Revista Mexicana de Astronomía y Astrofísica, **42**, 291–297 (2006)

SEARCHING FOR BALMER SELF-ABSORPTION IN PLANETARY NEBULAE

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Received 2006 January 15; accepted 2006 July 1

RESUMEN

Analizamos la distribución de 482 nebulosas planetarias (NP's) en los planos $H\alpha/H\beta$–$H\gamma/H\beta$ and $H\delta/H\gamma$–$H\gamma/H\beta$. Mientras que la mayoría de las fuentes parecen tener cocientes de línea caso B, y decrementos normales de su desenrojecimiento, algunas parecen estar afectadas por auto-absorción Balmer. Hemos identificado 9 casos posibles, y 11 ejemplos probables donde tal absorción es importante. Aproximadamente la mitad de estas nebulosas son compactas y probablemente jóvenes.

La mayoría de las identificaciones previas de auto-absorción son dudosas, y no hay coincidencia entre nuestros candidatos y los de análisis anteriores.

ABSTRACT

We analyse the distribution of 482 planetary nebulae (PNe) within the $H\alpha/H\beta$–$H\gamma/H\beta$ and $H\delta/H\gamma$–$H\gamma/H\beta$ planes. Whilst most sources appear to possess case B line ratios, and normal reddening decrements, certain of them also appear to be affected by Balmer self-absorption. We are able to identify 9 possible cases, and 11 probable examples where such absorption is important. Approximately half of these nebulae are compact, and probably quite young.

Most previous identifications of self-absorption are shown to be open to doubt, and there is no overlap at all between our present candidates, and those of previous analyses.

Key Words: **ISM: JETS AND OUTFLOWS — PLANETARY NEBULAE: GENERAL**

1. INTRODUCTION

Balmer line intensities in planetary nebulae are usually determined by assuming that Lyα optical depths are high, and that case B conditions prevail. This leads to ratios $H\alpha/H\beta$, $H\gamma/H\beta$, and so forth, which are only weakly dependent upon density and temperature. However, these ratios may change appreciably where level 2^2S populations are large, and $H\alpha$ optical depths are appreciable. Under these circumstances, whilst $H\alpha$ intensities would remain relatively unchanged, those of $H\beta$ and $H\gamma$ may vary quite appreciably. The self-absorption of $H\beta$ photons leads to their transformation into $P\alpha$ and $H\alpha$, and similar processes apply for $H\gamma$ as well.

Where shell $H\alpha$ optical depths are large, therefore, then the ratios $H\gamma/H\beta$, $H\alpha/H\beta$ and $H\delta/H\gamma$ are all expected to increase. Analyses of this mechanism have been published by Cox & Mathews (1969), Capriotti (1964a, 1964b) and Netzer (1975).

The evidence for such variations is relatively meager, although it has been claimed that self-absorption is present in the sources M 1−2 (also known as VV8: see Adams 1975; Barker 1978; Ahern 1975, 1978; Gurzadyan 1997); M 3−27 (Adams 1975; Gurzadyan 1997; Barker 1978; Ahern 1975, 1978); M 1−67 (Gurzadyan 1997); V1016 (Ahern 1975, 1978; Gurzadyan 1997); IRAS 18062−2410 (Arkhipova et al. 1999); MWC 17 (Liebowitz 1977); He 2−467 (Kaler & Lutz 1980); Hb 12 (Barker 1978); IC 4997, Hu 1−2 and Vy 2−2 (Ahern 1975, 1978); NGC 7027 (Miller & Mathews 1972); M 2−9 (Balick 1989; Calvet & Cohen 1978); and M 1−91 (Calvet & Cohen 1978). Most (if not all of these) outflows appear to be dense, compact, and/or have compact cores.

The compilation of line intensities by Kaler et al. (1997) permits us to expand upon this work. We shall find, as a result, that as many as 20 PNe may display Balmer self-absorption. None of these correspond to previously detected sources. Indeed, we shall suggest that most prior claims of self-absorption may be open to doubt, and a consequence of errors in the results.

