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'Notches' in the Average Profiles of Bright Pulsars

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ABSTRACT
We discuss the discovery of 'notch-like' features in the mean pulse profile of the nearby, bright pulsar B0950+08. We compare these low-level features with those previously seen in the pulse profiles of pulsars J0437−4715 and B1929+10. While J0437−4715 is a binary millisecond pulsar and B0950+08 and B1929+10 are isolated, slow pulsars, all three pulsars are nearby and very bright. Furthermore, all three have detectable emission over an unusually wide range of pulse phase. We describe the similar properties of the notch features seen in all three pulsars and discuss possible interpretations.

1 INTRODUCTION

Detailed studies of the structure of radio pulsar pulse profiles are essential for understanding the pulsar emission mechanism and the forms of the pulsar emission beam. Pulse profiles are remarkably stable over timescales ranging from a few pulses to many years, indicating that these profiles are determined by permanent physical characteristics of the neutron star and its environment. Many profile properties can be explained very well by the "hollow-cone" model of pulsar emission developed by Radhakrishnan & Cooke (1969) and Komesaroff (1970), shortly after the discovery of the first pulsar. This "magnetic-pole" model, further developed by Sturrock (1971) and Ruderman & Sutherland (1975), involves charges streaming from the polar cap along the open field lines, radiating in the direction of their motion and forming an emission cone aligned with the magnetic axis of the star. As more pulsars were discovered, many were found to have two, three or even more pulse components, prompting various efforts to classify and interpret the various forms (*e.g.*. Backer 1973; Rankin 1983, 1993; Lyne & Manchester 1988).

In this paper we draw attention to the strange double "notches" in the profiles of B0950+08 and two other pulsars, J0437–4715 and B1929+10. All three stars exhibit very similar "double notch" features which appear to have virtually nothing to do with the component structures of their very different profiles. B0950+08 and B1929+10 have rotational periods of 253 and 227 ms, whereas J0437–4715 is a binary millisecond pulsar with a period of only 5.75 ms. Significantly, these stars are some of the very closest among the pulsar population—all with dispersion measures (DMs) of about 3 pc cm^{-3} and parallax-determined distances of some 262±5, 331±10 and 170±3 pc (Brisken *et al* 2000, 2002)—and, in spite of the fact that they all have rather ordinary spindown values, all have been detected in the optical/uv and/or soft x-ray region (Wang *et al* 1997; Mignani *et al* 2002; Zavlin *et al* 2002; Zharikov *et al* 2002; De Luca *et al* 2003; & Kargaltsev *et al* 2004). B0950+08 and B1929+10 are among the brightest pulsars in the radio sky (Taylor *et al* 1993), and J0437–4715 is well known as the brightest millisecond pulsar. In §2 we discuss our observations of B0950+08, present its average profiles and polarization properties, and describe the unusual features. In §3 we compare these features with similar ones seen in the profiles of J0437−4715 and B1929+10 and discuss possible physical interpretations.

2 OBSERVATIONS AND RESULTS

Observations presented in this section were made using the 305-m Arecibo Telescope in Puerto Rico. Observations at 430 MHz were obtained using the Arecibo Observatory Fourier Transform Machine (AOFTM⋆) with 1024 channels across a 10-MHz bandpass and with 409.6-μs sampling. B0950+08 was observed at 430 MHz on MJDs 51182, 51188 and 51189 (4th, 10th and 11th of January, 1999) for durations of 3000, 3700 and 2500 seconds, respectively. The 1475-MHz data presented were acquired with the Wideband Arecibo Pulsar Processor (WAPP†) with 64 or 128 channels across a 100-MHz bandpass and 256-μs sampling. Observations of B0950+08 at this frequency were carried out on MJDs 52187 and 52189 (5th and 7th of October, 2001) for durations of 1100 and 7200 seconds, respectively, as well as polarimetrically on MJD 52854 (3rd August 2003) using four 100-MHz bands between 1220 and 1625 MHz. The new polarimetric observations of B1929+10 were also carried out with the AO WAPP in a similar fashion on MJD 53028 (24th January 2004). Here

