Spectroscopically and Spatially Resolving the Components of Close Binary Stars
ASP Conference Series, Vol. nnn, 2004
R. Hilditch, H. Hensberge, K. Pavlovski, eds.

Pulsating Components in Close Binaries

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Abstract. We present an overview of pulsating stars in close binaries, focusing on the question what role the duplicity plays in triggering and/or modifying stellar oscillations and on how it can help us to interpret the oscillatory behaviour of (one of) the components. We give examples of characteristic types of oscillations observed in binaries: forced oscillations and free oscillations in both, short- and long-period binaries. The importance of studies of oscillations in eclipsing binaries is also pointed out. A list of line-profile and rapid light variables in close binaries with their basic properties is provided. No obvious relations among the orbital eccentricity, orbital frequency, rotational frequency and intrinsic frequencies of oscillations were found. The value and future prospects of asteroseismic studies of binary stars are briefly outlined while the complexity of the problem and its possible complications are also discussed.

1. Introduction

The study of non-radial stellar oscillations, nowadays called asteroseismology, has gained much interest after it became clear that their correct interpretation allows a fine tuning of the models of stellar interior structure. Such studies have proved very successful for the Sun and white dwarfs, and more recently also for the δ Scuti, roAp, β Cep and sdB stars. For recent highlights of the research of stellar oscillations, readers are referred to Thompson et al. 2003 and Kurtz & Pollard 2004 and references therein. Basic lecture notes on stellar oscillations can be downloaded from `http://www.eneas.info`. Considering that a significant fraction of oscillating stars are members of multiple systems, it seems legitimate

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to ask how much duplicity and atmospheric oscillations affect each other and what one can learn from studying such relations.

A more general motivation for studying stellar oscillations in binaries is at least threefold:
1. To understand whether duplicity plays an important role in triggering or modifying the stellar oscillations. This requires systematic studies of a large sample of oscillators in binaries.
2. To study rapid variations in suitably chosen binaries and to prove that they indeed arise from stellar oscillations and not from, e.g., corotating structures (see methodological remarks by Clarke 2003 on this matter). If so, to derive as many different oscillation frequencies as possible and to identify their correct pulsational modes. This will allow to derive the surface stellar rotational frequency Ω from the frequency splittings with an incomparably higher precision than that derived from $v \sin i$ and i estimates. A comparison with the orbital frequency would then permit to conclude whether a spin-orbit synchronism had been achieved or not, *independently of the knowledge of the orientations of the orbital and rotational planes*.
3. The ultimate goal is to apply asteroseismology in all details, i.e. to derive the internal rotation behaviour, accurate stellar ages and metallicities and to set limits on the amount of convective core overshooting. This latter quantity is probably the most uncertain quantity in the present-day stellar interior models while it has an enormous effect on the course of stellar evolution, especially for massive stars with large convective cores. The value of the overshooting parameter has long remained a subject of debate in the literature. It was estimated from evolutionary isochrone fitting for either some star clusters or components of eclipsing binaries. These estimates have invariably led to surprisingly large values from 0.25 to 0.6, expressed in the units of the pressure scale height. In contrast to it, a recent independent asteroseismic evaluation of the overshooting parameter for the very slowly rotating β Cep star HD 129929 led to a value below 0.15 (Aerts et al. 2003b). This clearly indicates that the large values of the overshooting parameter found earlier might stem from rotational mixing which affects the evolution in a very similar way as the convective overshooting. Clearly, a detailed asteroseismic study of a slowly rotating pulsator in an eclipsing binary (or in a cluster) would be the best way of attacking the difficult problem of the determination of the true value of the overshooting parameter.

In the following we highlight some illustrative examples of state-of-the-art studies of oscillations in binaries, deliberately omitting those discussed in some other contributions presented here (De Cat et al., Freyhammer et al., Fremat et al.). We also do not discuss either oscillations in sdB binaries, covered by Maxted (these proceedings) or the classical oscillators in binaries and their role in the PLC relation and the distance determinations.