2. OBSERVATIONAL DATA BASE, AND THEORETICAL TRENDS

We have, for the following analysis, used Balmer line intensities for 482 PNe culled from the Emission Line Catalog of Kaler et al. (1997). All of these measures refer to the centers of the nebulae, or were taken with apertures centered upon the nuclei of the outflows. Procedures for dereddening these results are often inconsistent, and may also be unreliable. The presence of self-absorption, in particular, may lead to anomalous results. We have therefore preferred to employ the original (reddened) line intensities where at all possible.

Multiple values of the line ratios are available for certain better known sources. Thus, some 79 spectra are listed for NGC 7027 alone, based upon 67 series of spectroscopic results. Of these, only 7 of the spectra are not extinction corrected, are centered upon the nebular core, and also measure all three of the principal Balmer transitions. Although the total number of spectra in this catalog is therefore very large indeed, only a very small fraction are of use for the purposes of our analysis.

In the few sources where such multiple measurements are available, we have taken what seem the most reliable (and typical) of the results. An analysis of the distributions of line ratios for individual objects suggests a scatter similar to that which will be noted below. We therefore conclude that the selection of individual (and representative) sets of ratios has no impact upon our discussion – it does not lead to skewing of the mean Balmer decrement, or any misidentification of likely self-absorbed nebulae.

The resulting ratios are illustrated in Figs. 1 and 2, where we show their variation within the $H\alpha/H\beta$–$H\gamma/H\beta$ and $H\delta/H\gamma$–$H\gamma/H\beta$ planes. We also show the theoretical trends predicted through the modeling of Capriotti (1964a, 1964b), where ratios vary as a function of outflow shell thickness (outer radius/inner radius), and $H\alpha$ optical depth. The more extended of these curves (with filled bullets representing the models) corresponds to self-absorption by atoms in the 2P state, whilst the shorter curve (+ symbols) is for atoms in the 2S state. The results are closely similar to those of Cox & Mathews (1969), but extend over a broader range of line ratios.

Finally, the diagonal solid lines represents the effect of IS extinction, and are determined using the standard IS reddening curve of Whitford (1958). This fits the data extremely well, and appears to be more representative than certain other curves in the literature (such as those of Savage & Mathis 1979; Pottasch 1984; or Cardelli et al. 1989). The upper left-hand limits of the lines correspond to non-reddened sources having densities $n_e = 10^4$ cm^{-3}, and temperatures $T_e = 10^4$ K. They are based upon the case B analysis of Hummer & Storey (1987). Variations in density from 10^2 through to 10^6 cm^{-3} cause little change to these ratios, and no discernible change to Figs. 1 & 2. Increasing extinction causes PNe to travel towards the lower right hand sides of the graphs.

Finally, the flanking dashed lines indicate the primary scatter regime – the region within which most of the measurements appear to be confined.

Several points are worth making. In the first place, the reddening variation in Fig. 2 is almost exactly opposed to the trend for self-absorption. This is not very helpful, and means that the effects of self-absorption are often masked by IS reddening. Nevertheless, two sources (A 65 and M 1−59) are located outside of the reddening regime, and represent strong candidates for self absorption. Various other PNe also extend into the regime of self-absorbed modeling, and are located in the range $-0.235 > log(I(H\gamma)/I(H\beta)) > -0.329$. Most of these are affected by errors in the results, however – they extend over a range comparable to the dispersion in $H\gamma/H\beta$.

A further point of interest concerns Fig. 1. It will be noted that the scatter about the reddening trend is quite appreciable, and encroaches upon a part of the graph in which self-absorption would be expected to occur – the regime, that is, which lies above the reddening locus.

The scatter in the results, which extends ~ 0.16 dex on either side of this line, is a consequence of observational errors in both of the axial ratios. However, the mean size of this scatter is very much less. If most of the uncertainty is assumed to apply to the $H\gamma/H\beta$ ratios, then we find that typical errors would be of order $\Delta(\mathrm{I(H\gamma)/I(H\beta)}) \sim 15\%$. Such a value is broadly consistent with quoted observational uncertainties. Acker et al. (1991), for instance, note that weaker transitions (such as $H\gamma$ and $H\delta$) may be uncertain by as much as $\sim 30\%$, whilst errors for

