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X-RAY EMISSION FROM THE PSR B1259−63 SYSTEM NEAR APASTRON

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ABSTRACT

The PSR B1259−63 system contains a 47 ms radio pulsar in a highly eccentric binary with a Be-star companion. Strongly time-variable X-ray emission was reported from this system as the pulsar was near apastron in 1992–early 1993. The variability was primarily deduced from an apparent nondetection of the PSR B1259−63 system during a first preapastron *ROSAT* observation in 1992 February. We have reanalyzed the *ROSAT* observations of the PSR B1259−63 system. Contrary to the results of a previous analysis, we find that the PSR B1259−63 system was detected by *ROSAT* during the first off-axis 1992 February observation. The intensity of the soft X-ray emission of the PSR B1259−63 system before and after the 1992 apastron appears to vary at most by a factor ∼2. Our results sensibly constrain theoretical models of X-ray emission from the PSR B1259−63 system.

Subject headings: binaries: close — pulsars individual (PSR 1259−63) — stars: emission-line, Be — stars: mass loss — X-rays: stars

1. INTRODUCTION

The 47.7 ms radio pulsar PSR B1259−63 was discovered in 1991 during a 1520 MHz radio survey of the southern Galactic plane (Johnston et al. 1992a). A study of timing residuals revealed that the pulsar was in a very eccentric binary ($e \sim 0.87$), large orbital period $P_{\rm orb} \sim 3.4$ yr, and large mass function. The massive companion was subsequently optically identified with the Be star SS 2883 (= LS 2883 = CPD-63 2495 = He 3-852) (Johnston et al. 1994). The PSR B1259−63 system is particularly interesting for many reasons. The companion star is a massive Be star (with probable mass $m \sim 10\ M_\odot$), and this system is a likely progenitor of high-mass X-ray binaries. Furthermore, it is the only known binary containing a rapidly rotating radio pulsar and a Be star. Since Be stars are characterized by large equatorial mass outflows, the PSR B1259−63 system is ideal for the study of Be star outflows and of the interaction of pulsar relativistic winds with gaseous nebulae (Tavani 1994).

The PSR B1259−63 system was observed by the *ROSAT* PSPC instrument three times during the period 1992 February–1993 February (see Table 1 for a log of *ROSAT* observations). The first *ROSAT* observation was carried out before apastron (∼1992 May 1) and two more observations were carried out after apastron. For a companion mass $m = 10\ M_\odot$, the apastron distance a between the pulsar and the Be star is $a \sim 10^{14}$ cm corresponding to $a/R_* \sim 350$–250, for a Be-star radius $R_* = (6$–$10)\ R_\odot$. The source was clearly detected during the second and third PSPC pointed observations in early 1992 September (at $\phi \sim 5°$ *after* apastron) and in 1993 February (at $\phi \sim 13°$ *after* apastron) (Cominsky, Roberts, & Johnston 1994, hereafter CRJ94). The PSPC count rates for these observations were reported to be between 0.024 and 0.035 counts s^{-1} (see Table 1) (CRJ94) and the implied soft X-ray luminosity (0.1–2 keV) to be in the range $L_{\rm X} \sim (1$–$10) \times 10^{33}$ ergs s^{-1} depending on the assumed spectrum (CRJ94).

The early *ROSAT* PSPC observation of PSR B1259−63 (at $\phi \sim 2.°7$ *before* apastron) was carried out in 1992 February with a 38′ off-axis angle. A first study of the data of this early *ROSAT* observation was carried out by Bailes & Watson (B&W), and the results are quoted in CRJ94. It was reported that the early preapastron *ROSAT* observation failed to detect the PSR B1259−63 system. The derived upper limit on the count rate for the preapastron observation was about a factor of 10 lower than the count rate measured during the later postapastron *ROSAT* observations. The implied asymmetry of the X-ray emission between the apastron-approaching and the apastron-receding parts of the orbit is potentially very important for the interpretation of the nature of the X-ray emission. The apparent X-ray asymmetry of PSR B1259−63 near apastron prompted an interpretation in terms of a velocity-dependent interaction of the pulsar with the Be-star outflow (King & Cominsky 1994, hereafter KC94).

