been calculated for two energy bands chosen to sample predominantly the soft component (1–7 keV) and the power-law component (14–30 keV). Between 1 and 7 keV (where the soft component contributes 67% of the observed counts), the source excess variability is $7.3 \pm 0.4\%$, while between 14 and 30 keV (where the power-law component contributes 97% of the observed counts) it is $3.7 \pm 0.6\%$, indicating that the soft component was a factor of 2 more variable than the power-law high-energy tail.

In order to check that we do not observe excess variability from a constant source, we have analyzed 6 hr of ME data from the Crab Nebula and set a limit to any excess variability of $<0.3\%$ for time scales of more than 10 s in the 1–7 keV energy band. For the 14–30 keV measurements, the source and background count rates are similar, and it is possible that some of the observed variability is caused by variations in the background on a time scale of minutes. The 1–7 keV source excess variability was much reduced during the 1984 May 10 observation of 4U 1630−47 with $\epsilon = 0.9 \pm 0.4\%$. Between 14 and 30 keV the 90% confidence limit to any excess variability is below 2.9%.

An average autocorrelation function (ACF) calculated from nine 600 s intervals of the 1–7 keV argon data obtained with a time resolution of 0.125 s when the source was bright and most variable on 1984 April 11 is shown in Figure 4. The effects of long-term variations ($\gtrsim 10$ minutes) on the ACF were removed by dividing the data by a second-order polynomial fit before calculating the ACF (for details see Stella, Kahn, and Grindlay 1984). The exponential decay of the ACF gives a characteristic *e*-folding time scale for the variability of ~ 20 s. The slope of the ACF continues to steepen for time delays <2 s, indicating the presence of an additional source of variability on time scales shorter than this. In order to estimate the minimum time scale on which fluctuations could be detected in the data, we computed the ACF of the 8 ms intensity data (rebinned into 16 ms bins) from the argon detectors, corresponding to an

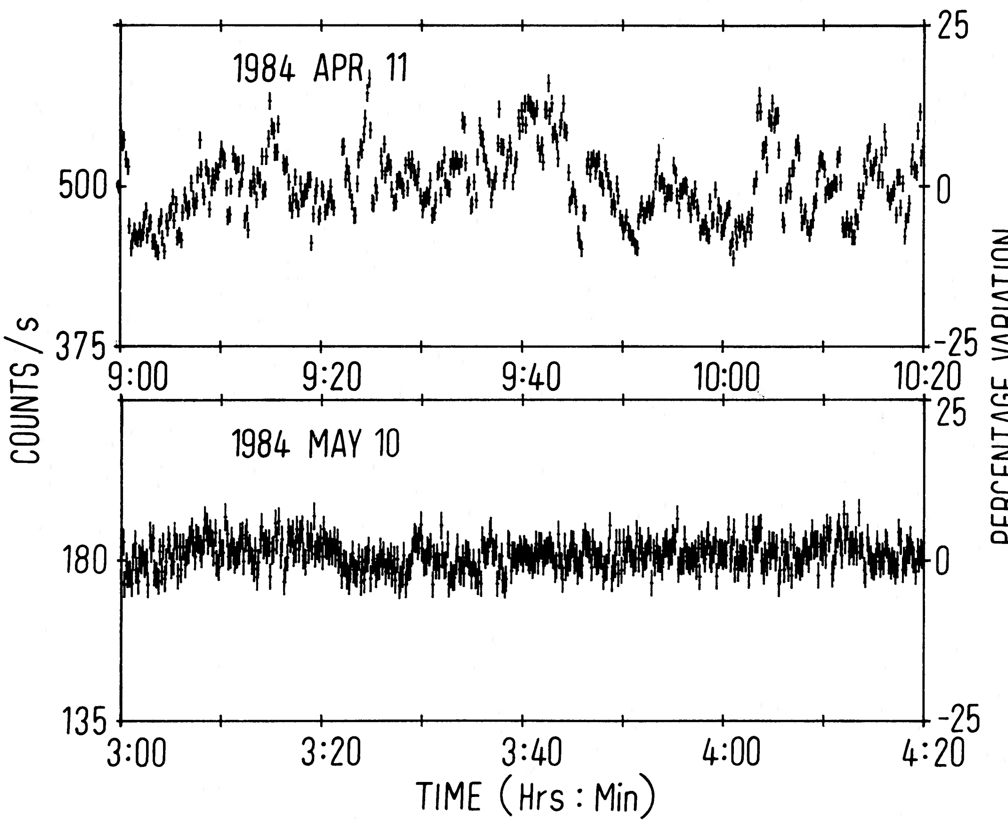

FIG. 3.—Part of the 3–7 keV ME light curve for 1984 April 11 (*upper panel*) and 1984 May 10 (*lower panel*). The time resolution is 10 s. The error bars are $\pm 1\,\sigma$ statistical uncertainties. The plots are scaled so that the ordinate extrema represent $\pm 25\%$ variations in source intensity. The different amounts of intensity variability present in the two observations can be clearly seen.

