Radio Observations of PSR B1259–63 through the 2004 periastron passage

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\textbf{ABSTRACT}

We report here on extensive radio observations of the binary system containing PSR B1259–63 and the Be star SS 2883, made around the time of the 2004 periastron. This is the fourth periastron to have been observed in detail. As in previous observations, changes in the pulsar’s dispersion and rotation measures are detected over a period spanning 200 days. We show that the eclipse of the pulsed emission lasts from 16 days prior to periastron to 15 days after periastron and is consistent from one periastron to the next. We demonstrate that the timing solution proposed by Wang et al. (2004) provides a good fit through the 2004 periastron. The light curve of the transient unpulsed radio emission is broadly similar from one periastron to the next. For this periastron, however, the light curve is strongly peaked post-periastron with rather little enhancement prior to periastron, in contrast to the 2000 periastron where the peak flux densities were more equal. These observations remain consistent with the interpretation that the pulsar passes through the dense circumstellar disk of the Be star just before and just after periastron. The observed differences from one periastron to the next can be ascribed to variations in the local disk density and magnetic field structure at the time the pulsar enters the disk.

\textbf{Key words:} pulsars:individual: PSR B1259–63

1 INTRODUCTION

PSR B1259–63 was discovered in a large-scale high-frequency survey of the Galactic plane (Johnston et al. 1992a). It is unique because it is the only known radio pulsar in orbit about a massive, main-sequence, B2e star (Johnston et al. 1992b). PSR B1259–63 has a short spin period of \(~\sim\)48 ms and moderate period derivative of \(2.28 \times 10^{-11}\), implying a high spin-down energy of \(8.2 \times 10^{35}\) erg s\(^{-1}\) and a characteristic age of only 330 kyr. It has a long orbital period of \(1237\) days, and a large eccentricity of 0.87, with a projected semi-major axis, \(a \sin i\), of \(~\sim\)1300 light-s.

The companion, SS 2883, is a 10th magnitude star with a mass of about \(10 M_\odot\) and a radius of \(6 R_\odot\). Assuming the pulsar mass is \(1.4 M_\odot\), it implies the inclination of the orbit to the plane of the sky is \(i \sim 36^\circ\). Be stars as a class have a hot, tenuous polar wind and a cooler, high density, equatorial disk. The expected mass loss rate from a B2e star is \(~\sim\)\(10^{-6}\) \(M_\odot\). Johnston et al. (1994) observed H\(\alpha\) emission lines from the disk at 20 stellar radii (\(R_\star\)), just inside the pulsar orbit of 24 \(R_\star\) at periastron. The density of the disk material is high near the stellar surface (\(10^7 - 10^{10}\) cm\(^{-3}\)), and falls off as a power-law with distance from the star. The disk is likely to be tilted with respect to the pulsar orbital plane, and PSR B1259–63 is eclipsed for about 35 days as it goes behind the disk.

This pulsar has been extensively observed since its discovery 15 years ago. Determining the timing properties of the pulsar has proved a difficult task. Initial timing solutions obtained by Manchester et al. (1995) and Wex et al. (1998) failed to accurately describe the data through subsequent periastron passages. The most recent update on the timing of PSR B1259–63 by Wang, Johnston & Manchester (2004) provides a comprehensive review of the many difficulties involved. Their model shows that the pulsar glitched in late 1997 and that the timing residuals are best modelled by including a jump in \(a \sin i\) at each periastron.

Transient unpulsed radio emission seen around the time of periastron has been discussed by Johnston et al. (1996), Johnston et al. (1999) and Connors et al. (2002), with physical models for the emission proposed by Melatos, Johnston & Melrose (1995), Ball et al. (1999) and Connors et al. (2002). Unpulsed emission has also been detected in the X-ray (summarised in Hirayama et al. 1996) and in the soft \(\gamma\)-ray band by Grove et al. (1995) and more recently Shaw et al. (2004),
with modelling of the emission described in Tavani & Arons (1997).

Kirk, Ball and Skjæraasen (1999) proposed that the system should be detectable at high energies through inverse Compton scattering of the UV photons from the Be star by the relativistic pulsar wind. This model has largely been confirmed through a recent detection of the system at TeV energies by Aharonian et al. (2004).

