Reconstruction of emission sites in the dwarf nova EX Draconis

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Abstract. We performed time–resolved spectroscopic studies of the double–eclipsing dwarf nova EX Dra (formerly HS 1804 + 6753) in order to locate line emitting sites in the system. Optical spectra recorded during the quiescent as well as during the outburst state have been analysed by means of Doppler tomography. The computed Doppler images map the system in a variety of emission lines and allow us to compare between different temperatures and accretion states.

Our studies revealed that the Balmer and He I emission of EX Dra during quiescence is mainly formed within a fully established disk and within the gas stream. The Doppler map of H shows a second emission spot in the accretion disk located far from the region of interaction between the gas stream and the accretion disk.

We have found a weak hint that secondary star emission contributes to the H line in quiescence, obviously caused by photospheric heating due to irradiation by the primary component. During outburst secondary star emission turns into a very strong emission source in the Balmer lines due to the increased accretion rate and an enhanced irradiation by the white dwarf or the boundary layer. The Doppler maps of the Balmer and He I lines during outburst further show emission from the accretion disk. During outburst the gas stream is rarely seen in the Balmer lines but clearly visible in He I and shows that the disk radius during this high accretion state is about 0.2 R_<L1> larger than during the recorded quiescent state.

The origin of the C II (4267 Å) line, which is only detectable during eruption can be located by Doppler imaging close to the primary component and may therefore be formed in the chromosphere of the white dwarf.

Key words: stars: cataclysmic variables -- accretion disks -- stars: individual: EX Dra (formerly HS 1804 + 6753)

1. Introduction

The cataclysmic variable EX Dra (formerly HS 1804 + 6753), was first detected in the Hamburger Quasar Survey in 1989 (Reimers D., 1991, private comm.). In the course of follow-up observations the system turned out to be a double-eclipsing dwarf nova of the U Gem class with a quiescence magnitude of about 14 mag, a relatively small outburst amplitude of 1 mag -- 2.3 mag and an orbital period of 5.04 h (Barwig et al. 1993).

Up to now two different approaches have been made to analyse this binary system. Billington et al. (1996) undertook spectroscopic observations of the red part of the optical wavelength range of EX Dra in 1994. Analysis of the H emission by means of Doppler tomography indicated that the H emission of EX Dra is dominated by the bright spot and the inner Langrangian region, whereas the accretion disk itself is rarely seen in H. Fiedler et al. (1997) used optical spectra covering the spectral wavelength range between 3500 and 8900 Å and long term photometric observations, both recorded during the quiescent as well as the outburst state, to determine the fundamental system parameters.

Cataclysmic variables (CVs) are close interacting binary systems containing an accreting white dwarf star and a Roche lobe filling secondary, typically a main sequence star, which loses mass via the inner Langrangian point into the Roche lobe of the white dwarf. Conservation of angular momentum causes the stream material in non-magnetic CVs to form a disk around the massive star, which is the dominating light source of the system as observations reveal. Dwarf novae are a subclass of CVs and frequently show outbursts, which are episodes of enhanced accretion through the disk and onto the central object.

Whereas this basic CV model is well established, the processes leading to mass transfer through the disk and the transport of angular momentum within the disk are still outstanding questions.

The energy flux of cataclysmic variables in the optical wavelength range is dominated by emission from the accretion disk represented by a continuum flux increasing towards a maximum in the UV and emission lines mostly originating from H and He. The line profile shapes depend on the distribution of line flux over the disk and therefore can be used to constrain it. Other components of the system, like the two stars, the gas
stream and disk outflows can also significantly contribute to the emission line flux. With Doppler tomography, an image reconstruction technique (Marsh & Horne 1988), two-dimensional images of the system in velocity space can be obtained, which allow one to ascertain the contributions from the two stars, the disk and other clear emission sites to the observed line flux. Doppler mapping can be used as a constraint for theories of line formation and can indicate the structure of the disk. The emission distribution over the disk in most of the known cataclysmic variables is far from being uniform or even symmetric. The interaction between the highly supersonic overflowing secondary star material and the edge of the rotating disk and the mass transfer through the disk lead to an inhomogeneous distribution of emission. A prominent region of enhanced emission, the so-called bright spot is often visible at the rim of the disk where the stream material impacts onto the disk. Recently a group found observational evidence for spiral structures in the disk where the stream material impacts onto the disk. Recently we have discussed by Fiedler et. al. (1997). Therefore in the present. A set of 137 optical spectra of EX Dra was recorded during the outburst and the quiescent state showing a series of emission lines allow us to compare Doppler maps of different temperatures and accretion states to reveal details of the accretion mechanism in the system EX Dra.