Motivated by the importance of a possible pre- and post-apastron asymmetry of the X-ray emission, we have reanalyzed all *ROSAT* observations of PSR B1259−63 which are now publicly available. In this *Letter* we focus our discussion on the detection by *ROSAT* of the PSR B1259−63 system before apastron. In the next section we describe the analysis and the results which substantially differ from the results previously quoted in the literature. We briefly comment on the implications of our results in the last section.

2. REANALYSIS OF *ROSAT* OBSERVATIONS OF THE PSR B1259−63 SYSTEM

The EXSAS package (Zimmermann et al. 1993) has been used for the data reduction. The adapted source detection technique consists of several steps: first, a mask is created to screen

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TABLE 1

SUMMARY OF THE *ROSAT* OBSERVATIONS OF THE PSR B1259−63 SYSTEM

			Previous Values		Values of Our Reanalysis	
Observation	Date	Phase[a]	Source Photons	PSPC Count Rate (counts s^{-1})	Source Photons	PSPC Count Rate (counts s^{-1})
B&W	1992 Feb 25–26	−2.7	<10	<0.0026	67	0.014 ± 0.003
CRJ94 no. 1	1992 Aug 30–Sep 4	5	254	0.024 ± 0.0018	204	0.020 ± 0.002
CRJ94 no. 2	1993 Feb 7–16	13	1136	0.0031 ± 0.0011	1007	0.029 ± 0.001

[a] Orbital phase (in degrees) with zero set at apastron and negative (positive) values for apastron-approaching (receding) pulsar positions in the orbit.

all the parts of the image where the support structure of the PSPC entrance window may affect the detectability of X-ray photons. Then, all possible sources are identified by means of a "sliding window" technique and removed from the data. A background map is produced with a bi-cubic spline fit to the resulting image. (Finally, a maximum likelihood algorithm is applied to the data (e.g., Cruddace, Hasinger, & Schmitt 1988) in three separate PHA channel ranges. If a source is detected in more than one energy band, a detection corresponding to a higher likelihood value is considered.

We apply this technique to the first *ROSAT* observation (1992 February) observation of the PSR B1259−63 system. For the whole PSPC field of view we detect a total of 20 sources. One of these sources is at the position $\alpha = 13^h02^m54^s.7$, $\delta = -63°49'06''$ (2000.0) which is roughly 1′ away from the nominal (radio) position of PSR B1259−63 (Johnston et al. 1994). In the following, we refer to this source as "source-X." We detect a total of $N_\gamma \sim 67$ photons from the source-X corresponding to a likelihood of detection $\mathscr{L} \sim 27$. Figure 1 (Plate L4) shows the *ROSAT* field near source-X with the pulsar position marked by a cross.

Since source-X is 38′ off-axis in the *ROSAT* field of view, its appearance is distorted by the relatively large and asymmetric point spread function of the *ROSAT* X-ray mirror for large off-axis angles. From previous off-axis *ROSAT* observations of bright X-ray sources, it is known that the best-fit centroid position of a Gaussian approximation to the asymmetric point spread function introduces a systematic error which increases with increasing off-axis angle. Therefore, we estimate that the apparent positional difference between source-X and the radio pulsar is within the statistical uncertainty of a typical off-axis observation. If, on the contrary, source-X were not related to the pulsar system, our results would indicate the existence of another X-ray source 1′ apart from the pulsar's position. However, this additional source has neither been reported by CRJ94 nor found by our reanalysis of the on-axis pointed *ROSAT* PSPC observations. The intensity decrease of this hypothetical additional X-ray source would have been at least by a factor of ∼40 within a half year interval. Although we cannot entirely exclude this possibility, it is more natural to relate the 1992 February source-X to the PSR B1259−63 system.[2] The count rate from the PSR B1259−63 system of the 1992 February observation is $\mathscr{C} \sim 0.014 \pm 0.003$ counts s^{-1}, which is lower by about 30% than the value of the subsequent postapastron observation in 1992 September. Table 1 gives a summary of all *ROSAT* observations of the PSR B1259−63 system. Columns (3) and (4) give the values reported in CRJ94. The CRJ94 analysis was carried out only for the 1992 September and 1993 February observations.