## 2 OBSERVATIONS

### 2.1 Pulsed emission

Observations of the pulsar were carried out with the 64-m radio telescope located in Parkes, NSW, at frequencies between 680 and 8640 MHz.

Two independent backend systems were employed; filterbank systems which recorded total power and a correlator system which retained full polarisation information. The filterbank system was used at 680 and 1500 MHz only. At the lower frequency it consists of 256 frequency channels each of width 0.250 MHz for a total bandwidth of 64 MHz and at the higher frequency consists of 512 frequency channels each of width 0.5 MHz for a total bandwidth of 256 MHz. In each case the analogue signal is one-bit digitised every 0.5 \( \mu \)s and written to tape for off-line analysis. This analysis involved de-dispersion and folding at the topocentric period to produce a pulse profile. Correlator data were obtained at frequencies around 1370, 3100 and 8640 MHz with a total bandwidth of 256, 512 and 512 MHz at the three frequencies. Channel bandwidths were 1 MHz and there were 512 phase bins across the pulsar period. The data were folded on-line for an interval of 60 s and written to disk. Off-line processing used the PSRCHIVE software application (Hotan, van Straten & Manchester 2004) specifically written for analysis of pulsar data. Processing involved calibration and de-dispersion and yielded full Stokes pulse profiles.

In a typical observation, data were obtained at 680, 1500, 3100 and 8640 MHz in the space of 3 h. The time-of-arrival (ToA) of the fiducial point in the pulsar profile was calculated for each observation by convolving with a standard template which is frequency dependent. The templates at different frequencies were aligned in pulse phase as shown in Figure 1 of Wang et al. (2004). Any offset between the arrival times at the different frequencies was then attributed to a change in dispersion measure (DM) of the pulsar and a fit was done to obtain the offset DM.

The polarisation information allowed us to obtain the rotation measure (RM) for each observation. There are two possible methods for obtaining the RM. The first is to measure the change in position angle across the band. This can be done either at a given pulsar phase or by time averaging across several phase bins. The second method is to maximise the linearly polarised flux by choosing trial RMs. This method works well for low signal to noise ratios as it uses the entire pulse window. In fact, for PSR B1259−63, there is very little change in the position angle across each component, and the two methods yield similar results.

Table 1 shows the log of the observations of the pulsar made with the Parkes telescope. The first column gives the date of the observation and the second column shows the offset in days from the 2004 periastron epoch (which we denote as \( T_o \) hereafter).

### 2.2 Unpulsed emission

Observations were also made with the Australia Telescope Compact Array (ATCA), an east-west synthesis telescope located near Narrabri, NSW, which consists of six 22-m antennas on a 6 km track. ATCA observations can be made simultaneously at either 1.4 and 2.4 GHz or 4.8 and 8.4 GHz with a bandwidth of 128 MHz at each frequency subdivided into 32 spectral channels, and full Stokes parameters. The ATCA is also capable of splitting each correlator cycle into bins corresponding to different phases of a pulsar’s period, and in our case the pulse period of \( \sim 48 \) ms was split into 16 phase bins. This allows a measurement of off-pulse and on-pulse flux densities to be made simultaneously.

Initial data reduction and analysis were carried out with the MIRIAD package using standard techniques. After flagging bad data, the primary calibrator was used for flux density and bandpass calibration and the secondary calibrator was used to solve for antenna gains, phases and polarisation leakage terms. After calibration, the data consist of 13 independent frequency channels each 8 MHz wide for each of the 16 phase bins. Subsequent analysis of the data was carried out as described in Connors et al. (2002).
3 RESULTS

3.1 Pulsed emission

3.1.1 Timing

Figure 1 shows the complete timing residuals from PSR B1259–63. There are more than 1200 independent timing points, with a data span from 1991 January to 2004 September including five periastron passages. As described in earlier papers, the DM of the pulsar changes near periastron and this extra DM needs to be accounted for in the timing solution. For this periastron, observations were made at frequencies between 0.64 and 8.4 GHz and the DM was calculated by measuring the time offset between the TOAs at the different frequencies (see e.g. Wex et al. 1998).

