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A narrowband imaging survey of symbiotic stars*

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Abstract. Narrowband images of 51 symbiotic stars were obtained at the ESO and ORM observatories to search for resolved optical nebulae. Ionized nebulae much larger than previously known are found around CH Cyg, HM Sge and V1016 Cyg, and they will be discussed in detail in forthcoming papers. A nebula with a deconvolved size between $0\farcs9$ and $1\farcs5$ is found around the symbiotic Mira H 1–36. The radio sources located few arcminutes aside of R Aqr (Hollis et al. 1987), which were suggested to be the remnant of a prehistoric eruption of the system, are found to be background galaxies.

We also present a bibliographical compilation, updated to October 1998, of all the extended nebulae around symbiotic stars detected at optical and radio wavelengths, as well as a list of optical non-detections.

The statistics of occurrence of these large ionized nebulae among symbiotic stars is discussed. Extended ionized nebulae appear to be a common component of the D–type symbiotics, and we infer that they are formed by the Mira wind and/or high velocity winds ejected by the hot component during outbursts.

On the contrary, very few nebulae are detected around the systems containing normal red giants[1].

Key words: surveys – stars: binaries: symbiotic – ISM: jets and outflows

1. Introduction

Symbiotic stars are interacting binary systems containing a cool giant whose wind is partly ionized by a hot companion, in most cases a hot white dwarf (e.g. Mikolajewska 1997). Mass transfer and accretion onto the hot component is necessary to explain its high temperature and luminosity (typical values are T$\sim$$10^5$ K and L$\sim$$10^3$ $L_\odot$), but affects only a small fraction of the mass lost by the giant. The rest distributes in some way around the binary system, forming an expanding gaseous nebula. Both the history and geometry of the red giant mass loss and the radiative and dynamical evolution of this circumbinary nebula can be strongly affected by the presence of the hot companion. In particular, phenomena relevant to a wide range of astrophysical topics can occur: aspherical mass deposition by the red giant envelope, collimated winds from accretion discs, colliding winds, mass loss induced by violent thermonuclear outbursts and its interaction with old circumstellar wind remnants.

Because of the energetic radiation field from the hot component and the shaping-exciting action of high velocity winds which are often observed in these systems, the circumbinary gas can show up as a large *ionized* nebula, which is observable in the light of characteristic emission lines. Such ionized nebulae have been discovered around several symbiotic systems, mostly those of the D–type, which contain a Mira variable as cool component, and contain dust. Being composed of the wind of an evolved AGB star and excited by a hot post–AGB star, these nebulae are very similar to planetary nebulae (PNe) in terms of excitation conditions and chemical abundances. The main distinction from PNe is expected in terms of smaller nebular masses, since only a fraction of the envelope of the AGB star was lost. These smaller masses might also imply shorter life–times (the nebulae should vanish in a shorter time). The fact that their morphology and kinematics are very similar to those of some PNe tells us that similar dynamical processes are likely to occur in both class of objects, and also that there could be some misidentifications in the literature (cf. Corradi 1995). In this respect, symbiotic stars provide a nice observable demonstration of the effects of binary interactions on the mass loss from evolved stars, providing clues to understand the origin of the shaping of certain morphological classes of PNe.

The ionized nebulae around symbiotic stars can be as large as $\sim$2 pc (BI Cru and V417 Cen, cf. Corradi & Schwarz 1997). Complete information is therefore obtained by adding the information which is provided, on the sub–arcsec scale, by radio and HST imagery for the innermost, bright regions of these systems, and by optical ground–based observations for the out-

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* Based on observations obtained at the 3.5m NTT and 1.5m DAN telescopes of the European Southern Observatory, and at the 2.6m NOT telescope operated on the island of La Palma by NOTSA, in the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias.

[1] Table 5 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 1. Observing campaigns

Telescope	Obs.	Date	CCD	Pix. size
3.5m NTT	ESO	5/7/91	Ford FA2048L	0.″35
2.6m NOT	ORM	4–5/6/96	Loral 2k x 2k	0.″11
1.5m DAN	ESO	9/4/97	Loral 2k x 2k	0.″39
2.6m NOT	ORM	13–16/7/97	Loral 2k x 2k	0.″19

ermost, faint zones. Often these "outer reaches" are in fact too faint to be imaged with the HST.

