JA

**Periodic Outbursts from the Ultra-soft X-ray Transient
4U 1630-47**

A.N. Parmar, L. Angelini, N.E. White

**Laboratory for High Energy
Astrophysics**

SCAN-9511003

CERN LIBRARIES, GENEVA

5-69545

**High Energy Astrophysics Science
Archive Research Center**

**NASA Goddard Space Flight Center
Greenbelt, MD 20771**

Periodic Outbursts from the Ultra-soft X-ray Transient
4U 1630-47

A. N. Parmar

Astrophysics Division,
Space Science Department of ESA,
2200 AG Noordwijk, The Netherlands

and

L. Angelini¹ and N. E. White

Laboratory for High Energy Astrophysics,
NASA Goddard Space Flight Center,
Greenbelt, MD 20771, USA

Received 13 June 1995; accepted 16 August 1995

To appear in the *Astrophysical Journal Letters*

¹Universities Space Research Association

ABSTRACT

Using *ROSAT* PSPC and *Einstein* SSS and MPC archival data we have found two previously unreported outbursts from the *ultra-soft* X-ray transient 4U 1630–47 that occurred in 1979 March and 1992 September. The times of these outbursts are consistent with a previously reported ~ 600 day outburst recurrence period, as is the subsequent non-detection of the source by *ROSAT* in 1993 March and August. Future outbursts are predicted to occur in 1995 November and 1997 July. 4U 1630–47 is a member of the class of transient X-ray binary systems that are thought to contain black holes. The 601.7 ± 3.0 day recurrence period of 4U 1630–47 is by far the shortest known for this class. The origin and possible triggers for the outbursts are discussed.

Subject headings: accretion – binaries: close – stars: individual (4U 1630–47)

– X-rays: stars

1. INTRODUCTION

4U 1630–47 is an X-ray transient that was discovered by *Uhuru* (Jones et al. 1976), with the first recorded outburst in 1969 detected by VELA 5B (Priedhorsky 1986). The first five outbursts were observed by a combination of the VELA 5B, *Uhuru*, *Ariel 5*, and *HEAO 1* satellites and seemed to occur every ~ 600 day (Jones et al. 1976; Priedhorsky 1986; Kaluzienski et al. 1978). The peak 2–10 keV flux was $\sim 2 \times 10^{-8}$ ergs cm $^{-2}$ s $^{-1}$ with the lightcurve exhibiting a characteristic “sawtooth” form with a rapid rise in a few days and a decay with a typical e-folding time of ~ 50 days. There has been no detected quiescent flux between the outbursts. A strict periodicity was apparently ruled out by an extended 1977 outburst which started ~ 70 days later than predicted and may have lasted for up to six months (Kaluzienski et al. 1978; Sims & Watson 1978). In 1984 the source was again found to be in outburst by *Tenma* (Tanaka et al. 1984). The decay was observed in detail by *EXOSAT* (Parmar, Stella, & White 1986; hereafter PSW).

No bursts or periodicities have been detected from 4U 1630–47 and close to the peak of the 1984 outburst the source exhibited irregular intensity variability with a characteristic timescale of ~ 20 s (PSW). During this outburst the 1–40 keV *EXOSAT* spectrum could be modeled by an absorbed soft ~ 1 keV Wien-like component with a high-energy power-law tail. As the outburst decayed, both the low-energy absorption and the relative contribution of the soft component compared to that of the power-law decreased. The *ultra-soft* spectral shape, the change in relative contributions, and the lack of detected pulsations or bursts are all properties that classify 4U 1630–47 as a black hole candidate. Similar behavior is seen from other X-ray transients such as A 0620-00, GS 1124-68 and GS 2023+338 which are thought to contain black holes on the basis of their masses derived from radial velocity measurements of the companion stars (McClintock 1992; Cowley 1994). The orbital periods range from 7.7 hr to 6.5 days, with the companions being late type stars. There are now at

least 15 similar black hole X-ray transient (BHXT) systems (White 1994; Tanaka & Lewin 1995).