2. Search for oscillations in binaries

There are two basic ways how to search for oscillations in binaries. One can observe a sample of close binaries and try to discover short-period variability in (one of) the components. The first such systematic search, nicknamed SEFONO, was initiated by Harmanec et al. (1997). While SEFONO has led so far to the detection of two binaries with line-profile variations (Holmgren et al. 1997, 1999) it turns out to be very difficult to prove that the rapid changes are indeed due to oscillations and not to some other (or additional) effect having a similar timescale. Moreover, hints of variability may turn out to be an overinterpretation (see Harmanec et al. 1997 vs. Janík et al. 2003). Yet, the SEFONO approach is the way to find new oscillating stars among eclipsing binaries.

The other method, to observe a sample of known oscillators and to discover the binary nature of some of them, turned out to be more rewarding. A fine example of the latter strategy is the discovery of the binary nature of the faint δ Scuti star XX Pyx (A4V, V=11.5). While the numerous oscillations of this star were well established from multisite campaigns (Handler et al. 2000), their seismic modelling had been unsatisfactory (Pamyatnykh et al. 1998). The first step to resolve the discrepancy was made by Arentoft et al. (2001) who discovered a low frequency of 1.73 c/d in the photometric variability, besides the intrinsic acoustic frequencies in the range 27 to 38 c/d. Such a low frequency either points towards gravity-mode oscillations or to duplicity. The latter hypothesis was shown to be the correct one by Aerts et al. (2002), who carried out the first spectroscopic study of the star. XX Pyx turns out to be a circular-orbit binary with a period of $1\overset{\mathrm{d}}{.}151$ and an M3V companion. A tidal distortion of the primary is the likely cause of the failure of the earlier seismic modelling, based on the assumption of a spherical star. De Cat et al. (2000) discovered several new spectroscopic binaries in the sample of southern slowly pulsating B stars selected for long-term spectroscopic and photometric monitoring by Aerts et al. (1999); see also De Cat et al. (these proceedings) and there are other recent reports of such discoveries.

3. Some characteristic case studies

In the following, we summarize results of several studies which are typical for various aspects of the problem. A space constraint does not allow us to review all known short-period variables in close binaries in detail. However, we include a list of such binaries, currently known to us.

3.1. Forced oscillations

Numerous theoretical studies predict the occurrence of forced oscillations in close binaries due to resonances between dynamical tides and free gravity-mode oscillations of spherical degree $\ell = 2$. Willems & Aerts (2002) provide amplitudes and shapes of the radial-velocity (RV hereafter) curves resulting from such oscillations. They find the RV amplitude to increase with increasing eccentricity. They obtained sinusoidal RV curves whenever the orbital period was an exact multiple of the one of an $\ell = 2$ free oscillation mode of the star. It is noteworthy, though, that irregular RV curves are predicted for forced oscillations whenever the orbital period differs slightly from an exact multiple of the free oscillation period, even for a point-source companion. It is therefore clear that the periodic changes in the shapes of the stars, as they pass from periastron to apastron, must imply very complex variability and perhaps small cyclic changes of the oscillation periods of tidally induced oscillations near resonance. Another obvious complication is that the observer detects oscillations via RV and line-profile variations coming to view as the star rotates. For eccentric binaries, a spin-orbit synchronization is impossible, of course, and as the star changes slightly its radius during its orbital motion, a small cyclic variation in the observed oscillation frequency becomes inevitable. At the same time, there is no chance to obtain an accurate value of the frequency separately at periastron or apastron since there is no reason they should be in phase during different periastron passages which means that observing the object for a longer time does not help unless one applies a proper model in the frequency analyses. A standard Fourier analysis of such variable signals would recover several close frequencies but this need not indicate a real multiperiodicity. One must therefore be very cautious before claiming observational evidence of intrinsic multiperiodic (forced) oscillations.

A good example of forced oscillations seems to be the slowly pulsating B star HD 177863, for which De Cat et al. (2000) found an eccentric ($e = 0.60$) orbit with a period of 11.9 days. The dominant intrinsic period in the RV residuals and in the multicolour photometric variations of the supersynchronous primary is 1.19 days, i.e. exactly 10 times shorter than the orbital period. Willems & Aerts (2002) showed that such a frequency is *compatible* with a forced oscillation of $\ell = 2, m = -2$ for radial orders n between 27 and 53. Additional variability was found for the star by De Cat & Aerts (2002) but the significance of these results needs further verification before an in-depth seismic analysis can be attempted.

