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THE ÉCLIPSE OF GAMMA PERSEI

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I. INTRODUCTION

In September 1990 the binary-star system γ Persei was seen by about a dozen people to go into eclipse when one of its components occulted the other.

Notwithstanding that the eclipse was detectable (although hardly conspicuous) to the naked eye, no such event had ever been noticed in the system previously. As an eclipsing binary, γ Per is distinguished by its brightness, which is second only to that of its neighbor β Persei (Algol), among systems exhibiting eclipses observable with the unaided eye. It is also one of the very few objects for which eclipses were predicted from other data rather than being discovered photometrically.

The duplicity of γ Per was first recognized by Miss Maury (1897), who perceived that late-type and early-type features were superposed in the spectrum of the system. Radial-velocity observations at the Lick Observatory showed that the object was also a spectroscopic binary in the sense of showing velocity variations (Campbell 1908); McLaughlin (1947) subsequently determined the orbit, which has a period of about 14.6 years. The system has not been reliably measured as a visual binary, but it was resolved, soon after the invention of speckle interferometry, by the originator of the method (Labeyrie et al. 1974). Since then it has been kept under reasonably regular surveillance, particularly by McAlister and his colleagues at Georgia State University. In 1987 Popper & McAlister published an elaborate synthesis of spectroscopic and speckle data, and concluded that there was a possibility of eclipses at the times of conjunction, the next of which would be in late 1990. At such a time the primary component, a red giant of spectral type about G8 III, would be in front of its much smaller but hotter A-type companion.

Meanwhile, the first-named author of the present paper had been observing the radial velocity of the primary star since 1981. As the time of the 1990 conjunction approached, he was able to refine the prediction of its date to September 15, with an uncertainty of only a few days (instead of a few months, as it had been before). Upon reviewing the evidence presented by Popper & McAlister he was pretty well convinced that there *would* be an eclipse then. Accordingly, he alerted a number of photometrists, including most of the other authors of this paper, to the likelihood and prospective nature of the event. He himself requested, and was granted, observing time on the Palomar Observatory 200-inch reflector to make spectroscopic observations. An informal report of the success of both the photometric and the spectroscopic campaigns has already been published elsewhere (Griffin 1991, Schroder & Griffin 1991); our paper now presents the photometric data and interprets them in terms of a physical model, based on that of Popper & McAlister, of the γ Per system.

II. PHOTOMETRY

The telescope apertures used by the respective authors are listed in Table 1, which also serves as a key to the meanings of the symbols used in plotting the observations in Figure 1. The sites from which the observations were made were at or near the authors' respective addresses as given at the head of this paper, with the exception that Schroder observed with his portable reflector while on vacation near Revest-du-Bion, France (a little to the north of the Haute-Provence Observatory). All observations were made in the UBV system, and were transformed as nearly as possible to the standard system. The Japanese observers have applied supplementary zero-point adjustments, which seemed to be needed to bring their measurements into systematic agreement with the majority of the others. The comparison star used by all observers was τ Per, which is only two degrees away from γ Per and is extremely well matched in its colors, although it is a magnitude fainter. By an extraordinary coincidence, τ Per is another composite-spectrum binary whose orbit has long been known but in which eclipses were only recently discovered; several of the present authors participated in a campaign to observe

TABLE 1.
Observers Contributing to the γ Per Eclipse Campaigns

Observer	Aperture in.	Symbol (Fig. 1)
Snyder	10	+
Schroder	6	◇
Pray		✡
Ohshima	8	✱
Tokoro	10	△
Clark	12	
Williams	11	×
Houchen	8	▽
Arai	11	○
Krisciunas	6	□
Watson	10	

the eclipse of τ Per in 1989 (Hall et al. 1991) when the respective roles of the variable and the comparison star were reversed! The check star was ι Per. No significant variability was noted in either the comparison or the check star.

A chronological list of the measurements made around the time of the primary eclipse of γ Per in September 1990 is given in Table 2. The data are plotted directly against time in Figure 1. They obviously show an eclipse that was total for about a week and had depths of about $0^m.28$ in V, $0^m.54$ in B, and $0^m.88$ in U.

III. MODELING THE PHOTOMETRY

One straightforward application of the eclipse photometry is to split the luminosity of the system between the component stars. During totality the late-type primary star is seen alone, so its magnitude and colors are measured directly; the increased brightness out of eclipse is due to the secondary star. In the presently described campaign, all magnitudes were measured differentially, and we therefore relied on the catalogued magnitudes of γ Persei (Hoffleit 1982) to provide the out-of-eclipse baseline. The magnitudes of the components, and of the system, are given in Table 3.

