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THE NEAR-INFRARED SPECTRA OF WOLF-RAYET STARS

M. K. V. BAPPU, K. S. GANESH and K. K. SCARIA

ABSTRACT

The near-infrared spectra of three Wolf-Rayet stars of the carbon sequence and five of the nitrogen sequence have been studied. Wavelength identifications and intensity scans are presented to show the emission line characteristics of these objects in the 6800Å to 8200 Å domain of the spectrum.

Key words: Wolf-Rayet stars—near-infrared spectra

1. Introduction

The study by Swings and Jose (1950) formed the first exploration of the spectrum of the Wolf-Rayet stars in the region 6700Å-8800Å. The observations were confined to seven objects accessible from northern latitudes. One of these was of the planetary nucleus, Campbell's hydrogen envelope star. A low dispersion of about 345 Å mm^{-1} enabled satisfactory exposures on Eastman I-N emulsion to be attained in durations not exceeding four hours. Little laboratory information was available at that time on the infrared spectra of ions that are commonly present in Wolf-Rayet spectra. Swings and Jose utilized Charlotte Moore's term tables (1949) to derive permitted transitions between known terms in this region of the spectrum. Such tables of predicted lines are not often the best means of line identifications in an observed spectrum.

The picture changed for the better in the late fifties and sixties when many investigations from Edlen's laboratories provided good wavelength lists of the different ions of carbon, nitrogen and oxygen that extended also into the near-infrared. On the astronomical side, knowledge of the Wolf-Rayet spectrum was extended to the long wavelength limit of the S-1 photosensitive surface commencing from 9000Å, by Kuhi who scanned the spectra of five objects with a low resolution spectrum scanner. Kuhl (1966) was able to identify many of the stronger features of C II, C III, C IV, found in the lists of Bockasten and Glad as well as from predicted hydrogenic transitions that could be determined from the data furnished by these investigators. The conclusions are similar to those we encounter in the blue-green region of the spectrum : the carbon stars have a profusion of lines belonging to the different ions of carbon while the stars of the WN sequence have mostly the lines of He I and He II with a sparse display of strong lines of nitrogen ions.

In this study we present spectra obtained with different values of dispersion of some stars in the northern and southern hemisphere. Three of the stars in our list of eight, HD 192103, HD 192163 and HD 151932 find a place in the study of Swings and Jose. Our spectra of the first two objects were obtained at Mount Wilson with the Cassegrain grating spectrograph on the 152-cm reflector at a dispersion of 111 Å mm^{-1}. Spectra of HD 151932, HD 50896 and the two stars in the Eta Carina region HD 93131 and HD 92740 were obtained at a dispersion of 250Å mm^{-1} with the Cassegrain grating spectrograph of the 61-cm reflector. The spectrum of HD 68273 (γ^2 Velorum) was obtained with the same spectrograph but with a different grating that gave a dispersion of 75Å mm^{-1}. The line identifications have been made from microphotometer tracings and are accurate enough to one angstrom. The wavelength lists of Glad (1953), Bockasten (1955, 1956), provided the basic laboratory information for identification of the carbon ions. Similar lists for N II (Eriksson, 1958), N IV (Hallin, 1966b) and N V (Hallin, 1966a) have aided this study. The relevent wavelengths for O IV, and O V were taken from the lists of Bromander (1970) and Bockasten and Johansson (1969). The identification of the lines were simplified greatly by these lists and the facility to compare excitation aspects for the different stars.

2. The nitrogen sequence

The principal contributors to the spectrum in this region are the lines of N III, N IV, N V and those of He I and II. In Figure 1 and Figure 2, we display

