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ACCURATE PERIOD DETERMINATION OF AN ECLIPSING BINARY X-RAY SOURCE IN M33

ERIC SCHULMAN AND JOEL N. BREGMAN
Department of Astronomy, University of Michigan, Ann Arbor, MI 48109-1090

ALFONSO COLLURA
Istituto per le Applicazioni Interdisciplinari della Fisica-CNR, Via Archirafi 36, Palermo, Italy

FABIO REALE
Instituto ed Osservatorio Astronomico, Piazza del Parlamento 1, 90134 Palermo, Italy

AND

GIOVANNI PERES
Osservatorio Astrofisico di Catania, Viale A. Doria 6, 95125 Catania, Italy
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ABSTRACT

We have analyzed the time variability of one of the X-ray sources in M33 observed by both the *ROSAT* and *Einstein Observatory* telescopes. The light curve of M33 X-7 exhibits a variability pattern of high and low states, suggesting an eclipsing binary X-ray source. The data suggest a binary period $P = 1.78572$ days (very close to that of Her X-1) and an eclipse duration of ~0.4 days. The low phase lasts about one-fourth of the period as in Cen X-3.

Subject headings: binaries: eclipsing — galaxies: individual: M33 — stars: individual (M33 X-7) — X-rays: galaxies — X-rays: stars

1. INTRODUCTION

In this *Letter* we report the results of a variability study of the X-ray source M33 X-7 (according to the classification of Trinchieri, Fabbiano, & Peres 1988 and Markert & Rallis 1983). The global morphological characteristics of M33 based on *Röntgensatellit* (*ROSAT*) observations will be presented in a complementay paper (Schulman & Bregman 1994). Previous variability studies of M33 X-7 were carried out by Long et al. (1981), Markert & Rallis (1983), and Peres et al. (1989, hereafter PRCF) using observations made with the *Einstein Observatory*. We use the *Einstein* observations together with new *ROSAT* observations to analyze the variability over a 13 yr timescale.

This *Letter* is organized as follows: In § 2 we discuss the observations, in § 3 we present the methods of analysis and the results, and in § 4 we draw our conclusions.

2. OBSERVATIONS

M33 has so far been observed twice by the *ROSAT* High-Resolution Imager (HRI). This instrument detects photons in the 0.2–2.6 keV band and is most sensitive below 1 keV. A more complete description of *ROSAT* and the HRI can be found in Trümper (1984). M33 was the target of five pointed observations made with the *Einstein* satellite: two with the Imaging Proportional Counter (IPC), which detected photons in the 0.2–4.5 keV band and was most sensitive near 2 keV, and three with the High-Resolution Imager (HRI), which detected photons in the 0.1–3 keV band and was most sensitive below 1 keV. A more complete description of the *Einstein* satellite and the instruments on board can be found in Giacconi et al. (1979).

The *ROSAT* observations were made within 7 months (1992 January–August) and the *Einstein* observations were made within 1 year (1979 August to 1980 August). In the following we will designate each observing sequence with two letters and a number: the first letter is the initial of the satellite, the second is the initial of the focal plane detector, and the number is the observing sequence number of the observation (this number identifies the particular observation among the entire database of observations made with the satellite). A lowercase letter after the number might identify any major section of the observing sequence. Therefore, for instance, RH600020a means the first section of the observing sequence 600020, obtained by the *ROSAT* satellite with the HRI in the focal plane. Table 1 summarizes, for each observation, the sequence number, the start and stop times, and the net observing times. As shown in Table 1, the two *Einstein* IPC observations were separated in time by 6 months, and each was followed by an HRI observation after a few days. A final *Einstein* HRI observation was then performed after another 6 month interval. The first *ROSAT* HRI observation took place almost 11.5 years after the last *Einstein* HRI observation, and the second *ROSAT* HRI observation took place 7 months later. We can identify, therefore, five groups of observations separated from each other by ~6 months except for the almost 12 year gap between the last *Einstein* and the first *ROSAT* observations. Each *ROSAT* and *Einstein* observation is composed of contiguous data sections separated by gaps during which useful data could not be obtained. Such contiguous data sections typically last a few thousand seconds. Thus, the "live time" of each observation listed in Table 1 is shorter than the overall observing time.