This paper presents phase–resolved studies of EX Dra by analysing the spectra presented in Fiedler et. al. (1997) in more detail. Our intention is to locate line emitting sites in the system and to obtain information of the line flux distribution over the disk by means of Doppler tomography: Steeghs et. al. (1997) found a two armed structure in the disk of IP Peg during outburst. Emission from the secondary star can also play a role, as detected for example for the H and H line of IP Peg during quiescence (Wolf et al. 1998). The knowledge of the distribution of line emission is in addition crucial for the measurement of the radial velocity of the white dwarf, since phase-dependent asymmetries in the emission lines distort measurements of this parameter.

2. Data acquisition and reduction

2.1. Spectroscopy

The acquisition and reduction of the spectroscopic data has already been discussed by Fiedler et. al. (1997). Therefore in the following only a short summary of the spectroscopic data is presented. A set of 137 optical spectra of EX Dra was recorded in an observing run at the Calar Alto 3.5 m telescope with the Cassegrain Twin Spectrograph in 1992. The choosen gratings provided a dispersion of 1.7 ˚A per pixel in the blue and 1.1 ˚A per pixel in the red spectral range with a wavelength coverage between 3440 and 5330 ˚A and 5690 and 6810 ˚A respectively. During these observations EX Dra was in quiescent state. An additional sequence of 32 spectra was taken in a second observing run at the Calar Alto 3.5 m telescope in 1993 during which EX Dra was found in (probably an early) outburst state. The wavelength coverage in the red part of the spectra was extended to longer wavelengths (6200 : : 8900 ˚A) at the cost of the spectral resolution leading to a dispersion of 2.7 ˚A per pixel in the red part of the spectra. The blue part of the wavelength range (3840 : : 5630 ˚A) was observed with a dispersion of 1.8 ˚A per pixel.

The exposure times varied between 200 s and 1200 s. Spectra of the spectrophotometric standard stars BD+28 4211 (Stone standard) and Wolf 1346 (Oke standard) were taken.

The spectroscopic data were reduced using the so-called Optimal Spectrum Extraction Algorithm (Horne 1986), taking into account bias–subtraction, flatfield–correction, sky–substraction and cosmic–ray elimination and performing a wavelength–calibration.

In order to correct for the wavelength–dependent sensitivity of the atmosphere and of the instruments a separate flux calibration was performed (see Sect. 2.3).

2.2. Photometry

Long term photometric observations of EX Dra in the quiescent as well as in the outburst state were performed with the Multichannel–Multicolour Photometer MCCP (Barwig et al. 1987) attached to the 80 cm Wendelstein telescope during the years 1991 to 1996 and to the 2.2 m telescope at Calar Alto observatory in 1992 and 1993. The data were recorded with a time resolution of 2 s and 1 s. The MCCP is a high–speed photometer providing three fiber channels to measure the object, a nearby comparison star and the sky background simultaneously. Atmospheric effects are eliminated using the so–called Standard Reduction Algorithm (Barwig et al. 1987) which subtracts the sky background of each of the five UBVRI colour channels from object and comparison star measurements afterwards. The simultaneous observing technique in combination with the reduction algorithm allows to perform photometric measurements even under non–photometric conditions. A detailed journal of the photometric observations from 1991 to 1996 is given by Fiedler et. al. (1997). The B and R light curves from these photometric measurements were used for the flux calibration of the spectra (see Sect. 2.3).

2.3. Flux calibration of the spectra

A flux calibration is required in order to account for the wavelength– and time–dependent sensitivity of the atmosphere, for the wavelength–dependent sensitivity of the tele-
scope, the spectrograph and the detector and to transform the
recorded flux distribution to an absolute scale.