Another remarkable candidate of forced oscillations is the A9/F0V star HD 209295. Handler et al. (2002) found it to be the primary of an eccentric ($e = 0.35$) binary with an orbital period of 3.1 days (frequency of 0.33 c/d). Among the numerous intrinsic frequencies derived by the authors there is the orbital frequency, low frequencies of 1.13 and 2.30 c/d, the acoustic-mode δ Scuti-type frequency 25.96 c/d, and their combinations. Handler et al. pointed out the *compatibility* of the measured low frequencies with resonantly excited $\ell = 2, m = -2$ modes provided the rotational frequency of the primary is supersynchronous at 1.85 c/d.

These two cases are currently the best candidates of true forced oscillations. However, for the reasons outlined above, they should still not be considered as proven beyond doubt.

3.2. Free oscillations in short-period binaries

Smith (1985) proposed that the free acoustic oscillations in the B1II+B2V binary α Vir (Spica, P=$4^{\mathrm{d}}.01$, $e = 0.15$) are modified by tidal effects but the idea was not developed since then. Multiple acoustic high-degree modes were recently found for the massive close binaries ψ^2 Ori (B1II+B2V, $P_{\mathrm{orb}} = 2.5$ days, $e = 0.05$, Telting et al. 2001) and ν Cen (B2IV+?, $P_{\mathrm{orb}} = 2.6$ days, $e = 0.0$, Telting & Schrijvers 2002). Here, the authors found the oscillations to remain unaltered by the tides. Another remarkable object in this respect is ϵ Per (B0.5IV, $P_{\mathrm{orb}} = 14.07$ days, $e = 0.52$, Tarasov et al. 1995), the archetype of line-profile variables among the early B stars. In spite of its numerous studies, there is no consensus whether its short-period variability is due to multiple oscillation modes (Gies et al. 1999) or other complex phenomena such as corotating structures (Harmanec 1999) or both. Finally, Lehmann et al. (2001) provided some evidence that the amplitude of RV oscillations of EN Lac increases near the periastron passage. All these stars, and a few others (see Table 1) are situated in the β Cep instability strip (cf., e.g., Pamyatnykh 1999) and one can expect free non-radial oscillations to be excited in them via the κ mechanism. A conservative conclusion is that none of available studies provided an ultimate proof that free oscillations are altered by the duplicity.

There is no doubt, however, that the studies of oscillations in binaries, especially the eclipsing ones, must be rewarding. Analyses of RV and light curves remain to be the most accurate method of determination of stellar masses, radii, and luminosities, and also effective temperatures, metallicities and age. Those values then represent an ideal starting point for the seismic modelling, once oscillation modes have been found and correctly identified. The range of values in the parameter space gets substantially limited this way. This applies also to the *overshooting* parameter discussed above. Unfortunately, only a very limited number of pulsating stars in eclipsing binaries has been identified so far. We mention two such objects below:

EN Lac is a β Cep star in an eclipsing binary. Unfortunately, only a shallow primary eclipse is observable in the optical region and no real solution of the light curve is available. The binary properties are not, therefore, well enough constrained as yet. The first seismic modelling has been carried out by Dziembowski & Jerzykiewicz (1996). However, their analysis was hampered by the lack of a unique identification of each of the three detected oscillation modes. Lehmann et al. (2001) recently analyzed a rich set of high-resolution spectra and refined both the orbital solution and the values of oscillation frequencies. Aerts et al. (2003a) used them to show that the two largest-amplitude modes are $(\ell, m) = (0, 0)$ and (2,0) modes, respectively. This identification was then used by Thoul et al. (2003a) in their recent seismic analysis of the star, which led to a tight mass-metallicity relation for each value of the overshooting parameter. Clearly, a detection and correct identification of additional frequencies on the one hand, and setting tighter constraints on binary properties via observing and solving the orbital light curve on the other hand, would help enormously to understand the internal structure of the oscillating primary. An on-going large multisite photometric and spectroscopic campaign on EN Lac led by G. Handler (Vienna University) promises such progress for the near future.

Another oscillating star in an eclipsing binary is V539 Ara (Clausen 1996). It consists of B3V and B4V pair moving in a slightly eccentric ($e = 0.05$) orbit with a $3\overset{d}{.}17$ period and exhibiting apsidal motion. Three candidate gravity modes were detected, with frequencies 0.74, 0.56 and 0.93 c/d. However, until the mode identification will become available, no seismic modelling is possible.