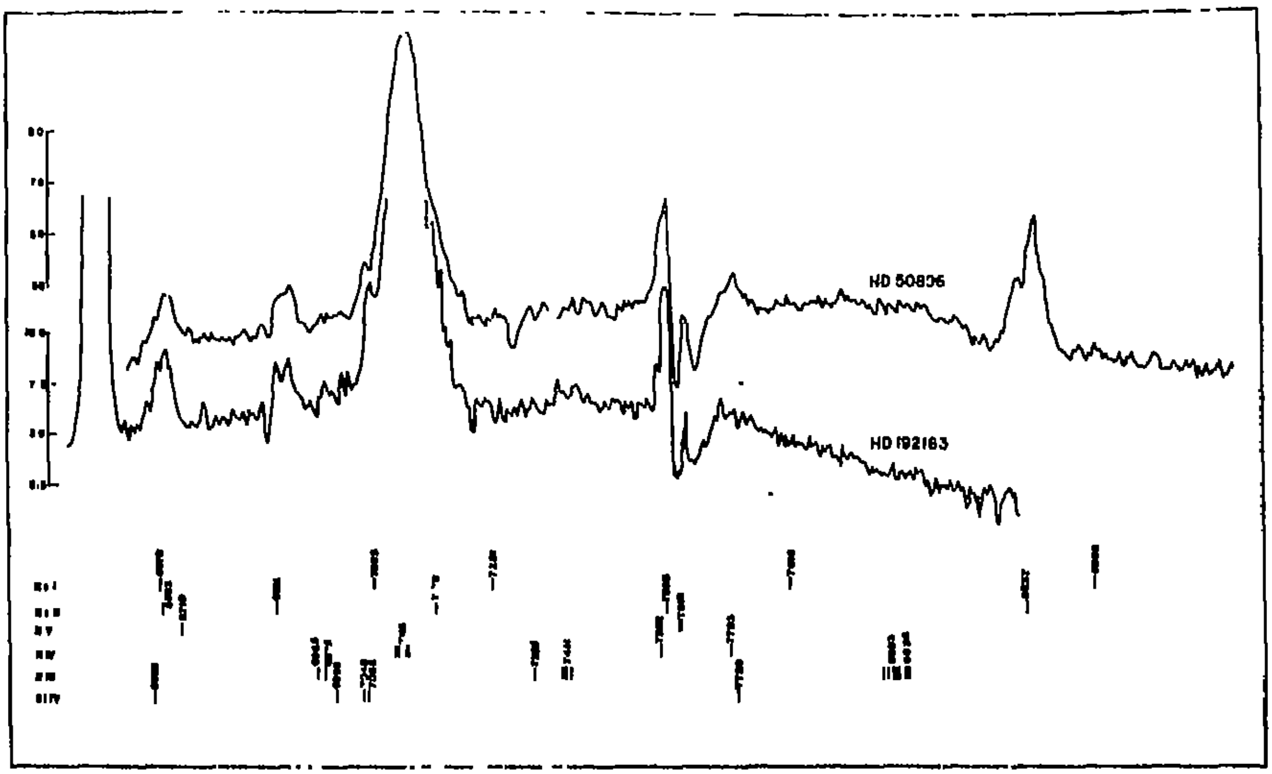

Figure 1 The near-infrared spectra of HD 50896 (WN5) and HD 192163 (WN6)