Another immediate deduction from the observations (although here we also need some input from the data of Popper & McAlister 1987) concerns the length of the eclipse chord, which sets a lower limit to the diameter of the primary star. The radial-velocity orbit of the primary furnishes an accurate value of 16.0 km s^{-1} for the velocity of that component in the direction transverse to the line of sight at the time of the eclipse. To obtain the relative velocity of the components, the velocity of the secondary must be added: it is q times that of the primary, where q is the mass ratio in the sense M_1/M_2 and its value according to Popper & McAlister is 1.5, so the total relative transverse velocity is 40 km s^{-1}. The duration of totality, multiplied by the relative velocity, evidently fixes the length of the eclipse chord between moments of internal

TABLE 2.
Magnitudes of γ Per with respect to τ Per

Date (1990)	m(γ) - m(τ) V	B	U	Observer
Aug 22.439	-1.010			Snyder
24.402	-1.010			Snyder
26.31	-1.016	-1.058		Williams
27.600	-0.993	-1.043	-1.051	Ohshima
30.648	-1.007	-1.077	-1.089	Ohshima
31.150	-0.993			Pray
Sept 1.106	-1.014			Pray
2.25	-1.003	-1.053		Williams
3.649	-1.028	-1.081		Tokoro
3.88	-1.00			Houchen
4.083	-1.017			Pray
5.080	-1.025			Pray
5.363	-1.013			Snyder
6.101	-0.988			Pray
8.396	-1.012			Snyder
8.694	-0.983	-1.009		Tokoro
8.93	-0.99:			Houchen
9.091	-1.013			Pray
9.684	-1.017	-1.079		Tokoro
10.94	-1.003	-1.047		Schroder
11.104	-1.001			Pray
11.280	-1.019			Snyder
11.706	-0.971	-0.992		Tokoro
12.01	-0.933	-0.902		Schroder
12.640	-0.791	-0.613		Tokoro
12.97	-0.735	-0.506		Schroder
15.92	-0.71:	-0.53:		Schroder
16.057	-0.727			Pray
16.292	-0.732			Snyder
17.35	-0.731	-0.514		Williams
17.38		-0.470		Krisciunas
17.83	-0.740			Houchen
18.00	-0.74	-0.51		Schroder
18.274	-0.738	-0.560		Pray
18.550	-0.849	-0.548		Arai
18.600	-0.794	-0.471		Tokoro
18.98	-0.749	-0.507	-0.178	Schroder
19.066	-0.741	-0.568		Pray
19.85	-0.717			Houchen
20.03	-0.730	-0.507	-0.162	Schroder
20.286	-0.744	-0.535		Snyder
20.589	-0.770	-0.543	-0.294	Ohshima
20.643	-0.779	-0.549	-0.301	Ohshima
20.666	-0.816	-0.560		Arai
20.930	-0.831	-0.591		Schroder
21.007	-0.86	-0.734		Schroder
21.260	-0.920	-0.865		Snyder
21.586	-0.984	-0.996	-0.996	Ohshima
21.627	-0.974	-0.996	-0.973	Ohshima
21.690	-0.974	-1.001	-0.980	Ohshima
22.29	-1.009	-1.051		Williams
22.673	-1.011	-1.069		Tokoro
22.747	-1.000	-1.060		Arai
24.157	-1.008	-1.045		Pray
24.93	-1.003	-1.066		Watson

TABLE 3.
Magnitudes of the γ Per System and of its Component Stars

	V	B	U	(B-V)	(U-B)
Total system (observed, out of eclipse)	2.93	3.63	4.08	0.70	0.45
Adopted difference from τ Per (comp. star)	1.010	1.052	1.07		
Measured depth of eclipse	0.28	0.54	0.88:		
Primary (observed alone, in total eclipse)	3.21	4.17	4.96:	0.96	0.79:
Secondary (system minus primary)	4.54	4.65	4.72:	0.11	0.07:

contact, and thereby provides a minimum value— in this case 25 Gm or 36 $R_\odot$ (1 Gm = 10^6 km = 1.44 $R_\odot$) for the difference in diameters of the components. Since Popper & McAlister give the radii of the components as 21 and 3.9 $R_\odot$, implying a difference in diameters of 34.2 $R_\odot$, it is clear that even the minimum size of the giant is slightly greater than their figure, unless indeed the secondary is considerably smaller than they suppose. An eclipse chord of given length is of course compatible with a stellar diameter that is greater by any arbitrary amount: the bigger the star the higher must be the inferred latitude at which the eclipse path is seen projected. See Figure 2.