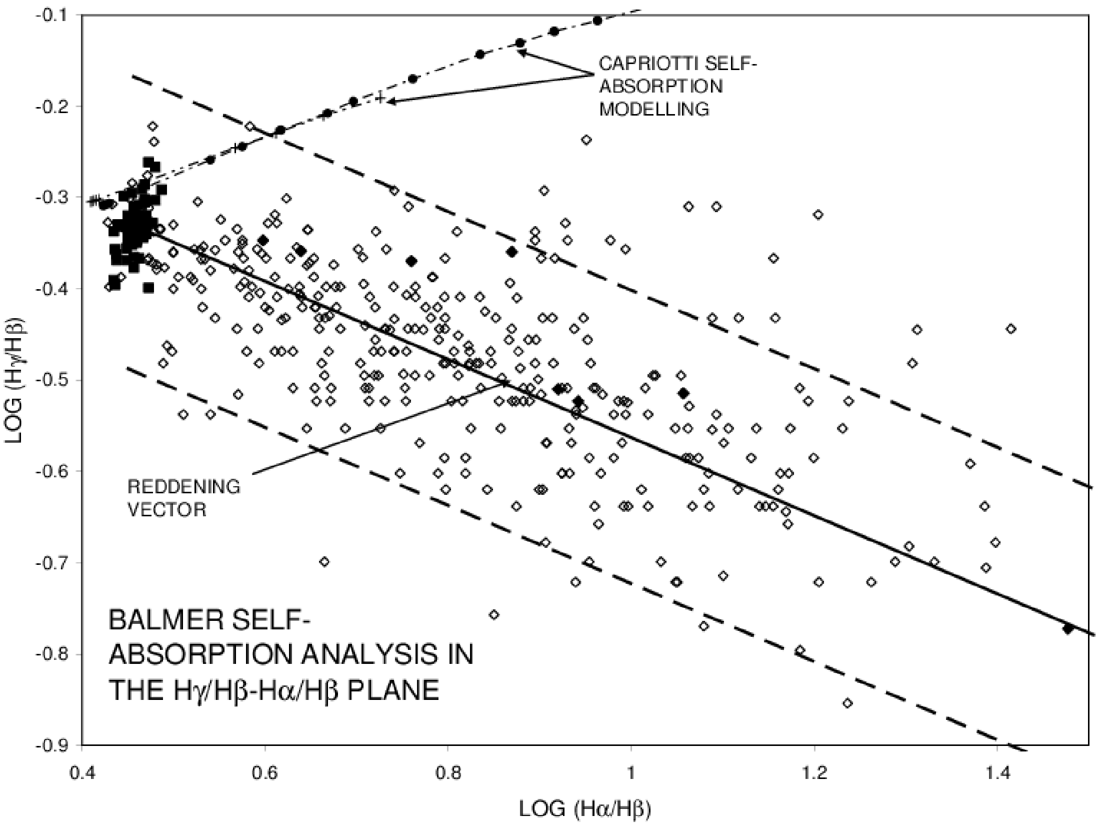

Fig. 1. The distribution of nebulae within the $H\alpha/H\beta - H\gamma/H\beta$ plane. The Capriotti (1964a,b) models of self absorption are represented by the upper-most curves, where each point corresponds to differing values of shell thickness (outer radius/inner radius) and $H\alpha$ optical depth. Reddened PNe are indicated by open lozenges, and de-reddened values by filled squares. Finally, sources which been previously identified as self-absorbed are indicated by filled lozenges. The solid diagonal line corresponds to the reddening vector (increased reddening to the lower right), whilst dashed lines delimit the primary scattering regime – the regime within which observational errors cause errors in the ratios. Most of the sources lying above the upper dashed line are probably self-absorbed.

the brighter lines are $\sim 5\%$. Similar uncertainties are quoted by other authors.

3. THE EVIDENCE FOR AND AGAINST SELF-ABSORPTION

It is apparent, for Fig. 1, that there are 32 more sources above the reddening line than are located below it. This might, at first sight, be taken to represent evidence for self-absorption, and suggest that whilst individual cases may be difficult to identify, some $\sim 7\%$ of PNe are affected by this mechanism. Such a conclusion would be premature, however, and is unlikely to be reliable. The excess of sources is not too much different from what is expected from statistical fluctuations alone. Similarly, the size of the disparity depends upon the reliability of the reddening curve – a shift one way or the other can affect the overall source statistics.

