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OSO-7 OBSERVATIONS OF THE X-RAY NOVA 3U 1543−47*

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ABSTRACT

The intensity and spectrum of the transient X-ray source 3U 1543−47 were measured by the MIT X-ray detectors on the OSO-7 satellite on 13 occasions between 1971 November and 1972 December. The results, together with observations of the same object by the *Vela* and *Uhuru* satellites, can be described in terms of four qualitatively distinct phases in the X-ray light curve: (1) outburst (1971 July 26); (2) relatively steady intensity and spectrum (1971 August 1 to 1971 November 20); (3) rapid decrease in intensity and decrease in apparent temperature (1971 November 20 to 1972 January 6); (4) irregular intensity fluctuations with complex spectra (1972 January 6 onward). The term "X-ray nova" is proposed to characterize this and similar transient sources, and a new model for such X-ray novae is proposed.

Subject headings: stars: novae — X-rays: sources

I. INTRODUCTION

The transient X-ray source 3U 1543−47 in the constellation of Lupus was first reported from *Uhuru* observations (Matilsky *et al.* 1972). It had not been detected 3 months earlier in a rocket-borne experiment that scanned its position on 1971 May 25 (Burginyon *et al.* 1972). Belian *et al.* (1973) apparently observed the initial outburst at 1952 UT on 1971 July 26 in data from a *Vela* satellite. In this paper we present results on the intensity and spectrum of the source derived from observations made on 13 occasions between 1971 October 30 and 1972 December 6 by the MIT X-ray detectors on the OSO-7 satellite.

II. OBSERVATIONS

The X-ray detectors were two banks of proportional counters behind 1° and 3° (FWHM) collimators, respectively. The designations and approximate energy ranges of the counters are TW (1–1.5 keV), NE (1–6 keV), AR (3–10 keV), KR (15–40 keV), and XE (25–60 keV). Experimental details are given elsewhere (Clark *et al.* 1973).

We determined the maximum likelihood position of 3U 1543−47 by analysis of the data from the first period of observation and found that the 1 σ error circle of radius 0°.1 included the position reported from *Uhuru*. No other source listed in the 3U catalog lies within 3° of this position, and we find no evidence of another source within 3° in our data. We are therefore confident that the X-ray intensities reported here are correctly attributed to the X-ray nova 3U 1543−47.

Assuming this fixed position, we found the maximum likelihood values of the average intensities in each energy range in 1-day intervals during each of the 13 observations. Only the data in the ninth and tenth periods show statistically significant variations from day to day. The data for each of the other periods were combined to form an overall average for the period. The results for the TW, NE, and AR counters are summarized in Table 1, and the variations in the NE rate are shown in Figure 1. The source was not detected in the KR and XE counters at any time.

To determine the spectral characteristics of the source, we compute ratios of the counting rates or their upper limits in the TW, AR, and KR counters to the corresponding rates in the NE counter and plot the results on intensity ratio diagrams. The grid lines on these diagrams show the expected positions of representative points for various two-parameter trial spectra: specifically, blackbody, thermal bremsstrahlung, and power-law spectra modified by photoelectric absorption (see Clark *et al.* 1972). Figure 2 shows the results for 3U 1543−47 with a grid calculated for thermal bremsstrahlung spectra of the form

$$dN/dE = A \exp [(-E_a/E)^{2.7}] [\exp (-E/2kT)K_0(E/2kT)][E\sqrt{(kT)}]^{-1} ,$$

where all energies are in keV. The formula, given by Chodil *et al.* (1968*b*) includes an approximate form of the Gaunt factor. The spectral parameters are tabulated in Table 2 for those observations in which they could be determined with meaningful accuracy.

If we consider only the observed AR/NE and TW/NE ratios, our data for observations 1, 2, and 3 are consistent with either a power-law or a thermal bremsstrahlung spectrum. The data of observation 1 are definitely inconsistent with a blackbody spectrum. Taking into account the upper limit on the KR counting rate, we find that the data from observation 1 are fitted significantly better by the thermal bremsstrahlung spectrum than by a power-law spectrum. For simplicity we have analyzed the data for observations 1, 2, 3, and 9 in terms of thermal spectra. The data of observations 7 and 10 are not consistent with any of the three ideal