Under stable atmospheric conditions the flux calibration
can be performed by using recorded spectra of spectrophotometric standard stars, or alternatively by using simultaneously
recorded broadband photometry. The latter can also be applied
under variable atmospheric conditions, when an instrument like
the MCCP is used which allows to obtain photometric measure-
ments even under non-photometric conditions.

Unfortunately the atmospheric conditions were not stable
during the observations and no simultaneous photometry was
available which could have been used to correct for the atmos-
pheric variations. In addition a careful check of the recorded
standard star spectra showed that a significant loss of light oc-
curred at the spectrograph slit.

Therefore a different approach had to be made: the short
term atmospheric variations were corrected by means of mean
photometric B and R light curves taken during the quiescent
and the outburst states of EX Dra, whereas the wavelength–
dependent sensitivity of the atmosphere and the instrument
were corrected by using the recorded spectra of the flux
stars BD +28 4211 (1992) and Wolf 1346 (1993). A significant
number of photons is lost when a narrow spectrograph slit is
used for both the object as well as the standard star spectra.
The lack of standard star spectra recorded with a wide slit pre-
vented us from calculating the so–called 'slit loss'. Therefore
the resulting spectral flux distribution of the object spectra is
accurate to a constant factor.

3. Analysis and results

3.1. Mean quiescence spectra

Fig. 3 presents the mean spectra of EX Dra in quiescence,
which are based on 69 single spectra in the blue and 68 in
the red wavelength range. Before averaging the single spec-
tra were shifted according to the radial velocity
which are based on 69 single spectra in the blue and 68 in
Fig. 1 presents the mean spectra of EX Dra in quiescence,

3.2. Mean outburst spectra

The mean spectra of EX Dra in outburst are displayed in Fig. 2
as the average of 16 single spectra for the blue and 16 for the
red spectral range. As discussed in Sect. 2.3 the spectra of the
spectrophotometric standard stars suffered from significant slit
loss and therefore the computed flux of the spectra of EX Dra is
accurate to a constant factor. The energy flux of the system ap-
pears to be higher in quiescence than outburst. The mentioned
slit loss should account for this contradiction, since we know
from photometric measurements taken the night after the spec-
trosopic observations in 1993 that the optical flux was signifi-
cantly enhanced compared to July 1992.

The most remarkable features in the outburst spectra are
dominant emission lines of the Balmer series and of neutral
helium, whereas outburst spectra generally show broad Balmer
absorption lines with weak emission cores. A similar behaviour
was also seen in IP Peg: Marsh & Horne (1990) recorded out-
burst spectra of IP Peg and observed enhanced emission line
fluxes of all Balmer and helium lines with He II (4686 Å) be-
coming the strongest line at visual wavelengths. The systems
Z Cha (Vogt 1982) and OY Car (la Dous 1991) also show emis-
sion lines during outburst. The high orbital inclination of these
systems probably account for the strong emission lines during
eruption, because the flux in the optically thick continuum of
the accretion disk is at large inclinations reduced by projection
and limb darkening in favor of emission lines formed above the
disk.

The profiles of the Balmer lines are almost single–peaked in
the mean spectra of EX Dra in outburst, although there are still
some small indications of double–peaked structures visible. As
a remarkable exception the He I (4471 Å) line clearly displays
a double–peaked profile in the mean outburst spectra.

High–excitation lines which are only weakly or not
at all present during quiescence emerge during outburst,
like He II (4686 Å), C II (4267 Å) and the C III/N III
(4634...4651 Å) blend.

He II emission is often a hint for a strong magnetic field of
the white dwarf, but there is no evidence for magnetic accre-
tion in EX Dra. Patterson & Raymond (1985) show that He II
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Fig. 1. Mean spectra of EX Dra observed during quiescence. Before averaging the spectra were shifted according to the radial velocity \( K_1 \sin ( \epsilon ) = 167 \text{ km s}^{-1} \sin ( \epsilon ) \). Intensities in \( \text{ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \). The energy flux is accurate to a constant factor, because of slit loss of the flux star spectra. See the text for more details.

Fig. 2. Mean spectra of EX Dra observed during outburst. Before averaging the spectra were shifted according to the radial velocity \( K_1 \sin ( \epsilon ) = 167 \text{ km s}^{-1} \sin ( \epsilon ) \). Intensities in \( \text{ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \). The flux is accurate to a constant factor, because of slit loss of the flux star spectra. This fact could explain why the energy flux of the system appears to be lower during outburst than during quiescence. See the text for further discussion.