3. ANALYSIS AND RESULTS

The *ROSAT* observations of M33 X-7 were reduced using IRAF Version 2.10.2 and PROS Version 2.2. The two observation sections have pointing centers which differ by ~5″ so RH600020b was shifted and then merged with RH600020a. The count rates were derived from the photon counts received within 10″ of the source, subtracting a background determined from an annulus with radii 60″ and 180″. We included photons with energies between ~0.3 and 1.8 keV (pha channels 2 to 10) in order to improve UV photon rejection at low energies and

TABLE 1

Einstein AND *ROSAT* OBSERVATIONS OF M33

Sequence Number	Start Day	Start Time	Stop Day	Stop Time	Live Time (s)
EI2090	1979 Jul 31	$20^{h}16^{m}40^{s}$	1979 Aug 3	$10^{h}05^{m}22^{s}$	21499
EH2724	1979 Aug 5	03 29 49	1979 Aug 7	11 45 36	39710
EI2091	1980 Jan 11	06 15 16	1980 Jan 12	01 29 39	13555
EH7577	1980 Jan 14	23 41 02	1980 Jan 15	20 45 20	26356
EH9907	1980 Aug 2	00 49 19	1980 Aug 2	11 36 28	20923
RH600020a	1992 Jan 8	10 32 06	1992 Jan 12	17 12 43	19206
RH600020b	1992 Aug 1	12 59 30	1992 Aug 3	11 33 23	15663