In this paper, we report on results of a search for optically resolved nebulae around symbiotic stars from ground–based observations using some of the best imaging facilities available worldwide. In addition to individual papers reporting discovery of single objects, a search for resolved Hα nebulae was presented by Munari & Patat (1993) for a sample of 18 southern symbiotic stars and by Kohoutek (1997) for 5 objects.

2. Observations and analysis

CCD narrowband images of 51 symbiotic stars were obtained between 1991 and 1997 during four observing runs at the European Southern Observatory (ESO), La Silla, Chile, and at the Observatorio del Roque de los Muchachos (ORM) on La Palma, Spain. The telescope used, date of observation, CCD type and pixel size are listed in Table 1.

When searching for extended ionized nebulae around symbiotic stars, the main problem is to avoid all the disturbing effects (saturation, instrumental internal reflections, extended wings of the point-spread function, etc.) produced by the strong emission from the unresolved central source (in the visible, mainly the cool giant and its ionized wind). Because of that, faint or small nebulae can easily escape detection because they are masked by the noise of the emission wings of the central source. For this reason using a filter centred on $H\alpha$, which is a typical choice to image ionized nebulae, is generally not a good solution in the case of symbiotic stars, since the hydrogen line emission from their cores is extremely strong. In our experience, the best choice is to use a narrow filter (FWHM$<$2.5 nm) centred on the [N II] line at λ=658.3 nm. The reason is that the [N II] emission is generally fainter than Hα in the central source, but strongly enhanced in the extended nebulae.

In particular, [N II]λ658.3 is the strongest optical line in most extended nebulae around symbiotics (e.g. Schwarz 1991, Corradi & Schwarz 1993, Corradi et al. 1999). The same occurs in related objects, such as bipolar planetary nebulae, where the [N II]λ658.3/Hα ratio is usually larger than unity and can be as high as ten (Perinotto & Corradi 1998). As an example, the large (30″) nebula around HM Sge escaped detection in images taken by us in 1991 using a relatively broad filter including both the Hα and [N II] emission, while it was clearly revealed in our 1996 images obtained through a narrow [N II] filter (Corradi & Schwarz 1997). An alternative to [N II] is to use a filter centred on the near–UV [O II] line at λ372.8 nm, with the advantage that the emission from the cool giant is several magnitudes fainter than in the red, but with the disadvantage that the nebular [O II] emission is also fainter than [N II]. Using filters in low excitation lines as [N II] or [O II] prevents detection of high excitation material, but this is usually confined to the innermost regions of the symbiotic nebulae. With very narrow filters, such as the 1.0 nm wide [N II] filter used in our campaigns at the NOT, high velocity outflows ($\geq$300 km s^{-1} or even less depending on the systemic velocity of the object) can also be missed, because the line is Doppler shifted out of the pass band of the filter. In our survey, we used a variety of filters depending on the choice available at the time of the observations (see Table 5).

To reveal small or very faint nebulae, excellent seeing conditions are also very important. The use of a proper coronograph also helps. In our observing run at the NOT in 1997, in some cases we used a coronographic spot placed in the focal plane of the telescope to stop the light from the central stars, which allowed us to take deeper exposures avoiding charge blooming due to oversaturation of central stars, but which did not eliminate the instrumental artifacts in the wings of the point–spread function (such as the diffraction spike image of the secondary mirror spider).

The detection limit in our survey varied according to the telescope, exposure time, pixel size, and relative strength of the "disturbing" emission from the central source; under the best conditions, it was $\sim$10^{-16} erg s^{-1} cm^{-2} arcsec^{-2} in the [NII]λ658.3 line.

Apart from the frames in which an extended nebula was obviously detected, in all the other frames we compared the full width at half maximum (FWHM) of the image of the symbiotic star with that of the field stars to check for the presence of nebulae only slightly larger than the seeing value. One limitation to this analysis is that, with some of the imagers that we used, the point–spread function varies throughout the field. For this reason, only variations larger than 10% and which are systematic in different images were considered to be significant for the detection of a resolved nebula. In these cases, an off-band image was also taken to check whether the extended region is an emission–line nebula. The results are reported in Tables 2 to 5, where symbiotic systems are listed in order of increasing right ascension.

