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Two years of observation of the x-ray pulsar Vela X-1 with the *Watch* instrument on the *Granat* observatory

I. Yu. Lapshov, R. A. Syunyaev, M. A. Chichkov, V. V. Dremin, S. Brandt, and N. Lund

Space Research Institute, Russian Academy of Sciences, Moscow;
and Danish Space Research Institute, Lyngby

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We present the results from a study of the x-ray pulsar Vela X-1 using the *Watch* instrument on the *Granat* observatory between January 1990 and September 1991. We have found a rotation period for the pulsar of 283.3 seconds. This is the longest period seen since observations of the system began. Light curves of this source indicate that there are strong outbursts of x-ray emission lasting several hours. On 9–10 January 1991, the *Watch* instrument discovered that the source was turned off for more than 10 hours. This turn-off started two days prior to the regular eclipse.

Introduction. Dozens of x-ray pulsars have been observed intensively by multiple spacecraft. Among these, special attention has been paid to the long-period pulsar Vela X-1 (4U 1900−40), which has a period of about 283 seconds. It is not simply the fact that the rotation period of the neutron star is anomalously long (and therefore difficult to reconcile with our concepts of disk accretion onto an object with a magnetic field of $10^{11\text{-}12}$ G). In all likelihood, in this system we are faced with accretion of a stellar wind where the accreting material has a relatively small specific angular momentum (Illarionov and Syunyaev, 1975). Even more surprising is the high rate at which the neutron star rotation is slowing down, and the fact that this phase has lasted so long. In the present article, we use data from the *Granat* observatory to show that the rotation of Vela X-1 continues to slow at a rate of roughly $\dot{P}/P = 10^{-4}\ \mathrm{yr}^{-1}$. We also show that the period has increased by 0.557 seconds since 1979, when Hakucho determined that the minimum period was 282.746 seconds (Nagase et al., 1984). At the same time, we have not seen any energetic phenomena such as starquakes, restructuring of the solid core of the neutron star, or the like. In the course of these 12.5 years, the mean rate of slowdown has been $\dot{P}/P = 1.57 \times 10^{-4}\ \mathrm{yr}^{-1}$. The simplest theories predict that an accreting pulsar will speed up when the accretion rate is large (and the object is in a high luminosity state), and that a propeller mechanism will be at work when the accretion rate is small, leading to a slowing down of the neutron star [for the theories, see, e.g., Illarionov and Syunyaev (1975), and a review of more recent work in the book by Lipunov (1987)]. While we were observing Vela X-1 in 1990 and 1991, there was no alteration in the rate of slowdown of the neutron star rotation. At the same time, we found significant variations in the flux. Moreover, the mean luminosity of the object in 1990 and 1991 was by no means any less than the level in 1975-1979, when the ratio was observed to be speeding up. The *Watch* instrument enables us to make a rather accurate determination of the period of Vela X-1 by storing the data for several scans during which the object was at a rather high flux level. At the same time, the object was bright enough that we could track its variability on time scales of several hours. During our two years of monitoring, we found the object to be highly variable. In particular, we found short-period flares during which the brightness of the object increased severalfold for several hours. On the other hand, on 9-10 January 1991, the flux from the source outside eclipse was greatly reduced. It is natural to hypothesize that the rapid variability in the light level is accompanied by fluctuations in the pulsar period. Unfortunately, our data do not permit us to check this hypothesis.

Observing sequence. The x-ray pulsar Vela X-1 was observed with the *Watch* instrument, which was developed at the Danish Space Research Institute. It was launched into orbit in December 1989 on board the Soviet *Granat* observatory. The *Watch* instrument consists of four x-ray detectors equipped with rotating modulation collimators (Lund, 1985; Mertz, 1968). The field of view of each detector was about 4 sr, and the effective area was close to 30 cm.^{2} The detectors can operate in the energy range 8-60 keV. The temporal resolution of the instrument was roughly 8 sec.

The *Granat* observatory has an orbital period of 4 days and a high apogee. Normally, the satellite observes for three days out of every four-day orbit. On the fourth day, the satellite passes through the earth's magnetosphere, and it is difficult to observe because of unfavorable radiation levels.