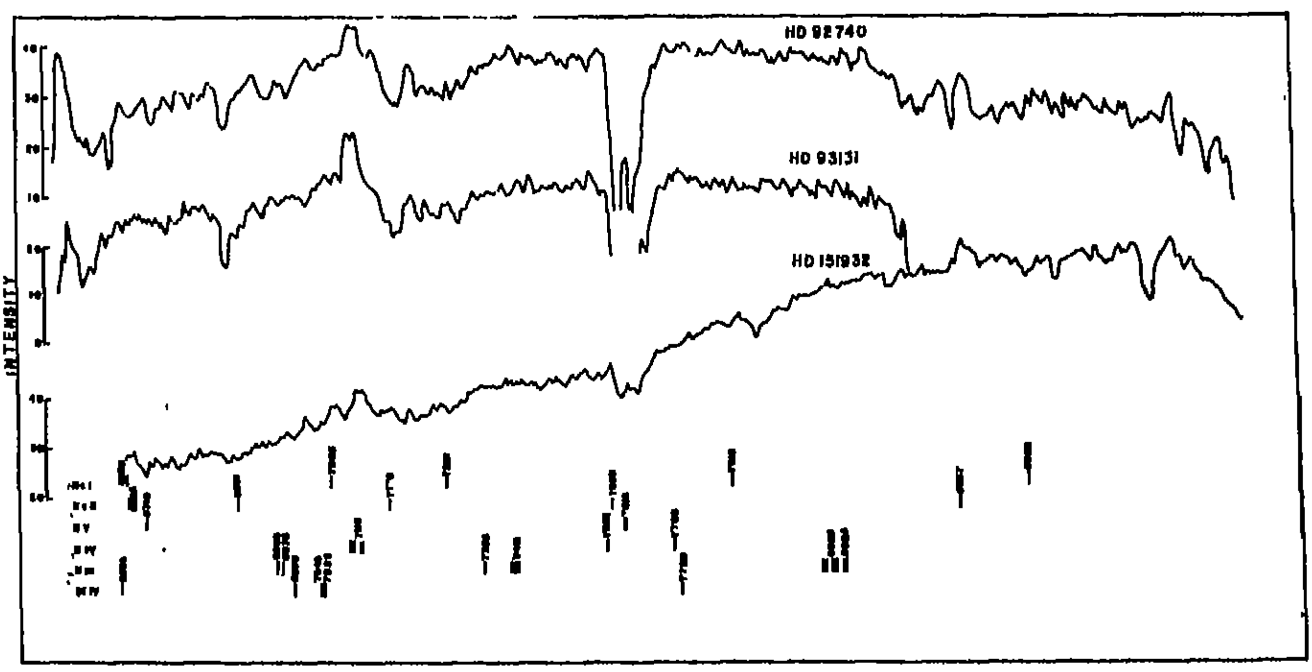

Figure 2. The near-infrared spectra of HD 92740 (WN7), HD 93131 (WN7) and HD 151932 (WN7)

intensity tracings of all five stars of the nitrogen sequence. A list at the bottom of the illustration gives all observed and predicted lines in this region of the spectrum that originate from ions that are possible contributors as judged from studies of the visual and blue regions of the spectrum. The spectra are arranged in order of increasing excitation. The classifications are due to Smith (1968).

The most striking aspect is the variation in excitation that we see along the sequence. The dominant role is played by N IV 7109, 7123 that is extremely intense in the WN 5 star HD 50896. The pair of lines, still unresolved, become less intense and narrow as we proceed along the sequence to HD 151932. The density tracings shown in Figure 3 indicate clearly these changes. Despite the enhancement in intensity of the He I line at 7065 Å as one goes down the temperature sequence from WN 5 to WN 8, the N IV lines are still the more intense ones in the region. The He II line at 7178 Å is almost completely obliterated in the spectrum of HD 92740, by telluric absorption, a consequence of the low elevation of the object at Kodaikanal.

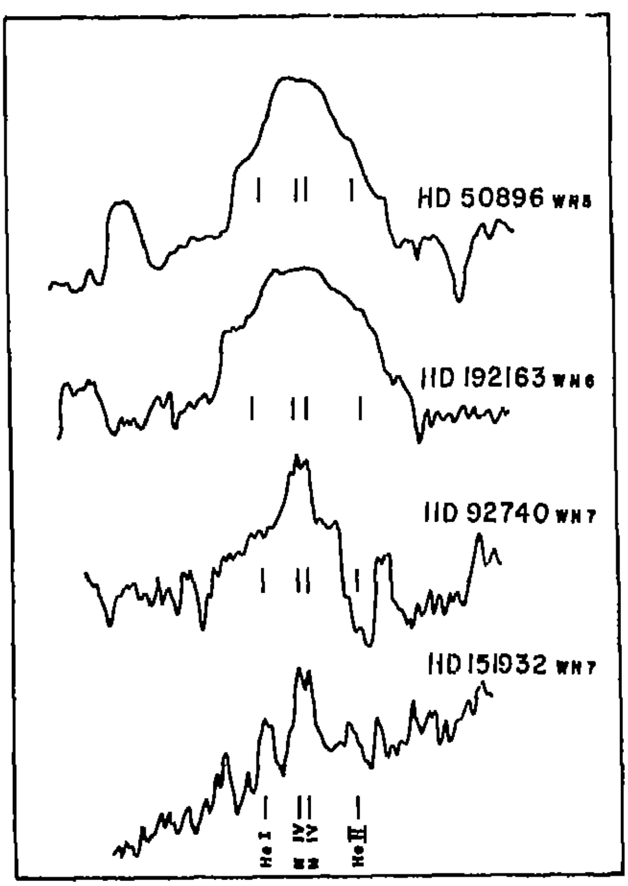

Figure 3. Intensity variation along the WN sequence of NIV 7109-7123 Å.