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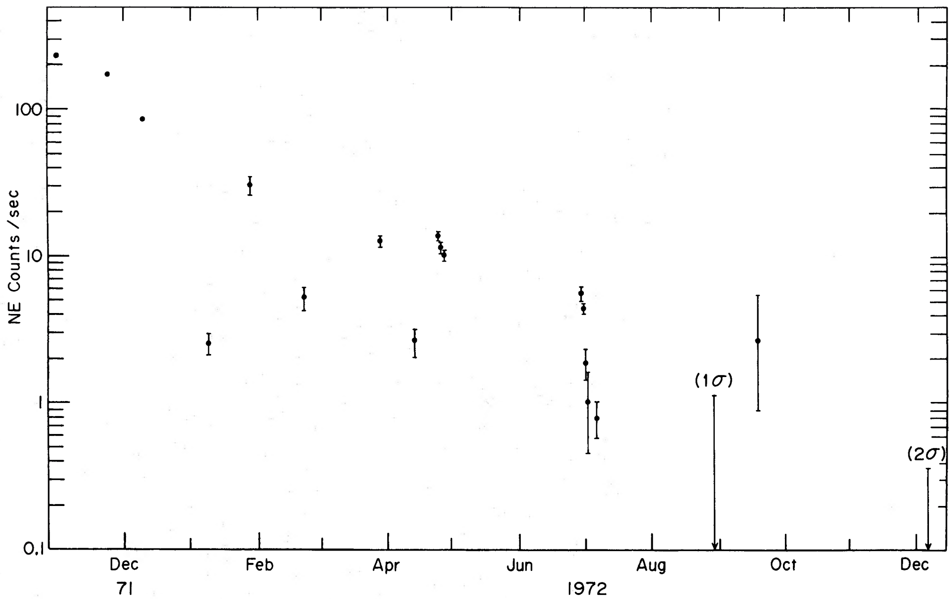

FIG. 1.—The average intensity of 3U 1543−47 in each observation in the NE detectors. In the ninth and tenth observations, the intensities in one-day intervals are shown separately.

TABLE 1

COUNT-RATES FOR 3U 1543−47 IN VARIOUS COUNTERS

Number	Observation Time	Collimator	Count-Rates in Counters: TW	NE	AR	Flux (1–6 keV in 10^{-8} ergs cm^{-2} s^{-1})
1....1971	Oct. 30.0 to Nov. 1.5	1°	26.2 ± 1.1	233.8 ± 1.9	46.1 ± 0.8	3.6 ± 0.3
2.........	Nov. 23.0 to Nov. 25.5	1°	15.1 ± 0.8	176.3 ± 1.5	28.3 ± 0.6	1.4 ± 0.1
3.........	Dec. 10.0 to Dec. 11.0	1°	8.2 ± 1.2	86.1 ± 1.4	10.3 ± 0.5	1.2 ± 0.3
4....1972	Jan. 5.0 to Jan. 12.0	1°	0.02 ± 0.24	2.6 ± 0.4	0.6 ± 0.1	...
5.........	Jan. 28.5 to Jan. 29.5	1°	4.1 ± 0.9	30.7 ± 4.0	0.5 ± 0.4	...
6.........	Feb. 21.5 to Feb. 24.0	1°	0.5 ± 0.9	5.2 ± 1.0	−0.5 ± 0.4	...
7.........	Mar. 28.0 to Mar. 29.0	1°	3.6 ± 1.1	12.9 ± 1.0	2.7 ± 0.5	...
8.........	Apr. 12.5 to Apr. 13.5	1°	0.4 ± 0.7	2.7 ± 0.6	1.6 ± 0.3	...
9.........	Apr. 24.5 to Apr. 28.0	1°	1.6 ± 0.6	12.0 ± 0.6	0.8 ± 0.3	0.23 ± 0.23
10*a**.......	June 29.5 to July 3.5	3°	0.7 ± 0.2	3.3 ± 0.3	1.0 ± 0.1	...
10*b**.......	July 3.5 to July 10.5	3°	0.3 ± 0.3	0.8 ± 0.2	0.6 ± 0.1	...
11.........	Aug. 29.0 to Aug. 30.0	1°	0.4 ± 1.4	0.0 ± 1.2	0.5 ± 0.7	...
12.........	Sept. 19.5 to Sept. 20.5	1°	0.8 ± 1.0	2.7 ± 1.9	0.3 ± 0.5	...
13.........	Dec. 5.0 to Dec. 6.5	1°	−0.1 ± 0.5	−0.6 ± 0.5	−0.1 ± 0.2	...