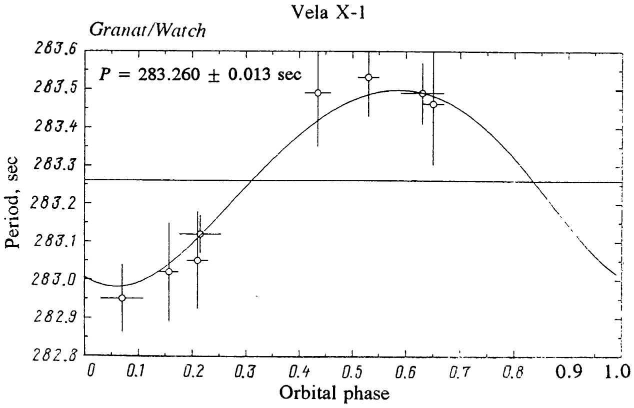

FIG. 1. Changes in the pulse period of Vela X-1 during February 1991. These changes are due to orbital motion in the binary system. Circles denote pulse periods obtained during individual observing runs, and are plotted at the appropriate phase of the x-ray pulsar orbit. Binary ephemeris was taken from Deeter et al. (1987).

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TABLE I

Date of measurement	Pulse period, sec	Per. measurement error, sec	Integration times, h	$\dot{P}/P$, 10^{-4} yr^{-1}
January 1990	283.230	±0.022	40	1.90
September 1990	283.244	±0.022	70	1.50
February 1991	283.260	±0.013	88	1.00

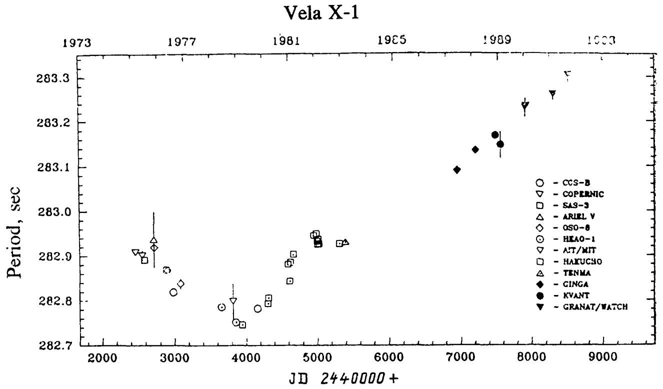

FIG. 2. History of measurements of the pulse period of the x-ray pulsar Vela X-1.

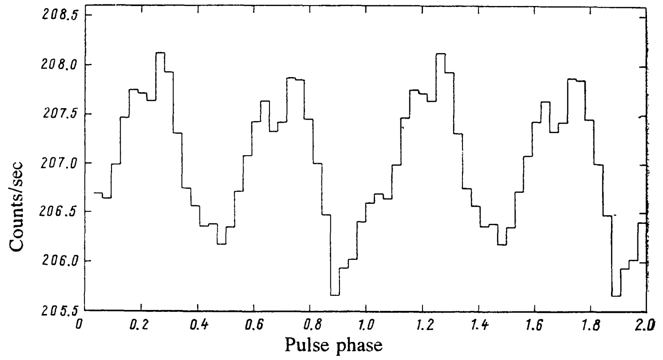

FIG. 3. Pulse profiles for the Vela X-1 x-ray pulsar obtained from 36 hours of observation in February 1991. We have not subtracted the background which does not belong to the source.

An observing run typically takes one day, and the data are then transmitted to earth. Thus, during each run, we have about 24 hours of continuous observations by the *Watch* instrument, no matter where the *Granat* observatory is pointing. It is therefore possible to perform temporal analyses of x-ray pulsars.

Timing. Certain difficulties arise when we carry out timing analysis of long exposures. In the first place, these are associated with the particular way in which time is measured by the *Watch* instrument. A high-stability 14.7456 MHz oscillator generates timing pulses for the on-board processor at 9600 Hz. These are then used to define instrument time. However, the integration time used in the timing analysis is not measured in terms of the instrumental timing pulses but by a fixed number of turns of the rotating collimator. The collimator rotation rate varies, depending on how each of the detectors is heated by the sun and on other external conditions. The variations span a relatively broad range not only from one run to the next but even in the course of a single observing run. This gives rise to variations in the duration of the time bins in the counting rate. Because of this, the data must be corrected to the real integration time. However, it is impossible to make these corrections in time intervals of less than 256 bins (corresponding to about 30 minutes) because we have no information on changes in the collimator rotation rate on such short time scales. As a result, there are systematic errors in determining periods of x-ray pulsars by the *Watch* instrument. In the results to be presented below, all of the possible systematic errors have been taken into account.