The stars of high excitation like HD 50896 and HD 192163 display the N V line at 7618 Å caused by the transition 7ghi-8ghik. The telluric oxygen band mutilates the line profile considerably, but the dominance of the N V intensity on the shortward side can be still seen. In the WN 7 types the intensity of N V 7618 Å must be very low and the lines may even be non-existent. Even the strong lines that characterize this ion in the blue are of very low intensity, as can be seen on reproductions of spectra of this class in the paper of Smith (1968).

Table 1. Wavelength identifications in the WN stars

λ	Origin.
6560	He II
6668	Si IV
6678	He I
6683	He II
6718	N V 6718
6891	He II
6972	N III 6965
	N III 6976
6998	Si IV 6998
7048	Si IV
7055	Si IV
7065	He I 7065
7116	N IV 7103
	7109
	7111
	7123
	7127
7178	He II 7178
7281	He I
7365	He I
7411	N III 7404
	7411
	7418
7582	N IV
7593	He II
7618	N V 7616
	7618
7703	N IV
7720	Si IV
7816	He I
8003	N III 7983
	7990
	8000
	8003
	8006
8026	N III 8022
	8026
8237	He II
8359	He I 8362

Immediately adjacent to the telluric oxygen band on the long wavelength side, weak emission may be seen at around 7705Å, principally in the representatives we have of WN 5 and WN 6. We identify this feature principally as due to N IV 7703 with possible contamination by Si IV at 7720Å. A weak contribution by N IV 7582 may also be present in the emission feature we have identified in the previous paragraph with N V 7618.

A weak contribution of N III can be seen in the spectra of HD 50896 and HD 192163 with certainty. Faint emission can be seen at 7410Å and 8020 Å that can be ascribed to the presence of a number of faint contributors of N III. In the WN 7 stars an apparent deformation of a smooth continuum in these wavelength regions is suggestive of the fact that N III contribution is still present, even though it is marginal.

One can say with certainty that N II lines are not present in this region of the spectrum since the strong lines at 7762, 8439 and 8680Å have not been detected so far in these spectra.

The rest of the emission features can be associated with He I and He II. Of these He II 8237 is the strongest with a distorted profile caused by the telluric water vapour band. He II also has a share in the emission feature at 7593 Å in the hotter stars, through the presence of the 7592.74 Å line. These are all members of the (5-n) series of He II. Support to such a conjectuie comes from the appreciable intensity of a later member of the series at 6891 Å. The He II line at 7178 Å which comes from the transition (5-11) has in the hot stars a share in the complex emission feature at 7130 Å of which N IV is the principal contributor. The asymmetry in the longward wing of this band may be taken to indicate a significant contribution by He II (5-11) to the complex. The cooler stars dispaly the presence of all members of the (5-n) series that fall in the region of the spectrum accessible to the I-N emulsion.