In Wang et al. (2004) we determined that the best fit solution involved adding jumps in the value of $a \sin i$ at periastron and that a small glitch occurred at MJD 50691. We have now extended that model to cover the 2004 periastron passage, obtaining successive jumps in $a \sin i$ of 60.7, −26.3, 2.8, 4.2 and −7.8 ms. The fitted jumps for the first 4 periastrons are within a few percent of those obtained by Wang et al. (2004).

3.1.2 DM variations

Column 3 of Table 1 lists the DM variations and these are displayed in Figure 2. The typical error in the DM values are $0.2 \text{ cm}^{-3} \text{pc}$. Although the pulsar was undetected at 1.4, 3.1 and 8.4 GHz on $T - 18.8$, the last detection before periastron occurred on $T - 17.8$ when the DM change was $19.5 \text{ cm}^{-3} \text{pc}$. Subsequent observations on $T - 15.8$ failed to detect the pulsar. The eclipse lasted until $T + 16.1$ although on this date the pulsar was not detected at 1.4 GHz. Two days later, there is a marginal detection of the pulsar at 3.1 GHz but not at higher or lower frequencies. After the exit from the eclipse the DM change was only 3.2 and decayed over an interval of $\sim 20$ days. This is broadly in line with changes seen during previous periastron passages (see Figure 2 in Wang et al. 2004).

3.1.3 RM variations

Column 4 of Table 1 shows the RM as a function of epoch. The typical error bars are of order 10 per cent. The RM changes significantly both in magnitude and in sign between the observations but there is little evidence of a change in RM within the duration of a single observation. On Feb 2 ($T - 34$) we were unable to measure an RM even at 8.4 GHz, on $T - 30$ the polarisation quality of the data is poor and on $T - 28$ the pulsar is very weak and no RM information could be extracted. Following the very large RM value on $T - 26$, the pulsar appeared completely depolarised at all frequencies. After the pulsar re-emerged from the eclipse, no RMs could initially be measured. A high, positive RM was measured on $T + 24$, subsequent values were negative thereafter. It is noticeable that the RM varies by more than a factor of 10 in the post-periastron observations and yet the DM varies only by a factor of 2. There are three potential explanations for the depolarisation of the signal. It is possible that the RM is so high that even across a single frequency channel the position angle varies significantly, thus depolarising the signal. This would imply an RM greater than $10^5 \text{ rad m}^{-2}$ for the 8.4 GHz observations. Secondly, the RM could be highly variable on the timescale of a few minutes, causing depolarisation when time averaging occurs. Finally, there may be different values of RM along different ray paths, especially when the pulsar becomes scatter broadened. We believe it is likely that all three occur close to the point of eclipse of the pulsar.

The RM values measured are significantly different from those obtained by Connors et al. (2002) for the 2000 periastron. In 2000 the pulsar was depolarised from $T - 46$ onwards, whereas in 2004 polarisation was detected up to $T - 27$. Large and variable polarisation was detected following periastron in both 2000 and 2004, although the large value of $-7700 \text{ rad m}^{-2}$ measured in 2000 was not repeated in 2004.

Armed with both the DM and the RM we can compute the magnetic field parallel to the line of sight, $B_{||}$ in mG via
flux density had dropped to around half its peak value, and 50 mJy at 1.4 GHz), significantly higher than the level at

\[ B_{\|} = 1.232 \times 10^{-3} \frac{\text{RM}}{\Delta \text{DM}} \]  

(1)

Values of \( B_{\|} \) are shown in column 5 of Table 1. The error bar in \( B_{\|} \) is dependent on the RM error for the pre-periastron data and the DM error for the post-periastron data.

### 3.2 Unpulsed emission

Table 2 lists the pulsed flux density and the total flux density detected at the four frequencies observed with the ATCA. Dashes indicate that the pulsar was not detected at that epoch. The dates of these observations were carefully selected to provide good sampling of the transient unpulsed emission based on the observations of the previous three periastron passages. The non detection of the pulsar at \( T-14.7 \) is consistent with the lack of pulsed emission observed at Parkes one day earlier. The re-appearance of the pulsar at \( T+16.1 \) at the higher frequencies is also consistent with the Parkes observations.

Figure 3 shows the flux density of the transient unpulsed emission detected from the PSR B1259–63 system through the 2004 periastron passage (top panel), together with the corresponding data from the previous three periastron passages (lower panels). Although the sampling rate was not as high in 2004 as in either 1997 or 2000, it is unlikely that any significant feature of the light curve has been missed.