Apart from 4U 1630–47, four other BHXT systems are known to recur. Archival optical plates reveal an outburst from A 0620-00 in 1917, suggesting a recurrence timescale, T_r , of $58/n$ year, where n is an integer to allow for missed outbursts (Elvis et al. 1975; Eachus, Wright, & Liller 1976). Other recurrent *ultra-soft* transients are: 4U 1543-475 which underwent outbursts in 1971 (Matilsky et al. 1972), 1983 (Kitamoto et al. 1984; van der Woerd et al. 1989) and 1992 (Harmon et al. 1992), giving $T_r \sim 10/n$ years; GS 2023+338 with outbursts in 1938 and 1989, giving $T_r \sim 51/n$ years (Kitamoto et al. 1989; Marsden 1989); and A 1524–62 in 1974 and 1990 giving $T_r \sim 16/n$ years (Kaluzienski et al. 1975; Barret et al. 1992). The other BHXT systems have been observed in X-ray outburst only once during the 25 years of satellite X-ray observations (White 1994; Tanaka & Lewin 1995). Whilst it is possible that some outbursts have been missed, this suggests a typical recurrence timescale of 10–50 year. The more prolific outburst activity of 4U 1630–47 is therefore unusual amongst the class.

We report on serendipitous detections of 4U 1630–47 during a pointed *ROSAT* observation of a nearby target and during a previously unreported *Einstein* SSS observation. These detections show that 4U 1630–47 continues to undergo regular outbursts and confirm the ~ 600 day period.

2. OBSERVATIONS

2.1. ROSAT

We searched the *ROSAT* archive for observations of the region of sky containing 4U 1630–47 and found three separate observations made with the Position Sensitive

Proportional Counter (PSPC; Trümper 1983). These were made on 1992 September 20–23, 1993 March 13–15 and August 25–26, with exposures of 3400, 10,100 and 5400 s during each interval. In all three observations, the primary target was the variable star NGC 6164–5. The position of 4U 1630–47 is 42' from the center of the field of view (FOV), well clear of the PSPC window support structures. In the 1992 observation a source at the position of 4U 1630–47 was detected at a count rate of 0.173 ± 0.013 counts s^{-1} . In contrast, during the 1993 March and August observations, the 3σ upper limits to any counts at the position of 4U 1630–47 are $< 7.1 \times 10^{-3}$ and $< 8.7 \times 10^{-3}$ counts s^{-1} , respectively. The position of the source was determined using a sliding-cell method. A box size of 5.6' was chosen to maximize the signal-to-noise ratio, taking into account the off-axis instrument point spread function and the background counting rate. This gives a best J2000 position for the source of R.A. = $16^h 33^m 57.1^s$, decl. = $-47^\circ 24' 00''$ with a 90% confidence radius of 50". This position is 38" from the center of the 90% confidence 10" radius *EXOSAT* position for 4U 1630–47 in PSW.

Counts were extracted from a circular region of radius 9.7'. The large off-axis angle precludes the use of the usual annular background region centered on the source and instead an identically sized region, located diametrically opposite in the PSPC FOV was used. Clear of the support structure, the variation in background counting rate with position in the FOV is $< 10\%$. This is too small to have a significant effect on the spectral fit results. The PSPC effective area was corrected for the offset of 4U 1630–47 in the FOV and the extracted spectrum was summed into 20 energy bins. Examination of the background subtracted spectrum showed that $> 90\%$ of the observed counts are in the energy range 1.0–2.0 keV, consistent with a heavily absorbed spectrum (see Fig. 1). Absorbed thermal bremsstrahlung, power-law and blackbody spectral models were convolved through the detector response giving similar χ^2 's of 32 for 17 degrees of freedom (dof) and best-fit low-energy absorptions, N_H , of $\sim 1.4 \times 10^{23}$ atoms cm^2 . This means that the underlying

continuum shape cannot be reliably determined using the *ROSAT* data. Figure 1 shows the observed PSPC spectrum together with the best-fit thermal bremsstrahlung model with $kT = 0.18 \pm_{0.05}^{0.50}$ keV and $N_H = (1.43 \pm 0.12) \times 10^{23}$ atoms cm^{-2} . (All spectral parameters are given at 68% confidence).