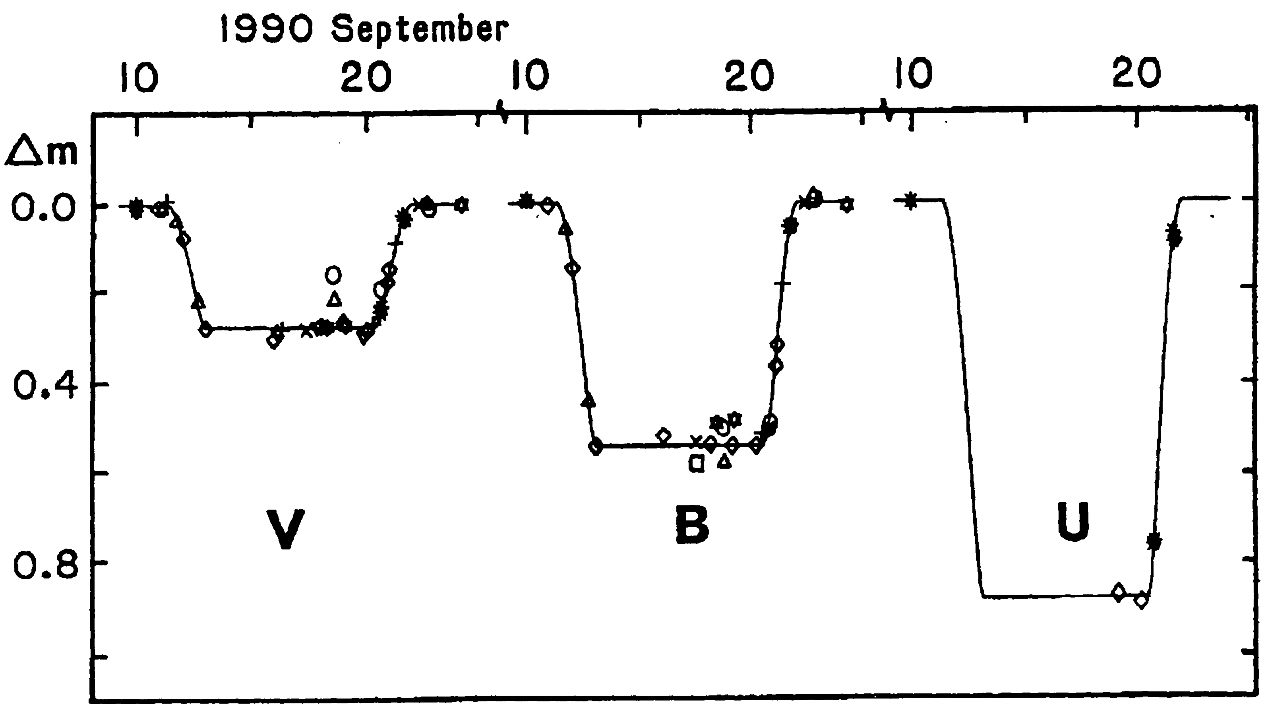

FIGURE 1. Light-curves of γ Persei during the eclipse of September 1990. The loss of light in magnitudes is plotted against the UT date in each of the three colors V, B, and U. The key to the symbols distinguishing the various observers' photometry is to be found in Table 1. Measures made before September 10 have been averaged for each observer individually and plotted as if made on that date. The lines represent the light-curves corresponding to the model adopted for the system.

In a calculation analogous to that of the eclipse chord across the giant component, we can use the duration of the partial phase to give the upper limit to the diameter of the secondary star. If the limb of the giant may be considered to be locally straight in the area relevant to the eclipse - which is an adequate approximation where the stars are of very disparate sizes and the eclipse occurs along a low-latitude chord, as is the case here - then the diameter of the dwarf is just the distance corresponding to the partial-eclipse duration times the cosine of the latitude of the eclipse chord (Figure 3).

