AN EXTENDED INVESTIGATION OF HELIOS 1 AND 2 OBSERVATIONS: THE INTERPLANETARY MAGNETIC FIELD BETWEEN 0.3 AND 1 AU

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Abstract. Helios-1 and 2 spacecraft allowed a detailed investigation of the radial dependence of the interplanetary magnetic field components between 0.3 and 1 AU. The behaviour of the radial component B_r is in a very good agreement with Parker's model ($B_r \sim r^{-2}$) and the azimuthal component B_ϕ also shows a radial dependence which is close to theoretical predictions ($B_\phi \sim r^{-1}$). Experimental results for the normal component B_θ and for the field magnitude B are consistent with those from previous investigations. The relative amplitude of the directional fluctuations with periods less than 12 hr is essentially independent of heliocentric distance, while their power decreases approximately as r^{-3} without any appreciable difference between higher and lower velocity regimes.

1. Introduction

Recent and ongoing planetary missions provided in the last several years detailed investigations of the interplanetary magnetic field (IMF, hereafter) between 0.46 and 5 AU. The observed gradients of the IMF parameters have been recently compared with Parker's theoretical predictions by Behannon (1978) who concluded that while the behaviour of the radial component $|B_r|$ is consistent with the expected r^{-2} dependence (r being the heliocentric distance), the azimuthal component $|B_\phi|$ decreases more rapidly than the r^{-1} dependence predicted by simple theory. Moreover the observations of the normal component $|B_\theta|$ (which is zero in the solar equatorial plane in the Parker's model) is roughly consistent with an heliocentric distance dependence as $r^{-1.4}$ and the total magnitude behaviour is well described by Parker's formulation. Finally, the observed amplitude of the vector field fluctuations with period less than 1 day approximately decreases as $r^{-3/2}$ in agreement with models proposed by Whang (1973) and by Hollweg (1975).

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The primary mission of Helios-1 allowed an extension of these investigations up to heliocentric distances of 0.3 AU: the experimental observations of Helios-1 ((Mariani *et al.*, 1978, hereafter referred as Paper 1) agree with the conclusions drawn by Behannon (1978) except that the observed gradient of the azimuthal component $|B_\phi|$ (at least during high velocity conditions) is closer ($r^{-1.08\pm0.13}$) to theoretical predictions ($B_\phi \sim r^{-1}$). In this paper we extend this kind of analysis to the primary mission of Helios-2 and to three consecutive perihelion passages of Helios-1.

2. Trajectory and Data Analysis

The Helios-1 and Helios-2 spacecraft were launched from Cape Canaveral on 10 December, 1974 and 15 January, 1976 respectively. For details about instrumentation and data reduction, the reader is referred to Scearce *et al.* (1975), Bavassano (1976), Villante and Mariani (1977). The spacecraft trajectories as projected on the ecliptic plane, are shown in Figure 1 for the periods of interest: the heliographic latitude of both spacecraft was always in the range ±7.23° with rapid variations between the two extremes close to perihelions.