During the 1984 outburst, the *EXOSAT* spectra could be fit by an absorbed model of the form $E^{-\Gamma_s} \exp(-E/kT) + E^{-\Gamma_h}$. Close to the peak of the outburst the 1–50 keV luminosity was 2.8×10^{38} ergs s^{-1} (for an assumed distance of 10 kpc) and N_H 6.5×10^{22} atoms cm^{-2} . This reduced to 1.1×10^{22} atoms cm^{-2} by the time of the final *EXOSAT* observation when the luminosity was 1.0×10^{36} ergs s^{-1} (PWS). When Γ_s , kT , and Γ_h are constrained to lie in the range observed by *EXOSAT* and the above two component model is fit to the *ROSAT* spectrum the χ^2 is 32 for 14 dof, similar to that of the single component fits. The best-fit N_H is $(1.09 \pm 0.27) \times 10^{23}$ atoms cm^{-2} and the 1–50 keV luminosity 4×10^{38} erg s^{-1} . Both of these values suggest that the *ROSAT* detection occurred close to outburst maximum. We caution however, that the decrease in N_H observed by *EXOSAT* may be due to inadequate modeling of the low-energy spectral shape (PWS). During the final *EXOSAT* observation, the best-fit values of Γ_s , N_H , Γ_h and kT are 2.0, 1.1×10^{22} atoms cm^{-2} , 0.6, and 0.6 keV (PSW). If this spectral shape is assumed during quiescence, then the *ROSAT* upper-limit corresponds to a 2–10 keV flux of 5×10^{-12} ergs $\text{cm}^{-2} \text{s}^{-1}$. This is a factor $\sim 4,000$ less than the flux measured during outburst maxima. This flux ratio is comparable to those seen from other *ultra-soft* transients (e.g., Verbunt et al. 1994).

We have searched for intensity variability from the source. We divided the 1992 observation into the three on-source intervals of September 20 10:25–10:41, September 23 02:03–02:25, and September 23 11:44–12:02 with 958, 1302, and 1091 s exposure, respectively. The mean count rates of 0.194 ± 0.025 , 0.169 ± 0.021 and $0.154 \pm 0.023 \text{ s}^{-1}$ are consistent at 90% confidence with a constant source intensity, but may nevertheless

indicate a decreasing source intensity during the three days spanned by the observation.

2.2. Einstein

The *Einstein* solid state spectrometer (SSS) and monitor proportional counter (MPC) observed 4U 1630–47 in outburst on 1979 March 10 between 13:56 and 17:03 UTC with an exposure time of 4833 seconds (Christian 1993). The SSS and MPC spectra and lightcurves were extracted from the archive. The SSS spectrum is heavily absorbed below 1 keV, consistent with the *EXOSAT* and *ROSAT* observations (see Fig. 2). The 0.5–4.5 keV SSS spectrum can be represented by an absorbed power-law with $\alpha = 2.7 \pm 0.3$ and $N_{\text{H}} = (8.0 \pm 0.5) \times 10^{22}$ atoms cm^{-2} . The reduced χ^2 is 1.89 for 81 dof, with most of the residuals occurring around 2.7 keV. Fitting the same model to the combined SSS and MPC spectra and fixing α to the best-fit SSS value gives a reduced χ^2 of 4.2 for 86 dof. If α is allowed to vary, the fit improves slightly and the reduced χ^2 is 3.0 for 85 dof. Using the *EXOSAT* two component spectral model described in § 2.1 gives a reduced χ^2 of 1.65. The best-fit values of Γ_{s} , N_{H} , Γ_{h} , and kT are 2.4 ± 1.0 , $(5.5 \pm 1.0) \times 10^{22}$ atoms cm^{-2} , 2.7 ± 1.2 and 0.74 ± 0.11 keV, respectively. The observed spectrum together with this fit are shown in Fig. 2. The 1–50 keV luminosity is 3×10^{37} ergs s^{-1} . The SSS+MPC spectral parameters and the derived luminosity are similar to those observed during the second *EXOSAT* observation, $\gtrsim 40$ days after the start of the 1984 outburst.

An independent estimate for the start of the 1979 outburst is obtained by comparing the SSS+MPC variability with that observed by *EXOSAT*. During the first *EXOSAT* observation, 4U 1630–47 was highly variable with 7.3% *rms* variability in the 1–7 keV energy range and 3.7% between 14–30 keV (PSW). This decreased to $< 1.3\%$ in the second observation, 30 days later. The SSS (0.5–4.5 keV) and MPC (3–15 keV) lightcurves do not exhibit significant variability, with an *rms* upper limit of $< 2\%$ in both cases. Although

the *EXOSAT* and *Einstein* measurements cover different energy ranges, and so cannot be directly compared, the lack of observed variability also suggests that the *Einstein* observation occurred $\gtrsim 40$ days after the outburst start.

