KNOTS IN THE OUTER SHELLS OF THE PLANETARY NEBULAE IC 2553 AND NGC 5882

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ABSTRACT

We present images and high-resolution spectra of the planetary nebula IC 2553 and NGC 5882. Spatiokinematic modeling of the nebula shows that they are composed of a markedly elongated inner shell and of a less aspherical outer shell expanding at a considerably higher velocity than the inner one. Embedded in the outer shells of both nebulae are found several low-ionization knots. In IC 2553, the knots show a point-symmetric distribution with respect to the central star: one possible explanation for their formation is that they are the survivors of preexisting point-symmetric condensations in the asymptotic giant branch wind, a fact that would imply a quite peculiar mass-loss geometry from the giant progenitor. In the case of NGC 5882, the lack of symmetry in the distribution of the observed low-ionization structures makes it possible that they are the result of in situ instabilities.

Subject headings: ISM: jets and outflows — ISM: kinematics and dynamics — planetary nebulae: individual (IC 2553, NGC 5882)

1. INTRODUCTION

Many planetary nebulae (PNs) are known to possess intriguing low-ionization small-scale structures, which usually appear in the form of low-ionization knots, bullets, filaments, ansae, etc., embedded in the main bodies of the nebulae or outside them. These structures have received a great deal of attention in the last several years (e.g., Balick et al. 1998, and references therein) because they might provide important insights into the processes governing PN formation and evolution, such as the role of dynamical instabilities and clumpiness, the collimation mechanisms of the mass outflow from single and binary asymptotic giant branch (AGB) stars, or the occurrence of discrete mass-loss episodes in the post-AGB phase. Presently, we are still quite far from understanding their origin (Balick et al. 1998).

We are carrying out an observational program aimed at investigating the properties of these low-ionization microstructures. Most of our targets were selected by Corradi et al. (1996b) by computing ([N II] + Hz)/[O III] ratio maps in the image catalogs of Schwarz, Corradi, & Melnick (1992) and Görny et al. (1999). In previous papers (Corradi et al. 1997, 1999, 2000a), we have reported the results for several PNs, highlighting the occurrence of extended highly collimated structures (e.g., NGC 3918 and K 1-2), high-velocity symmetrical knots (K 4-47), precessing outflows (NGC 6337 and He 2-186), and multiple collimated ejecta (IC 4593 and Wray 17-1). From this work, it appears that different dynamical/radiative processes are needed to explain the variety of low-ionization structures observed.

In this paper, we discuss the results for IC 2553 and NGC 5882, which present an additional type of low-ionization structure: systems of knots located in the outer shells of the nebulae. IC 2553 and NGC 5582 are two southern PNs that have not been extensively studied in the past, apart from several statistical studies that are referenced throughout the paper. A chemical study of the different morphological structures of NGC 5882 was recently presented by Guerrero & Manchado (1999). In this paper we present high-resolution long-slit spectra and narrowband images, which allow us to determine the geometry and kinematics of the main shells of IC 2553 and NGC 5582, with particular emphasis on the low-ionization structures contained therein.

2. OBSERVATIONS

Images and spectra of IC 2553 (PN G285.4−05.3) and NGC 5882 (PN G327.8+10.0) were obtained on 1996 April 28 at ESO’s 3.5 m New Technology Telescope (NTT) at La Silla (Chile), using the EMMI multimode instrument. With the TEK 2048² CCD ESO 36, the spatial scale of the instrument was 0.27 pixel⁻¹ for both imaging and spectroscopy. The central wavelength and FWHM of the [N II] filter used for imaging are 658.8 and 3.0 nm, and those of the [O III] filter 500.7 and 5.5 nm. Further details of the observations are listed in Table 1. As with the spectroscopy, EMMI was used in the long-slit, high-resolution mode (Corradi, Mampaso, & Perinotto 1996a), providing a reciprocal dispersion of 0.004 nm pixel⁻¹ and a spectral resolving power of λ/Δλ = 55,000 with the adopted slit width of 1”0. The slit length was 6’’. The echelle order selected by using a broad Hz filter includes the He II line at λ = 656.01 nm, Hz at λ = 656.28 nm, and the [N II] doublet at λ = 654.81 and 658.34 nm. The slit was positioned through the center of the nebulae at the position angles listed in Table 1.