Under the premise that Doppler shifting is the only broadening mechanism of significance it is possible to locate the line forming regions of the binary system by means of Doppler tomography.

The Doppler broadened line profiles represent a projection of the velocity distribution in the direction of the observer’s line of sight, while rotation of the binary gives the observer a continuously varying sequence of velocity projections. This combination of Doppler shifting and binary rotation provides sufficient information for the assembly of two–dimensional maps in velocity space \((V_x; V_y)\).

While the observed line profiles are a projection of the velocity distribution, a back–projection algorithm applied to the observed data yields the emission distribution in velocity space.

The computation of a Doppler tomogram is based upon the fundamental fact, that a spot of emission in the binary system traces an ’S–wave’ in the phase–sorted (‘phase–folded’) spectra, most evidently displayed by the features of the bright spots in many cataclysmic variables. The coordinate system is defined by the X–axis pointing from the white dwarf to the secondary star and the Y–axis in the direction of motion of the secondary star. The sinusoidal ’S–wave’ radial velocity curve

\( (4686 \text{ Å}) \) emission can be produced in the upper layer of the disk by reprocessing soft X–rays from the boundary layer when the mass transfer rate \( \dot{M} (d) \) exceeds \( 10^{-9} M_\odot \text{ yr}^{-1} \). Under the premise that \( \dot{M} (d) \) in EX Dra in the recorded outburst state satisfies this condition the detected \( \text{HeII} \) outburst line could be formed in the (upper layer of the) disk by recombination following photoionization by the boundary layer. \( \text{HeII} \) is blended by \( \text{CIII}/\text{NIII} \) emission, which prevents us from Doppler imaging this line. The time–resolved line profiles show that the line forming region can not be too extended since most of the \( \text{HeII} \) emission is eclipsed at phase \( \delta = 0 \) by the secondary star.

3.3. Doppler imaging in the quiescent state

Line profiles broadened by Doppler shifting retain an imprint of the line emission region from which it originated. The Doppler tomography is an imaging technique, developed by Marsh & Horne (1988), which makes use of the close relationship between the observed emission line flux and the velocity profiles to obtain the distribution of line emission over the surface of the disk in velocity space.
The outer edge of the disk seen in the H, H and H light of EX Dra is represented by the inner edge of the ring–like structure in velocity coordinates, located somewhere between 350 and 500 km s$^{-1}$.

Emission from the gas stream is detectable in all of the Balmer lines as well as in the HeI ($\lambda\lambda$ 6678, 4471 Å) lines. Except in H it is the brightest region in the emission distributions. The series of small circles along the gas stream mark the distance from the white dwarf at intervals of 0.1 R$_{1}$ starting from R$_{1}$. There is detectable emission between 0.5 :: :0.3 R$_{1}$ in H, H and HeI ($\lambda$ 4471 Å).

The quiescence data are quite noisy and the time resolution is not sufficient to resolve the obviously existing complex structures in the line profiles. However, an enhancement in intensity around phase 0.2 and 0.8 can be attributed to the bright spot emission. The corresponding S–wave is not visible during the whole binary orbit as it is for an anisotropically emitting spot. Doppler tomography is based on the assumption that the integrated flux is constant with phase which is violated by any anisotropically emitting spot. This leads to a discrepancy between observed and reconstructed spectra.

Billington et al. (1996) also observed H emission from the gas stream in EX Dra. The center of this emission is located at $V_x$ 500 km s$^{-1}$, which is in agreement with the center of the gas stream emission in our quiescence H map. But we do not observe the strong broadening of the gas stream emission ranging over velocities of 1000 km s$^{-1}$, detected by Billington et al. (1996).

The H map deviates significantly from that of the other Balmer lines and the HeI lines. A second dominant emission spot is present in H at velocity coordinates $V_x$ 0...+500 km s$^{-1}$ and $V_y$ 200 :: : 500 km s$^{-1}$. This feature is even brighter than the one associated with the gas stream. It is remarkable that a similar feature at about the same velocity coordinates (although fainter) has also been detected in the H map of EX Dra performed by Billington et al. (1996). Obviously this feature must be attributed to an emission site within the disk opposite to the bright spot.