3. Resolved nebulae

In Table 2, we present a compilation of all the optically resolved nebulae around symbiotic stars known up to October 1998 with references to the discovery papers and to the most relevant imaging works published. The extended nebulae around CH Cyg, HM Sge, and V1016 Cyg, with apparent sizes of up to fifty times larger than previously known, were discovered during the present survey (NOT, 4.6.1996), and their first images were presented in Corradi & Schwarz (1997). No images are shown here, and the reader is referred to the preliminary results in the paper above, or to individual spatiokinematical studies which are to be published soon (Corradi et al. 1999).

Discovery of a nebula around H 2–2 was reported by Kohoutek (1997). The nebula is 1.″4 long, elongated along

Table 2. Nebulae resolved at optical wavelengths

Name	IR Type	Line	Size [″]	Shape	Notes
RX Pup	D	[N II]	4	jet?	15
AS 201	yellow D′	Hα+[N II]	13	circular	18
H 2-2	S	[O III]	1.4	elliptical?	11, to be confirmed
BI Cru	D	[N II],Hα	150	bipolar	19,2
V417 Cen	yellow D′	Hα+[N II]	100	irregular	23
He 2–104	D	[N II],Hα	95	bipolar	20,2
He 2–147	D	[N II],Hα	5	ring	14,4,5
H 1–36	D	[N II],Hα+[N II],Hα cont.,[O III]	0.9–1.5	–	24, reflection nebula?
CH Cyg	S	[N II]	32	jet? irregular	4
HM Sge	D	[N II],[O II]	30	jet, irregular	4,5
		†198.0/27.4,219.8/70.0,255.0/23.6	0.28	jet?	7(HST)
V1016 Cyg	D	[N II],[O II]	20	elliptical	1,4,5
HBV 475	S	[O III]	0.4	irregular	17(HST)
AG Peg	S	Hα	8	irregular	6
R Aqr	D	Hα,Hβ,[N II],[O III]	120	bipolar	12‡,21,13,8,9,22,7,3,4
		[O III],†198.0/27.4,255.0/23.6	60	jet	9,16(HST),10

† The central wavelength and the FWHM (nm) of the relatively broad HST filters are given.
‡ No–filtered image on photographic emulsion.

Notes:
1 Bang et al. 1992; 2 Corradi & Schwarz 1993; 3 Corradi & Schwarz 1995; 4 Corradi & Schwarz 1997; 5 Corradi et al. 1999; 6 Fuensalida et al. 1988; 7 Hack & Paresce 1993; 8 Hollis et al. 1989; 9 Hollis et al. 1990; 10 Hollis et al. 1997a; 11 Kohoutek 1997; 12 Lampland 1923; 13 Michalitsianos et al. 1988; 14 Munari & Patat 1993; 15 Paresce 1990; 16 Paresce & Hack 1994; 17 Schild & Schmid 1997; 18 Schwarz 1991; 19 Schwarz & Corradi 1992; 20 Schwarz et al. 1989; 21 Solf & Ulrich 1985; 22 Solf 1992; 23 Van Winckel et al. 1994; 24 This paper.

Table 3. Nebulae resolved at radio wavelengths

Name	Type	λ [cm]	Size [″]	Shape	References
RX Pup	D	2,6	1	spherical wind	12,24,27
Hen 3-1383	symbiotic?		4	jet?	27
SS 96	S	2	0.17	axisymmetrical	27
H 1-36	D	2, >2	5	knotty	27
RS Oph	S	2,6,18	0.2	bipolar	9,22,27,28
CH Cyg	S	2,6	1.5	jet,irregular	26,27,19
HM Sge	D	1.3,6,18	4	bipolar?	23,27,18,5
V1016 Cyg	D	1.3,6,18	4	irregular	21,27,18,6,7
AG Peg	S	1.3,2,6,20	60	elliptical, bipolar	8,17,18,3
R Aqr	D	2,3,3.6,6,18,20	120	bipolar,jet	25,15,10,11,13,16,20,3,4
		0.7 (SiO maser, cont.)	0.25	binary stars, ring	14,1

