Simultaneous photometry and echelle-spectroscopy of the dwarf nova BZ Ursae Majoris during the 2005 January Outburst

V. V. Neustroev1, S. Zharikov2 and R. Michel2

1 Computational Astrophysics Laboratory, National University of Ireland, Galway, Newcastle Rd., Galway, Ireland
2 Observatorio Astronomico Nacional, Instituto de Astronomia, UNAM, Ensenada, BC, Mexico

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ABSTRACT

We report simultaneous photometric and echelle-spectroscopic observations of the dwarf nova BZ UMa during which we were lucky to catch the system at the onset of an outburst, the development of which we traced in detail from quiescence to early decline. The outburst had a precursor, and was of a short duration (~5 days) with a highly asymmetrical light curve. On the rise we observed a ‘jump’ during which the brightness almost doubled over the course of half an hour. Power spectra analysis revealed well-defined oscillations with period of ~42 minutes. Using Doppler tomography we found that the unusual emission distribution detected in quiescence held during the outburst. After the maximum a new emission source arose, from the inner hemisphere of the secondary star, which became the brightest at that time. We analyse this outburst in terms of ‘inside-out’ and ‘outside-in’ types, in order to determine which of these types occured in BZ UMa.

Key words: methods: observational – accretion, accretion discs – binaries: close -stars: dwarf novae - stars: individual: BZ UMa - novae, cataclysmic variables

1 INTRODUCTION

Cataclysmic Variables (CVs) are close interacting binaries that contain a white dwarf (WD) accreting material from a companion, usually a late main-sequence star (see review by Warner (1995)). Dwarf novae (DNs) are an important subset of CVs, which undergo recurrent outbursts of 2–6 mag on timescales of days to years, identified with the release of gravitational energy when rapid accretion occurs from an accretion disc onto the WD. It is now widely accepted that the reason for this is a thermal instability in the accretion disc, which switches the disc from a low-viscosity to a high-viscosity regime (Smak 1984, Osaki 1990, Lasota 2004).

In order to explain the rich variety in outburst behaviour of DNs, the current disc instability model (DIM) has become rather complex. To restrict its free parameters, whose number has recently significantly increased, observations of DNs just prior to and during the early phases of the outburst are necessary. Unfortunately, it is difficult to obtain such observations because of the nonperiodic nature of the outbursts and the impossibility of predicting subsequent events.

In this paper we describe the observations of the little-studied dwarf nova BZ UMa – a quite unusual system with an orbital period of 97.9 minutes (Ringwald et al. 1993, Jurcevic et al. 1994). A SU UMa classification of this star based on the short orbital period is uncertain because no superoutbursts/superhumps have ever been detected. We observed BZ UMa in January 2005 in order to investigate its extremely unusual emission structure recently discovered by us (Neustroev et al. 2002) when we found the system was going to the outburst. This is especially important as BZ UMa is characterized by infrequent outbursts with mean intervals of 313 days between them (Price et al. 2004), and no one has observed the early phases of its outbursts to date. We have traced the development of the outburst in detail and here present our results.

2 OBSERVATIONS AND DATA REDUCTION

Photometric observations of BZ UMa in the Johnson V band were performed at the Observatorio Astronomico Nacional (OAN SPM) in Mexico on the 1.5 m telescope for a total of 5 nights (2005 January 12–13 and 15–17). The exposure times were ranged from 80 s on Jan 12 to 5 s on Jan 17.
The magnitudes of the object were determined using the calibration stars reported by Misselt (1996).

Echelle observations have been obtained with the RE-OSC Espresso spectrograph (Levine & Chakrabarty, 1995) on the 2.1 m telescope at the same site. This instrument gives a resolution of 0.234 Å pixel$^{-1}$ at H$\alpha$ using the UCL camera and a CCD-Tek chip of 1024x1024 pixels with a 24 μm$^2$ pixels size. The spectra cover 27 orders and span the spectral range 3720-6900 Å. Test observations of BZ UMa performed on 2004 December 10 in order to investigate the quality of the resultant spectra showed that observations with this spectrograph are acceptable and suitable for analysis. In the next program observations, in order to improve the signal-to-noise ratio we obtained a series of phase-locked spectra: 15 spectra were taken at equal phase intervals over a single orbital period $P_{or} (=97.9$ min) with an exposure time of 325 sec per spectrum. This sequence of spectra was repeated at exactly the same phase intervals for subsequent periods and subsequent nights. This allows us to calculate the phase-averaged spectra, summarizing the spectra of the same orbital phase obtained during one night and the whole set of observations without further decreasing the time resolution. Such averaging has been performed at the stage of the primary reduction, before the extraction of the spectral information from the CCD images. The bulk of the spectra was obtained during the 3 consecutive nights of 2005 January 15-17, simultaneously with photometry.