1 Based on observations obtained at the 3.5 m New Technology Telescope (NTT) of the European Southern Observatory and with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA for NASA under contract NAS5-26555.
TABLE 1

| Object     | Telescope | Images Filter* | Long-Slit Spectra | Seeing (arcsec) |
|------------|-----------|----------------|-------------------|-----------------|
| IC 2553    | NTT       | [NII] (180), [OIII] (120) | P.A.* (deg)       | 0.9             |
| NGC 5882   | NTT       | [NII] (600) | -142 (600), -69 (600), -1 (600) | 0.8             |
|            | HST       | F555W (24) | -85 (600), -45 (600), -19 (600) | ...             |

* Quantities in parentheses are exposure time in seconds.

We also retrieved from the Hubble Space Telescope (HST) archive images of NGC 5882 obtained on 1995 July 27 with the WFPC2 camera (PC CCD, 0.0455 pixel⁻¹) in the F555W filter (525.2/122.3 nm, total exposure time 24 s). Note that the emission of NGC 5882 in this broadband filter is expected to be dominated by the strong [O III] lines at λ = 495.9 and 500.7 nm (cf. the spectrum in Guerrero & Manchado 1999). However, various other nebular lines fall within the transmission range of the filter and may be important at specific positions in the nebula.

Images and spectra were reduced in a standard way using the Munich Image Data Analysis System MIDAS and IRAF.

3. IC 2553

3.1. Morphology

The [O III] and [N II] NTT images of IC 2553 are presented in Figure 1. In [O III], IC 2553 appears to be composed of a roughly rectangular 9'' × 4'' inner nebula that has two protrusions along its short axis. This inner nebula shows some evidence for limb brightening, suggesting that it is in fact a shell. Around it, there is a faint outer nebula whose surface brightness rapidly falls below the detection limit of the present observations. In [N II], the inner shell is also clearly visible but around it there is a system of low-ionization knots located at various position angles. Some of them are clearly paired and located symmetrically with respect to the central star (labeled AA' and BB' in Fig. 1).

In addition to the knotlike features, a faint low-ionization lane extends for about 4'' from the bright shell toward the north.

3.2. Kinematics

The long slit of the spectrograph was positioned through the central star at P.A. = −69° (minor axis of the inner shell), P.A. = −1°, and P.A. = −142° (along the diagonals of the cylindrical shell), intersecting some of the low-ionization knots. Gray-scale plots of the spectra are presented in Figure 2. First, note that the knots identified in the images are prominent in [N II] but are often not even detected in Hα. Second, the point symmetry observed in the [N II] image for some pairs of knots is also found in the velocity data. This applies not only to the knots AA' at P.A. = −142° but also to the bright knot C, which is seen projected close to the center of the nebula and which is found in all spectra to have a kinematical counterpart (C' in Fig. 2) with opposite symmetrical radial velocities.

Probably caused by the large thermal width of Hα, the corresponding position-velocity plots do not allow us to separate kinematically the different morphological components of the nebula. This is instead clearly achieved in the [N II] spectra, where one can immediately see that the emis-

![Fig. 1](image-url) NTT images of IC 2553, on a logarithmic intensity scale. The positions of the slit used for spectroscopy are indicated by short lines on either side of the nebula. Point-symmetric low-ionization knots are labeled with capital letters (see text).
sion from the inner bright shell is clearly separated from that of the (higher velocity) outer nebula and knots. To get an insight into the geometrical, orientational and kinematic properties, we have applied the same kind of spatiokinematic analysis as for NGC 3918 in a previous paper (Corradi et al. 1999). First, we measured by multiple-Gaussian fitting the [N II] radial velocities in the different regions of the nebula at all slit position angles. That was done with 2 pixel spatial binning along the slit for the inner shell and for the regions that are spatially extended, while we used larger binnings (1"–3") to measure the average velocity of each knot. The [N II] velocities are shown in Figure 3: small dots refer to the smaller binnings, large dots to the knots' velocities. Note that, along the short axis of the nebula (P.A. = −69°), the [N II] spectrum clearly reveals the existence of two separate shells, the outer one expanding at a faster velocity than the inner one.