⋆ http://www.naic.edu/∼aoftm
† http://www.naic.edu/∼wapp

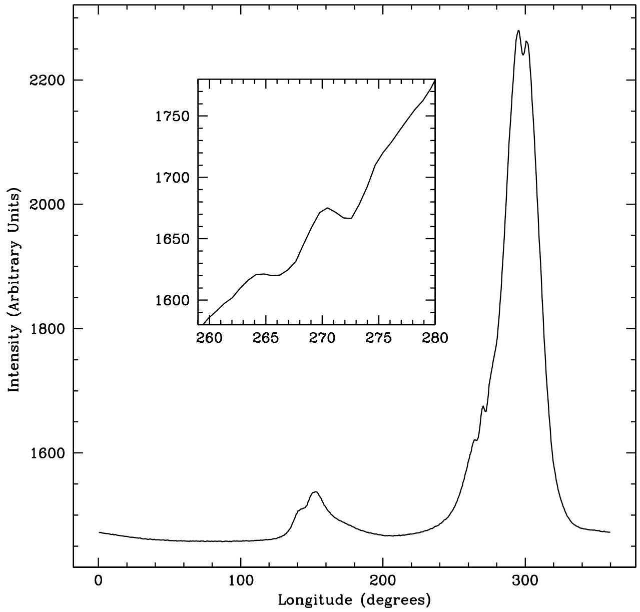

Figure 1. Pulse profile for B0950+08 observed on MJD 51188 at 430 MHz for a total duration of 3700 s. A bandwidth of 10 MHz and sampling time of 409.6 μs were used. Data were folded using 512 bins across the pulse period of 253 ms. The "notch" pair at about 270° longitude is also shown on an expanded scale in the inset panel. Identical features with the same morphology and phase were seen at this frequency in observations on MJDs 51182 and 51189.

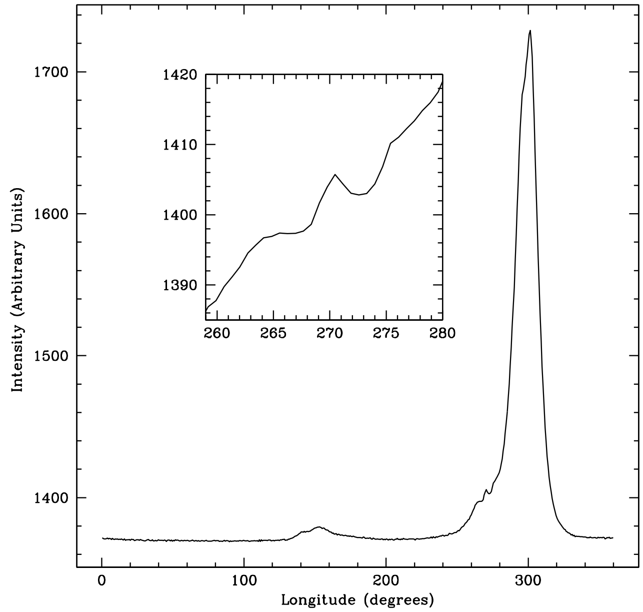

Figure 2. Pulse profile for B0950+08 on MJD 51189 at 430 MHz for a total observation length of 2500 s as in Fig. 1. Note that while this profile and the foregoing one have very different forms, their "notch" pairs fall at precisely the same longitude (see text).

the Stokes profiles reflect only a preliminary calibration of the measured correlation functions, being corrected for differential instrumental phase, Faraday rotation across the passband and parallactic angle, but not instrumental cross-coupling.

For each B0950+08 observation, pulse phases were calculated using the software package TEMPO[‡] (Taylor & Weisberg 1989) and an ephemeris obtained at Jodrell Bank Observatory (Hobbs 2002). Data were folded to create mean pulse profiles. The up-to-date ephemeris allowed alignment of the profiles acquired on different dates and at different frequencies. The 430-MHz average profiles for the MJD 51188 and 51189 observations are presented in Figs. 1 and 2. Remarkably, the two profiles are distinctly different in overall form, perhaps indicating a type of long-term mode-changing. The low-level features, however, are seen at just the same $-30°$ longitude before the main pulse (MP) peak. Moreover, a similar pair of features is seen in the MJD 51182 data (not shown).