Unpulsed emission was detected at a low level on the first day that observations were made, at \( T-22 \). The flux density at all four frequencies observed then increased steadily, reaching a maximum \( \sim 17 \text{ mJy at 1.4 GHz} \) between \( T-10 \) and \( T-3 \), and subsequently decreased to a minimum around \( T+7 \). The flux density at all frequencies then increased quite rapidly peaking around \( T+22 \) (nearly 50 mJy at 1.4 GHz), significantly higher than the level attained prior to periastron. Just 5 days later, at \( T+27 \), the flux density had dropped to around half its peak value, and it subsequently decreased more slowly. The unpulsed emission was still detectable at levels of a few mJy at the time of the final observation around \( T+65 \). There is some suggestion of absorption at frequencies below 2.4 GHz in the emission observed at the earliest times, \( T-22 \) and \( T-15 \). At other epochs the spectrum is well fitted by a simple power law of the form \( S_v \propto \nu^\alpha \) with \( \alpha \sim -0.6 \).

### 4 COMPARISON OF PERIASTRON PASSAGES

The top panel of Figure 3 shows the light curve for each of the four frequencies from the 2004 periastron. Below that panel we show the data from the three preceding periastron passages in 1994, 1997 and 2000. Figure 4 shows the unpulsed emission at 1384 MHz from all four periastron passages superposed, to allow for easy comparison of the observed light curves.

The similarities between the four periastron passages are striking. In the three cases where pre-peliastron observations were obtained, the unpulsed emission was detectable by \( T-20 \), subsequently increased to a maximum around \( T-7 \) and then decayed slowly to a local minimum around \( T+10 \). In all four cases the flux density after periastron increased from a local minimum around \( T+10 \) to a maximum close to \( T+20 \), then decreased relatively rapidly until \( T+30 \), and subsequently declined more slowly.

The general behaviour of the unpulsed emission has been interpreted as resulting from the interaction of the pulsar and its wind with the dense disk surrounding the Be star companion (Ball et al. 1999). The pulsar passes through the disk twice, once a few days before periastron and then again a few days afterward. The unpulsed emission has been broadly interpreted as resulting from two emission regions associated with these interactions.

However, there are also significant differences between

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Figure 3. Transient radio emission around the time of periastron for four different periastron passages. Each plot displays four different frequencies, 1384, 2496, 4800 and 8640 MHz, in order from top down. The 1994 and 1997 data were previously published in Johnston et al. (1999) and the 2000 data published by Connors et al. (2002).

Figure 4. Light curves of the unpulsed emission at 1384 MHz from the four periastron passages. Solid line denotes 2004 data, dashed line denotes 2000 data, dash-dot line is 1997 data and dotted line is 1994 data.

Table 3. Observations bracketing the disappearance and reappearance of pulsed emission at the four periastron epochs. Asterisks indicate days on which the source was both detected and not detected in separate observations.

<table>
<thead>
<tr>
<th>periastron epoch</th>
<th>last detection</th>
<th>first non-detection</th>
<th>last non-detection</th>
<th>first detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994 Jan 9</td>
<td>−20.1</td>
<td>−</td>
<td>13.9</td>
<td>23.9</td>
</tr>
<tr>
<td>1997 May 29</td>
<td>−18.9</td>
<td>−17.5</td>
<td>13.2</td>
<td>15.2*</td>
</tr>
<tr>
<td>2000 Oct 17</td>
<td>−18.4</td>
<td>−16.5</td>
<td>13.3</td>
<td>18.5</td>
</tr>
<tr>
<td>2004 Mar 7</td>
<td>−18.3</td>
<td>−15.3</td>
<td>13.7</td>
<td>15.7*</td>
</tr>
</tbody>
</table>

The light curves at these periastron passages appear to be robust despite the different data sampling intervals. In 1997 and 2000 the flux density rises rapidly to its pre-periastron value over ~10 days. In 2004 the increase appears to occur more slowly, at least at 1.4 and 2.4 GHz, but this could be due to decreasing optical depth. In 1997 and 2004 the first maximum is not well defined, but in 2000 it appears as a distinct peak between \( T-10 \) and \( T-8 \). In 1997 and 2004 the peak flux detected after periastron is approximately twice that seen before periastron, but in 2000 the peak before periastron is comparable to that after periastron. In 1994, 2000 and 2004 the peak after periastron occurs between 20 and 25 days after periastron, while in 1997 the post-periastron peak is significantly earlier, occurring between \( T+15 \) and \( T+20 \).