Furthermore, Doppler tomography maps a small amount of the H emission into the Roche lobe of the secondary star (cp. Fig. 3). Imaging in velocity coordinates does not allow to unequivocally distinguish whether this emission originates at the secondary star or within the disk. This is a general problem of Doppler tomography that two particles at different spatial positions but with the same Doppler velocities map into the same pixel in velocity space. Since the emission displays velocities smaller than 200 km s$^{-1}$ where no disk emission is expected and since it is visible on that side of the secondary facing the primary it could be caused by photospheric heating of the secondary due to irradiation by the primary component. The emission seems to be concentrated near the poles of the irradiated side of the secondary and the L$_1$ point does not seem to be affected. This suggests the white dwarf or the boundary layer as the ionizing source and a shadowing of the equatorial parts, including the L$_1$ point by the disk.
Fig. 3. Doppler maps of H, H and H during the quiescent state of EX Dra (right column), the observed phase-folded spectra (left column) and the spectra reconstructed from the maps (middle). The Doppler maps show a broad ring–like structure and emission from the gas stream. The map of H displays further a second bright emission spot at V<sub>a</sub> ~ 500 km s<sup>-1</sup> and a faint hint of secondary emission.

Billington et al. (1996) also found evidence for irradiation of the secondary in their H Doppler map. In contrast to our result they observed strong broadened secondary star emission uniformly distributed over the secondary including L<sub>1</sub>. This might be due to their incomplete phase coverage and fewer number of spectra compared to our data set.

The disk structures in the H, H and He I (4471 Å) maps are superposed by several emission features weaker than the bright spot. The features in H and H are consistent. Since such features can be caused by a low phase resolution they might be artificial. Further spectroscopic observations with higher time and velocity resolution are required to verify their existence.

3.4. Doppler imaging in the outburst state

Interpretation of Doppler tomograms of the outburst state is hampered by the fact that the outburst data set covers only 56% of the binary orbit, which could result in artificial effects. Due to a non uniform distribution of the available spectra across the
Fig. 4. Doppler maps of H and HeI (6678 and 4471 Å) during the quiescent state of EX Dra (right column), the observed phase-folded spectra (left column) and the spectra reconstructed from the maps (middle). The H map shows similar features as the H and H map (cp. Fig. 3). The HeI maps display emission from the gas stream and the disk, but the data are quite noisy within this lines.

binary orbit we obtain a decreased resolution in the V_x direction in the maps.

As in many dwarf novae during outburst, EX Dra shows strong Balmer emission from the secondary star in the high accretion state (Fig. 5). The secondary star displays no emission of the HeI triplet line at 4471 Å (Fig. 5) whereas there are indications of HeI (6678 Å) emission from the secondary during outburst.

Because of the mentioned artificial smearing in the V_x direction the bright emission region in the H outburst map can be a superposition of emission from the irradiated secondary and the gas stream. Emission from the gas stream is further detectable in the HeI maps, most prominently in the line at 4471 Å. A comparison with the HeI (4471 Å) quiescence map locates the impact region in outburst about 0.2 R_L closer to the L_1 point than in quiescence. This can be attributed to the enhanced accretion during outburst, which causes an enlargement of the outer disk regions due to conservation of angular momentum within the disk.
The system seen in the light of the single ionized carbon (Fig. 6) differs totally from the other images. The C II emission which is only marginally detectable in quiescence is powerful enhanced during outburst. The S–wave in the observed phase–folded spectra (lower left picture in Fig. 6) indicates that the C II line flux is emitted at relatively low radial velocities. In the Doppler image the C II emission is concentrated in the center of the disk suggesting a line forming region close to the white dwarf. Whether C II originates in the chromosphere of the primary or in parts of the inner boundary layer or in a wind from the white dwarf is not clear. The reconstructed data (lower middle picture in Fig. 6) indicate a reliable back–projection, but the interpretation of the C II line is hampered by the low S/N ratio of the data recorded within this line and by possible artificial effects due to the incomplete phase coverage and the low phase resolution. However, it is obvious that during outburst the C II
line is not emitted from the same sites, where the Balmer or helium lines originate.