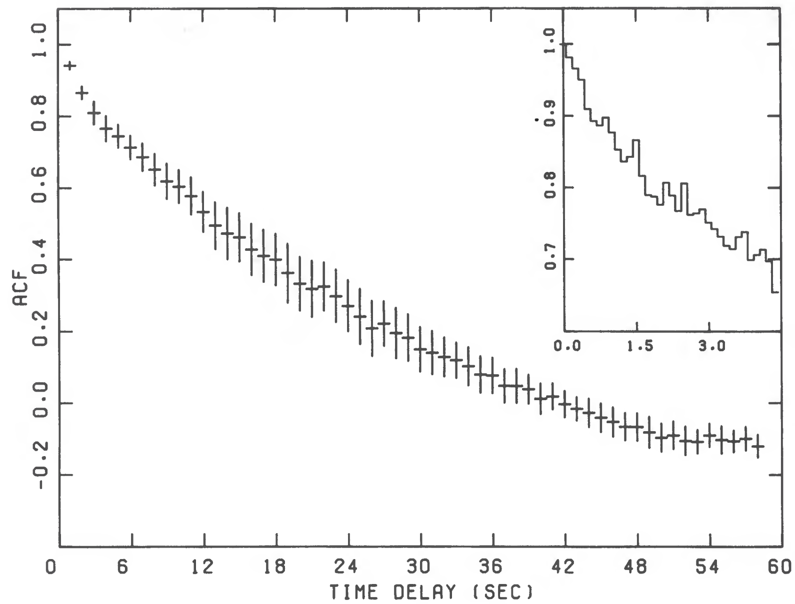

FIG. 4.—The ACF for the 1984 April 11 observation. Long-term trends ($\gtrsim$10 minutes) have been removed from the data, which cover the range 1–7 keV and are from the ME argon detectors. The insert shows the steepening of the ACF for time delays shorter than 2 s, providing evidence for an additional short time scale component in the source variability. This component has been further investigated by computing the ACF of the 1–15 keV 8 ms argon intensity data (not shown in the figure), which provides evidence for variability down to time scales of $\sim$50 ms (see text).

energy range of 1–15 keV. The failure to detect a turnover in the shape of the ACF sets a lower limit to the shortest time scale on which variations are detected of $\sim$50 ms. (cf. Priedhorsky *et al.* 1979). Due to a large uncertainty in the estimate of the third moment, it was not possible to characterize the source variability in terms of the shot-noise model used for Cyg X-1 (Sutherland, Weisskopf, and Kahn 1978).

IV. POSITION

During the first observation, the channel multiplier array (CMA) detector at the focus of a low energy imaging telescope using a 4000 Å lexan filter (cf. de Korte *et al.* 1981) detected a source close to the expected position of 4U 1630−47 at R.A. = $16^h30^m19^s.4$, Decl. = $-47°17'24''$ (1950) with a 90% confidence error radius of 10″. This position is drawn on a CCD image of the region in Figure 5 along with previously reported positions. The centroid of the *EXOSAT* circle is respectively 49″ and 44″ away from the previously reported nonoverlapping 20″ position of Reid *et al.* (1980) and the 28″ position of Wilson *et al.* (1977). The *EXOSAT* error circle does not include the candidate star of Grindlay (1977) which is 83″ from the center. We believe that the CMA source is 4U 1630−47 since, besides the positional coincidence, the observed count rate of $8.9 \pm 0.9 \times 10^{-3}$ counts s^{-1} is consistent with an extrapolation of the ME spectrum to lower energies. In addition, while the CMA was not operated during the second and third observations, during the fourth observation, when 4U 1630−47 had decayed, this source was no longer detected. The 3σ upper limit of 2.2×10^{-3} counts s^{-1} is consistent with the extrapolation of the ME spectrum at that time which predicts a count rate of $(4.3^{+14.4}_{-2.4}) \times 10^{-3}$ counts s^{-1}.