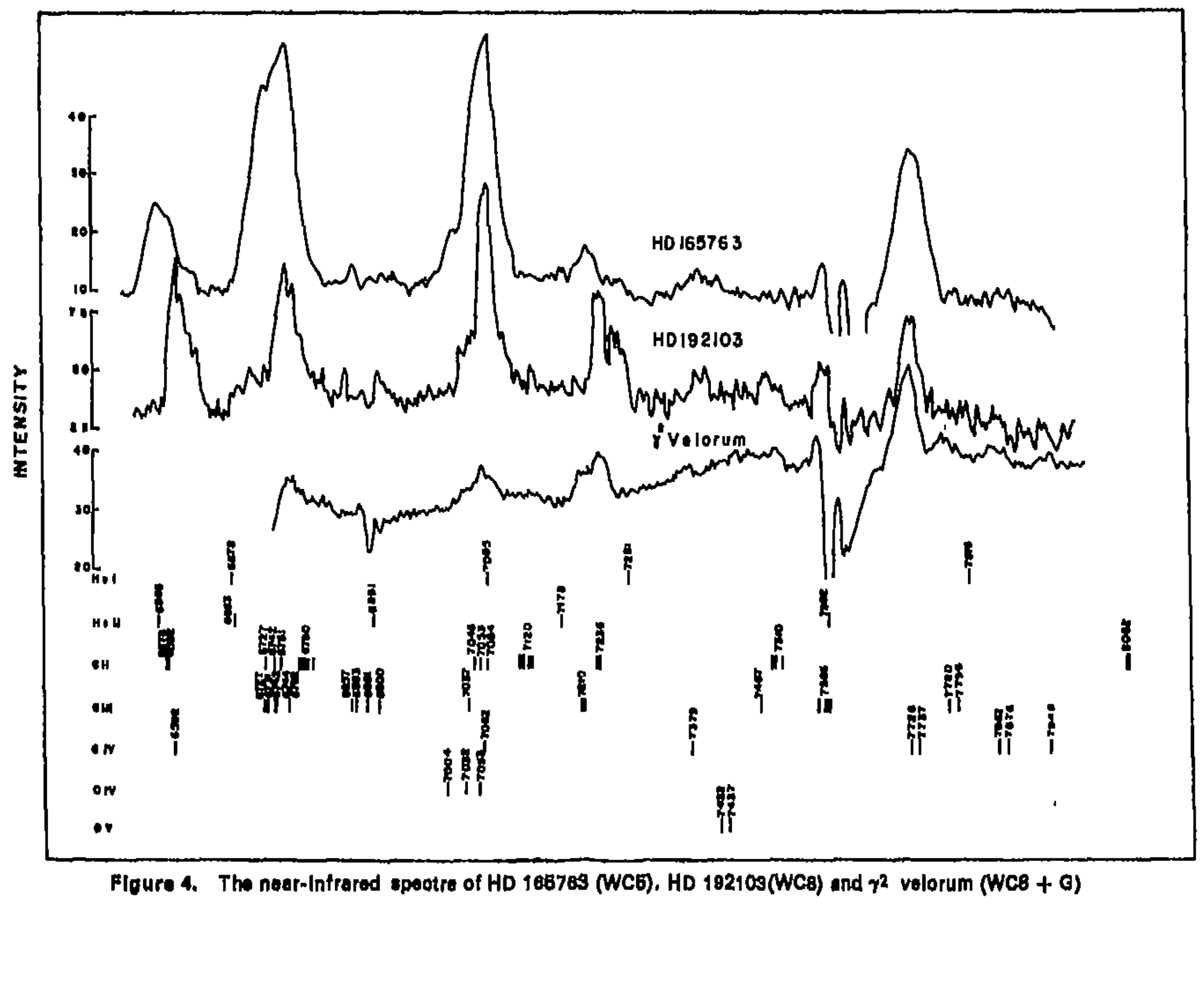

Figure 4. The near-infrared spectra of HD 165763 (WC5), HD 192103(WC8) and γ^2 velorum (WC8 + G)

The contribution by He I to the infrared spectrum of a Wolf-Rayet star is significant but not striking. With the exception of 7065 Å none of the lines at 7281 Å or 8361 Å are of intensity comparable to that of 6678 Å.

A noteworthy feature is the increase in intensity of the continuum as one goes to longer wavelengths in HD 151932. While the curves of Figure I do not represent a spectrophotometric assessment of continuum variation, one can in a qualitative sense say that the continuum of HD 151932 at 8200 Å is much brighter than that at 7000 Å. The comparison with the continuum of a similar spectral type as in the case of HD 92740 or HD 93131 demonstrates the tendency of an " excess " of continuum radiation at 8000 Å in the case of HD 151932. Kuhl (1966) has photoelectrically scanned the continuum of several Wolf-Rayet stars. But his list does not contain any WN 7 star and difficult as it is to extrapolate the energy curves he has derived to that of the later spectral type, there is nothing to suggest the possibility of the " excess " seen in HD 151932. Much the same can be said of the study of Andrillat (1957) where again the coverage of spectrophotometry to type WN 7 is sparse. The problem of the continuum of HD 151932 is best studied with the photoelectric spectrum scanner. It is very possible that we may be witnessing here an " excess " of radiation caused by the presence of a red physical or optical companion. Such a situation has its attractive feature of novelty since all known physical companions of Wolf-Rayet stars are early type stars.