We first analyzed the velocity field of the inner shell. Its kinematic, geometrical, and orientational parameters were derived using the heuristic spatiokinematic model of Solf & Ulrich (1985). We fitted the [N II] position-velocity plots and the shape of the inner shell with an axisymmetric model in which the nebular expansion velocity, $V_{\text{exp}}$, increases from the equatorial plane toward the polar axis, following the equation (Solf & Ulrich 1985)

$$V_{\text{exp}}(\phi) = V_e + (V_p - V_e)\sin^\gamma(|\phi|),$$

where $\phi$ is the latitude angle (0° in the equatorial plane, 90° in the polar directions), $V_p$ and $V_e$ are the polar and equatorial velocities, and $\gamma$ is a shape parameter. The other quantities involved in the model are the heliocentric systemic velocity, $V_0$, the inclination, $i$, of the nebula (the angle between the polar axis and the line of sight), and the product $tD^{-1}$, containing the inseparable effects on the apparent nebular size due to the distance, $D$, and to the kinematic age, $t$. 

**Fig. 2.** NTT long-slit spectra of IC 2553 on a logarithmic scale
To avoid the knots and better highlight the shape of the inner shell, we have used for the fit the \([\text{O III}]\) image (contour plot in the lower right panel of Fig. 3). The best fit of both the shape and kinematics of the inner shell (thick line in Fig. 3) is obtained with the following parameters: \(i = 78^\circ\), \(t D^{-1} = 0.55\ \text{yr pc}^{-1}\), \(V_p = 35\ \text{km s}^{-1}\), \(V_e = 17\ \text{km s}^{-1}\), \(V_\odot = 30\ \text{km s}^{-1}\). The fit of the spectra at P.A. = \(-142^\circ\) and P.A. = \(-69^\circ\) is good, as is that of the \([\text{O III}]\) shape if the two equatorial protrusions are not considered (in the \([\text{N II}]\) image of Fig. 1, they in fact appear to be equatorial knots separated from the inner shell). Some deviations from the model are visible for the spectrum at P.A. = \(-1^\circ\) along the polar directions, in connection with the northern extended lane and on the symmetrically opposite side. They probably reflect a peculiar kinematics in these regions.

In spite of these local deviations, the overall fit is fairly good, and we conclude that the inner nebula of IC 2553 is an elongated shell seen slightly inclined to the plane of the sky and with a slight equatorial waist, the polar velocities being about twice the equatorial ones.

As noted above, the short-axis spectrum clearly highlights the existence of an outer, higher velocity shell. That spectrum indicates, in fact, the existence of an equatorial torus detached from the inner shell and expanding with a velocity twice as large (35 km s\(^{-1}\), assuming the same polar axis as for the inner shell). Since the low-ionization knots also have a higher velocity than the inner shell, we investigated the possibility that the equatorial torus and the knots are in fact part of an outer shell expanding with larger velocities than the inner one. We then repeated the spatio-kinematic modeling, looking for a solution for the outer shell that is geometrically not too different from that of the inner one. A reasonable fit to the short axis and knot velocities and to the \([\text{O III}]\) surface brightness of the outer shell is indicated by the dashed lines in Figure 3 and corresponds to the following parameters: \(i = 78^\circ\) (fixed from the solution for the inner shell), \(t D^{-1} = 0.50\ \text{yr pc}^{-1}\), \(V_p = 58\ \text{km s}^{-1}\), \(V_e = 35\ \text{km s}^{-1}\), \(\gamma = 4\), and \(V_\odot = 33\ \text{km s}^{-1}\). This means that the outer shell would be slightly more spherical than the inner one (as also suggested by the image plot contours) and would have equatorial velocities twice as large. In addi-
tion, and more importantly, the whole system of low-ionization knots would be contained within this outer shell and would not be moving with peculiar velocities within it.

From the average of the values derived from the two fits, we adopt a heliocentric systemic velocity for IC 2553 of $31 \pm 4$ km s$^{-1}$, in good agreement with the value $37 \pm 6$ km s$^{-1}$, which is the weighted mean of the values in the compilation by Durand, Acker, & Zijlstra (1998).

Finally, the low-ionization lane extending toward the north has low radial velocities (see upper left panel of Fig. 3). If we assume that it is directed roughly along the polar axis of the shells, then its deprojected expansion velocity would be increasing from inside to outside from $\sim 30$ to $\sim 50$ km s$^{-1}$, which is, as in the case of the knots, similar to the general expansion velocity of the outer shell gas in these polar regions.