Our results imply that the soft X-ray flux of the PSR B1259−63 system is only marginally time-variable (within ∼30%) between the preapastron observation in 1992 February and the first postapastron observation in 1992 September. Between 1992 February and 1993 February the soft X-ray flux of the PSR B1259−63 system appears to have increased by a factor ∼2. This moderate increase of detected X-ray flux during a 1 yr period is probably intrinsic to the PSR B1259−63 system and partly caused by instrumental effects.

Due to the limited number of photons detected in the 1992 February observation, a spectral fit of the *ROSAT* PSPC data cannot be performed without additional assumptions. As a first step in comparing the X-ray spectrum of the 1992 February versus the 1992 September, we studied the binned count rate spectra without any fitting. Within the uncertainties, the two spectra appear to the identical. As a second step, in order to fit the absorbing column density N_H, we have adopted a single power-law model with photon index chosen to be either 1.9 or 1.6 (taken from ASCA observations near periastron [Tavani et al. 1994b; Kaspi et al. 1994] and at $\phi \sim 125°$ after periastron [Hirayama et al. 1995]). Again, our results are consistent with both X-ray spectra having the same absorbing column density $N_H = (2.5 - 8) \times 10^{21}$ cm^{-2}. If we denote by $\mathscr{A}$ the ratio of column densities N_H for the 1992 February and for the 1992 September observations, we find that $\mathscr{A} \simeq 1$ within the uncertainties of the spectral analysis of these PSPC data. While a value of $\mathscr{A} \lesssim 3$ is marginally possible, any value of $\mathscr{A} \gtrsim 4$–5 is certainly excluded. The upper limit on $\mathscr{A}$ is estimated by a conservative assumption about the PSPC spectral capability and taking into account the low number of photons detected in the two pointings.

We also performed a timing analysis of the X-ray data from the PSR B1259−63 searching for periodic pulsations with the radio pulsar spin period Near apastron the orbital correction due to the Doppler shift is negligible, and the nominal pulsar spin period can be obtained from the pulsar ephemeris of Johnston et al. (1994). We do not detect any X-ray pulsation with the pulsar spin period (CRJ94). We used standard X-ray timing techniques (e.g., Leahy et al. 1983), with $n = 5$ phase bins and an assumed sinusoidal pulsed signal. The 90% confidence limits on the pulsed fraction are $f \lesssim 25\%$ for the 1992 Septem-

[2] The upper limit to the February 1992 *ROSAT* PSPC flux is now known to be erroneous due to an incorrect source position used to determine the source flux from the PSR B1259−63 system. A new determination made independently by Watson is entirely consistent with the value quoted here. (M. G. Watson, private communication.)