* This observation lasted 12 days and is broken into two periods when count-rates are averaged because of the differences in intensity during these 12 days (see Fig. 1).

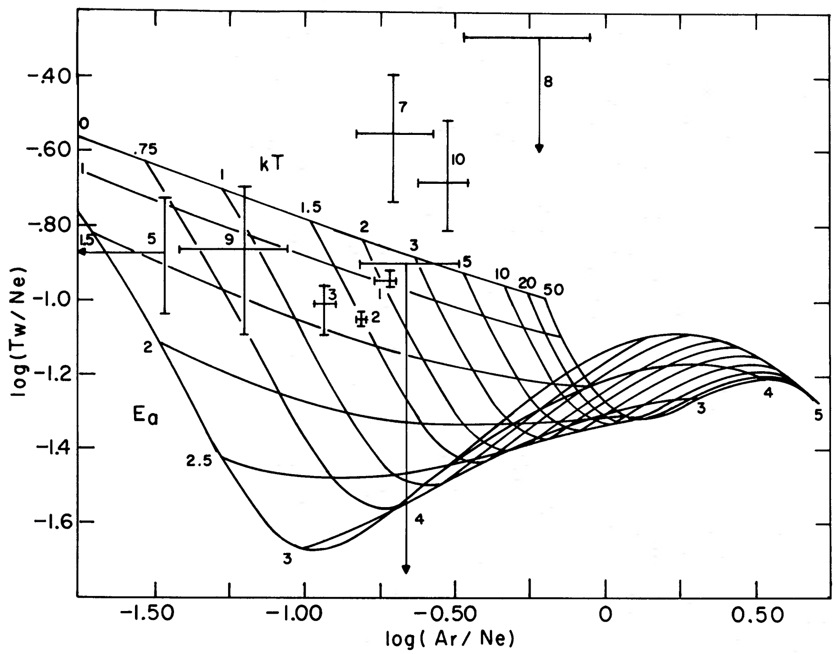

FIG. 2.—The spectra of 3U 1543−47 in various observations are shown with the grid lines of representative thermal bremsstrahlung spectra. The number in Fig. 2 is the observation number in Table 1.

simple spectra, and the data for the remaining observations are too sparse to permit meaningful spectral analysis. We note that the fitted values of the cutoff energy E_a in observations 1, 2, 3, and 9 are significantly and consistently greater than zero. This is also the case when the data are fitted by a power law. We conclude, therefore, that the spectra show evidence of an absorption cutoff with $E_a \approx 1$ keV which corresponds to a column density of $N_H \approx 5 \times 10^{21}$ H atoms per cm^2 (Brown and Gould 1970).

Figure 3 shows the combined data on the intensity of 3U 1543−47 observed by the *Uhuru* (Matilsky *et al.* 1972) and OSO-7 satellites. For this figure, the OSO-7 intensities were multiplied by a constant factor that adjusts the average NE intensity in the first observation (1971 October 30) to the intensity as observed by *Uhuru* at approximately the same time. The adjusted intensities in the second, third, and fifth observations then agree well with those obtained by *Uhuru*, so we can combine *Uhuru* and OSO-7 data without risking large errors in the overall history of the source intensity.

III. DISCUSSION

Examining the combined light curve, we distinguish four qualitatively distinct phases. The first phase is the initial outburst, lasting for around 2 days. The second phase, lasting about 110 days until ~1971 November 20, is characterized by a slow irregular decrease in intensity at an average rate of ~0.7 percent per day. The spectrum is generally steady (Matilsky *et al.* 1972). The third phase, from ~1971 November 20 to ~1972 January 6, shows a much faster decline in the intensity at a rate of ~8 percent per day. The fourth phase, after ~1972 January 6, shows irregular periods of high and low intensities. The temperature parameter of the thermal bremsstrahlung spectra fitted to the OSO-7 data from observations 1, 2, and 3 (see Table 2) shows a monotonic decrease from ~1971 November 1 to ~1971 December 10, although the quantity A which characterizes the total emission did not, being greatest at the time of the second observation. In the fourth observation period, the intensity was very low and the spectrum, though poorly defined, was consistent with a low temperature (see Fig. 2).