3.3. Oscillations in long-period binaries

The reason why we treat long-period binaries (those having the orbital periods at least two orders of magnitude longer than their oscillation periods) separately is that one does not expect tidal forces would measurably affect their rapid changes.

A textbook example of oscillations in a wide binary is α Cen A. This binary ($P_{\rm orb} = 79$ years, $e = 0.52$) is currently the subject of intense seismic modelling after the detection of 28 solar-like oscillation modes in the frequency range 1.8 to 2.9 mHz in the G2V primary by Bouchy & Carrier (2001) and more recently of 12 such modes in the frequency range 3 to 4.6 mHz in the K1V secondary by Carrier

& Bourban (2003). The excitation mechanism and nature of these modes are entirely the same as for the Sun which permits direct helioseismic applications, this time in a well-known binary. Earlier seismic studies have already provided some insights into the internal structure of this binary and led to a very accurate age estimate (Bouchy & Carrier 2002, Thévenin et al. 2002, Thoul et al. 2003b). However, those studies were carried out before the discovery of the oscillations of the secondary. A refinement of the knowledge of internal structure, based on a simultaneous seismic analysis of both components, is to be expected soon.

β Cen is another interesting long-periodic binary, albeit of an entirely different nature than α Cen. Ausseloos et al. (2002) have shown β Cen to be an eccentric ($P = 357\overset{d}{.}02$, $e = 0.814$) binary with two virtually identical massive components. *Both stars* show clear line-profile variability while *no* photometric variations above the detection treshold were found. It is therefore likely that we are dealing here with high-degree non-radial oscillation modes that tend to cancel out mutually in photometric data. Seismic modelling for this star is ongoing.

Guided by the discovery that β Cep is a long-period (∼90 yrs) binary, Pigulski & Boratyn (1992) showed that the secular variation of the main pulsational period of this archetype is a direct consequence of the light-time effect on the motion in the binary orbit. If this fact would go unrecognized, the Fourier analysis would lead to detection of several close frequencies and a false claim of multiperiodicity. Clearly, the claims of multiperiodicity and/or evolutionary period changes should always be scrutinized from this perspective, even for seemingly single stars. For example: Harmanec's (1998) showed that the $1\overset{d}{.}37$ RV period of the Be star ω CMa undergoes slow cyclic changes with a possible period of 5650 d. Subjecting RVs and synthetic data to a standard Fourier analysis, he recovered three periods: $1\overset{d}{.}3719$, $1\overset{d}{.}3464$ and $1\overset{d}{.}3536$.

A remarkable case is δ Sco with its extreme 0.92 orbital eccentricity and a nearly 10-yr period. A strong Balmer emission and a large optical brightening with overlapping cyclic variations on a time scale of a few months accompanied the latest periastron passage in 2000. The natural question is to what extent a steep gradient in the tidal forces is responsible for these phenomena (see Miroshnichenko et al. 2003 for a discussion). Note that also β Cep itself developed Balmer emission during its recent periastron passage, but no notable light changes. The ongoing intensive photometric and spectroscopic monitoring of both stars may shed light on these questions.

4. Sample of line-profile variables in binaries

In Table 1 we collected basic information on binaries with rapid variations known to us at the time of writing. Objects from several phenomenologically defined groups (β Cep, δ Sct, SPB, Be, X-ray, WR etc.) are included. We were unable to find out any clear relations among the various characteristics of the binary orbits and the rapid frequencies from this limited sample. Rapid variations are found for stars in circular as well as highly eccentric orbits. There is some preference for the values of ω between 90° and 130°. Indeed, there are 8 such binaries out of 26 with eccentric orbits while less than 3 would be expected for a uniform distribution. This is a bit disturbing since a formal solution of RV

Table 1. A list of line-profile variables in binaries. The longitude of periastron is quoted always for the optical primary, 'APS' denotes a measurable apsidal motion. In column 'Type' the usual notations SB1, SB2, EB, VB, EL, and LT stand for spectroscopic, eclipsing, visual, ellipsoidal a light-time orbits. Because of limited space, we refer the reader with apologies to the ADS library for the references on particular objects. See also Frémat et al. for DG Leo, and Freyhammer et al. for V381 Car in these proceedings.