4. NGC 5882

4.1. Morphology

The HST and NTT images of NGC 5882 are presented in Figure 4. In the HST image, NGC 5882 appears to be composed of a bright elliptical inner shell measuring $11'' \times 6''$ surrounded by a fainter more spherical outer shell with a diameter of about $15''$. The surface of the inner rim seems to be composed of several bubble-like structures. Note that the central star is not at the center of symmetry of the rim but is displaced toward its western side. We do not discuss further this deviation from axisymmetry, which may be the result of large-scale instabilities in the mass-loss process and/or of the interaction with a binary companion (cf. Soker 1999) and might therefore provide additional information about the formation mechanism of the markedly elliptical rim.

The outer shell might in turn be subdivided into two regions with different surface brightnesses, the inner, brighter one having a sharp outer edge and a more elongated shape than the outer one. The present data do not allow us to discern whether they are indeed two distinct shells, and therefore in future we shall refer to the whole region as the “outer shell.”

In the low-ionization emission of [N II], several knots appear in the outer shell. The brightest ones, located in the northwest quadrant (indicated by arrows in Fig. 4), are also visible, albeit much fainter, in the HST images, in which they are resolved as complex systems of filaments and knots lying at the sharp edge of the outer shell. Similar low-ionization structures are seen in the PN NGC 7662 (Balick et al. 1998, who called them “tail-head microstructures”: see their Figs. 1, 2, and 5). At variance with IC 2553, the low-ionization structures of NGC 5882 do not show any clear symmetry around the center.

The faint extended halo with a radius of up to 160” that is known to surround NGC 5882 (Guerrero & Manchado 1999) is only weakly revealed by our NTT images and is not further discussed in this paper.

4.2. Kinematics

The long slit of the spectrograph was positioned through the central star at P.A. $\sim -85^\circ$ (approximately the minor axis of the inner shell), P.A. $\sim -19^\circ$, and P.A. $\sim -45^\circ$, intersecting the low-ionization knots found in the [N II] image. Gray-scale plots of the spectra are presented in Figure 5. There are several similarities with IC 2553. First, in both Hα and [N II] we observe an elliptical kinematic figure typical of an expanding, hollow ellipsoidal shell identified with the inner shell of NGC 5882. Second, the knots in the outer shell are clearly visible only in [N II] and generally have larger radial velocities than the inner shell.

We then attempted the kind of spatiokinematic modeling used for IC 2553. Radial velocities were measured by means of multiple-Gaussian fitting of the spectra at the different slit position angles. For NGC 5882, beside the [N II] velocities (filled circles in Fig. 6), we also display the Hα velocities (open circles), which present a slightly more regular velocity pattern than [N II]. The fit in Figure 6 is not as good as in the case of IC 2553 but is still fair enough to draw general conclusions about the geometrical, orientation, and kinematical properties of the inner shell of NGC 5882 and its low-ionization knots. First, the inner shell is found to be an ellipsoid only slightly inclined to the plane of the sky. The
parameters obtained by fitting the Hα velocities and the shape in the HST image are the following: \( i = 80° \ (\pm 10°) \),
\( tD^{-1} = 0.65 \text{ yr pc}^{-1} \), \( V_p = 38 \text{ km s}^{-1} \), \( V_\gamma = 22 \text{ km s}^{-1} \),
\( \gamma = 2.8 \), and \( V_\odot = 12 \text{ km s}^{-1} \). The [N II] velocity field of the inner shell is more irregular, but on average the expansion velocity in this ion is only slightly larger than for Hα.

Previous kinematic studies of NGC 5882 quoted an expansion velocity of 12.5 \text{ km s}^{-1} in Hβ and [O III] (Banerjee et al. 1990), 16.5 \text{ km s}^{-1} in Hα, and 23.5 in [N II] (Ortolani & Sabbadin 1985). Note, however, that those studies did not spatially resolve the nebula, while we have shown that the expansion velocity is not isotropic but varies with direction.