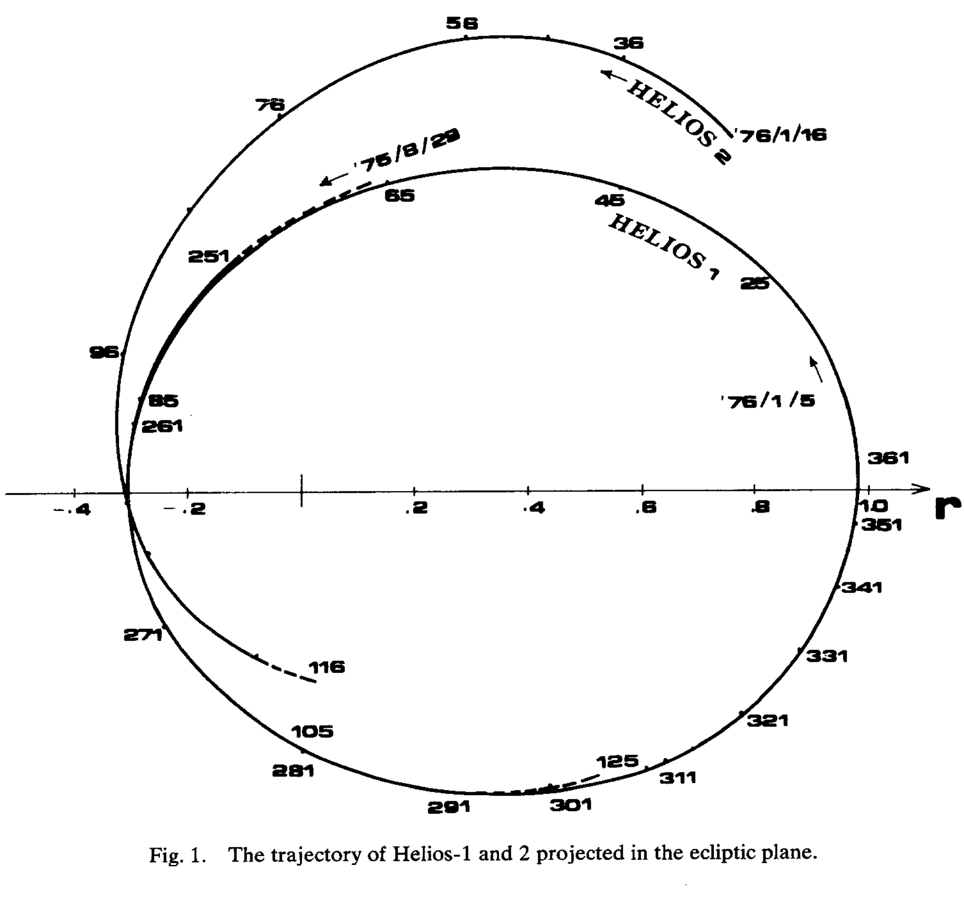

Fig. 1. The trajectory of Helios-1 and 2 projected in the ecliptic plane.

Starting with individual data points (the time interval between two consecutive vector field measurements is 0.187 s at the highest bit rate), we computed 12 hr averages of the field components ($\langle B_r \rangle$, $\langle B_\phi \rangle$, $\langle B_\theta \rangle$, $\langle |B_r| \rangle$, $\langle |B_\phi| \rangle$, $\langle |B_\theta| \rangle$) and magnitude ($\langle B \rangle^2 = \langle B_r \rangle^2 + \langle B_\phi \rangle^2 + \langle B_\theta \rangle^2$) as well as a total variance of the field components given by $\sigma_c^2 = \sigma_r^2 + \sigma_\phi^2 + \sigma_\theta^2$ where σ^2 is the variance over 12 hr of the individual field components. The coordinate system adopted in this paper has both $\hat{r}$ and $\hat{\phi}$ in the ecliptic plane while $\hat{\theta}$ is perpendicular to that plane. In this coordinate system, the average angle between the lines of force and the radial direction has been defined by $\mathrm{tg}\ \phi = \langle B_\phi \rangle / \langle B_r \rangle$.

The radial gradients of the field components have been estimated in the following by performing a least squares approximation (log-log scales) of the experimental points to the analytical expression $A(r) = A_0 r^\alpha$ where $A(r)$ is the field element, r is the heliocentric distance, A_0 and α are the parameters of the power law variation; in particular A_0 represents the average estimated value of $A(r)$ at 1 AU. For each quantity $A(r)$ we also determined the value of the correlation coefficient R between $\log A(r)$ and $\log r$.

3. Experimental Results from Helios-2

More than three complete solar rotations have been examined during the primary mission of Helios-2 (the first perihelion, $r = 0.290\,326$ AU, was reached on 17 April (day 108), 1976 at ~02:30 UT). The spacecraft tracking was very good in the period of interest so that we have a nearly continuous sampling of the IMF conditions. Helios-2 observations are shown in Figure 2. Clearly, the IMF sector structure was stable in that period with two recurrent unipolar regions per solar rotation.

The radial gradients of the magnetic field elements are shown in Figure 3 where we plotted vs heliocentric distance the 12 hr average values of each quantity together with the best estimates of the power law variation (solid lines). The detailed results are summarized in Table I, which also includes results from an analysis of two sets of data corresponding to high velocity ($V > 550$ km s^{-1}) and low velocity ($V < 450$ km s^{-1}) solar wind conditions (Rosenbauer, private communication). Regions of velocity gradients have been excluded from this analysis.