Log of observations is presented in Table 1.

The reduction procedure was performed using IRAF. Comparison spectra of Th-Ar lamps were used for the wavelength calibration. The absolute flux calibration of the spectra was achieved by taking nightly echellograms of the standard stars HD93521 and HD19445 (actually, only HD93521 was used for calibration, while HD19445 was as a control star). Though we used a wide slit (2″) with seeing usually noticeably less than the slit width, this does not warrant excellent flux calibration, since only an average curve for atmospheric extinction and a permanent E-W orientation of the slit were used. At the same time, due to an unexpectedly observed outburst we found it useful to obtain some colour informations from our spectra. For this we defined an internal photometric system comprising four colour bands $u', b', v', r'$ centered at 3850 Å, 4550 Å, 5590 Å, 6380 Å with widths of 50 Å, 100 Å, 120 Å, 150 Å respectively. The colour indices were calculated as $C = -2.5 \log(f_1/f_2)$, where $f_1$ and $f_2$ are the fluxes averaged across the corresponding bands. To check the stability and the flux calibration accuracy we have determined the $u' - b'$, $b' - v'$ and $v' - r'$ colours of the control star HD19445 using our nightly spectra, and compared these with its published spectral energy distribution. The colours did not differ by more than 0.03 mag between

### Table 1. Log of observations of BZ UMa.

| UT Date    | HJD Start (+2453000) | Exposure Time (s) | No. of Exps | Duration |
|------------|----------------------|-------------------|-------------|----------|
| Photometry |                      |                   |             |          |
| 2005-Jan-12| 382.889              | 80                | 169         | 24h:14   |
| 2005-Jan-13| 383.841              | 60                | 281         | 5h:33    |
| 2005-Jan-15| 385.806              | 30                | 556         | 8h:97    |
| 2005-Jan-16| 386.727              | 30, 15            | 978         | 8h:38    |
| 2005-Jan-17| 387.743              | 65, 10            | 2030        | 8h:14    |
| Spectroscopy |                    |                   |             |          |
| 2005-Jan-15| 385.787              | 325               | 60          | 6h:52    |
| 2005-Jan-16| 386.698              | 325               | 81          | 8h:80    |
| 2005-Jan-17| 387.704              | 325               | 60          | 6h:52    |

The V light curve is also shown for reference.

![Figure 1. Light curve of BZ UMa during its Jan 2005 outburst.](image1)

![Figure 2. Power spectra of the nightly light curves.](image2)

![Figure 3. $u' - b'$, $b' - v'$ and $v' - r'$ light curves during the outburst.](image3)
any of our observations, and our colours were within 0.06 mag of the published spectra.

To improve the confidence of the results presented in this paper we also acquired the period-averaged spectra obtained by means of co-adding of 15 consecutive spectra. Additionally we obtained the phase-averaged spectra for the first three periods of Jan 16, which corresponds to the first stage of the outburst rise (see below).

3 RESULTS

3.1 Light curves and power spectra

During the first three nights of observations (Jan 12, 13 and 15) the system appears to have been in a quiescent state. Even on Jan 15, just before the outburst, the medium brightness remained almost as before: $\sim$16.5 mag. At the beginning of the next night (Jan 16) we found the system to be $\sim$1 mag brighter than 16 hours previously. During the following 8.5 hours the brightness increased by another 2.9 mag. This rising can be clearly divided into 3 stages. In the first stage (during 4.3 hours) the flux was rising almost linearly at a rate of $\sim$0.34 mag hour$^{-1}$. This was followed by a ‘jump’ when during 30-40 minutes the brightness increased by 0.7 mag. Subsequently we observed a linear increase in luminosity but with a rate less than during the first stage: $\sim$0.2 mag hour$^{-1}$. However, according to amateur observations (Fig. 1) the rate increased again just prior to maximum resulting in a maximum flux of $\sim$11.4 mag at about JD 2453387.52. We continued our observations $\sim$6 hours after the maximum and observed the decline with a nearly constant rate (in flux units).