These differences in the unpulsed emission most likely reflect differences in the properties of the disk at the site of the pulsar crossings. The behaviour of the pulsed emission provides a coarse probe of the disk geometry, since the disappearance of pulsed emission pre-periastron, and its reappearance post-periastron, are interpreted as marking the times when the pulsar passes into the disk and then re-emerges from behind it. The epochs of the observations which bracket the start and end of the eclipse of the pulsed emission are summarised in Table 3.

The best constrained are the epochs of re-appearance after periastron in 1997 and 2004. On both these occasions observations with the Parkes telescope on \( T+15 \) included both detections and non-detections of the pulsed emission — consistent with that being the actual day of re-emergence. The epoch of the pulsar disappearance before periastron in 1997 is also well constrained. Parkes observations on \( T-18.9 \) detected the pulsar and ATCA observations on \( T-17.5 \) did not. Unfortunately the other eclipse epochs are less well determined, but all are consistent with an eclipse starting on \( T-18 \) and ending between \( T+14 \) and \( T+15 \).

Comparison of the epochs of the pulsar eclipse with the light curve of the unpulsed emission suggests the following. Just before the pulsar goes into the eclipse prior to periastron, and at the time when the dispersion measure has changed dramatically, the unpulsed emission starts to rise. The implications are that the onset of the unpulsed emission occurs as the pulsar enters the Be star disk. The re-detection of the pulsed emission occurs just before the post-periastron peak of the unpulsed emission. This is consistent with the peak of the unpulsed emission coinciding with the end of the interaction between the pulsar and the disk, and hence the
ceasing of the supply of relativistic electrons to the pulsar wind – Be star disk bubble.

Figure 5 combines all the DM variations measured since 1990 onto a single plot. Again, the results are largely consistent from one periastron to the next (although the sampling is far from uniform). The eclipse of the pulsated emission is clearly delineated. The asymmetry between the pre- and post-periastron data is striking. This is largely because of the geometry of the system; the pulsar is on the far side of the Be star with respect to the observer prior to periastron and on the near side following periastron. The path length is therefore correspondingly larger resulting in a larger DM variations pre-periastron.

5 DISCUSSION

The differences between the light curves of the unpulsed emission observed through the 1997, 2000 and 2004 periastron passages are difficult to reconcile with the simple models so far proposed. Melatos, Johnston & Melrose (1995) established that free-free absorption in an inclined disk provided a good fit to the observed variations in DM and RM through periastron.

Ball et al. (1999) proposed that the unpulsed emission was synchrotron radiation from two populations of electrons impulsively accelerated as the pulsar passed through the Be star disk before and after periastron. They showed that the qualitative behaviour of the unpulsed emission was consistent with a situation where two such sources cooled primarily as a result of synchrotron losses. The rise times to the two emission peaks were taken to be the same, around 10 days, corresponding to the interaction time between the pulsar wind and the Be star disk, roughly twice the time taken for the pulsar itself to pass through the disk. The unpulsed emission observed during the 2000 periastron showed a somewhat different behaviour, and Connors et al. (2002) presented a model based on that from Ball et al. (1999), but with the two synchrotron emitting regions cooling primarily through adiabatic losses as the emitting region is advected outward in the expanding radial flow of the Be star disk.

The observed epochs of the eclipse of the pulsated emission provide little evidence of gross differences in the disk geometry between the different periastron passages, although the sparse sampling of the observations does not rule out some variation between the periastron eclipse epochs. On the other hand, differences in the DM and RM variations between periastron passages as the pulsar enters and re-emerges from eclipse indicate that there are significant differences in the local properties of the Be star wind/disk encountered by the pulsar. These local properties, particularly the number density of the wind and disk, will have a direct effect on determining the properties of the pulsar wind bubble and hence the observed radio emission from the pre-periastron and post-periastron encounter.