Evolution of the neutron star rotation period. Among the x-ray pulsars which can be observed by *Watch*, Vela X-1 is the brightest. It is a massive binary with an orbital period of 8.965 days. The pulsation period has been measured in data taken in January 1990, February 1991, and September 1991. Due to insufficient sensitivity of the *Watch* instrument, it turned out to be impossible to accurately determine the period of the source from a single scan. We therefore used the following technique. The pulse period and its error were determined during each run (or part of a run). Since the orbital parameters of Vela X-1 in the binary system are known (Deeter et al., 1987), we can fold this information into the data and compute corrected values for the period. By

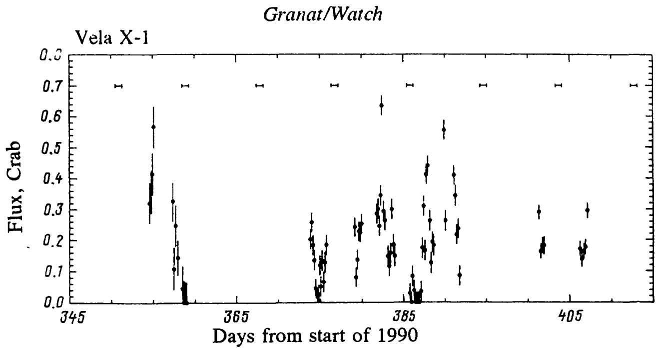

FIG. 4. Light curve of the Vela X-1 pulsar from December 1990 to February 1991. Horizontal bars in the graph indicate calculated periods when the pulsar is in binary eclipse.

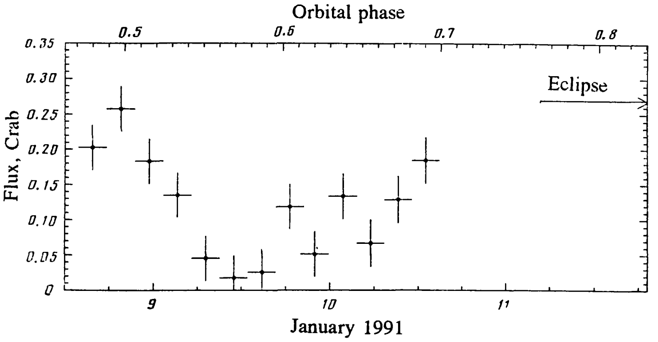

FIG. 5. Light curve of the x-ray pulsar Vela X-1 plotted at the time of a significant decrease in the flux from the source around 9 January 1991.

way of illustration, data from eight runs in February 1991 are presented in Fig. 1. We treated data from three runs in January 1990 and six runs in September 1991 in an analogous manner. By reducing the same data, Brandt et al. (1990) have derived a period of 283.233 ± 0.015 sec for Vela X-1 in January 1990. Our result is in good agreement with this (to within the errors). Results from the three observing periods are presented in Table I.

In the fifth column we give the relative rate of change of the period between the previous measurements and the current measurements. For January 1990, the previous measurements were those obtained in November 1989 by the TTM instrument on the *Kvant* module (Gil'fanov et al., 1989).

We have also determined the rate of change of the period between January 1990 and September 1991; the result is $\dot{P}/P = (1.5 \pm 0.5) \times 10^{-4}\ \mathrm{yr}^{-1}$.

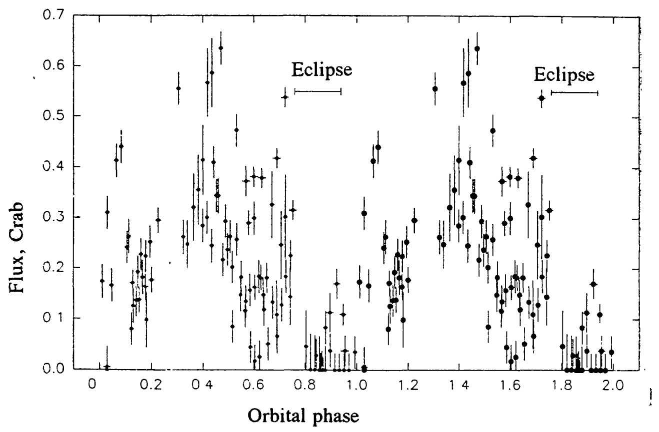

FIG. 6. Orbital light curve of the x-ray pulsar Vela X-1. (Filled circles: actual values obtained in the course of the observations.)

Figure 2 contains the history of measurements of the pulse period of Vela X-1. We should point out that during the time when the *Watch* instrument was observing Vela X-1, its period increased monotonically, and it reached the largest value it has even had during the entire history of its measurement. Data on the previous observations have been taken from the review by Nagase et al. (1984) and from the article by Gil'fanov et al. (1989). Citations of previous work can be found in these references.

Pulse profiles for Vela X-1 are presented in Fig. 3, which corresponds to orbital phase 0.2 of the binary. The figure was constructed from data obtained during two runs. We integrated over roughly 36 hours of observation. In the energy range where the *Watch* instrument is sensitive (8-20 keV), we find two pulses of practically equal intensity per period.