Notes:
1 Boboltz et al. 1997; 2 Chigo & Cohen 1981; 3 Dougherty et al. 1995; 4 Dougherty et al. 1996; 5 Eyres et al. 1995; 6 Eyres et al. 1996a; 7 Eyres et al. 1996b; 8 Hjellming 1985; 9 Hjellming et al. 1986; 10 Hollis et al. 1985; 11 Hollis et al. 1986a; 12 Hollis et al. 1986b; 13 Hollis et al. 1987; 14 Hollis et al. 1997b; 15 Kafatos et al. 1983; 16 Kafatos et al. 1989; 17 Kenny et al. 1991; 18 Kenny et al. 1993; 19 Kenny et al. 1996; 20 Lehto & Johnson 1992; 21 Newell 1981; 22 Porcas et al. 1986; 23 Purton et al. 1983; 24 Seaquist & Taylor 1987; 25 Sopka et al. 1982; 26 Taylor et al. 1986; 27 Taylor 1988; 28 Taylor et al. 1989.

P.A.=172° and observed in the [O III] light but curiously not in the Hα+[N II] filter. Further observations with subarcsec seeing are needed to obtain better information on this nebula.

A bibliographical compilation of the radio detections of resolved symbiotic nebulae is presented in Table 3.

3.1. H 1–36

H 1–36 is partially resolved in our optical images. Its FWHM is slightly but systematically larger than that of nearby field stars. We were very careful in considering possible instrumental effects, such as the variation of the point-spread function through the field (but comparison stars well distributed around the symbiotic system were taken, and some small systematic effects taken into account), or possible non–linearity of the CCD (but different exposure times and luminosities of the comparison stars give the same results). Moreover, similar results are obtained for images taken at different epochs, under various seeing conditions, and with different telescopes (the ESO 3.5m NTT and 1.54m Danish). In Table 4, we list the FWHM of H 1–36 and the average value for the comparison stars both along the X and Y directions in the frames and in the different filters. The surprising results is that the nebula appears resolved also in a continuum image, suggesting that it might be a reflection nebula. The deconvolved diameter of the nebula around H 1–36 was estimated using the recepies in Bedding & Zijlstra (1994). It is computed to be between $0''.9$ and $1''.5$, depending on the intrinsic geometry of the nebular model (hollow shell, disc, or uniform sphere).

At a distance of 7.5 kpc (Whitelock 1987), this optical nebula would have a diameter between 7000 and 11000 AU. Note that H 1–36, according to several studies (Allen 1983, Ivison et al. 1994), is an extreme symbiotic system having a binary separation of $\sim$1000 AU. The two components of the system are possibly resolved in the radio (Taylor 1988). The size of the optical nebula, a few times the binary separation, would agree with the prediction by Taylor & Seaquist (1984). Further optical observations at higher spatial resolution (HST) of this object are however needed to investigate the properties of the nebula (emission? reflection?).

3.2. Uncertain cases: MWC 560

Kohoutek (1997) also suggested the possible detection of a resolved nebula around MWC 560, with a deconvolved diameter smaller than half an arcsec. The difference in FWHM between the symbiotic system and the field stars, however, is only marginal (see his Table 2), and we do not consider it as significant. Further observations, under good seeing conditions, will provide more precise information on this object.

4. Non-detections

Finally, the list of symbiotic stars for which no nebula was detected with the present technique is reported in Table 5. The object names, telescopes, filters, exposure times, seeing, and notes are given, to allow the reader to estimate the quality of the data and plan improved observations. Details on the each column are given in the *legenda* at the end of the table. For the sake of completeness, also the samples of Munari & Patat (1993) and Kohoutek (1997) are included. In Table 5, we also list RX Pup, whose extended nebula was revealed by Paresce (1990) using coronographic images and after careful subtraction of a stellar profile, to show how very faint nebulae which have escaped detection in the present survey could be revealed using appropriate observing techniques. HBV 475, which has a sub-arcsec nebula revealed by HST images (Schild & Schmidt 1997), does not show evidence for more extended emission. The optical Hα nebula around AG Peg detected by Fuensalida et al. (1988) is not visible in our short [N II] and [O II] images (also listed in Table 5.