The fourth phase in the light curve, from ~1972 January 6 on, is characterized by large fluctuations in the intensity which, however, did not at any time exceed ~1/10 of that in 1971 August. We cannot determine the spectrum for the low intensity states in this period. For the high intensity states in which we

TABLE 2

SPECTRAL PARAMETERS FOR 3U 1543−47

Observation	A	E_a (in keV)	kT (in keV)
1............	19.5 ± 1.4	0.95(+0.15, −0.45)	2.13 ± 0.08
2............	30.1 ± 3.1	1.35 ± 0.05	1.48 ± 0.05
3............	18.9 ± 5.4	1.30 ± 0.15	1.23 ± 0.11
9............	3.8 ± 3.8	1.15(+0.60, −1.25)	0.92 ± 0.26

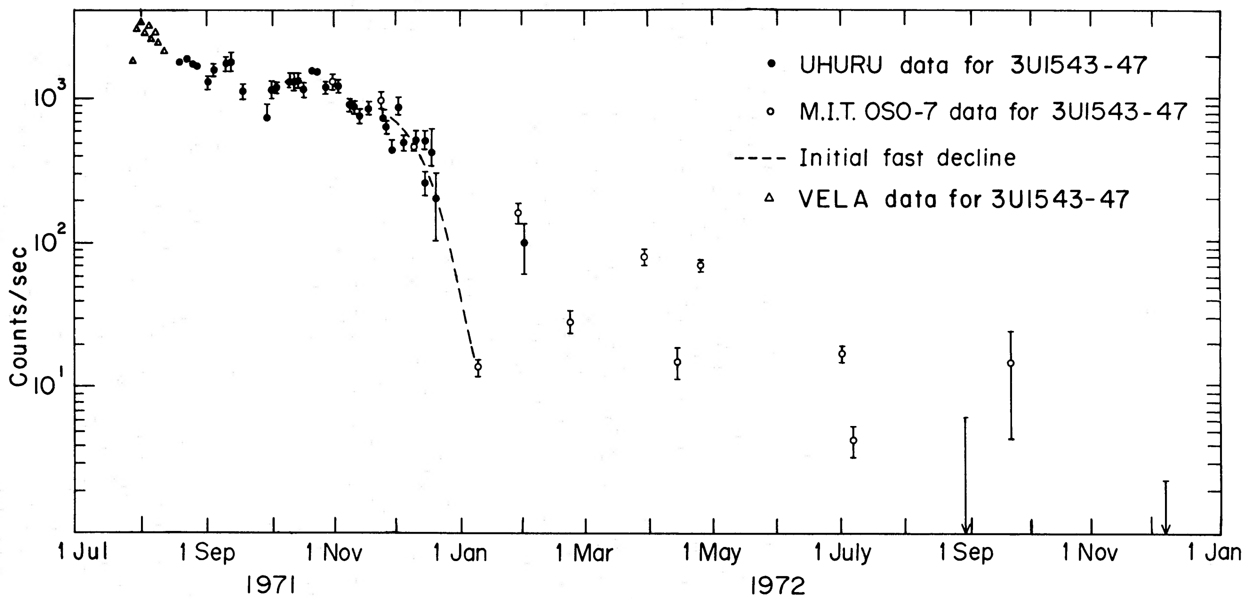

FIG. 3.—Combined data from the *Vela, Uhuru*, and OSO-7 satellites, normalized to the *Uhuru* count-rates

can determine the intensities with statistically significant values in the three energy channels, i.e., the seventh, ninth, and tenth observations, we find plausible values of spectral parameters only for the ninth. Data from the other two are not fitted well by any of the simple spectral functions we have tried, indicating that the emission region may be highly inhomogeneous.

The X-ray light curve of 3U 1543−47 is similar to that of Cen X-4 observed earlier by the *Vela* satellites (Evans *et al.* 1970). Both resemble the typical light curve of optical novae. It therefore seems appropriate to use the term "X-ray novae" to describe sources which, like Cen X-4 and 3U 1543−47, exhibit the following phenomena: (1) initial outburst (several days); (2) slow decline lasting several months with a fairly steady spectrum; (3) fast decline in about 1 month; (4) possible recurrence with intensity reaching $\sim 1/10$ of the initial maximum.