The size of scatter also has other serious consequences. The sources in which self-absorption has been detected previously are represented by the filled lozenges in Fig. 1. It will be noted that none of these sources are located outside of the dashed lines, and that they have a scatter comparable to those of other sources in this study. In addition, two of the nebulae are actually located on the reddening line itself, although one of these is obscured by the de-reddened nebulae (indicated by solid squares). It is therefore probable that many of these cases are quite normal, and possess case B emission. The suggestion that they are self-absorbed may be a result of observational error – and a failure to realize the degree of uncertainty to which such observations are prone.

Before we leave this question, however, it is important to investigate one further (and possibly ameliorating) factor. Many previous cases of self-

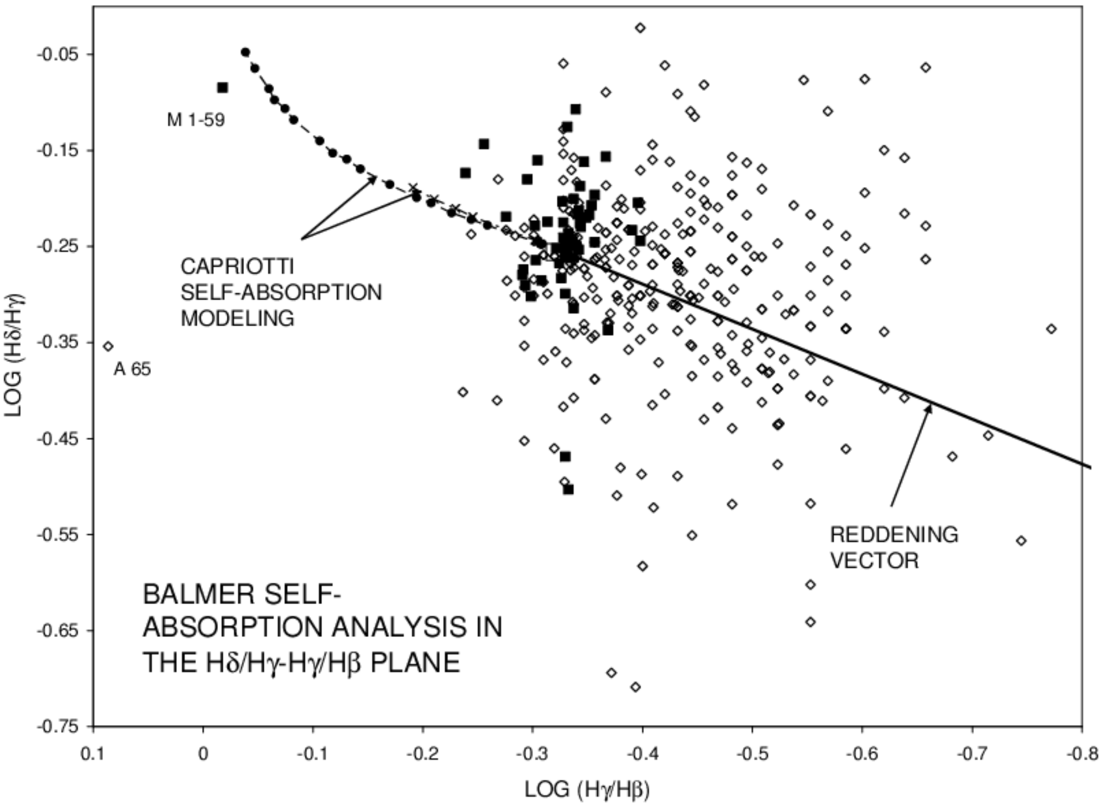

Fig. 2. As for Fig. 1, but for the $H\delta/H\gamma{-}H\gamma/H\beta$ plane. In this case, reddening and self-absorption lead to opposing trends, and it is possible that various extincted, self-absorbed nebulae are located on the right hand side, towards lower values of $H\gamma/H\beta$.

absorption appear to be associated with physically compact sources and/or cores. The typical surface brightness of these sources are therefore expected to be large – larger, certainly, than is the case for more evolved (and equivalently reddened) outflows.

Given that this is so, then one might expect that these sources might show a lesser degree of scatter – that their higher surface brightnesses lead to smaller errors in the line ratios, and less dispersion than is evident in Fig. 1.

This, if it is the case, may mean that where compact sources are located above the reddening curve, then there is a greater chance that we are measuring a real effect, rather a simple error in the results.