3. The Carbon Sequence

Ionized helium and C II, C III and C IV dominate the spectrum in this wavelength region. Intensity tracings of the three stars we have studied are seen in Figure 4 together with the relevant identifications outlined in Table 2. Our sample of variety in excitation is limited but it has a WC 6 and WC 7 along with the spectrum of HD 68273. The latter typifies the contamination in the continuous spectrum caused by the O companion in the binary system.

The strongest emission features in the region between 6560 Å and 8000 Å are 6747 Å, 7065 Å and 7726 Å. The first two are essentially composite features and hence neither is virtually unblended to a degree wherein the intensity of the feature can be used for a quantitative assessment of the physical conditions in the stellar atmosphere. The feature at 6747 Å is principally a composite of 6742 Å and 6744 Å, both of C III with contributions from C II flanking on either wing. The emission at 7065 Å consists of the (7-9) hydrogenic transition of C VI as the primary feature with appreciable contributions from He I 7065 Å and C II 7064 Å. However, the emission line at 7726 Å is entirely due to the C IV ion. The possible components of this feature are the (6-7) hydrogenic transition of C IV at 7726.54 Å and the (8-11) transition of the same ion at 7736.0 Å. The contribution of the latter to the overall intensity is

Table 2 Wavelength identification in the WC stars

λ	Origin	λ	Origin
6565	He II	7178	He II 7178
6583	C II 6578	7210	C III 7210
	6582		7212
6592	C IV	7235	C II 7231
6609			7236
6678	He I		7237
6683	He II 6683	7282	He I 7281
6729	C II, C III 6727	7379	C IV
	C III 6731	7418	O V 7422
6747	C II, C III 6742		7437
	C III 6744	7488	C III, 7487
	C II 6751	7510	C II 7505
6764	C III 6762		C II 7509
6790	C II 6780		C II 7520
	6783	7586	C III 7577
	6787		7578
	6791		6567
	6801		7592
6857	C III 6857		He II 7592
	6863		C III 7595
6891	C III 6881	7729	C IV 7726
	He II 6891		7737
	C III 6900	7800	C III 7780
7012	O IV 7004		7796
7035	O IV 7032		He I 7816
	C III 7037	7862	C IV 7862
7053	O IV 7053		7876
	C II 7046	7951	C IV 7946
	7063	8062	C II 8062
	7064		8063
7065	C IV 7062	8240	CI V 8236
	C II 7064		He II 8237
	He I 7065	8260	C III 8256
7120	C II 7112		8272
	7113	8300	C III 8297
	7116	8341	C III 8333
	7119		8342
	7126		8348
	7132	8360	C III 8358
	7134		8359
			He I 8362

apt to be small and cannot certainly be evaluated with the dispersion we have used. A higher dispersion study of the profile of this line would be of interest.

Most of the other emission features of low intensity seen on the tracings, are essentially blends of lines of the three carbon ions and the neutral and ionized helium atom. Weak feature at 7120 Å and 7235 Å is of C II while a single feature at 7210 Å is of C III. Ratios of these lines originating from the different ions can be taken as criteria for special classification in this region of the spectrum. The 5-n series of He II can be seen easily but are quite weak and with the exception of 7178 Å (5-11) are blended with lines from the other ions. The exception provides little advantage, however, since the line is very weak in intensity. The helium line at 6678 Å is perhaps the strongest neutral helium line. But its longer wavelength wing is blended with the He II line at 6683 Å. The He I line at 7065 Å is possibly strong but is quite well blended with C IV at 7062 Å.

Perhaps the only line that can be assigned an unique wavelength for radial velocity measures is C IV 7726. It would undoubtedly be advantageous to use this line for the determination of velocity curves for binary stars that have WC components.

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