V. DISCUSSION

In general the X-ray properties of the X-ray transients in outburst closely resemble those of their persistent counterparts (cf. White, Kaluzienski, and Swank 1984). When bursts or pulsations are absent, it is not possible to conclude that the

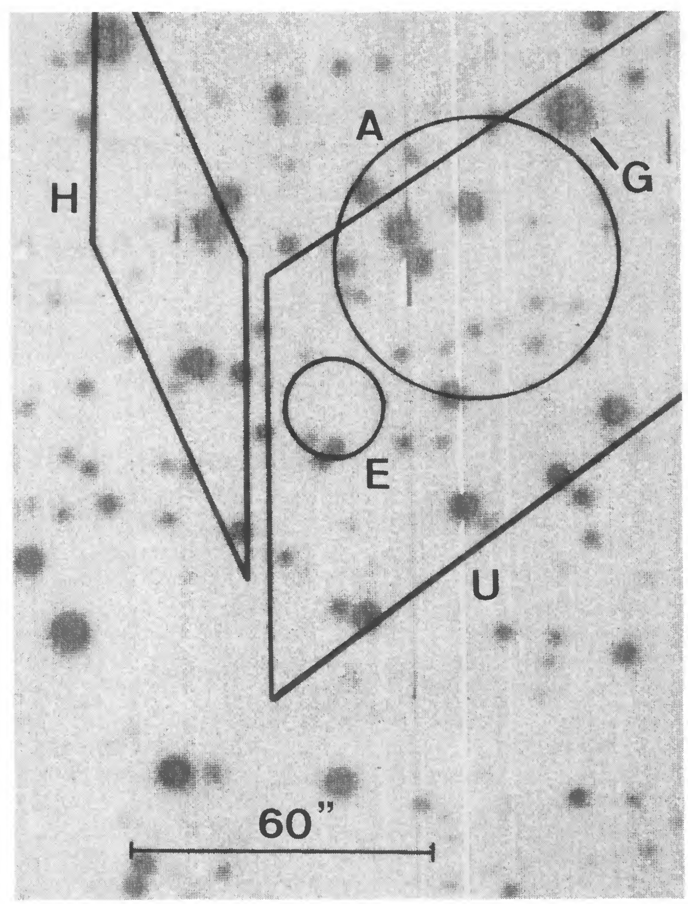

FIG. 5.—A finding chart for 4U 1630−47 obtained using the 1.5 m Danish telescope at the European Southern Observatory, a CCD detector, and a *V*-band filter. The exposure time is 15 minutes. The vertical lines in the image are caused by flaws on the CCD chip. North is up and east to the left. "E" indicates the *EXOSAT* position given in the text. "A," "H," and "U" indicate the *Ariel 5*, *HEAO 1*, and *Uhuru* positions of Wilson *et al.* (1977), Reid *et al.* (1980), and Forman *et al.* (1978) respectively. Grindlay's (1977) candidate star is indicated by "G."

underlying compact object is a neutron star (cf. Joss and Rappaport 1984). In the remaining cases, if the mass of the underlying object is estimated by radial velocity measurements to be $\gtrsim 3\ M_{\odot}$, the largest plausible value currently allowed for a neutron star, then it seems likely that the X-ray source is caused by accretion onto a black hole. Unfortunately, such measurements are difficult to make, and to date convincing cases for black hole candidacy have been made for only Cyg X-1, LMC X-3, and (possibly) LMC X-1. In the remaining cases, comparative study of the properties of X-ray sources is the only way to identify the nature of the compact object (cf. White and Marshall 1984). The X-ray absorption in the line of sight to 4U 1630−47 of $\gtrsim 3.0 \times 10^{22}$ H cm^{-2}, if interstellar, implies up to ~ 15 mag of extinction in the B band, and it seems doubtful that radial velocity measurements will be possible. Thus, a comparative study seems the best approach in this case as well.