We calculated the power spectra for each detrended night’s light curve and found no evidence for orbital variability or superhumps. To the best of our knowledge, there is only two sets of BZ UMa’s photometry during outbursts (Kato 1999, Price et al. 2004). In both cases the authors reported an appearance of (quasi)-periodic oscillations (QPO) on the decline from outbursts with the period of oscillations close to 0.03 ($\sim$42 min). These oscillations were also observed by us during the decline, and also before the outburst (on 12th and 13th of January). Additionally, during the rise and probably after the maximum we have detected strong enough oscillations with the period of $\sim$18.4 min (Fig. 2).

We have found that Price et al. (2004) had also observed similar oscillations during the decline stage of the previous outburst though they did not mention the strongest peak in their power spectrum for unknown reasons (see Fig. 5 in their paper).

We have compared the light curves in all four spectral passbands and the $V$-band and found no time delays between them in any of the outburst stages. But the colour indices demonstrate dramatic changes with time (Fig. 3). One can see noticeable reddening of the flux distribution during the first outburst stage which stopped and even turned back to blueing just after the ‘jump’.

3.2 Spectral changes

The spectrum of BZ UMa in quiescence is dominated by extremely strong hydrogen emission lines with a flat Balmer decrement. Apart from hydrogen, numerous fairly strong emission lines of neutral helium are present, and in addition to them also weak He II $\lambda4686$ are observed (Bruch 1989).

Fig. 4 shows the changes of the averaged profiles of the major spectral lines of BZ UMa during all the outburst stages. Prior to the outburst the spectrum looks like the usual spectrum for BZ UMa’s quiescent state with strong Balmer and He I emission lines. During the first stage of the rise there was little qualitative change in the spectrum. In a quantitative sense these changes became apparent by the
decreasing of FWHM, EW and flux of the emission lines (Fig. 5). The qualitative changes appeared during and after the jump when the broad absorption troughs showed up around the Balmer and He I emission lines. Their full width at continuum level corresponds to a velocity of 3500 km s\textsuperscript{−1}. This is very close to the value for the wings of emission lines during quiescence and can be explained by broadening effects due to rapid rotation of particles in the innermost parts of the optically thick accretion disc. After the jump the line flux began to grow and during the following rise all emission lines with the exception of H\textsc{alpha} were present deep in the absorption troughs but never disappeared. However, the emission lines became stronger relative to the absorption lines after the outburst maximum.

Of particular interest is tracing the changes of the high excitation lines (such as the He\textsc{II} and C\textsc{III}/N\textsc{III} blend emissions) which are good tracers of irradiation. Unfortunately, due to the weakness of these lines and the poor sensitivity of the CCD at short wavelengths we were able to detect their presence only during the decline stage of the outburst. However, having in hand the published low-resolution spectra of BZ UMa in a quiescent state (Bruch 1988; Jurcevic et al. 1994; Ringwald et al. 1994; Neustroev et al. 2002) we can at least note that although absent in quiescence, the C\textsc{III}/N\textsc{III} Bowen blend has appeared during the outburst. But unlike some other dwarf novae which show strengthening of the He\textsc{II} and C\textsc{III}/N\textsc{III} line emissions during an outburst, these lines have remained quite weak in the outburst spectra of BZ UMA (Fig. 5).

We also note that in spite of the high spectral resolution, all the emission lines show not the double-peaked profiles but are rather multi-peaked. However the profiles are highly variable.

3.3 Doppler Tomography

The orbital variation of the emission lines profiles indicates a non-uniform structure for the accretion disc. In order to study the emission structure of BZ UMa and its change during the outburst we have used Doppler tomography. Full technical details of the method are given by Marsh & Horne (1988) and Marsh (2001). Examples of the application of Doppler tomography to real data are given by Marsh (2001).

Figures 6 and 7 show the tomograms computed using the code developed by Spruit (1998). These figures also show trailed spectra in phase space and their corresponding reconstructed counterparts.