If synchrotron losses dominate, the initial flux density decay following each peak is linear, with the decay time of the pre- and post-periastron sources determined by the magnetic field strength within the relevant source region. Ball et al. (1999) proposed that the 1997 observations were consistent with a decay time of approximately 72 days for emission region associated with the pre-periastron disk crossing, and just 9 days for the post-periastron source. Taking \( T-18 \) and \( T+13 \) as the epochs of the pre- and post-periastron crossings, the corresponding orbital separations are 40 \( R_\odot \) and 33 \( R_\odot \). If the disk of the Be star was homogeneous this would imply a stronger magnetic field – and hence shorter decay time – for the post-periastron source than the pre-periastron source, because the smaller pulsar/Be star separation will result in a smaller pulsar wind bubble. After the initial linear decay, synchrotron losses produce a distinct break in the light curve once losses become significant at the energy of the electrons responsible for the emission at the observing frequency. This break is followed by a rapid frequency-dependent decay in the radio flux. No obvious evidence for such a break has been detected.

Connors et al. (2002) suggested that the unpulsed emission associated with the 2000 periastron fitted better with adiabatic losses as the dominant mechanism for the decay. In this case the flux density decay follows a power law, with the difference between the decay of the pre- and post-periastron sources determined by the relevant pulsar Be star separation. This provides a good qualitative match to the 2000 periastron light curves although it is difficult to account for the emission plateau between \( T \) and \( T+15 \). This model does not provide a good fit to the emission observed in 1997.

The 2004 light curves are difficult to fit with either of these models for two reasons. The first phase of emission prior to \( T+5 \), with its apparently slower increase and poorly-defined peak, is qualitatively different to that seen in either 1997 or 2000. The combination of a rapid initial post-periastron decrease followed by a much slower decrease is similar to the behaviour in 1997 and 1994, but at the time of the transition the flux is much higher than the extrapolated pre-periastron decrease.

The system has recently been detected at TeV energies by Aharonian et al. (2004) in observations using the HESS telescopes. An initial detection was made 10 days prior to the 2004 periastron. After a gap in the observing because of the full moon, observations started again at \( T+10 \), after an initial non-detection the flux rose sharply, peaking at \( T+20 \).
It then began a slow decay with some detectable flux still present 100 days after periastron. The maximum flux above 230 GeV was 7 per cent of that of the Crab Nebula, and the spectrum between 0.4 and 3 TeV is well fitted by a power law with photon index $\sim 2.7$. Both the amplitude and the spectrum were close to that predicted by the Kirk et al. (1999) model in which the Be star photons are scattered by electrons in the shocked region of the pulsar wind. The observed TeV light curve is poorly sampled, but appears remarkably similar to the radio light curve. Aharonian et al. (2004) show that the TeV peak following periastron occurs at approximately the same epoch as the second radio peak, and like the radio flux the TeV gamma ray emission decays over 100 days or so.

6 CONCLUSIONS

It is now apparent that while the gross features of the radio emission from the PSR B1259–63/SS2883 system are repeated through each periastron passage, the details of both the pulsed and the transient unpulsed emission differ considerably from one periastron to the next.

The data from the four periastron encounters so far observed at radio frequencies remain consistent with the interpretation that the pulsar passes through a dense disk around its Be star companion just before periastron and is obscured for some 33 days before re-emerging. The data imply that there is little difference between the geometry of the encounter between the pulsar and the Be star disk from one pass to the next. Unpulsed emission appears near the onset of the encounter between the pulsar and the Be star disk and the proposal that it originates from the two regions where the pulsar passes through the disk remains consistent with the observations. However, there are significant differences between the DM and RM of the pulsar and the transient unpulsed emission from one periastron to the next. These differences all suggest that the local properties of the Be star disk encountered by the pulsar, such as the number density and magnetic field, vary considerably between periastron passages. Modelling the detailed dependence of emission observed through each individual periastron is therefore unlikely to be productive.

The similarity between the light curves of the unpulsed radio emission and the TeV emission is intriguing. It raises an apparent contradiction, in that the radio emission is most likely associated with the pulsar–disk interaction while the properties of the TeV emission are very well fitted by model predictions that do not involve the disk. This is certain to become clearer as more detailed comparisons of the radio, X-ray and gamma-ray observations and the models of the system are completed.

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