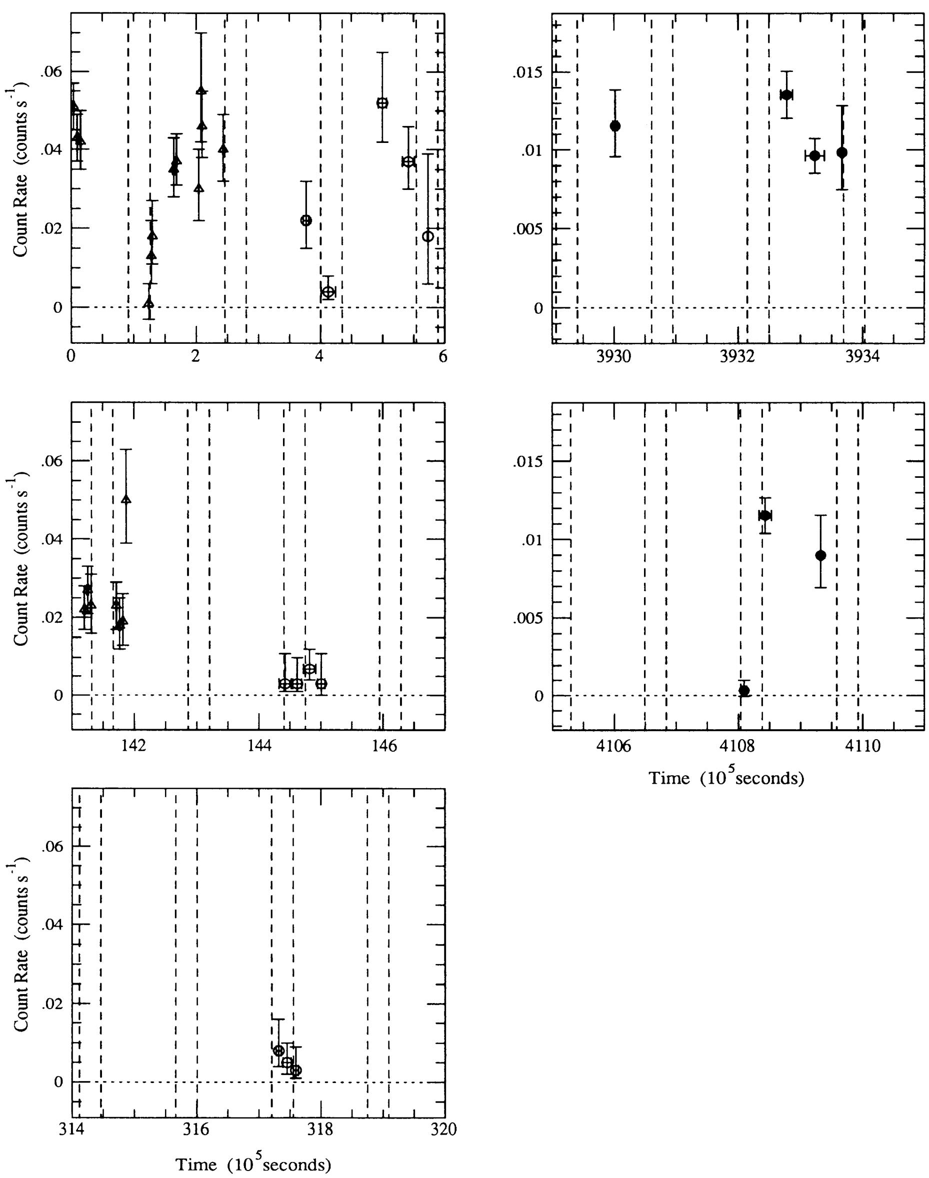

FIG. 1.—*ROSAT* HRI and *Einstein* HRI and IPC light curves of M33 X-7. *Einstein* IPC points are represented by *open triangles*, *Einstein* HRI points by *open circles*, and *ROSAT* HRI points by *filled circles*. The horizontal bar of each data point shows its time span. The abscissa gives the time since the beginning of the first *Einstein* observation of M33. The vertical dashed lines represent the recurrent minima, under the assumption that the source varies with a period $P = 1^{d}.78572$. The *Einstein* HRI count rates have been multiplied by 17 to make them consistent with the *Einstein* IPC count rates.

noise rejection at high energies. Variability within the new *ROSAT* observations has been studied with three independent methods: the Kolmogorov-Smirnov method and the Cramer-Smirnov-Von Mises method (Eadie et al. 1971) which compare the cumulative distribution of photon arrival times with the distribution expected from a constant source, and a modified χ^2 test able to provide binning independent results (Collura et al. 1987). All three methods determine that the source is variable and that all of this variability is concentrated in RH600020b. The probability that the source was constant during the entire *ROSAT* observation is less than 0.001%.

M33 X-7 was interpreted to be an eclipsing binary by PRCF based on *Einstein* observations. PRCF found that a period $P = 1^{\rm d}.7857$ could account for all the *Einstein* minima, with an approximate duration of the minima of $\sim 0^{\rm d}.4$. Our *ROSAT* data confirm this interpretation and allow us to measure the period much more accurately. The light curve is shown in Figure 1. The Einstein HRI count rates have been multiplied by 17 to correct for the greater sensitivity of the *Einstein* IPC compared to the *Einstein* HRI. Each *Einstein* IPC point represents the average count rate in each contiguous data segment. For the *Einstein* HRI data, where the count rate is much lower, and the *ROSAT* HRI data, where the contiguous data segments can be as short as 2 s, we averaged the count rate over consecutive contiguous data segments such that each data point is made up of at least 800 s of observations. The error bars on each data point have been determined according to the method of Gehrels (1986), which uses Poisson statistics. The flux from the source is at least a factor of 15 lower in the "low" (eclipsed) state than in the "high" state. In addition, there is a "medium" (transition) state. The source is seen in all three states in EI2090 and EH2724, in the medium and high states in EI2091, is not detected at all in EH7577 and EH9907 (presumably the source was in the low state during these observations), is seen in only the high state in RH600020a, and is seen in both the high and low states in RH600020b.

Because of the 12 yr interval between the *Einstein* and *ROSAT* observations we can obtain a much more accurate period determination. We assume, as a starting hypothesis of our analysis, that the *ROSAT* minimum occurred exactly in the middle of an eclipse and then adjust the resulting period and phase slightly, producing light curves with different periods and phases until the *ROSAT* minimum occurs during an eclipse and the other *ROSAT* points do not occur during eclipses. We find a best-fit period $P = 154286 \pm 1$ s ($1^{\rm d}.78572 \pm 0^{\rm d}.00001$). This periodicity is plotted on Figure 1 with the vertical dashed lines indicating the locations of the predicted minima. The *ROSAT* data folded according to this period are shown in Figure 2 and the *ROSAT* and *Einstein* data together are shown in Figure 3. The *ROSAT* HRI count rates have been multiplied by 4 and the *Einstein* HRI count rates by 17 to make them consistent with the *Einstein* IPC count rates. We do not directly compare the *Einstein* and *ROSAT* fluxes because of