The results in Table I confirm that the behaviour of the radial component of the IMF is consistent with Parker's model; moreover the radial dependence of the azimuthal component $\langle |B_\phi| \rangle$ is always very close to theoretical predictions and the observed gradient of the normal component $\langle |B_\theta| \rangle$ is essentially as found by other investigations. As regards to the total field magnitude, Helios-2 observations show agreement with the same model, although the exponent α corresponding to the higher conditions is somewhat larger than usually observed (-1.4–-1.7). In agreement with Behannon (1978), the present observations suggest that the amplitude of the field fluctuations varies with r in the same way that the field strength varies, thus the relative amplitude is only weakly dependent on the heliocentric distance. The observed r^{-3} dependence of total variance of the field components is

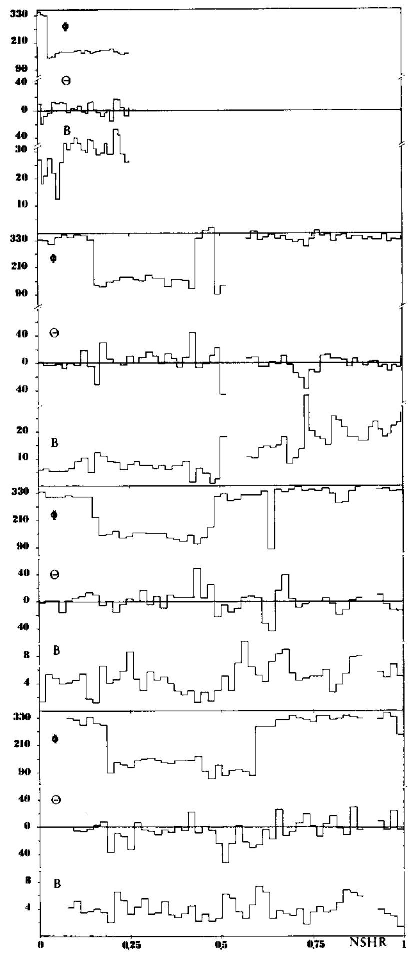

Fig. 2. Magnetic field observations (12 hr averages) by Helios-2 organized per solar rotation. Here $|\mathbf{B}|$ is the field magnitude, θ is the angle between **B** and the ecliptic plane; ϕ is the angle between the ecliptic plane component of **B** and the radial direction.

also consistent (Belcher and Burchsted, 1974) with a negligible local generation (or damping) of Alfvénic fluctuations.

As we suggested in Paper 1, a comparison of high and low velocity data sets confirms that the gradients of the field components are essentially unaffected by the amplitude of the solar wind velocity. It is, however, significant that during high velocity conditions the correlation coefficients are always remarkably larger and the uncertainties in either A_0 or α are significantly smaller. This clearly favors the idea of a more organized field geometry during high velocity conditions. This feature is confirmed by the observed behaviour of the tg ϕ parameters which, (although with low correlation coefficients) are much closer to the expected r^{+1} dependence during higher velocity conditions. Our estimates of the average field components at 1 AU