3. THE EPHEMERIS

These observations of 4U 1630–47 in outburst in 1979 and 1992 provide important confirmation of the ~ 600 day outburst cycle first suggested by Jones et al. (1976). Table 1 lists the known outbursts from 4U 1630–47. For the first five, the observations spanned a large fraction of the outburst, and it is possible to make a good estimate of the time of peak flux from the figures given in Jones et al. (1976) and Friedhorsky (1986). There is no published lightcurve for the 1977 outburst, but the time of maximum flux is reported in Kaluzienski & Holt (1977). The time of the first detection of the 1984 outburst is given in Tanaka et al. (1984). We have assigned uncertainties to these outburst times of 15 days, based on the accuracy that the peaks can be established from the plots. The observations presented here are only snapshots of two previously unreported outbursts. Although the outburst starts were not observed, the observed spectral and temporal properties suggest that both observations occurred within ~ 70 days of the start of an outburst (see § 2). Since the other outbursts have a typical e-folding time of 50 days, we have made a conservative estimate for the *Einstein* and *ROSAT* outburst start times by subtracting 40 days from the times of observation, and using an uncertainty of ± 40 days (Table 1). A linear fit to the outburst times listed in Table 1 gives a mean outburst recurrence interval of 601.7 ± 3.0 day, with an epoch of JD 2,440,394.8 ± 14.2 . The residuals from this fit are shown in Fig. 3. The fit is not formally acceptable having a χ^2 of 33 for 6 dof. The average deviation of the outburst times from this linear relation is ± 24 day. Using this ephemeris the 1977 outburst occurred ~ 65 days late, which is similar to the ~ 70 days reported in Kaluzienski

& Holt (1977). The *Einstein* observation is on the following cycle and it is notable that this outburst occurs ~ 102 days early. The *ROSAT* detection indicates that 4U 1630–47 has undergone regular outbursts for at least 23 years, or 14 cycles. The stability of the outburst cycle suggests that the underlying mechanism may be periodic, perhaps with an additional “noise” process that affects the outburst start time and duty cycle.

4. DISCUSSION

4U 1630–47 is the first BHXT for which a periodic recurrence interval for the X-ray outbursts is now well established. It is interesting to compare 4U 1630–47 with other BHXT systems, where the outburst recurrence time scales are significantly longer (10–50 year). The BHXT outbursts are probably due to a mass transfer instability. This could result from either a disk instability (Mineshige & Wheeler 1989; Tuchman et al. 1990), or a mass transfer event from the companion (Hameury, King, & Lasota 1986). The disk instability models are analogous to models for dwarf novae with the accreting object changed from a white dwarf to a black hole. Irradiation models assume that a quiescent X-ray flux heats the atmosphere of the companion triggering a mass-loss instability due to the expansion of the companion’s atmosphere past the inner Lagrangian point. This increases the accretion rate onto the compact object until the disk has become sufficiently large to shield the companion from further illumination. There are problems with reconciling this model with the low-level of X-ray flux from transients in quiescence (Verbunt et al. 1994; McClintock, Horne, & Remillard 1995). The ~ 600 day outburst cycle of 4U 1630–47 may be an extreme example of a mass transfer instability. The noise in the outburst times may reflect fluctuations in the instability process. However, it is curious that the instability is able to maintain phase over so many cycles. An alternate explanation is that the ~ 600 day recurrence interval of 4U 1630–47 reflects an orbital period. The black hole could be in a highly eccentric orbit

with outbursts occurring near the times of closest approach to the companion.

Another possibility is that 4U 1630–47 is a low-mass X-ray binary in a hierarchical triple system where the outbursts are triggered by periodic perturbations of the inner binary orbit by the third star. The observed changes in absorption could then be accounted for by the presence of a massive companion. The identification of an optical counterpart would help distinguish between these possibilities, but there is no obvious candidate (PSW). The measured absorption is high and if this is interstellar, the counterpart will be highly reddened with $E_{B-V} \sim 2 - 20$. The detailed *EXOSAT* spectral measurements show a reduction in absorption as the 1984 outburst evolved. If this is real, and not caused by uncertainties in the spectral modeling, it indicates that much of the absorption is intrinsic to the source. The 4U 1630–47 outbursts seem to be predictable to within a few months, with the next two expected in 1995 November and 1997 July. Multi-waveband monitoring during outburst will allow the long term stability of the outburst cycle to be further investigated and may allow the identification of a radio, IR and optical counterpart.

This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center, provided by the NASA-Goddard Space Flight Center. We thank Jean Swank for pointing out the *Einstein* SSS observation of 4U 1630–47 in outburst and the referee for comments.