Variable star name	HD number	P_{short} (days)	P_{orb} (days)	e	ω (°)	Type	Spectral class
ϑ Tuc	3112	0.049-0.053	7.1036	0.0	–	SB2	A7IV
γ Cas	5394	0.07-1.487	203.59	0.260	48	SB1	B0.5e+X??
φ Per	10516	0.6	126.6731	0.0	–	SB2	B0.5IVe+sdO
RZ Cas	17138	0.016-0.018	1.195257	0.0	–	EB	A3V+K0IV
HIP 14871	19684	0.347-0.366	31.9456	0.0	–	SB1	F0IV
X Per	24534	0.93	250.3	0.111	108	LT	O9.5e+X
τ^8 Eri	24587	0.86423	459	0.18	106	SB1	B5V
ε Per	24760	0.1598-1.19	14.069	0.52	109	SB1	B0.5IV
ϑ^2 Tau	28319	0.037-0.093	140.728	0.75	49	SB1	A7III
η Ori Aab	35411	0.132-0.432	7.989255	0.011	205	EB	B0.5V
ψ^2 Ori	35715	0.093-0.095	2.529	0.053	APS	SB2	B1II+B2V
V1046 Ori	37017	0.901	18.65612	0.468	118	SB2	B2e+B7
ζ Tau	37202	0.09-1.6	132.9735	0.0	–	SB1	B1e
V696 Mon	41335	3.6?	80.860	0.0	–	SB1	B2e
XX Pyx	–	0.026-0.035	1.151	0.0	–	EL	F+M3
γ^2 Vel	68273	0.35-1.94	78.519	0.38	261	SB2	WC8+O7.5e
NO Vel	69144	?	4.82306	0.0	–	SB1,EL	B2.5IV
HY Vel	74560	1.5511	8.378	0.24	93	SB1	B3IV
GP Vel	77581	8.96?	8.9644	0.14	355	EB	B0.5Ibe+X
DG Leo	85040		4.14675	0.00	–	SB2	A8IV+A8IV
		0.0818	70000:	>0	?	VB	A8IV
V381 Car	92024	0.1397-0.1773	8.32457	0.03	65	EB	B1III
V514 Car	92287	4.6555	2.90457	0.0	–	SB1,EL	B3IV
κ Dra	109387	0.54-0.89	61.5549	0.0	–	SB1	B5IIIe
β Cru	111123	0.183-0.359	1828.0	0.38	293	SB1	B0.5IV
α Vir	116658	0.174	4.01454	0.15	APS	SB2	B1II+B2V
NY Vir	—	0.002	0.101016	0.0:	–	EB	OBVI+M5V:
ν Cen	120307	0.17	2.622	0.00	–	SB1	B2IV
β Cen	122451	0.153-0.503	357.02	0.814	63	SB2	B1III
V869 Cen	123515	1.459	26.036	0.264	340	SB2	B9IV
ε Lup	136504	0.170-0.177	4.5598	0.26	330	SB2	B2IV+B3V
PT Ser	140873	0.86836	38.927	0.731	202	SB2	B8III
δ Sco	143275	0.0975-0.78	3865.	0.92	24	VB+SB1	B0.5IV
β Sco A	144217	0.17?	6.828245	0.30	APS	SB2	B0.5IV+B1.5V
σ Sco	147165	0.240-0.247	33.012	0.40	287	SB1	B1III
		?	>18000	?			
V600 Her	149881	0.18	5.20065	0.11	128	SB1	B0.5III
V861 Sco	152667	0.614??	7.8482	0.04	0	EB	B0Iae+B2V:
κ Sco	160578	0.1998	195.65	0.488	93	SB2	B1.5III+B
V539 Ara	161783	1.08–1.78	3.1691	0.053	APS	EB	B3V+B4V
V2502 Oph	167858	0.623-1.307	4.4852	0.0	–	SB1	F1V+M
β Lyr	174638	4.71?	12.935	0.0	–	EB	B8II+B0e::
V4198 Sgr	177863	1.1896	11.9154	0.603	182	SB1	B8V
V1765 Cyg	187459	3 or 8:	13.37383	0.335	APS	SB2	B0.5Ibe+B0V:
BW Vul	199140	0.20104	12200.	0.46	116	LT	B2III
V832 Cyg	200120	0.07-0.28	28.1702	0.20	271	SB1	B1.5e
V1931 Cyg	200310	0.300-1.20	146.6	0.0	–	SB1	B1e
β Cep	205021	0.19048	33000	0.65	194	VB,LT	B1IV
NSV 25820	209295	0.388-0.886	3.10575	0.352	31	SB1, EL	F0V
V360 Lac	216200	1.6738	10.08541	0.0	–	SB2	B3e+F9IV
EN Lac	216916	0.169-0.182	12.0969	0.04	65	EB	B2IV
KX And	218393	0.35-4.86	38.918	0.0	–	SB2	B0.5e+K1III
AR Cas	221253	0.510??	6.0663	0.24	APS	SB2	B4V+A6V:

curves of Cepheid variables leads to a similar range of ω values and one has to keep in mind that – unless the secondary is directly observed – the duplicity of particular objects remains unproven. This is yet another warning we wish to express here.

5. Concluding remarks and prospects

Given the recent progress in seismic modelling of single stars, we conclude that the prospects of similar studies in close binaries are very promising though the task is all but simple. Particularly important is the chance to constrain the overshooting parameter via asteroseismic analyses of non-radial oscillations found in eclipsing binaries (or in clusters). As for single stars, the study of oscillations in binaries requires huge observational effort and long-term monitoring, even when the individual oscillation modes have short periods. The beat-periods of the oscillations are of the order of weeks to years, and aliases have to be excluded from the frequency analyses. Multisite campaigns are by far the most efficient way to proceed, but they require considerable organisational efforts and large international teams of observers. A breakthrough may be expected as soon as the data from dedicated satellites like MOST or COROT will become available. However, even then, supporting spectroscopic campaigns will be needed.

We tried to point out the inherent difficulties involved. One is to discriminate properly between forced oscillations and modified or unaffected free oscillations in close binaries. A way to proceed is to gather numerous multicolour photometry and high-resolution spectroscopy of an oscillating star in a close binary, to cover many binary periods. Other problems are related to possible small cyclic variations of the oscillation frequencies, due to variable shape of the star in close eccentric-orbit binaries, and the light-time effect in the wide ones. Especially the first situation is a very challenging one. As already pointed out, even if enough observations are accumulated, the data cannot simply be splitted into subsets obtained near peri- and apastron since the phase of the varying frequency cannot preserved between two consecutive passages though the same point in the orbit. A model of a cyclically varying frequency will have to be applied before the cases of a single cyclically variable frequency and several close frequencies could safely be distinguished. One also has to exclude the possibility that the rapid variations are due to corotating structures in, or slightly above the stellar photospheres. This is certainly a conceivable possibility considering that, for instance, several β Cep stars were found to be Be stars and resonances in circumstellar disks are well established for certain types of binaries. All these phenomena can lead to variations on time scales quite comparable to stellar pulsations.

In spite of all obstacles, however, the study of multiple non-radial oscillations in close binaries is very desirable since it offers several advantages over similar studies for single stars. The binary nature is the best way how to constrain tightly the basic stellar properties, as it was clearly demonstrated during this meeting on the examples of not only eclipsing but also astrometric binaries. The number of the latter ones can be expected to increase dramatically with the current exciting progress in the optical and IR stellar interferometry.

We end this short review with the hope that at least some readers of it will be convinced and inspired and will select some of the objects from our list for their systematic observations and studies.

Acknowledgements

This joint study was made possible thanks to the senior fellowship awarded to PH by the Research Council of the Catholic University of Leuven which allowed his 3-month stay at the Institute of Astronomy in the Department of Physics and Astronomy. CA is acknowledges financial support from the Fund for Scientific Research of Flanders through several grants which made it possible to perform long-term monitoring of pulsating stars during the past decade. The research of PH was also supported from the research plan J13/98: 113200004 of the Ministry of Education, Youth and Sports, research plan AV 0Z1 003909 and project K2043105 of the Academy of Sciences of the Czech Republic and from the grant GA ČR 205/2002/0788 of the Granting Agency of the Czech Republic. We gratefully acknowledge useful suggestions and a careful proofreading of this manuscript by Dr. David Holmgren.

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