Table 4. Images of H 1–36

Telescope	Filter	Exp.time (sec)	FWHM ($''$) H 1–36 X	H 1–36 Y	Stars X	Stars Y
3.5m NTT	Hα+[N II]	0.5	1.3	1.3	1.1	1.1
3.5m NTT	Hα+[N II]	30	1.5	1.4	1.3	1.3
1.5m DAN	[N II]	60,300	2.0	2.0	1.8	1.8
1.5m DAN	[N II]	60,240	1.6	1.6	1.4	1.4
1.5m DAN	[N II]	240	1.8	1.7	1.6	1.5
1.5m DAN	Hα cont.	300	1.7	1.7	1.6	1.6
1.5m DAN	[O III]	60	1.8	1.8	1.6	1.6

4.1. R Aqr

From radio observation, Hollis et al. (1987) suggested the possible existence of an extended fragmented halo located a few arc–minutes south–west of R Aqr, which might be the remnant of a prehistoric eruption of the system. A 1 hour Hα+[N II] exposure that we took with the NOT in 1997, however, shows that the radio sources are in fact background galaxies in a cluster.

5. Discussion

Including all the information in the literature, 71 symbiotic stars, 35 of S type (excluding the "yellow" ones), 21 of the D type, 9 "yellow" systems and 6 with unknown/uncertain IR classification were searched for extended optical nebulae. Note that the sample represents about one third of the total number of symbiotic stars known in the Galaxy to date.

8 D–type symbiotic stars (40% of the sample observed) have an extended optical nebula. Thus, as already remarked by Corradi & Schwarz (1997), the presence of a PN–like nebula is a common property of the symbiotic Miras. In principle, the nebulae around D–type symbiotics could be either the AGB remnant of the hot white dwarf (its PN), material from the Mira ionized by the hot component (and possibly also shaped by high velocity winds from the hot companion), or material ejected directly from the hot component during outbursts. We use the same statistical argument as in Corradi & Schwarz (1997) to show that these nebulae are not the PNe of the white dwarfs. If so, it would in fact imply that the white dwarf is in a very early post–AGB phase (few tens of thousands years after the envelope ejection, which is the typical life time of a PN). A young post–AGB star and a late AGB star would then co-exist in the same system. Considering the short evolutionary life times in these phases (e.g. Renzini 1993), this would imply an extremely small difference in the initial mass m between the two stars ($\Delta m/m < 0.002$). And it is extremely unlikely that this applies to such a large fraction of the D-type systems. The nebulae have therefore to be composed of material lost by the Miras, likely mixed with

the ejecta from the hot component (and thus are not genuine PNe). Note that this same argument of unlikely negligible mass differences between the two components can be used to prove that the hot component is not just a post–AGB star passing naturally through the phase of high luminosity/temperature in its early post–AGB evolution, but is an older object which must be continuously fed via mass accretion to explain and maintain the high luminosity and temperature which are typical of these compact stars.

Another important property of the nebulae around D–type symbiotic stars is their wide variety of shapes (see Tables 2 and 3) and sizes (cf. Corradi & Schwarz 1997). Elliptical or ring nebulae, collimated/bent jets, marked bipolar morphologies and irregular geometries are found. Without going into further details, it is clear that different dynamical processes must be taken into account in order to explain this complex and varied phenomenology. This is rich and challenging field of work for the future. Fast *vs.* slow wind interactions as proposed for the shaping of planetary nebulae (cf. Balick & Frank 1997 and reference therein) might possibly also work to explain the shapes of some of the extended nebulae around symbiotic stars (with appropriate changes of the wind parameters and initial conditions), and especially those which most resemble bipolar PNe (e.g. He 2–104, R Aqr, BI Cru). Very likely, however, more ingredients (such as the action of magnetic fields, collimation by accretion discs, or the formation of non-azimuthally symmetric mass distribution due to the binary orbital motions) will have to be included to account for all the complex phenomenology observed in the outflows from symbiotic stars.