The preoutburst map (Fig. 6 left) displays a quite unusual and very nonuniform distribution of emission. Due to the non-double-peaked emission line profiles of BZ UMa, we did not expect a Doppler map to have an annulus of emission centered on the velocity of the white dwarf, and the observed tomogram does not show it. Instead of this the tomogram shows two extended bright areas.

The first bright area, centered on \(V_x \approx 0\) km s\textsuperscript{−1}, \(V_y \approx 170\) km s\textsuperscript{−1}, looks like a segment of a circle and occupies an area extending from azimuths about 315° to 45° (the corresponding phase of the intersection of the line-of-sight with this bright region is about 0.9 – 1.1). The source of this feature is not clear. There can be speculations on its stream origin, but the shape and position of this feature raise a doubt.

The brightest area is located in an unusual place, on the bottom-right part of the map, in exactly the same place as observed for BZ UMa before (Neustroev et al. 2004). This extended bright area has a complex multi-spot structure. This is far from the region of interaction between the stream and the disc particles. None of the theories predict the presence of any bright spots here, which are connected with such an interaction. Additionally, we would like to note the existence of emission from the area around the WD.

Surprisingly, this extremely unusual emission structure remains present in all major details during all the outburst stages. After the maximum a new emission source arose which became the brightest at that time (Fig. 7). It is situated close to the first bright area on the quiescent tomogram but most likely they are not directly linked. The new source can be unequivocally contributed to emission from the inner hemisphere of the secondary star. This emission seen in hydrogen and neutral helium lines, is likely caused by increased irradiation from the accretion regions during the outburst.

It is interesting to trace what the emission from the donor star was doing during the rising stages of the outburst. Actually, it was incorrect to calculate the Doppler maps using these spectra because they have been obtained under conditions obviously breaking one of major principles of Doppler tomography: that flux from any point is constant in time (Marsh 2001). However, for display and comparison purposes we have produced the tomograms of the H\textsc{alpha} emission during the first and third stages of the outburst rising (Fig. 6 middle and right panels). They appear to be very similar to the quiescent map (Fig. 6 left), without any clear indications for the emission from the secondary. Figure 8 separately shows all the trailed H\textsc{alpha} spectra from rise to outburst.
Figure 6. Observed and reconstructed trailed spectra (bottom) and corresponding Doppler maps (top) of BZ UMa before the outburst (Jan 15) and during the rise to it (Jan 16, stage 1 and 3).

Figure 7. Observed and reconstructed trailed spectra (bottom) and corresponding Doppler maps (top) of BZ UMa after the maximum of the outburst (Jan 17).
3.4 Radial velocities and zero phase

In CVs the most reliable parts of the emission line profile for deriving the radial velocity curve are the extreme wings. They are presumably formed in the inner parts of the accretion disc and therefore should represent the motion of the white dwarf with the highest reliability. We measured the radial velocities using the double-Gaussian method described by Schneider & Young (1980) and later refined by Shafter et al. (1986). In order to test for consistency in the derived velocities and the zero phase, we separately used the emission line Hα in December’s spectra, in the phase-averaged spectra for the nights of Jan 15 and 17, and in the phase-averaged spectra for the first three periods of Jan 16. All measurements were made using a Gaussian FWHM of 100 km s$^{-1}$ and different values of the Gaussian separation $\Delta$ ranging from 300 km s$^{-1}$ to 3000 km s$^{-1}$ in steps of 50 km s$^{-1}$, following the technique of ‘diagnostic diagrams’ (Shafter et al. 1986). For each value of $\Delta$ we made a non-linear least-squares fit of the derived velocities to sinuosids of the form $\gamma - K \sin \left(2\pi (T - T_0)/P\right)$ with the orbital period fixed to 97.9 min, and we find the maximum useful separation to be $\Delta \simeq 1200–1400$ km s$^{-1}$. We obtain very consistent results for both the radial velocity semi-amplitudes and the $\gamma$-velocities for the quiescent and outburst states, and we adopt the mean values $K = 43 \pm 2$ km s$^{-1}$ and $\gamma = -29 \pm 3$ km s$^{-1}$.