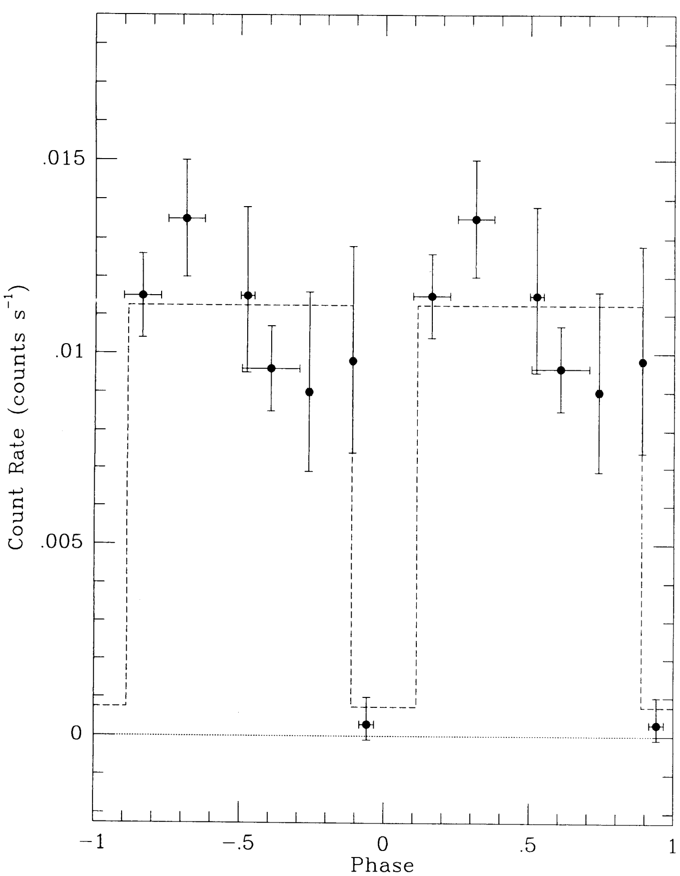

FIG. 2.—*ROSAT* HRI light curve of M33 X-7 folded with a period of $1^{\rm d}.78572$. The dashed line sketches an average light curve. The data are plotted twice to show two cycles.

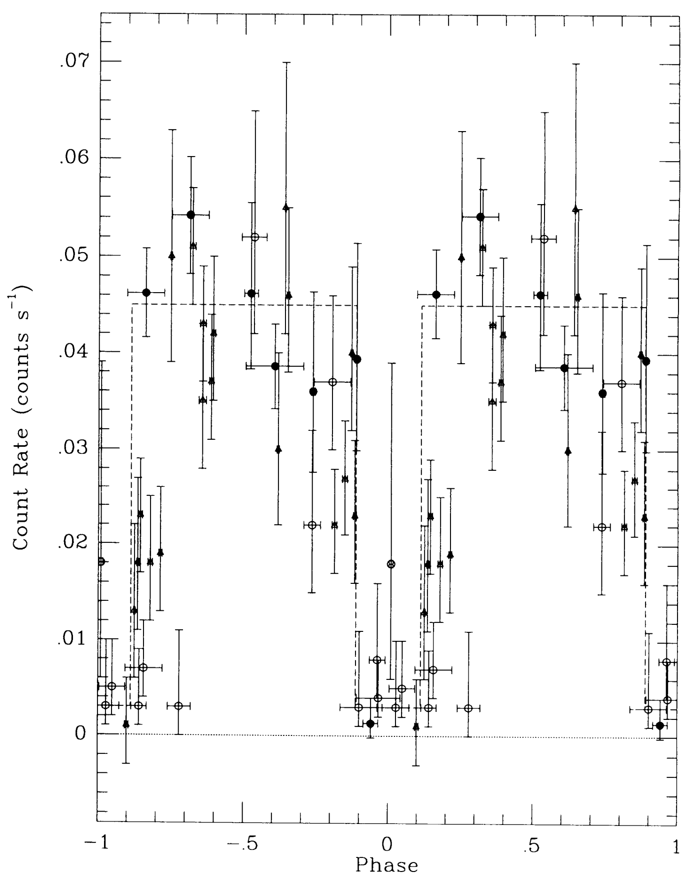

FIG. 3.—*ROSAT* HRI and *Einstein* HRI and IPC light curves of M33 X-7 folded with a period of $1^{\rm d}.78572$. The dashed line sketches an average light curve. The data are plotted twice to show two cycles. The *ROSAT* HRI count rates have been multiplied by 4 and the *Einstein* HRI count rates have been multiplied by 17 to make them consistent with the *Einstein* IPC count rates.

the large uncertainties in the cross-correlation between the two instruments. The maxima in the light curves of binary X-ray sources have been seen to disappear sometimes from cycle to cycle or to be lower than their usual value (Tananbaum & Tucker 1974), and therefore a simple characterization of the light curve is not always possible. This could explain why the minima in EH7577 and EH9907 do not contain all of the upper limits; it is possible that the minima simply lasted longer than 0.4 days during those eclipses.