The spectral properties of the transient X-ray sources and their relation to the persistent X-ray sources have been considered in detail by White, Kuluzienski, and Swank (1984), building on earlier work by Cominsky *et al.* (1978) and Maraschi *et al.* (1976). Three classes of spectral behavior are typically seen that can be classified as *hard*, *soft* and *ultrasoft*, names that refer to the 2–10 keV spectral shape. The *hard* transients are generally X-ray pulsars and are found to be associated with OB star companions. The *soft* transients display spectra that are either exponential with an *e*-folding temperature of 5–10 keV or power-law with energy indices of 1–2. X-ray bursts are a common feature of these objects, and their indentification with faint blue optical counterparts indicates that they are related to the low-mass X-ray binaries. The *ultrasoft* transients, also identified with optical novae (e.g., A0620−00; Coe, Engel, and Quenby 1976), show extremely soft X-ray spectra below 10 keV with $kT \approx 1$ keV, but at high energies have power-law tails that in some cases extend out to at least 100 keV (e.g., Wilson and Rothschild 1983). The only spectral analogy for these objects among the persistent sources is the accreting black hole candidates such as Cyg X-1, during its high state, and LMC X-3.

During the decay of the 1984 outburst of 4U 1630−47, both the spectral and temporal properties underwent a distinct evolution. When the source was close to its peak luminosity of $\sim 2.8 \times 10^{38}$ ergs s^{-1} (for an assumed distance of 10 kpc), 7% excess variability was present with a characteristic decay time of ~ 20 s. Rapid variations on time scales of at least ~ 50 ms were detected. Thirty days later, on May 10, the 1–7 keV excess variability was only ~ 1%. The spectrum could be described as a two-component combination consisting of a very soft Wien-like component with $kT \approx 1$ keV and a high-energy power-law tail. The ratio of the hard to soft component decreased by at least a factor of 2 as the total luminosity decayed. In addition, the photon index of the high-energy power law decreased from 2.5 to ~ 1.0, i.e., the spectrum tended to become harder.

The spectral properties of 4U 1630−47 indicate that this is a member of the *ultrasoft* class of X-ray transients. The tendency for the contribution of the soft component to the total luminosity to decrease as the source intensity decreases is similar to the behavior seen from Cyg X-1 as it makes the transition from a high to a low state (cf. Coe, Engel, and Quenby 1976), further strengthening the spectral analogy. The rapid variability observed close to maximum intensity may also be related to that seen from Cyg X-1, although the characteristic time scale given by the ACF of ~ 20 s is a factor of ~ 40 larger than that of Cyg X-1 (e.g., Sutherland, Weisskopf, and Kahn 1978). In addition, in Cyg X-1 the rapid variability is usually less evident in the high state (cf. Sutherland, Weisskopf, and Kahn 1978; Oda *et al.* 1976), whereas in 4U 1630−47 the opposite seems to be the case, although we note the limits to variability from 4U 1630−47 when it was faint are not very restrictive (<20%). We caution, however, that the detection of rapid variability from the X-ray pulsar V0332+53 indicates that the detection of such variations does not provide direct evidence for a black hole candidate, unless considered in conjunction with other properties such as spectral signatures (Stella *et al.* 1985).

Of the X-ray transients recorded to date, ~ 30% can be classified as *ultrasoft* (cf. White, Kaluzienski, and Swank 1984), whereas only less than 5% of the persistent sources show similar spectral characteristics (cf. White and Marshall 1984). One possible explanation for this discrepancy is that the distinctive spectral characteristic of the *ultrasoft* transient sources is caused by their transient nature, and that their similarity to that of Cyg X-1 and LMC X-3 is coincidental. However, the fact that ultrasoft transients do not show the classic signatures of accreting neutron stars of X-ray pulsations or X-ray bursts suggests that the analogy with Cyg X-1 and LMC X-3 is to be preferred.

VI. CONCLUSION

The spectral evolution of 4U 1630−47 during the decay phase of its outburst in 1984 is very similar to that seen from Cyg X-1 as it makes the transition from a high to a low state. During an observation made near the time of peak flux, short time scale intensity variations were observed with a characteristic time scale of ~ 20 s. A comparison of these properties with those of Cyg X-1 indicates that the compact object in this system may be an accreting black hole.

Note added in manuscript 1985 November 19.—A recent preprint by McClintock and Remillard has come to our attention. From optical observations of the *ultrasoft* X-ray transient A 0620−00, these authors find that the minimum mass of the compact object is 3.4 $M_{\odot}$ with a most probable value of 7 $M_{\odot}$. This significantly exceeds the maximum allowed mass of a stable neutron star, suggesting that the A0620−00 system contains a black hole. This supports the view that the *ultrasoft* X-ray transients, as a class, contain black holes.

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