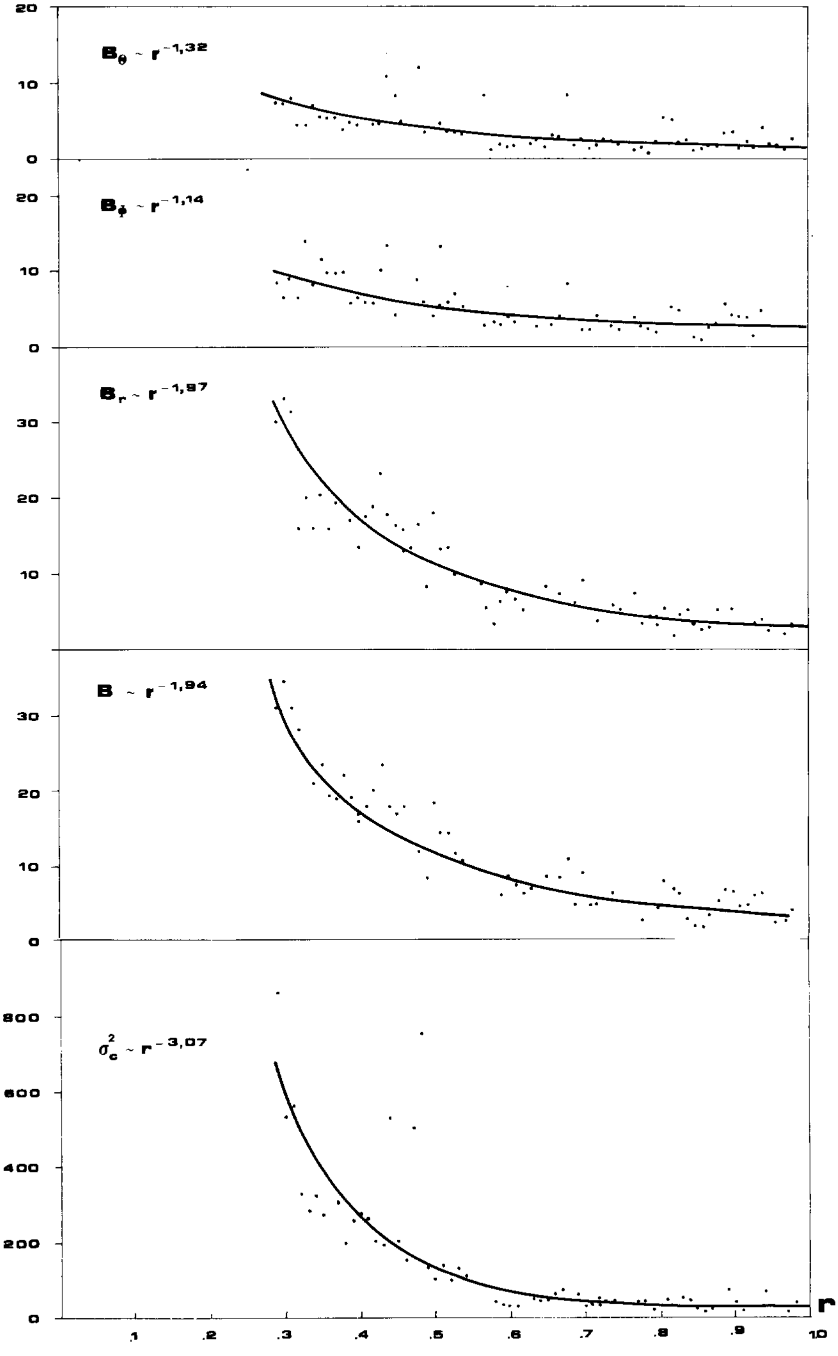

Fig. 3. 12 hr averages of the field elements by Helios-2 vs the heliocentric distance. Solid line corresponds the least squares approximation of the experimental points.

TABLE I

Results from Helios-2

	All data $0.29 \leq R \leq 0.98$			High velocity ($550\ \mathrm{km\ s^{-1}}$) $0.29 \leq R \leq 0.98$			Low velocity ($450\ \mathrm{km\ s^{-1}}$) $0.31 \leq R \leq 0.98$		
	A_0	α	R	A_0	α	R	A_0	α	R
$\langle \lvert B_r \rvert \rangle$	2.77 ± 0.10	-1.97 ± 0.06	0.93	2.77 ± 0.10	-1.97 ± 0.05	0.97	2.47 ± 0.23	-2.02 ± 0.16	0.87
$\langle \lvert B_\phi \rvert \rangle$	2.43 ± 0.11	-1.14 ± 0.08	0.74	2.19 ± 10	-1.13 ± 0.07	0.86	2.96 ± 0.34	-1.07 ± 0.20	0.61
$\langle \lvert B_\theta \rvert \rangle$	1.59 ± 0.09	-1.32 ± 0.09	0.74	1.44 ± 0.07	-1.34 ± 0.08	0.88	1.95 ± 0.29	-1.32 ± 0.25	0.59
$\langle B \rangle$	3.29 ± 0.17	-1.84 ± 0.08	0.87	3.28 ± 0.11	-1.86 ± 0.05	0.97	3.45 ± 0.48	-1.64 ± 0.24	0.69
σ_c^2	14.80 ± 1.0	-3.07 ± 0.12	0.89	14.10 ± 0.73	-3.20 ± 0.08	0.98	16.31 ± 3.22	-2.97 ± 0.34	0.78
$\sigma_c / \langle B \rangle$	1.17 ± 0.06	0.30 ± 0.08	0.27	1.14 ± 0.05	0.26 ± 0.06	0.43	1.17 ± 0.16	0.16 ± 0.23	0.09
$\mathrm{tg}\, \phi$	0.89 ± 0.09	1.21 ± 0.17	0.23	0.65 ± 0.08	1.09 ± 0.18	0.32	1.59 ± 0.38	1.47 ± 0.40	0.46