We note that the available data on Cen X-2 (summarized by Chodil *et al.* 1968*a*) are consistent with the assumption that it too was an "X-ray nova" by this definition. The data are too sparse, however, to permit its definite identification as such. Several other "transient" sources, e.g., Cep X-4 (Ulmer *et al.* 1973) and GX 359+2 (Kellogg *et al.* 1971) declined too rapidly after reaching their maximum intensities to conform to our definition.

Several models have been put forward previously to explain "transient sources." None so far appears able to explain the phenomenon we describe as that of "X-ray novae." The following are among these models:

a) *Expanding Isothermal Gas Cloud*

Manley (1967) proposed that the X-rays are emitted by an optically thin isothermal gas cloud which is ejected by some unspecified mechanism. However, the constancy of the spectrum in the slow-decline phase implies that the temperature of the cloud is constant. The luminosity L of a spherical, isothermal, constant temperature gas cloud is proportional to

$$L \propto n^2 V \propto \frac{1}{R^3} ;$$

where n is the electron density, V is the cloud's volume, and R is the cloud's radius. If the expansion rate is steady, $R \propto t$, where t is time after outburst; so $L \propto t^{-3}$, which is not what is observed.

b) *Flash Burning of Hydrogen Accreted on a Neutron Star in a Close Binary System*

Van Horn and Hansen (1974) proposed that hydrogen is accreted slowly from the primary of a binary star system by the secondary which is a neutron star. A hydrogen shell is built up on the surface of the neutron star until the moment when the density at the base of the shell is high enough to cause a flash hydrogen burning. This corresponds to the outburst of an X-ray nova. The shell continues to burn until all the hydrogen is exhausted.

Our data show that the initial spectrum is best fitted by a thermal bremsstrahlung spectrum. No satisfactory fit can be obtained for a blackbody spectrum. However, the Van Horn and Hansen model predicts that the emitting region is optically thick so that its spectrum should be one of a blackbody at $\sim 10^7$ K. Also, the rise-time of the outburst in their model is on the order of minutes whereas the actual one is a few days (Belian *et al.* 1974). Finally, there is no possibility in their model to provide a mechanism for the observed recurrences after the fast decline. The hydrogen shell is consumed completely after the fast decline, and the accretion rate is so slow that a new flash-burning shell cannot accumulate in the time of a few months.

c) Initial Phase of a Smothered Accretion Source

Van den Heuvel (1975) considers a binary system in which the primary is in the mass range 2–10 $M_{\odot}$ and the other member is a collapsed star. When the primary goes into its post–main-sequence expansion, there is a brief period between the moment when the expanding star first overflows its Roche lobe and spills matter onto the collapsed star which then emits X-rays, and the moment when the collapsed star is buried under the accreted matter. The system is an X-ray nova during this brief period. The model seems implausible in view of two points. The model predicts that the turning-off of an X-ray nova is due to increasing absorption as the collapsed star is swamped by the expanding star. However, our spectral data indicate that there was no significant increase in absorption cutoff energy when 3U 1543−47 first went into the fast-decline phase. Another serious difficulty is that the normal expansion rate of an evolving post–main-sequence star is too low to explain the rapid rise of the outburst.

We propose a new model which accounts for the principal nova phenomena and can be tested observationally. Plaveč and Horn (1969) have studied the evolution of binary systems in which the masses of the two stars are 5 $M_{\odot}$ and 3 $M_{\odot}$, respectively. The 5 $M_{\odot}$ star evolves rapidly and at some point mass exchange occurs. A plausible intermediate stage is then a system with a 3 $M_{\odot}$ and a 5 $M_{\odot}$ star in which the 3 $M_{\odot}$ star is the more massive one originally. This 3 $M_{\odot}$ star continues its evolution, at the end of which it undergoes a supernova explosion that leaves a neutron star or black hole orbiting the 5 $M_{\odot}$ star. It is difficult to estimate the radius of the final orbit for the collapsed star. The radius of the HZ Her and Her X-1 system, with the mass of HZ Her being $\sim 2\ M_{\odot}$, is $\sim 10^{12}$ cm. We also know that if half of the mass of the binary system is ejected in the supernova explosion, the system will become unbound. Thus, there appears to be a continuum of possible values for the radii of the orbits from $\sim 10^{12}$ cm to infinity after the supernova explosion. For our model, we adopt a value of 4×10^{12} cm, $\approx 60\ R_{\odot}$.