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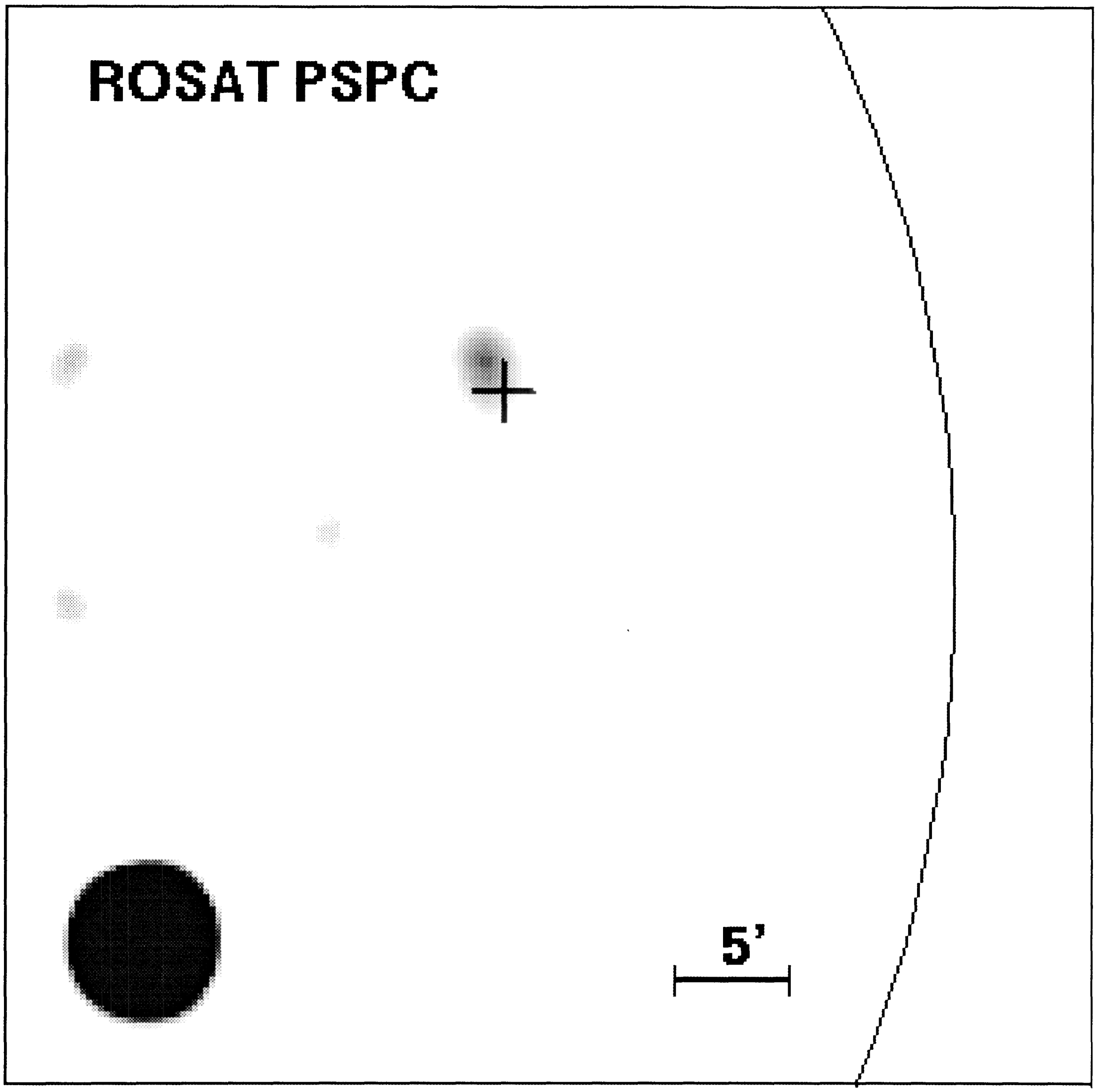

FIG. 1.—Western part of the *ROSAT*-PSPC image of the 1992 February observation of the field around the PSR B1259−63 system. The cross shows the position of the radio pulsar PSR B1259−63 [$\alpha = 13^h02^m47^s.72$, $\delta = -63°50'08''$ (2000.0)]. The X-ray source ("source-X"), which is almost coincident with the position of PSR B1259−63, appears elongated and blurred due to the degraded point spread function of the *ROSAT* X-ray mirror for large off-axis angles. The bright object in the lower left corner is the 9.5 mag star HD 113466. The circular arc is the edge of the *ROSAT* field of view. The scale of 5′ is indicated in the lower part of the figure.

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ber observation ($N_\gamma \sim 200$) and $f \lesssim 13\%$ for the 1993 February observation ($N_\gamma \sim 1000$).

3. DISCUSSION

A possible source of the observed X-ray emission of the PSR B1259−63 system is coronal emission of the Be-star companion (also considered in CRJ94). The likelihood of the interpretation depends on the spectral classification of the SS 2883 star and on its distance. Since no specific spectral type determination is available, Johnston et al. (1994b) derive it indirectly from the colors of the SS 2883 star (in the range O9–B2). The system distance is also uncertain. By assuming a main-sequence star of luminosity class V, the distance range of SS 2883 is $d \sim 0.6$–1.6 kpc (Johnston et al. 1994b). However, a pulsar dispersion measure model gives a larger estimate of the distance, $d \sim 3$–4 kpc (Taylor & Cordes 1993). The system distance is most likely $d \sim 2$ kpc; we note that this is approximately the distance of the first Galactic spiral arm in the direction of PSR B1259−63.