(A_0 values in Table I) are also in agreement with the expected spiral model ($B_\phi = B_r$ tg $\Omega r/V_{sw}$). Indeed, while the higher velocity data agree with a 550 to 560 km s^{-1} solar wind, the lower velocity observations would be more consistent with a solar wind velocity of 350–370 km s^{-1}, and this is in agreement with the experimental observations (Rosenbauer, private communication).

4. Experimental Results from Helios-1

The analysis of Helios-1 observations has been here extended to the time period 8 September (Day 251), 1975 to 28 April (Day 119), 1976. In that period, the spacecraft made a complete revolution around the Sun (see Figure 1) and went back to a heliocentric distance of 0.6 AU. The time interval has been divided into two periods (8 September to 24 December and 25 December to 28 April) and for each period we determined the radial gradients of the field elements. Unfortunately the spacecraft telemetry coverage was not as good as in the case of Helios-2. The 12 hr averages of the field components were computed only when at least 3 hr of data were available. In this sense the percentage of available 12 hr averages is 74% and 88% respectively. For this reason, Helios-1 observations have been analyzed without any internal separation between higher and lower solar wind velocities. This does not imply any special limitation. The experimental results provided in Paper 1 and in the previous paragraph show that the observed gradients are not appreciably affected by the amplitude of the solar wind velocity. Results of our analysis are summarized in Table II.

TABLE II

Results from Helios-1

	8 September to 24 December			25 December to 28 April		
	A_0	α	R	A_0	α	R
$\langle\lvert B_r\rvert\rangle$	2.75 ± 0.17	−1.94 ± 0.10	0.85	2.36 ± 0.16	−2.06 ± 0.09	0.86
$\langle\lvert B_\phi\rvert\rangle$	2.83 ± 0.19	−1.05 ± 0.11	0.62	2.42 ± 0.17	−1.13 ± 0.10	0.67
$\langle\lvert B_\theta\rvert\rangle$	1.74 ± 0.14	−1.24 ± 0.12	0.62	1.41 ± 0.10	−1.35 ± 0.10	0.71
$\langle B\rangle$	4.44 ± 0.27	−1.58 ± 0.10	0.80	3.85 ± 0.24	−1.56 ± 0.09	0.80
σ_c^2	9.89 ± 1.17	−3.21 ± 0.18	0.81	9.46 ± 0.94	−3.24 ± 0.14	0.87
$\sigma_c/\langle B\rangle$	0.71 ± 0.05	−0.03 ± 0.11	0.02	0.80 ± 0.07	−0.05 ± 0.12	0.04
tg ϕ	1.52 ± 0.25	1.58 ± 0.25	0.44	1.07 ± 0.21	1.20 ± 0.27	0.32

Results of Table II are essentially similar to those obtained by Helios-2 and shown in Table I. Some differences in the correlation coefficients and the higher values of the statistical uncertainties may well be a consequence of less smoothing of data due to longer data gaps. The data gaps are also likely to be responsible for the smaller values of both the absolute and relative amplitudes of the field fluctuations; most of the σ_c values have been computed over time intervals between 6 and 8 hr.

5. A Discussion of the Combined Helios-1 and 2 Observations

Detailed analysis of the 12 hr averages of the IMF components observed by Helios-1 and 2 spacecraft (we are here also referring to Paper 1) allowed an investigation of the gradients of the field parameters between 0.3 and 1 AU. The results support most of the conclusions drawn by previous investigations. However some new results are obtained when the combined Helios-1 and 2 observations are compared with theoretical models. Briefly however the principal conclusions of our investigation are the following:

5.1. The Radial Component B_r

As suggested by previous investigations (Behannon, 1978) the agreement between the observed gradient of the radial component B_r and the theoretical predictions is always very good and essentially independent of the solar wind velocity, as expected from theory. The correlation coefficient between B_r and r (on log-log scale) is usually large (between 0.85 and 0.97) and the exponent α of the power law variation is -2 within the natural variation and the experimental uncertainties.