Table 1: 4U 1630–47 OUTBURST OBSERVATIONS

Cycle	Year	Outburst Peak Date (MJD)	ΔT^a (days)	Comment	Reference
0	1969	40396 ± 15	1.6	Most of outburst	1
1	1971	41005 ± 15	8.9	Entire outburst	1,2
2	1972	41589 ± 15	–8.7	Entire outburst	1,2
3	1974	42167 ± 15	–32.3	Entire outburst	1,2
4	1976	42795 ± 15	–6.0	Entire outburst	1,2
5	1977	43468 ± 15	65.3	Entire outburst	3,4,5
6	1979	43902 ± 40^b	–102.3	Single observation	This <i>paper</i>
9	1984	45791 ± 15	–18.3	Short observations	6,7
14	1992	48845 ± 40^b	27.4	Single observation	This <i>paper</i>

^aObserved – predicted outburst time

^bThe outburst time is determined by subtracting 40 days from the observation time.

¹Priedhorsky (1986); ²Jones et al. (1976); ³Kaluzienski & Holt (1977); ⁴Kaluzienski et al. (1978); ⁵Sims & Watson (1978); ⁶Tanaka et al. (1984); ⁷PSW.

REFERENCES

- Barret, D., et al., 1992, ApJ, 392, L19
- Cowley, A. P. 1994, AIP Conf. Proc., 308, 45
- Christian, D. J. 1993, Univ. of Maryland Ph. D. Thesis
- Eachus, J. L., Wright, E. L., & Liller, W. 1976, ApJ, 203, L17
- Elvis, M., Page, C. G., Pounds, K. A., Ricketts, M. J., & Turner, M. J. L. 1975, Nature, 257, 656
- Hameury, J-M., King, A. R., & Lasota, J-P. 1986, A&A, 162, 71
- Harmon, B. A., et al., 1992, IAU Circ., 5504
- Jones, C., Forman, W., Tananbaum, H., & Turner, M. J. L. 1976, ApJ, 210, L9
- Kaluzienski, L. J., Boldt, E. A., Holt, S. S., Mushotzky, R. F., Serlemitsos, P. J., & Rothschild, R. E. 1978, IAU Circ., 3197
- Kaluzienski, L. J., et al., ApJ, 201, L121
- Kaluzienski, L. J., Boldt, E. A., Holt, S. S., Mushotzky, R. F.,
- Kitamoto, S., Miyamoto, S., Tsunemi, H., Makishima, K., & Nakagawa, M. 1984, PASJ, 34, 799
- Kitamoto, S., et al., 1989, Nature, 342, 518
- Marsden B. G. 1989, IAU Circ., 4783
- Matilsky, T., Giacconi, R., Gursky, H., Kellogg, E. M., & Tananbaum, H. D. 1972, ApJ, 174, L53.

- McClintock, J. E. 1992, in: X-ray Binaries and Recycled Pulsars, eds. E. van den Heuvel & S. Rappaport, NATO ASI Series C, 377, 27
- McClintock, J. E., Horne, K., & Remillard, R. A. 1995, ApJ, 442, 365
- Mineshige, S., & Wheeler, J. G. 1989, ApJ, 343, 241
- Parmar, A. N., Stella, L., & White, N. E. 1986, ApJ, 304, 664 (PSW)
- Priedhorsky, W. C. 1986, Ap&SS, 126, 89
- Sims, M. R., & Watson, M. G. 1978, IAU Circ., 3227
- Tanaka, K., et al. 1984, IAU Circ., 3936
- Tanaka, K., & Lewin, W. H. G. 1995, in X-ray Binaries, eds. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 121
- Trümper, J. 1983, Adv. Space Res., 2, 241
- Tuchman, Y., Wagner, R. M., Starrfield, S. G., Hjellming, R. M., & Han, X. H. 1990, ApJ, 359, 164
- van den Woerd, H., White, N. E., & Kahn, S. M. 1989, ApJ, 344, 320
- Verbunt, F., Belloni, T., Johnston, H. M., van der Klis, M., & Lewin, W. H. G. 1994, A&A, 285, 903
- White, N. E. 1994, AIP Conf. Proc., 308, 53

Fig. 1.— The *ROSAT* PSPC spectrum of 4U 1630-47 from the 1992 observation. The upper panel also shows the best-fit thermal bremsstrahlung model (see text) as a histogram. The lower panel shows the residuals from this model.

Fig. 2.— The *Einstein* SSS+MPC spectrum of 4U 1630-47 from the 1979 observation. The upper panel also shows the best-fit two component model (see text) as a histogram. The lower panel shows the residuals from the best-fit model.

Fig. 3.— The time residual in days after a linear fit of the outburst times to cycle number. The error bars reflect the uncertainties in deriving the outburst start times (see text).