Some red giants, of spectral type K or M, are known to be long period variables (Glasby 1970). They have masses around one to a few $M_{\odot}$ (Hayashi 1964). Their optical magnitudes vary with irregular intervals between peaks of ~ 100 days to ~ 1000 days. In a typical optical pulse the surface expands at a typical speed of ~ 10 to ~ 20 km s^{-1} (Glasby 1970), and the radius of the star may change by 20 percent or more. We assume that the red giant system discussed above became such a long period variable. In one of its large pulses, the radius increases rapidly, and matter overflows the Roche lobe and is accreted onto the collapsed star.

Let δ be the fraction of the surface of the giant that is accreted onto the collapsed star when it overflows the Roche lobe. In one day's time, the envelope expands by $\sim 10^{11}$ cm, and the density at $\sim 10^{11}$ cm inside a 1 $M_{\odot}$ giant is $\sim 10^{-11}$ g cm^{-3} (Rose 1973). The luminosity the accreted matter produces is:

$$L \approx \frac{1}{10} \frac{GM_{\rm cs}}{r_{\rm cs}} 4\pi (30\ R_{\odot})^2 \rho V \delta ,$$

where $M_{\rm cs}$, $r_{\rm cs}$ are the mass and radius of the collapsed star, ρ is the density at Roche lobe surface, V is velocity of expansion, and 1/10 is the efficiency for conversion of gravitational to radiation energy. For the observed luminosity of 3U 1543−47, which is $\sim 10^{37}$ to 10^{38} ergs s^{-1} assuming it is from ~ 1 to ~ 3 kpc away, and assuming $M_{\rm cs} \approx 1\ M_{\odot}$, $r_{\rm cs} \approx 10^6$ km, we get $\delta \approx 10^{-2}$ to $\sim 10^{-3}$.

Matter accreted on the collapsed star will probably first form a disk around it (Pringle and Rees 1972). Viscosity causes the matter to drift in toward the collapsed star. The orbital velocity of the collapsed star is ~ 100 km s^{-1}, so the radius where the accreted matter is gravitationally captured by the collapsed star is:

$$r_c \approx \frac{GM_{\rm cs}}{V_{\rm rel}^2} \quad \text{for } V_{\rm rel} \approx 100 \text{ km s}^{-1} ,$$

$$r_c \approx 7 \times 10^{11} \text{ cm} .$$

The drift-in velocity is highly uncertain. For a value of 1/10 of the orbital velocity, the captured matter will drift in in several days to produce the observed X-ray luminosity. The ratio of the capture surface to the surface of the giant is $\pi r_c^2 / 4\pi (30\ R_{\odot})^2 \approx 10^{-2}$, which agrees with the number we estimated above.

Matter will continue to overflow for a while, but the accretion will be regulated partially by the radiation pressure. When the giant contracts back, there is still a disk remaining around the collapsed star. The matter in that disk, too, will drift in afterward, and the depletion of the disk corresponds to the fast-decline phase.

Superposed on the quasi-periodic optical variations of these giants are some erratic smaller variations. Some of these can cause secondary, but smaller, Roche lobe overflow which may explain the recurrence phase observed in 3U 1543−47.

This model predicts that X-ray novae recur in the time scale of years. However, the mass transfer phenomena may change the envelope of the giant so much that pulsations are terminated or that, in subsequent pulsations, the star does not overflow its Roche lobe. Moreover, the magnitudes of their pulsations are known to be variable, and X-ray nova outbursts may represent only the largest ones.

A critical test of this or any other model is the identification of the optical counterpart of an X-ray nova. In fact, a suggested counterpart for 3U 1543−47 (Forman and Liller 1973) is a variable M giant as required by our model. However, the identification is uncertain because of the size of the error box for the location of the X-ray source.

Tsygan (1975) recently suggested that X-ray novae are wide binary systems in which a collapsed star is moving around a main-sequence star in a highly eccentric orbit. In the region of close approach near periastron, mass transfer is high enough to make the system an X-ray source. This model predicts that X-ray novae should recur *periodically*. However, observations by OSO-7 indicate that 3U 1543−47 did not recur in ~2 years. Further observations of the site of this X-ray nova may decide if the eccentric orbit model is correct.

We note that if our model proves correct, then X-ray novae offer opportunities to observe the dynamical properties of accretion disks since the turn-on and turn-off of the matter supply causes time-dependent effects.

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