5.2. The Azimuthal Component B_ϕ

Temporal and longitudinal variations of the solar wind velocity are expected to influence the behaviour of the azimuthal component B_ϕ. This might explain the smaller correlation coefficients which are determined for this component. In any case it is significant that the gradients which we determined are very close to theoretical predictions whereas results from previous investigations did not find such agreement. This might be considered a consequence of the fast approach of the Helios spacecraft to the Sun: it allows us to get data which are less affected by the long term evolution of the steam structure of the solar wind.

5.3. The Spiral Model

The poor correlation coefficients and some unrealistic estimates at 1 AU suggest that the tg ϕ behaviour is much too affected by the local fluctuations in the field geometry to allow a detailed investigation of its radial dependence. A comparison with the expected spiral direction can still be conducted by deducing the average solar wind velocity using the estimated values of B_r and B_ϕ at 1 AU. Helios-2 observations are consistent with theory during both higher and lower velocity conditions.

5.4. The Normal Component B_θ

The normal (to the ecliptic plane) component B_θ shows a radial dependence very much the same as in previous investigations. Its amplitude moreover is of the order of 60% of B_ϕ at 0.3 AU.

We also investigated the behaviour of this perpendicular component in a coordinate system in which $\hat{r}'$ and $\hat{\phi}'$ lie both in the solar equatorial plane and $\hat{\theta}'$ is perpendicular to this plane. Results of our analysis are in Table III.

TABLE III
The normal component of the IMF

	Helios-2 (all data)			Helios-1 (8 September to 24 December)			Helios-1 (25 December to 28 April)		
	A_0	α	R	A_0	α	R	A_0	α	R
B_θ	2.33 ± 0.12	-0.78 ± 0.09	0.56	2.00 ± 0.20	-0.77 ± 0.15	0.61	2.00 ± 0.18	-0.86 ± 0.12	0.69

These results are quite interesting: indeed they are consistent (cf. Tables I and II) with a less steep gradient of the normal component and an increased amplitude at ~1 AU. The other field components, of course, are essentially unaffected by the rotation of the coordinate system.

5.5. The Amplitude of Directional Fluctuations

Our definition of the total variance σ_c^2 is such that this parameter includes contributions from all fluctuations with period less than 12 hr (of course we are here particularly referring to Helios-2 observations which are less affected by the data gaps). Since the power of magnitude fluctuations is much smaller than the power of purely directional fluctuations (Behannon, 1978 and papers therein referred), σ_c^2 has been usually considered a good indicator of directional fluctuations of the IMF. When compared with Mariner 10 observations, (Behannon, 1978) the experimental results by Helios would suggest a relative amplitude of directional fluctuations $\sigma_c/\langle B\rangle$ essentially independent of heliocentric distance. As expected, our estimates of $\sigma_c/\langle B\rangle$ at 1 AU are larger than those provided by Mariner 10 which include only contributions of periods less than 3 hr. On the other hand Helios observations are consistent with the conclusions drawn by Behannon (1978) who proposed that fluctuation amplitudes with periods ~1 day may become larger than the mean field strength.

The observed r^{-3} dependence of σ_c^2 (extensively confirmed by Helios spacecraft) has been often interpreted (see for example, Belcher and Burchsted, 1974) in terms of negligible local generation or damping of Alfvén waves in the solar wind. As explicitly remarked in Paper 1, our feeling is that the observed gradients might be considered a necessary, but not sufficient, condition for stable transverse Alfvén waves in the solar wind. In particular we emphasize that Helios-2 observations confirmed (see also Paper 1) that the power law variation is essentially independent of the amplitude of the solar wind velocity while a large contribution of Alfvén waves to the total variance is expected during higher velocity conditions.

5.6. The Relationship to the Velocity Pattern

The correlation coefficients between the field elements and the heliocentric distance and the uncertainties of the power law parameters are remarkably better during higher velocity conditions. This feature might be interpreted in terms of more regular organization of the field geometry during higher velocity conditions.

This is well consistent with the current understanding of the solar wind flow in terms of a more or less regular sequence of high velocity streams.

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