Such a presumption can be checked. To do so, we have analyzed PNe with 5 GHz brightness temperatures T_B greater than 50 K. This has several advantages. High T_B sources tend to have large visual surface brightnesses, and compact physical dimensions (see e.g. Phillips 2004). One is therefore considering a similar subset of outflows to the "self-absorbed" sources above. The sample should also have a reduced level of scatter in the $H\alpha/H\beta{-}H\gamma/H\beta$ plane, and permit the self-absorbed sources to stand out – to show that they really are different from the commonality of PNe.

One further advantage of this procedure is that there are many estimates of T_B currently available, and we have used the compilation of Zhang (1995) in the present analysis.

We find that the scatter of higher T_B sources is indeed reduced. The bad news, however, is that the self-absorbed sources are again unexceptional, and would appear to have similar Balmer ratios to those of other PNe. Similar conclusions arise where one also analyses samples with higher T_B, such as say $T_B \geq 200$ K, or $T_B \geq 1000$ K.

Although this is disappointing, there are various sources which do stand out from the crowd. Three examples (not shown in Fig. 1) are likely to be in error. M 1−28 and Pe 1-11 have values $H\gamma/H\beta$ in excess of 1.19 (Acker et al. 1991); esti-

TABLE 1

POSIBLE AND PROBABLE SELF-ABSORBING PLANETARY NEBULAE ANALYSIS IN THE $H\alpha/H\beta$–$H\gamma/H\beta$ PLANE

Source	PNG	DIAM arcsec	T_b(5GHz) K	$H\gamma$[c]	$H\alpha$[c]	SELF ABS	REF.
M 3−19	000.4−02.9	7	10.67	51	803	PROB	1
H 1−15	001.4+05.3	4.3	49.69	46	785	POSS	1
M 2−26	003.6−02.3	9	4.36	45:	852	POSS	1
KFL 6(SS 122)[a]	003.7−02.7	–	–	35.9	2053	PROB	2
M 3−13	005.2+04.2	–	–	36	2600	PROB	1
H 2−44	005.5−04.0	–	–	58:	893	PROB	1
TH 4−1	007.5+04.3	–	–	37	1310	POSS	1
M 2−34	007.8−03.7	–	–	45:	949	POSS	1
MaC 1−4	007.9+10.1	–	–	47	847	POSS	1
TH 4−4[b]	008.0+03.2	–	–	37	1437	POSS	1
M 1−59	023.9−02.3	4.8	331.3	96	–	PROB	3
M 2−53	104.4−01.6	20	1.94	45	785	POSS	4
He 2−111	315−00.3	12	35.83	44	986	PROB	5
Pe 1−5	333.4+01.1	11	114.5	37	1226	POSS	5,6
M 3−38	356.9+04.4	1.8	458.1	49:	1239	PROB	1
M 3−41	357.3+03.3	4.2	300.5	49	1155	PROB	1
M 3−8	358.2+04.2	2.9	168.1	43	1431	PROB	1
H 1−19	358.9+03.4	1.4	937.6	33	2028	POSS	1

[a]Not found in the Catalogues of Kohoutek (2001) or Acker et al. (1989).

[b]Designated as a possible PNe in Kohoutek (2001).

[c]Intensities relative to $H\beta = 100$. Intensities flagged with a colon are particularly weak, and susceptible to error.

References to Table 1. 1. Acker et al. (1991); 2. Costa & de Freitas Pacheco (1994); 3. Razmadze (1961); 4. Kaler et al. (1990); 5. Acker et al. (1989); 6. Gutierrez-Moreno et al. (1994).

mates which place them well outside of the trends for self-absorbed outflows. Similarly, M 1−72 has a ratio $I(H\gamma)/I(H\beta) \simeq 0.07$ which is extraordinarily low, even given the steepness of the decrement between $H\alpha$ and $H\beta$ ($I(H\alpha)/I(H\beta) \simeq 58.9$; Acker et al. 1989). It would be difficult to explain this in terms of normal physical mechanisms.

These values are clearly worrisome, and should be independently confirmed.