In Fig. 3 we present a corresponding 1475-MHz profile for the MJD 52189 observation, where again a low-level feature is seen at some $-30°$. At 430 MHz the feature consists of two dips in the profile intensity with half widths of some 2° and their centers separated by some 7°. The total width of the feature at 430 MHz is 11°. At 1475 MHz—in both this observation and another (not shown) on MJD

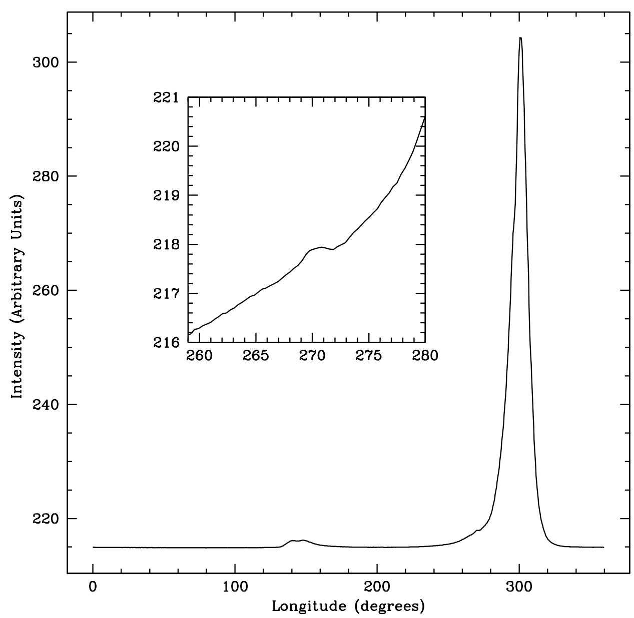

Figure 3. Pulse profile for B0950+08 at 1475 MHz on MJD 52189 for a total observation length of 7200 s. A bandwidth of 100 MHz and sampling time of 256 μs were used, and the data were folded using 1024 bins. The "notch-pair" feature at 270° longitude is barely apparent on the full scale but somewhat more so on the expanded scale of the inset panel. An identical "notch" feature with the same morphology and phase was seen on MJD 52187.

‡ `http://pulsar.princeton.edu/tempo`

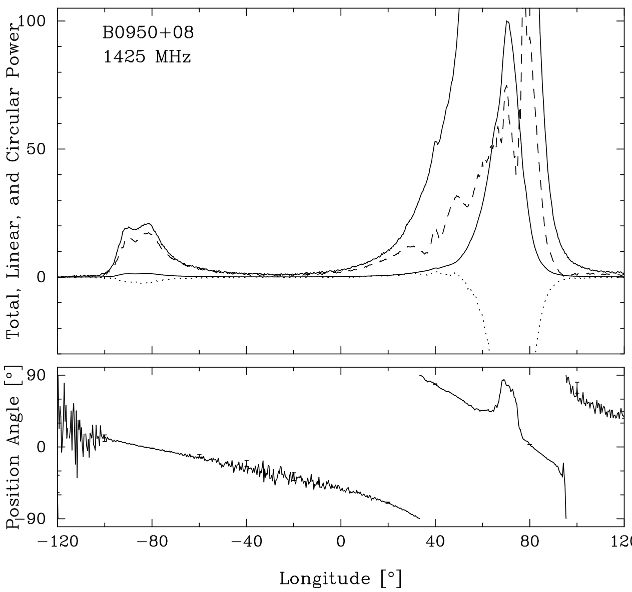

Figure 4. Polarized pulse profile for B0950+08 at 1425 MHz on MJD 52854 for a total duration of 1800 s. In the top panel the total power (Stokes I) is first plotted at full scale, and then Stokes I, L $(=\sqrt{(Q^2+U^2)})$ and V are shown at $\times 15$ scale. The "notch-pair" feature, here at $+40°$ longitude, is again barely apparent in total intensity. However, the "notches" are very clearly seen in the linearly polarized power, Stokes L, and seem also to slightly deflect the linear position angle ($\chi = \tan^{-1} U/Q$) given in the lower panel. A bandwidth of 100 MHz and sampling time of 256 μs were used, and the data were folded using 988 bins. Similar "notch" features were observed in other 100-MHz bands between 1100 and 1600 MHz.

52187—the feature appears as a single peak with a width of 3°.