In the previous Section we have detected the extremely unusual emission structure of BZ UMa (particularly, the spot(s) in the lower-right of the Doppler maps), so we must be sure of the correct phasing of the input spectra used for producing the tomograms. The best way to determine the zero phase is the eclipse observations but eclipses are not present in BZ UMa. Assuming that the wings of the emission lines come from disc material orbiting close to the white dwarf, the red-to-blue crossing of the radial velocities provides an estimate of the moment of inferior conjunction of the secondary star. In general, a value for the zero phase obtained in this way may be influenced by additional emission sources, if they exist on the line wings. However, we believe we could avoid this as the detected strong emission spot is situated well inside of the chosen Gaussian separation. Moreover, for the Doppler mapping we have phased the input spectra separately for each night, in accordance with their respective moments of inferior conjunction of the secondary star $T_0$, however all these $T_0$’s are consistent with each other and with the chosen orbital period of 97.9 min. Finally we note that the correctness of the used zero phases are strongly supported by the detected emission from the donor star.

4 DISCUSSION

The nonperiodic nature of outbursts makes any observations of their early stages very important. The presented simultaneous photometric and high resolution spectroscopic observations should be useful to constrain current models of outburst behaviour.

Although significant theoretical advances have been made in recent years, there remains many unsolved problems (see review of Lasota 2001). One of the major issues is that the system brightness in the models almost always increases between the outbursts but the optical observations show that the mean flux remains approximately constant throughout quiescence. In the case of BZ UMa, the changes in the system had already begun before the outburst event. On the basis of the December spectroscopy we have determined that the system was redder and ~0.9 mag fainter one month before the outburst than in the last few ‘quiescent’ days preceding the outburst. Moreover, though the hydrogen emission lines prior to the outburst still remained extremely strong (EW$_{H\alpha}$ ~ 140 Å), they were the weakest we have ever observed (Neustroev et al. 2002, 2004). For example, in December the EW$_{H\alpha}$ was ~225 Å. These changes were not caused by an enhancement of the mass-transfer rate: The Mass-Transfer Instability model predicts an increase of the brightness of the hot spot before and during the outburst but the Doppler maps (Fig. 8 and 11) do not show any sign.

Table 2. Elements of the radial velocity curves of BZ UMa

| Date        | $\gamma$-velocity (km s$^{-1}$) | $K$ (km s$^{-1}$) | $T_0$ (HJD)     |
|-------------|---------------------------------|------------------|-----------------|
| 2004-Dec-10 | -42±8                           | 38±9             | 2450101.264±0.001 |
| 2005-Jan-15 | -27±5                           | 42±6             | 2450101.265±0.001 |
| 2005-Jan-16 | -27±4                           | 42±7             | 2450101.263±0.002 |
| 2005-Jan-17 | -55±2                           | 44±3             | 2450101.265±0.004 |
| Mean        | -29±3                           | 42.8±3           | 2450101.264±0.001 |

Figure 8. Observed trailed Hα spectra of BZ UMa during the rise to the outburst (Jan 17). First three periods, averaged together into one period, are shown in the bottom panel, then all the other spectra are shown one after another in the upper panel.
of the hot spot. At the same time, in the Disc Instability Model no such effects are expected.

According to the DIM, there can be two types of outbursts depending on where the instability in the accretion disc begins. When the trigger is in the inner disc, a heating wave pushes outward, creating an ‘inside-out’ outburst; if the trigger is in the outside of the disc, the heating wave pushes inward, creating an ‘outside-in’ outburst. Which type of outbursts occur depends sensitively on the mass transfer rate from the secondary star and the viscosity. An outside-in outburst results if the transfer rate is high while the inside-out outburst occurs if the viscous evolution within the disc is more effective. For constraining these parameters, it is important to be able to determine which of these types of observed outbursts is occurring in a particular system.

The large outburst amplitude and the long recurrence time of BZ UMa, together with one of the strongest Balmer emission spectra of any known CV, indicates a low accretion rate for the system (Patterson 1984). As $\dot{M}$ is an important parameter in the following discussion, we present our considerations concerning its value in BZ UMa.