The period we determine for M33 X-7 is very close to that of Her X-1 (Tananbaum et al. 1972) and the low phase lasts about one-fourth of the period as in Cen X-3 (Schreier et al. 1972). We therefore repropose the analogy of M33 X-7 to the bright close accreting systems found in the Galaxy, as suggested by PRCF.

PRCF suggest that a period twice as long ($P = 3^{\mathrm{d}}.5714$) could account for most of the minima, the others being produced by depressed maxima such as have been observed in the light curve of Cen X-3 (Schreier et al. 1976). Figure 4 shows the *ROSAT* and *Einstein* data folded with a period of $3^{\mathrm{d}}.57144$. The dotted line shows the minima predicted by a period of $1^{\mathrm{d}}.78572$. It is unlikely that the minimum around phase 0.5 could have been produced by depressed maxima since the points come from several independent observations and the minimum falls almost exactly at the center of the maximum phase.

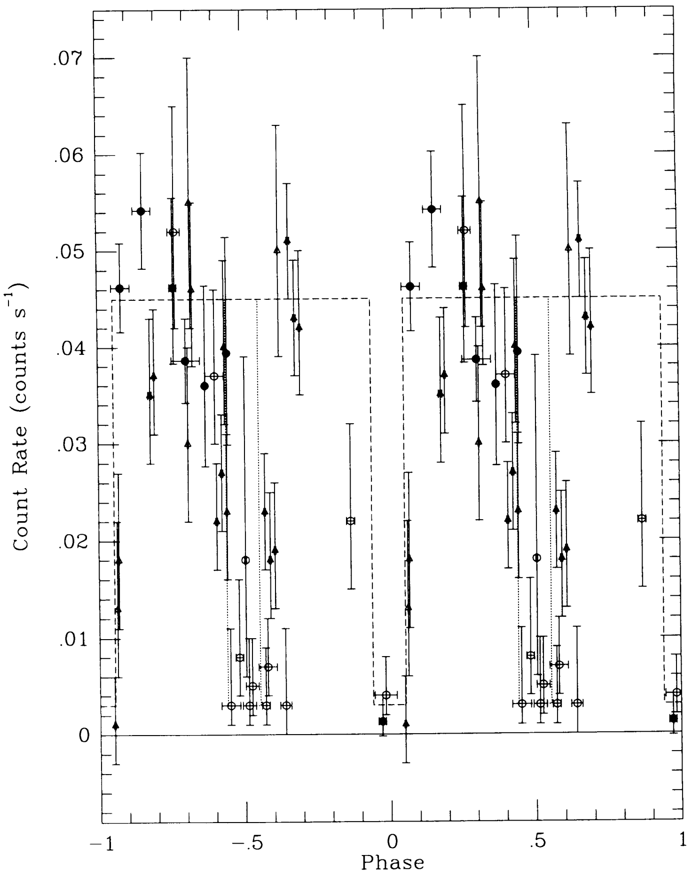

FIG. 4.—*ROSAT* HRI and *Einstein* HRI and IPC light curves of M33 X-7 folded with a period of $3^{\mathrm{d}}.57144$. The dashed line sketches an average light curve. The dotted line shows the minima which would occur if the period were $1^{\mathrm{d}}.78572$. The data are plotted twice to show two cycles. The *ROSAT* HRI count rates have been multiplied by 4 and the *Einstein* HRI count rates have been multiplied by 17 to make them consistent with the *Einstein* IPC count rates.

4. CONCLUSIONS

M33 X-7 is a compact accreting eclipsing binary, similar to X-ray sources detected in the Galaxy. Our *ROSAT* data confirm the binary interpretation and allow us to measure the period to an accuracy of 0.001%. The binary period of this source ($1^{\mathrm{d}}.78572$) and the duration of the X-ray eclipse ($\sim$0.4 days) are reminiscent of those of galactic X-ray sources. The low phase lasts about one-fourth of the period as in Cen X-3, and the period itself is very close to that of Her X-1. A period twice as long as does not appear to be consistent with the data.

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