Interestingly, the 21-cm features are much more clearly seen in the total linear polarization. In Figure 4 we see the "notch" features at a longitude of about $+40°$ where the fractional linear polarization is only some 20%. Their separation appears to be about the same as at 430 MHz, but their depth is some 20-25% of the linear power. Note also the very slight decreases of the polarization angle at the "notch" positions, and while these deflections are only a degree or so they are clearly well determined in terms of the systematic errors.

Several published observations also appear to record the B0950+08 "notches". They are very clear in the 430-MHz time-aligned profile of Hankins & Rankin (2004), but cannot be discerned in the lower quality observations at various other frequencies. Moreover, the "notches" can probably be seen in the polarimetric observations of both Gould & Lyne (1998) and Weisberg *et al* (1999). The former very high quality profiles seem to show pairs of features at the correct phase at 408, 610 and 925 MHz, and in the latter we appear to see a *pair* of features at 1418 MHz. This latter observation (see their Fig. 5) is especially interesting because the features appear to involve the linear polarization also—just as we saw above—which is again 20–30% in the region on the far leading edge of the profile.

It must be said that the total power features in B0950+08 are rather weak, at best reducing the intensity at their centers by a few percent. It might even be regarded as surprising that such features would be found in a star which is well known for its sporadic emission (It may not be known, for instance, whether the pulsar ever nulls, because the dynamic range of intensities exhibited by its pulses is so large.) In this context, it is very interesting that Nowakowski *et al* (2003) have shown that this pulsar's profile is comprised of different intensity fractions which have quite different partial-average profile forms. These studies indicate that the MP has three main "components": the trailing one which is usually strongest, the middle one which varies in relative intensity, and a leading one which can only be discerned in certain populations of weak pulses. It would therefore appear that the distinct 430-MHz profiles seen above represent distinct profile "modes" in this star. Finally, the above study finds that the "notches" are seen only in the very weakest populations of pulses, which nonetheless contribute significant power to the profile. This leading MP emission is also associated with a trailing "component" of IP emission which is completely linearly polarized; this suggests that the MP radiation which becomes "notched" is similarly highly polarized and perhaps explains why the 21-cm "notches" are more easily discerned above in the linear polarization. The above authors believe that the weakest pulses represent emission from higher altitudes than the stronger fractions.

3 DISCUSSION

Unusual features similar to those presented in §2 have been observed in two other pulsars. Rankin & Rathnasree (1997) reported a double notch-like feature in the average profile of B1929+10 at 430 MHz, and a display similar to theirs using the same observations is given in Fig. 5. As can be seen there, the "notches" follow the main pulse peak by roughly 100° and have a total width of approximately 10°. More accurate scaling reveals that they have widths of some 2.3° and that their centers are separated by just twice this interval. Note also that B1929+10's profile is generally fully linearly polarized, so that the features are most clearly seen in both the total power and total linear polarization[§]—where they represent about a 40% diminution of the power at their centers—but here we see no discernible effect on the position angle. The "notches" do appear to be just visible in a sensitive 430-MHz observation of Blaskiewicz *et al* (1991: see their Fig. 22), though they are not seen at 1.4 GHz either in this paper or in Rankin & Rathnasree. This may be due to the overall weakening of the broad low-level emission feature that follows the MP as well as the poorer signal-to-noise of their 21-cm observations. Neither, unfortunately, were

§ The possible origin of this strange "superpolarization", that was also seen by Phillips (1990), is discussed in Rankin & Rathnasree (1997). Phillips, however, seems to have plotted his Figs. 1 & 2 with some unreported smoothing, so that the "notches" are not visible, though there is a broad dip in the power just were they should be.

the recent observations of Weisberg *et al* (2004) sufficiently sensitive to detect the features.

We are then pleased to report the first detection of B1929+10's "notches" at above 1 GHz. Figure 6 gives a full period polarimetric display at 1170 MHz similar to that for 430-MHz in the foregoing figure. Here, we see a much weaker emission feature following the MP and a somewhat weaker pair of "notch" features within it (also virtually no IP "shoulder"). Interestingly, the "notch" pair seems to be slightly earlier at this higher frequency (relative to the MP central core component) and the two "notches" slightly closer together, though there is no evidence (at either frequency) of any effect on the polarization angle.