At variance with the D–type symbiotics, only 4 S–type systems out of 35 have an optically resolved nebula. For one of them (H 2–2), however, the detection needs further confirmation. Another one, HBV 475, has a small ($\sim$500 a.u.) high-excitation nebula, mainly distributed along the orbital plane (Schild & Schmid 1997). The nebula around CH Cyg (Corradi & Schwarz 1997) is also relatively small ($\sim$5000 a.u.) and is probably the result of the recent outburst phases. Finally, AG Peg has a complex multiple shell radio nebula (Kenny et al. 1991), which is partially detected in the optical (Fuensalida et al. 1988), which is ascribed to the interactions between slow and fast winds preceding and following its major outburst of 1850. We conclude that ionized, PN–like large nebulae are rare around S–types. Probably the main reason is that the mass loss from their cool giants (the main ingredient of the nebulae) is two orders of magnitude smaller than in D–types (Whitelock 1987, Kenyon et al. 1988). The scarcity of observable circumstellar material around S–type symbiotic stars has also implications on the suggested identification of these objects with the precursors of supernovae of type Ia (Munari & Renzini 1992). One of the key points here is the ability of the white dwarf companions to accrete enough material to reach the Chandrasekhar limit and explode by carbon deflagration. The higher the efficiency of mass accretion, the lower is the amount of material which is lost from the system and which might show up as a ionized circumstellar nebula (cf. Boffi & Branch 1995). Thus the fact that these nebulae are not observed, while it does not prove that the accretion rate is high enough, it certainly does not contradict the hypothesis that S–type symbiotics can evolve to the SN Ia phase.

As for yellow symbiotics, 2 out of 9 have an extended nebula. In this case, the argument as used for the nebulae around D–types does not hold, and the observed nebulae could be the AGB-remnant of the hot white dwarfs of these systems. If so, the hot components would be very young post–AGB stars surrounded by quite massive nebulae. This is consistent with the large size and kinematical age of V417 Cen (Corradi & Schwarz 1997).

6. Conclusions

We have presented an optical search for extended nebulae around symbiotic stars. The frequent occurrence of these nebulae (40% of the observed sample) among symbiotic Miras, as well the paucity of objects for systems with normal giants, is confirmed.

Several things remain to be done. A complete search among D–types would possibly detect new nebulae. Even for those objects in which no nebula was found in the present survey, coronographic observations and careful subtraction of the point–spread function might reveal faint nebulae, as done in the case of RX Pup (Paresce 1990). In particular, some objects should be definitely reobserved. One is RR Tel, for which a deep [N II] image would be needed. Another one is H 2–2 (see Sect. 3). AG Peg would also need new Hα images (none were taken during the present survey) as well as deeper [N II] exposures, to confirm the nebula detected by Fuensalida et al. (1988) and to look for optical counterparts of the multiple–shell radio nebula found by Kenny et al. (1991).

Detailed studies of individual nebulae are also necessary. Spatiokinematical modelling will set constraints on the geometry, dynamics, and age of the outflows, providing basic information on the mass loss history of the systems in the last few thousand years; information which is not obtainable any other way. Radio and HST imagery will also measure the apparent expansion of the nebula on time scales of a few years for objects as far as 1 kpc (giving detailed 3-D information, and in some cases a fundamental parameter: the distance). Study of the physico-chemical abundances in the extended nebulae, to be compared with the stellar abundances, will also be possible with the new generation of 10m-telescopes even for the faintest objects.

The relative orientation of the nebulae and the orbital planes is a basic piece of information to understand the mass loss processes in symbiotic stars. In this respect, spectropolarimetric studies seems to be a promising way to determine the orbital parameters even for wide binaries as the D–type symbiotics (Schild & Schmid 1996). Alternatively, it has been beautifully shown by Hollis et al. (1997b) in the case of R Aqr that in the closest objects a direct observations of the two components of the binary system is possible by comparing high–resolution images at 7 mm in the SiO maser (associated with the extended atmosphere of the cool giant) and in the nearby continuum (mainly produced close to the hot companion).

Finally, theoretical studies are needed to explain the complex phenomenology of the observed outflows. Especially, a theoretical framework which considers the relationships between the processes in the innermost regions of the systems (accretion discs, magnetic fields, binary influence on the red giant mass loss, mass release during outbursts) and the large scale jets, bipolar nebulae, rings, etc., would provide new important constraints on the formation and evolution of symbiotic stars and of related objects (PNe, novae, supernovae).

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