X-ray variability of Vela X-1. Any instrument which surveys the entire sky has, as an obvious aim, the tracking of long-period variability in the brightest x-ray sources. In this note we present the results of long-term monitoring of the Vela X-1 pulsar. The light curve of the source has been constructed from a two month stretch of observations between December 1990 and February 1991, and is presented in Fig. 4. Horizontal bars near the top indicate eclipses. Clearly, there are times when the source becomes much fainter, and sometimes one sees bright flares lasting several hours. Unfortunately, we were not able to determine how much the period changes in the course of each flare; this would be advisable if we are to check the hypothesis that the rotation slows down between flares but speeds up in the course of a flare. The periods presented above are average values.

On 9-10 January 1991, the flux from the source underwent a significant and extremely interesting decrease. This decrease occurred outside eclipse. This part of the data is

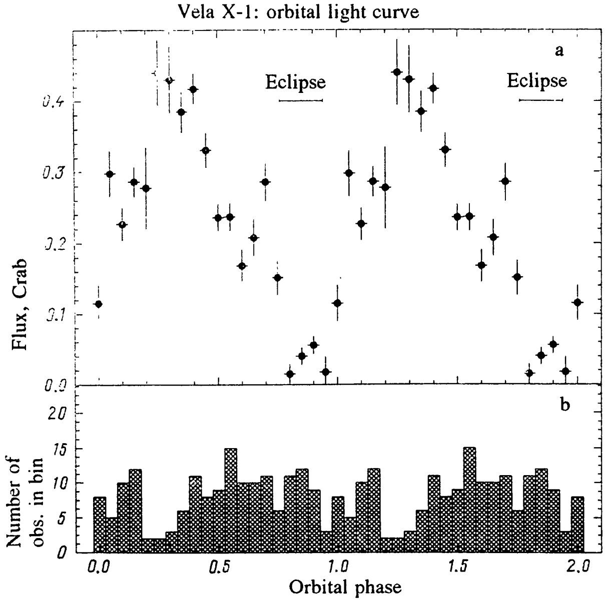

FIG. 7. Orbital light curve of the Vela X-1 pulsar. (a) Averaged data. (b) Data summed over the integration time in each phase bin. $T_{\rm int}$ (days) = $N \times 8^d.964/N_{\rm bin}$, where N_d is the number of observations falling in a particular phase bin, $N_{\rm bin} = 20$ and $8^d.964$ is the orbital period in days.

shown in more detail in Fig. 5. Obviously, the pulsar was essentially turned off for more than 10 hours.

The data in Fig. 5 refer to the energy range 8-15 keV, where the principal contributors to the opacity of low-density plasma are Compton scattering from electrons which are either free or are bound in hydrogen atoms and photoabsorption by *K*-electrons in iron atoms and ions. At energies $h\nu$ between 12 and 15 keV, photoabsorption is not very important, and Compton scattering dominates the opacity.

It does not seem very likely that such a severe and long-lasting reduction in the brightness could be associated with a cloud of gas eclipsing the source. To do so, the cloud would have to be large (the eclipse lasts for more than 10 hours), and there would have to be an immense number of electrons in the line of sight, $N_e l > 10^{24}$ cm^{-2}. Moreover, the time for photons to escape from the tenuous plasma cloud ($l\tau_T/c$) should also be much less than 10 hours if the cloud dimensions are taken to be less than the dimensions of the binary and we use reasonable values of the optical depth ($\tau_T < 10$). Here, τ_T is the Thomson scattering optical depth of the cloud.

Hence, the only explanation for both the abruptness and the duration of the flux decrease on 9-10 January 1991 may be an abrupt reduction in the accretion rate. In turn, the reduction in the accretion rate may be associated with a change in the density and velocity of the material in the stellar wind.

Orbital light curve. The orbital curve of the Vela X-1 pulsar is shown in Fig. 6. We plot as the abscissa the orbital phase of the source. We plot as the ordinate the flux from Vela X-1 (normalized to the flux from the Crab nebula). This particular light curve was based on data obtained at different times by two of the detectors in the *Watch* instrument. The eclipse of the Vela X-1 pulsar is clearly visible in the graph. We should point out a characteristic feature – an appreciable increase in the flux from Vela X-1 after mid-eclipse. The increase is roughly four standard deviations. Between eclipses one can readily trace an envelope below which the flux from the pulsar does not fall. Bright flares can be identified against the background of this envelope; during these flares, the flux from the source exceeds half the flux from the Crab nebula. Note that in many scans, the field of view of a single detector includes both Vela X-1 and the Crab nebula, and this offers the possibility of direct flux calibration. The orbital light curve is also presented in Fig. 7a using the same data as before; the difference is that in contrast to the previous light curve, the curve in Fig. 7b has been constructed by averaging. The overall orbital period is divided into 20 bins, and we average over the data which fall into each phase bin. In Fig. 7b we present the integration time for each phase bin.

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