In order to estimate $\dot{M}$ one needs to know the distance to the system. Distances can be derived from the absolute magnitude at outburst $M_V$ (max) versus the orbital period relation of Warner (1995) or from a more recent relationship by Harrison et al. (2004). Analysis of the last sixteen outbursts of BZ UMa, particularly documented in the AAVSO database, reveals a roughly uniform distribution of peak magnitude from 10.5 mag to 11.5 mag. This yields 110–175 pc. These independent estimations are consistent with the $110^{+55}_{-34}$ pc value of Ringwald et al. (1994), leading us to the final estimation of 110–154 pc. To determine $\dot{M}$ we could use a standard-candle method. The dwarf nova HT Cas shows many close similarities to BZ UMa including the outburst behaviour and system parameters, thus their comparison could be useful to determine $\dot{M}$. The mass-transfer rate in HT Cas is $\sim 2 \times 10^{15}$ g s$^{-1}$ (Wood et al. 1992), but this system shows the outburst amplitude and the EW of emission lines substantially less than in BZ UMa, and it appears to be more intrinsically bright than BZ UMa. From this we expect $\dot{M}$ for BZ UMa to be several times less than in HT Cas. Using the approximate method of Patterson (1984) we derive $\dot{M}$ for BZ UMa to be even less than $10^{14}$ g s$^{-1}$.

A very low mass-transfer rate for BZ UMa implies that theoretically, its outbursts should be of an inside-out type. Unfortunately, the only way to be sure of the outburst type is from eclipse profile observations during outbursts and BZ UMa is not an eclipsed system. Nevertheless, there is some additional circumstantial evidence to support the inside-out type of the outburst of BZ UMa.

The strongest indication comes from the spectra obtained during the rising stage. For the case of the inside-out outburst one can expect the lines wings change before their cores. Such is indeed the case in BZ UMa (Fig. 4). Already during the jump the wings of the emission lines were replaced by the broad absorption troughs. This can be explained by the transition of the innermost parts of the accretion disc from a cool, optically thin state to a much hotter and optically thick state. This transition on the earliest stages of an outburst can occur only in the case of the inside-out type.

In favour of the inside-out outburst may speak also a noticeable difference in peak magnitudes of BZ UMa during outbursts (see above). Smak (1984) showed that there exit two types of the inside-out outbursts: in one the heating front does not reach the outer disc regions while in the other the front propagates all the way to the outer edge. Consequently, the first type is of lower magnitude and shorter duration than the second, conforming with the observations.

However, some of our observations raise an interesting and related question. Theory predicts that the inside-out outburst produces a fairly symmetric light curve with respect to rise and decline while the outside-in outburst develops more quickly and produces an asymmetric light curve (Smak 1984). Actually, the outburst light curve of BZ UMa is highly asymmetrical, with the rise of $\sim 0.8$ days and the decline of $\geq 3.5$ days, relative to a level of 15.5 mag, testifying against the inside-out type. In principle, this guess may be correct because the inside-out outburst has been directly observed in HT Cas (Ioannou et al. 1999), another system with a low mass-transfer rate. Such an outburst in this system can be explained only if the disc is significantly smaller than the tidal truncation radius (Buat-Ménard et al. 2001). This is in agreement with observations of HT Cas but it is unlikely for BZ UMa. BZ UMa exhibits a transfer rate well below the level of the transition between inside-out and outside-in outburst, and we do not see how one could get outside-in outbursts in this system even with the small accretion disc.

It is known that in some conditions inside-out outbursts may produce an asymmetrical light curve. This is possible when the inner disc is truncated, for example due to the presence of a magnetic field (Lasota et al. 1999). We found no clear sign of the truncated accretion disc, though evidence for a weak magnetic WD in BZ UMa may be indicated by its relatively strong X-ray emission (Verbunt et al. 1999), by the presence of modulations with the period of 42 min (and/or 18 min), and by emission from an area around WD in the Doppler maps.

5 SUMMARY

In this paper we reported simultaneous photometric and echelle-spectroscopic observations of the dwarf nova BZ UMa during which we were lucky to catch the system at the onset of an outburst. On the base of the spectral changes during the rising stage we conclude that the 2005 January outburst of BZ UMa was of the inside-out type. Nevertheless, a highly asymmetrical light curve with a ‘jump’ during which the system brightness almost doubled over the course of half an hour, shows that this outburst cannot easily be fit into the framework of the current Disc Instability Model.

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1 We suppose that smaller values are more probable if outbursts of lower magnitude correspond to the case when the heating front does not reach the outer disc regions (see discussion below).
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