A recent *ROSAT* X-ray survey of 12 nearby near–main-sequence B stars shows that the ratio $\mathscr{R}$ of X-ray to bolometric luminosity is a sensitive function of spectral type, ranging from $\mathscr{R} \sim 10^{-6}$ for O9 stars down to $\mathscr{R} \lesssim 10^{-8}$ for B2 stars (Cassinelli et al. 1994). We notice that even for an adopted maximum ratio $\mathscr{R} \sim 10^{-6}$ and distance $d \gtrsim 1.5$ kpc, the early-type star SS 2883 is expected to have an X-ray luminosity $L \sim (2$–$3) \times 10^{32}$ ergs s^{-1}), that is, a luminosity lower by a factor ~ 10 than the estimated X-ray luminosity near apastron. We are therefore left with two possibilities: (1) either an early spectral type SS 2883 star produces the observed X-ray luminosity being at a distance $d \ll 1.5$ kpc; or (2) the PSR B1259−63 distance is $d \gtrsim 1.5$ kpc and the observed X-ray flux cannot be produced by the SS 2883 star (CRJ94).

For a more likely distance $d \gtrsim 1.5$ kpc, other X-ray emission mechanisms need to be considered (Kochanek 1993; CRJ94). Accretion of material onto the surface of the neutron star is believed to quench the radio pulsar mechanism and the pulsar relativistic wind. Since pulsed radio emission from PSR B1259−63 was visible near the 1992 apastron (Johnston et al. 1994), any gaseous material from the Be-star companion cannot penetrate the pulsar light-cylinder radius $R_{\rm lc} = cP/2\pi \sim 2.8 \times 10^8$ cm, with c the speed of light and $P = 47$ ms the pulsar spin period. Accretion onto the surface of the neutron star is therefore clearly inhibited near the 1992 apastron of the PSR B1259−63 system. The observed X-ray emission can be the result of gravitational capture of gaseous material near the pulsar light-cylinder radius (KC94). Alternately, unpulsed X-ray emission of luminosity $L_{\rm X} \sim 10^{33}$ ergs s^{-1} near the periastron of PSR B1259−63 can be radiated by shocked relativistic particles of the pulsar wind stopped at a shock radius $R_s \sim 10^{12}$–10^{13} cm $\gg R_{\rm lc}$ (Tavani, Arons, & Kaspi 1994a, hereafter TAK94). In the "pulsar-driven" mechanism of X-ray emission, pressure balance is established at R_s between the pulsar radiation pressure and the ram pressure of the Be star outflow (TAK94).

These two mechanisms differ in the dependence of the X-ray emission on the relative velocity $\boldsymbol{v}_{\rm rel}$ between the pulsar and the Be-star outflow. The KC94 model, which assumes that the pulsar radiation pressure plays no role in the gravitational capture process, depends critically on $\boldsymbol{v}_{\rm rel}$. This model can explain a possible asymmetry of the X-ray emission as the pulsar approaches to and recedes from apastron. An X-ray asymmetry can be produced as the radial and/or tangential components of $\boldsymbol{v}_{\rm rel}$ become small for an assumed low-velocity Be-star outflow (KC94). In order to produce any significant asymmetric effect on the mass captured by the pulsar gravitational field, the velocity of the Be-star outflow near apastron must have a small value, with radial and tangential components near $v_w \sim (10$–$30)$ km s^{-1} (KC94). The gravitational capture model predicts a variation of the ratio $\mathscr{A}$ of absorbing column densities before and after apastron. The value of $\mathscr{A}$ is calculated to be in the range $4 \lesssim \mathscr{A} \lesssim 15$ for $v_w \sim (10$–$15)$ km s^{-1}, and $\mathscr{A} \sim 3$ for $v_w \sim 30$ km s^{-1} (KC94). The results of our analysis constrain the gravitational capture model of X-ray emission from the PSR B1259−63 system near apastron. An apastron outflow velocity slightly larger than the escape velocity from the binary, $v_w \gtrsim 30$ km s^{-1}, can be consistent with the observed level of X-ray emission and with the upper limit of the allowed range of $\mathscr{A}$ (A. King & L. Cominsky 1994, personal communication). There is no need to invoke a cool, very slow wind ($v_w \lesssim 20$ km s^{-1}) at large distance from the Be star.