The heliocentric systemic velocity of NGC 5882 derived from our modeling is 12 ± 4 \text{ km s}^{-1}, which is comparable to values found by previous authors: 9.8 (Bianchi 1992) and 7.7 \text{ km s}^{-1} (Campbell et al. 1981). However, Acker (1978) quotes 21 \text{ km s}^{-1} for this object.

As far as the outer shell of NGC 5882 is concerned, the [N II] radial velocities of the knots and of other regions in this shell suggest that also in this object expansion velocities in the outer shell are systematically larger than in the inner one. The morphology and velocity field are quite irregular and fragmentary, so we did not attempt to make a spatio-kinematic fitting as for the inner rim. Nevertheless, the present data suggest that we might well be in the same situation as for IC 2553, the knots being part of the outer shell, which would be expanding with a velocity between 10 and 20 \text{ km s}^{-1} larger than that of the inner shell.

Note that some of the knots of NGC 5882 present a complex kinematic pattern. The structure at P.A. = –85° at a distance from 2.4 to 4.5 from the center (circles in Figs. 4 and 5) is in fact split, in the position-velocity plot, into four subcomponents, each pair having a velocity difference of about 15 \text{ km s}^{-1}. In the HST image, however, this structure corresponds to a diffuse region of faint emission within
the outer shell and is not associated with any obvious morphological feature.

5. DISCUSSION

According to the present data, IC 2553 and NGC 5882 share several properties. For the following discussion, we assume that both nebulae are indeed composed of an elongated inner shell, as well as of a higher velocity, more spherical outer shell. The latter, when observed in a low-ionization emission line, contains several knots that do not show evidence of moving with peculiar velocities compared with the general expansion motion of the outer shell.

The main differences between the two PNs are the following. First, the inner and outer shells of IC 2553 are more aspherical than those of NGC 5882. Second, the velocity field of IC 2553 is more regular, and thus our modeling gives clearer evidence that the outer shell is expanding faster than the inner one and that the knots participate in the expansion velocity of that shell. Third—and probably the most important difference—the system of knots of NGC 5882 does not show the point symmetry displayed by the knots of IC 2553.

A two-shell configuration is common in PNs. A large fraction of PNs (see, for example, Chu, Jacoby, & Arendt 1987; Stanghellini & Pasquali 1995) have, in fact, outer shells that are “attached to” or “detached from” their bright inner rims. Theoretically, a double-shell configuration is expected to develop as a consequence of the combined action of photoionization and fast versus slow wind interaction; Marten & Schönberger (1991) and Mellema (1994) showed that the outer shell is formed by the ionization front while the inner shell is swept up by the fast wind. Because of the action of the ionization front, the outer shell can acquire a velocity larger than that of the inner shell. This is indeed observed in several PNs (cf. Chu 1989; Mellema 1994; Guerrero, Villaver, & Manchado 1998). According to Mellema (1994), a common characteristic of the PNs with outer shells faster than the inner ones is that they are relatively young. Later in the evolution, in fact, the inner shell accelerates and ends up moving with the same or an even higher velocity than the outer shell (Mellema 1994; see also Corradi et al. 2000b).

The distance of IC 2553 is uncertain, and determinations in the literature span from 0.5 to 4 kpc (Zhang & Kwok
are found in symmetrical pairs with respect to the central star. This symmetry rules out the possibility that the knots are formed by in situ instabilities (for instance, thermal instabilities being enlarged by the expansion of the ionization front) since instabilities would not give rise to any clearly symmetrical pattern. The possibilities that remain are the following: (1) the knots are preexisting (fossil) point-symmetric structures in the AGB wind that have survived the dynamical and ionization effects (or have been exacerbated) until the present age (García-Segura & Franco 1996; Mellema et al. 1998; Soker 1998); (2) they are the traces, on the surface of the outer shell, of the passage of high-velocity material ejected from the central star in a point-symmetric fashion.