Similar features have also been observed by Navarro *et al* (1997) in the average profile of the millisecond pulsar J0437−4715. These "notches" fall on the trailing edge of this star's very broad profile, some 70° after the bright central component. Here, the pair is separated by about 3.3°, the half-power widths are about a degree, and the fractional intensity decrease at their centers is about 50%. These characteristics are clearly seen in the 1512-MHz polarization profile of Navarro *et al* (their Fig. 4) which we reproduce here as Fig. 7. However, this paper reports additional detections at frequencies of 438 and 660 MHz, and the three total-power profiles appear together in our Fig. 8, aligned (according to their Fig. 5 caption) on the basis of the anti-symmetric circularly polarized signature associated with the central component. One can see that the "notches" at the three frequencies do not quite align, falling slightly earlier at 660 and 1512 MHz. However, were the profiles aligned more nearly according the the centroids of the central component, the "notches" might well fall at just the same profile phase. It would be interesting to see the results of a timing alignment as carried out for B0950+08 above. Finally, the features do appear to exhibit some spectral evolution, becoming wider and more separated at lower frequencies.

It is noteworthy that, for all three pulsars, these unprecedented features appear at almost exactly the same longitude in all epochs and bands, and have roughly the same forms and angular widths—thus implying that their overall scale is some nearly fixed fraction of the rotational cycle of the star. Such spectral width constancy is reminiscent of pulsar microstructure (*e.g.*, Popov *et al* 2002), perhaps suggesting that the two phenomena have some physical connection in the pulsar magnetosphere.

B0950+08 and B1929+10 have remarkably similar properties. Both are very bright, have quarter-second rotational periods, and are very nearby. Both pulsars have detectable emission over an unusually broad fraction of their rotation cycle and both exhibit interpulses. With a rotation period of 5.75 ms, J0437−4715 has very different spin-down properties; however, it is also nearby, extremely bright, and, while it has no interpulse, it has detectable emission over more than 180° of longitude.

The identification of these features in the three brightest pulsars with broad pulse profiles suggests that such features may be common among pulsars with broad profiles. As they are apparently seen over a substantial portion of the

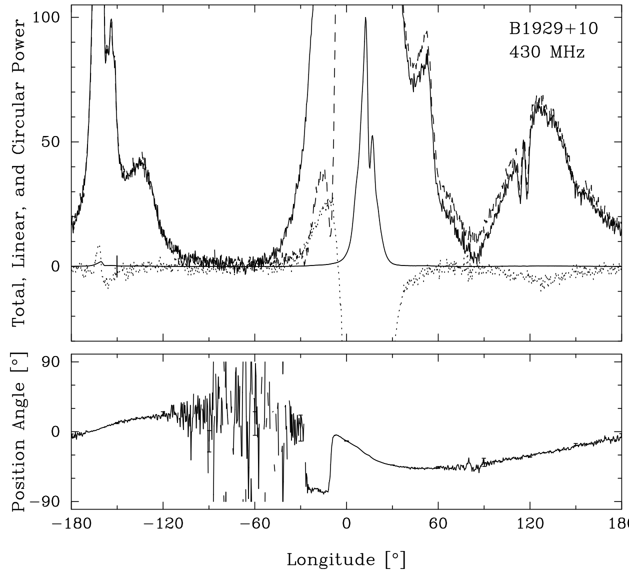

Figure 5. Full-period average polarization profile of B1929+10 at 430 MHz after Rankin & Rathnasree (1997). The total power (Stokes I) is plotted first at full scale and then at a ×250 expanded scale, so that only features below 0.4 percent of the MP amplitude are now visible. The linear (L) and circular (V) polarization are then plotted at the expanded scale. The PA is plotted in the lower panel. Note the double "notch" feature which follows the MP by about 100°. This region exhibits complete linear polarization (see text), so the "notches" are clearly visible in both I and L, representing an intensity decrease at their centers of some 40%.