The two He\textsc{i} outburst maps (cp. Fig. 6) clearly display emission features in the disk almost opposite to the bright spot. Recently detected spiral structures in the outburst accretion disk of IP Peg [Steeghs et al. 1997] suggest that tidally induced spiral shocks (first proposed by Sawada et al. 1986, 1987) may also play a role in the accretion processes during outburst in other dwarf novae. Unfortunately the low spectral and phase-resolution of our outburst data permit no reliable statement about spiral structures in the disk of EX Dra. The detection of spiral patterns by means of Doppler tomography demands a spectral resolution of 80 km s\(^{-1}\) and a time resolution of 40 spectra per binary orbit [Steeghs & Stehle 1999], which is not met by our outburst data set.

4. Discussion and conclusion

EX Dra in quiescence is dominated by emission from a fully established accretion disk and by emission from the gas stream interacting with its outer rim. The center of the gas stream emission located at \( V_x = 500 \) km s\(^{-1}\) during quiescence is in
agreement with that in the H  map of Billington et al. (1996),
but our data set does not confirm the strong broadening
detected by Billington et al (1996).

Unlike most other dwarf novae, the emission lines of
EX Dra remain strong during outburst. This behaviour is also
seen in other deeply eclipsing dwarf novae like IP Peg (Marsh &
Horn 1990), Z Cha (Vogt 1982) and OY Car (la Dous 1991).
The high orbital inclinations of these systems probably accounts
for the strong emission line features during eruption, because at large
inclinations the flux in the optically thick continuum of the accretion
disk is reduced by projection and limb darkening in favor of emission lines formed above the disk.

Reemission of the secondary star in EX Dra is detectable
during quiescence in H  and during outburst in H , H  and H ,
where it becomes the dominating emission source during outburst. The emission is concentrated near the poles of that
side of the secondary facing the primary and indicates photospheric heating caused by irradiation by the white dwarf or the boundary layer.

Emission lines from highly excited species, like He II ( 4686 Å), C II ( 4267 Å) and C III/N III ( 4634 :::
4651 Å) are only marginally or not at all detected during quiescence but become strongly enhanced during outburst.

The Doppler image of the C II line during outburst locates its line forming region close to the white dwarf. This suggests the chromosphere of the white dwarf or the inner boundary layer or an outflow as possible emission sites. Radial velocity measurements of this line should in principle reproduce the radial velocity of the primary with higher precision than the distorted disk emission lines do. However, due to the low S/N of the C II line and the incomplete phase coverage of the recorded outburst spectra, we were not able to determine the radial velocity of the C II line.

The He II line is superimposed by C III/N III emission, for
that reason no reliable Doppler map of this line can be performed. Provided that the mass transfer rate M d exceeds
10  M  (Patterson & Raymond 1985) the He II emission
during outburst might be produced by reprocessing of soft X–rays from the boundary layer in the disk.

It is further conceivable that He II (and C II) is formed in
outflowing material, but this would require a very slow wind.
However, the material emitting the He II and C II lines can not be too extended, but must be closely confined to the orbital plane since both emission lines are eclipsed at phase = 0.

A comparison between the location of the gas stream emission in the Doppler maps of He I ( 4471 Å) in quiescence and outburst show that the disk radius is enlarged by about 0.2 R d during outburst.

The brightest line forming region in quiescence in the Doppler map of H  is located far from the gas stream trajectory. We have no explanation which line forming processes are involved to produce this feature. Since this emission spot is only detectable in the H  line and not in lines reflecting higher temperatures it is unlikely to be caused by a second impact region, as discussed e.g. by Lubow (1989). This emission spot is partly responsible for the complex H  line profiles and the asymmetric profile in the averaged spectra in form of an enhanced red–shifted peak.

The He I maps computed for the outburst spectra show evidence for emission structures in the right and top right region of the Doppler maps. Unfortunately the quality of the outburst spectra does not allow to draw a clear decision whether these structures may be attributed to spiral structures within the accretion disk of EX Dra, as detected for IP Peg during outburst (Steeghs et al. 1997), or not.

Our results show that EX Dra is a very interesting CV and that the next step should be spectroscopy with higher time and spectral resolution. The fact that the system can be frequently found in the outburst state should make further investigation possible throughout its outburst cycle.

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