The idea of fossil knots, e.g., condensations in the AGB wind, may find support in the recent observations of some AGB stars, such as TT Cyg for which Olofsson et al. (2000) suggest a clumpy structure with a typical size of $\lesssim 10^{16}$ cm. In the PN phase, these AGB clumps will interact with the ionization front. Along these lines, several models were previously developed to explain the formation of low-ionization microstructures in PNs (e.g., Mellema et al. 1998; Soker 1998; Soker & Reveg 1998). The main physical process to be taken into account here is the disturbance due to the ionization of a preexisting clump. The timescale for the ionization of the entire clump depends on several parameters, such as size, density and temperature, the ionizing flux, etc. The analytical and numerical calculations by Mellema et al. (1998) consider a neutral clump with a size of $2 \times 10^{16}$ cm being photoevaporated by the ionizing radiation from the central star; the corresponding timescale for ionization would be of the order of $10^4$ yr. While being ionized, the cross section of such a clump would increase with an expansion time of the order of 300 yr (Soker & Reveg 1998). Thus, after ionization, the volume of the clump would increase and its density decrease, to end up as a region with a density not strongly different from that of the surrounding gas.

In the case of IC 2553, the fact that the knots are barely resolved, coupled with the large uncertainty in the distance to the object, allows us to put only an upper limit of $6 \times 10^{16}$ cm to the linear size of the largest observed low-ionization knots. Even if they were smaller, of the sizes considered by Mellema et al. (1998) or derived by Olofsson et al. (2000), the above modeling clearly shows that they would survive photoionization effects for at least $10^3$ yr, which is consistent with the kinematic post-AGB age of IC 2553 computed from our observations.

If the low-ionization knots in this nebula are the survivors of preexisting structures in the original Mira wind, this implies a peculiar AGB mass-loss geometry in which mass is ejected in very different directions in a point-symmetric fashion. Such point-symmetric mass ejection might be related to nonradial pulsation of the red giant and/or to the interactions in a binary system (Soker & Harpaz 1992; Livio & Pringle 1997). It should also be calculated at some stage whether these AGB condensations can be accelerated by the ionization front to the considerable velocities that we have measured.

The second possibility for the formation of these pairs of knots is that they are the imprints of the interaction on the outer shell of some high-velocity material recently ejected by the central star (but not the ejecta themselves, given the relatively low velocity observed). If so, one has still to explain the special geometry of the ejecta required to be accelerated by the interaction.
produce the observed point symmetry. Should the ejecta be a system of high-velocity clumps, neither is it clear whether they would not leave certain signatures while crossing the inner rim or even be evaporated and disrupted during this interaction, nor why we do not now see them at farther distances from the central star. For these reasons and implying a progenitor mass-loss history even more peculiar than in the case where they were the survivors of preexisting structures in the AGB wind, we consider the latter hypothesis to be more plausible.

As far as NGC 5882 is concerned, since the constraint of a point-symmetric knot distribution does not apply here, the simpler hypothesis that the low-ionization structures in the outer shell are in situ instabilities is also indeed viable. These instabilities would be related to the expansion of the slow wind through the interstellar medium (ISM; or through circumstellar matter from previous mass-loss episodes) or to the expansion of the ionization front. In principle, with the appropriate velocity regimes the expanding slow wind in a nonhomogeneous medium could be the source of Rayleigh-Taylor, Kelvin-Helmholtz, and Vishniac instabilities (García-Segura & Franco 1996).

6. SUMMARY AND CONCLUSIONS

The origin of the low-ionization microstructures that are observed in a large number of PNs is intriguing. From the data collected in this paper and in previous ones (see § 1), it turns out that they appear with so wide a variety of morphological, kinematic, physical, and topographical properties that one can hardly think of a common physical mechanism able to account for all of them.

In this article, we have focused our attention on the nature of low-ionization knots in the outer shells of PNs (see also Balick et al. 1998). Since they are found within nebular regions that supposedly have not yet been affected by the action of the fast AGB wind that shapes the bright rims of PNs, some of the mechanisms proposed to explain their origin can be excluded (such as the occurrence of instabilities in the fast versus slow winds interaction). One attractive option is that they are the product of instabilities in the interaction of the AGB wind with the ionization front, the ISM, or previous AGB ejecta. This might well apply in the case of NGC 5882, but the point symmetry shown by the knots in IC 2553 indicates instead that they are the remnants of preexisting, symmetric condensations in the AGB wind. Clumpy AGB winds have been observed in molecular lines (Olofsson et al. 2000), but the additional requirement of a point-symmetric distribution of the clumps would imply a very specific mass-loss geometry from the progenitor star. Understanding the physical processes causing this kind of mass loss in AGB stars clearly deserves further observational and theoretical study.

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