On the other hand, the pulsar-driven model based on standard features of Be-star outflows (Waters et al. 1988) predicts a shock X-ray emission near periastron which is marginally dependent on the temporal behavior of $\boldsymbol{v}_{\rm rel}$. For a constant Be-star outflow rate, approximately constant values of the X-ray flux and of $N_{\rm H}$ near apastron are expected (TAK94). A time-variable X-ray emission near apastron might be caused by a change of shock emissivity due to time variation of the shock radius. The shock radius near apastron can change as a consequence of a time-variable mass outflow rate from the Be-star companion.

4. CONCLUSIONS

We have reanalyzed the *ROSAT* observations of the PSR B1259−63 system near apastron. We show that the PSR B1259−63 system was detected by *ROSAT* also during the first *ROSAT* PSPC off-axis observation on 1992 February when the pulsar's orbital phase was $\phi = 2\overset{\circ}{.}7$ before apastron. By comparing the first and second *ROSAT* observations of the PSR B1259−63 system and taking into account the different quality of off-axis versus pointed *ROSAT* observations, we conclude that the X-ray emisson from the PSR B1259−63 system was approximately constant (within 30%) near the 1992 apastron. We find evidence for a possible increase (within a factor of $\lesssim 2$) of the postapastron X-ray emission in early 1993.

We also obtained the value of the absorbing column density before and after apastron. We find that the value of the $N_{\rm H}$ ratio $\mathscr{A}$ is consistent with being approximately constant for the PSPC observations of the PSR B1259−63 system studied here. A large value of $\mathscr{A} \gtrsim 4$–5 is excluded, and the allowed range $1 \lesssim A \lesssim 3$ constrains the gravitational capture model of X-ray emission (KC94).

X-ray observations of the PSR B1259−63 system near apastron are important in determining the nature of the high-energy emission in a regime when accretion onto the surface of the neutron star is inhibited. Future X-ray observations of the PSR B1259−63 system near apastron to be carried out by *ROSAT* and *ASCA* will be valuable in monitoring possible orbit-to-orbit variations of the X-ray emission which can be caused by a time-variable Be star outflow rate. Spectral information and a determination of $\mathscr{A}$ will be available from *ASCA* observations to be attained in coincidence with the 1995 apastron of the PSR B1259−63 system. These observations will provide crucial information in determining the nature and properties of the shock emission near apastron.

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REFERENCES

Cassinelli, J. P., Cohen, D. H., MacFarlane, J. J., Sanders, W. T., & Welsh, B. Y. 1994, ApJ, 421, 705
Cominsky, L., Roberts, M., & Johnston, S. 1994, ApJ, 427, 978 (CRJ94)
Cruddace, R. G., Hasinger, G. R., & Schmitt, J. H. M. M. 1988, in Astronomy from Large Databases, ed. F. Murtagh & A. Heck (Garching: ESO), 177
Hirayama, M., et al. 1995, in preparation
Johnston, S., Lyne, A. G., Manchester, R. N., Kniffen D. A., D'Amico, N., Lim, J., & Ashworth, M. 1992a, MNRAS, 255, 401
Johnston, S., Manchester, R. N., Lyne, A. G., Nicastro, L., & Spyromilio, J. 1994, MNRAS, 268, 430
Kaspi, V., et al. 1994, in preparation
King, A., & Cominsky, L. 1994, ApJ, 435, 411 (KC94)
Kochanek, C. 1993, ApJ, 406, 638
Leahy, D. A., et al. 1983, ApJ, 266, 160
Tavani, M. 1994, in The Gamma-Ray Sky with *COMPTON GRO* and *SIGMA*, ed. M. Signore, P. Salati, & G. Vedrenne (Dordrecht: Kluwer), in press
Tavani, M., Arons, J., & Kaspi, V. M. 1994a, ApJ, 433, L37 (TAK94)
Tavani, M., et al. 1994b, Nature, submitted
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Waters, L. B. F. M., et al. 1988, A&A, 198, 200
Zimmermann, H. U., et al. 1993, MPE report 244

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