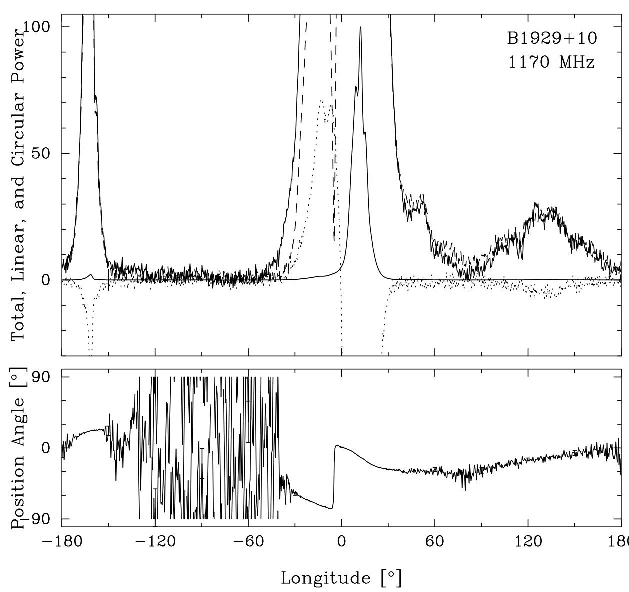

Figure 6. Full-period polarization profile of B1929+10 at 1170 MHz as in Fig. 5, again with a ×250 expanded scale. Here we see a much weaker emission feature following the MP and somewhat weaker "notch" features within it. Careful alignment of the two B1929+10 profiles show that the "notches" fall slightly earlier at the higher frequency and are slightly more closely spaced. It is not clear whether from the two diagrams whether there is any diversion of the polarization angle.

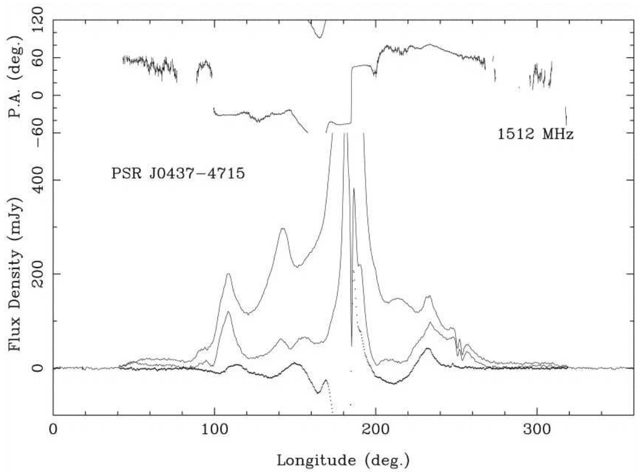

Figure 7. Polarized pulse profile for J0437−4715 at 1512 MHz from Navarro *et al* (1997); their Fig. 4.

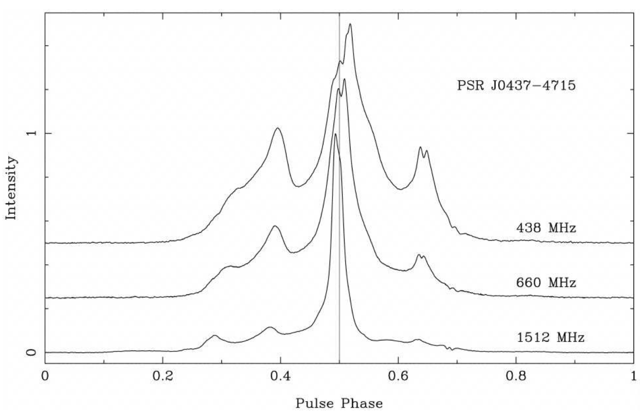

Figure 8. Total-intensity profiles for J0437−4715 at 438, 660 and 1512 MHz, which have been aligned according to the zero-crossing point of the anti-symmetric circular polarization under their central components from Navarro *et al* (1997); their Fig. 5. Note that the "notches" almost align—and that they could even do so more closely if only a slightly different alignment had been used.

radio band and evolve little with frequency, it would seem that they cannot be attributed to absorption in any usual sense. Thus it would seem that they are either due to some very puzzling aspect of the emission process or represent an equally puzzling obscuration of the emission along our sight line. While we cannot more than speculate about the causes of these features, a very novel mechanism is being suggested by Wright (2003) in a companion paper, based on the unique geometric properties of a coherently-radiating magnetosphere. Clearly, few pulsars show emission so far from the main pulse or interpulse, so observing this feature in more pulsars will be very difficult until the advent of more sensitive pulsar instruments such as the SKA. However, future more sensitive multi-frequency observations of the pulsars discussed above may yield more clues as to the origin of these unusual features.

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