Apart from these three, however, it is clear that whilst 7 sources lie below the lowermost dashed line, fully 19 nebulae are above the upper dashed line – and it is precisely in this latter regime where self-absorption is expected to occur. We propose that most of these latter sources (of order ∼ 63%) are self-absorbed, although a fraction may represent cases of observational error. These sources are listed in Table 1, and designated as being "possible" or "probable" according to their height above the line. The two self-absorbed nebulae in Fig. 2 are listed in Table 2. One of these (M 1−59) is common to both lists.

4. THE CANDIDATE SOURCES

We have listed possible and probable cases of self-absorption in Tables 1 & 2, as described in Sect. 2. We have also summarized details of line ratios and radio brightness temperatures.

Several characteristics are of interest. Firstly, many of the sources appear to be reasonably extended, and greater than 5 arcsec in size. Second, the brightness temperatures represent a mixed bag of values, and only half can be regarded as high, or moderately high. Both of these factors together suggest that many of these outflows may be moderately evolved.

TABLE 2

PROBABLE SELF-ABSORBING PLANETARY NEBULAE ANALYSIS IN THE $H\delta/H\gamma$–$H\gamma/H\beta$ PLANE

Source	PNG	DIAM arcsec	T_b(5GHz) K	$H\delta\lambda$ 4102[b]	$H\gamma\lambda$ 4304[b]	REF.
A 65	017.3−21.9	104	0.03	54	122	1
M 1−59	023.9−02.3	4.8	331.3	79[a]	96[a]	2

[a]Results corrected for extinction.

[b]Intensities relative to Hβ = 100.

References to Table 2. 1. Perinotto et al. (1994); 2. Razmadze (1961).

The characteristics of most of these nebulae are ill-defined, although two of the sources (M 1−59 and He 2−111) correspond to Type I bipolar outflows (e.g. Maciel & Chiappini 1994; Kingsburgh & Barlow 1994; Meaburn & Walsh 1989). The nature of KFL 6 is rather uncertain (it is not found in the catalogues of Kohoutek (2001) or Acker at al. (1992)), whilst Th 4−4 is only listed as a possible PNe (Kohoutek 2001).

Finally, it is worth noting that He 2−111 is particularly unusual, and that its violent kinematics and unusual abundances have resulted in a broad range of studies (see e.g. Pottasch et al. 2000; Meaburn & Walsh 1989, & references therein). It has even been proposed that it may not be a planetary nebula at all (Kohoutek & Pauls 1985; Webster 1978), although much other evidence appears to confirm this designation. Kingsburgh & Barlow (1994) suggest that it is a particularly extreme example of the Type I phenomenon, although they find de-reddened Balmer ratios which are relatively normal. By contrast, the anomalous nature of these ratios is confirmed by Gutierrez-Moreno et al. (1994, 1995), although it seems that they have difficulty in attributing them to Balmer self-absorption. They prefer, rather, to think in terms of internal nebular extinction – although it is clear that any such reddening would have to be very unusual indeed.

One "possible" self-absorbed source, H 1−15, has also been observed by Cuisinier et al. (2000). Their Balmer ratios are much more normal, and suggest that it may require removing from Table 1. Similar comments apply to Th 4−4 as well, which has also been observed by Kondratyeva (1989).

We therefore conclude that analyses in the $H\alpha/H\beta$–$H\gamma/H\beta$ and $H\delta/H\gamma$–$H\gamma/H\beta$ planes may be very useful for identifying self-absorbed sources. Although certain of our identifications will undoubtedly fall by the wayside (viz. the possible cases of H 1−15 and Th 4−4 cited above), the majority are likely to prove valid. In any case, further spectroscopy of these nebulae would be of considerable interest.

5. CONCLUSIONS

The distribution of PNe in the $H\alpha/H\beta$–$H\gamma/H\beta$ and $H\delta/H\gamma$–$H\gamma/H\beta$ planes is useful for identifying possible cases of Balmer self-absorption. It has been used, previously, to identify some 14 such outflows.

We have undertaken a new analysis of 482 PNe, and find that most previous identifications of this phenomenon are likely to be doubtful – that the line ratios for the sources fall within the normal error range.

Certain other sources, however, are clearly located outside of the scatter range, and we have identified 9 possible, and 11 probable examples of this phenomenon. Approximately half of the nebulae have small angular sizes, and appear to have high radio brightness temperatures TB. It is therefore possible that they are both compact and young. Further confirmatory observations would be of considerable interest.

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