To obtain a more rigorous modeling of the eclipse light-curve we have made use of a computer program written by R.E.M. Griffin. The program is based on simple principles that are readily explained here, as follows. The dwarf (secondary) star travels at a specified rate along a trajectory that is treated as consisting of a series of suitably small steps. The trajectory passes at a certain minimum distance, the 'impact parameter', from the center of the giant star, which is regarded as fixed. The impact parameter and the radii of the two stars are disposable parameters in the model. At each successive

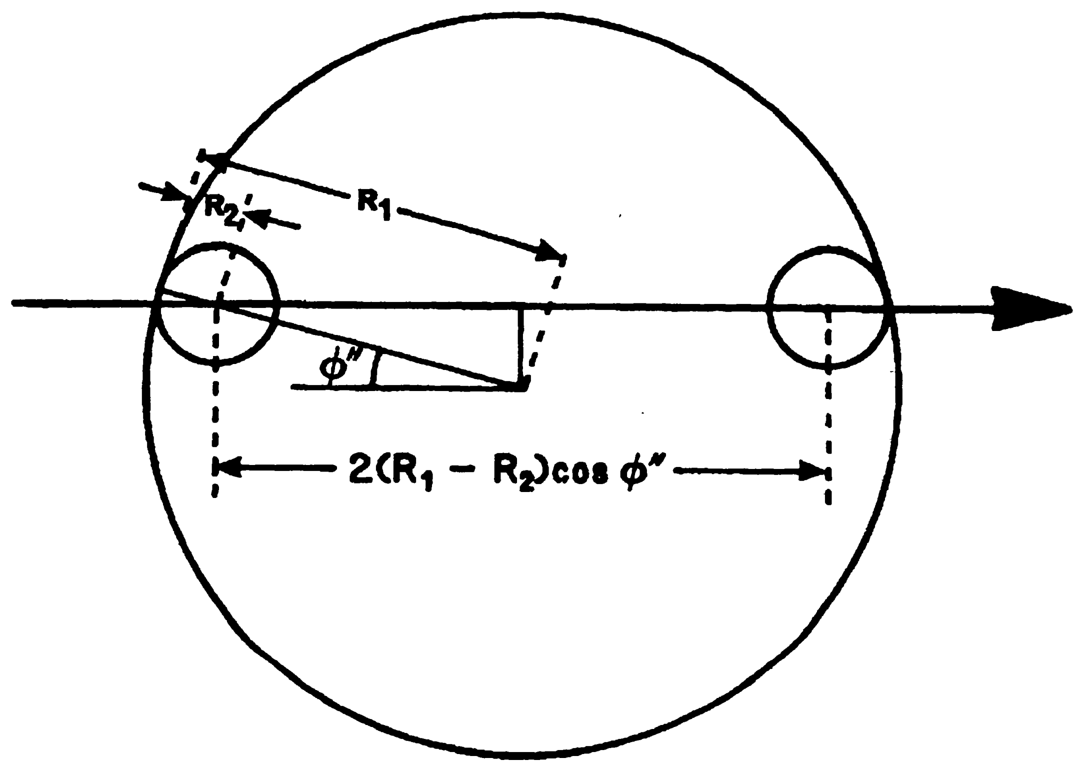

FIGURE 2. Geometry of the eclipse. The length of the total-eclipse chord, between the internal contacts as shown, is $V_1(1 + q)D$, where V_1 is the transverse velocity (known from the orbit) of the primary star, q is the mass ratio, and D is the duration of totality. It is also $2(R_1 - R_2)\cos\phi''$, as the diagram attempts to show. When ϕ'' is small it is very nearly the same as the latitude ϕ of the eclipse chord; also, its cosine is then close to unity, so $2(R_1 - R_2) \approx V_1(1 + q)D$. That is certainly the case for γ Per, so all that we can say about the latitude of the eclipse chord is that its cosine is about 1, so the latitude is indeterminately low.

position in its trajectory the dwarf's brightness is determined as follows. The star is viewed by the computer as being the sum of a lot of elementary areas constituting a square grid; the fineness of the grid can be specified, but in practice there is no advantage in going finer than a 20x20 mesh, so we have used elements that are each one-tenth of the dwarf's radius on a side. The computer looks at each of the 400 elements in turn: if it sees that that particular element is inside the boundary of the dwarf star but outside the limb of the giant, it knows that the brightness is non-zero and must be assigned according to a specified degree of limb-darkening and its distance from the center of the star's disk. The brightnesses of all the elements are summed; the total brightness of the dwarf outside eclipse is normalized to a value that bears the correct ratio to that of the giant, and the same normalization is maintained throughout. As the dwarf star in the model is stepped along its trajectory the light-curve is built up.

When applied to the case of interest, the program readily models the eclipse light-curves in all three colors as accurately as the light-curves themselves are defined by our observations; the model curves have been superimposed on the photometry in Figure 1. It is, however, possible to fit the photometry with a whole family of models, and it is necessary to appeal to other considerations to make an informed choice. The reason for the non-uniqueness of the solution is easily explained. The length of the eclipse chord can be maintained, as remarked above, at the required value despite any increase of the size attributed to the giant star above some lower limit. The larger the giant, the larger

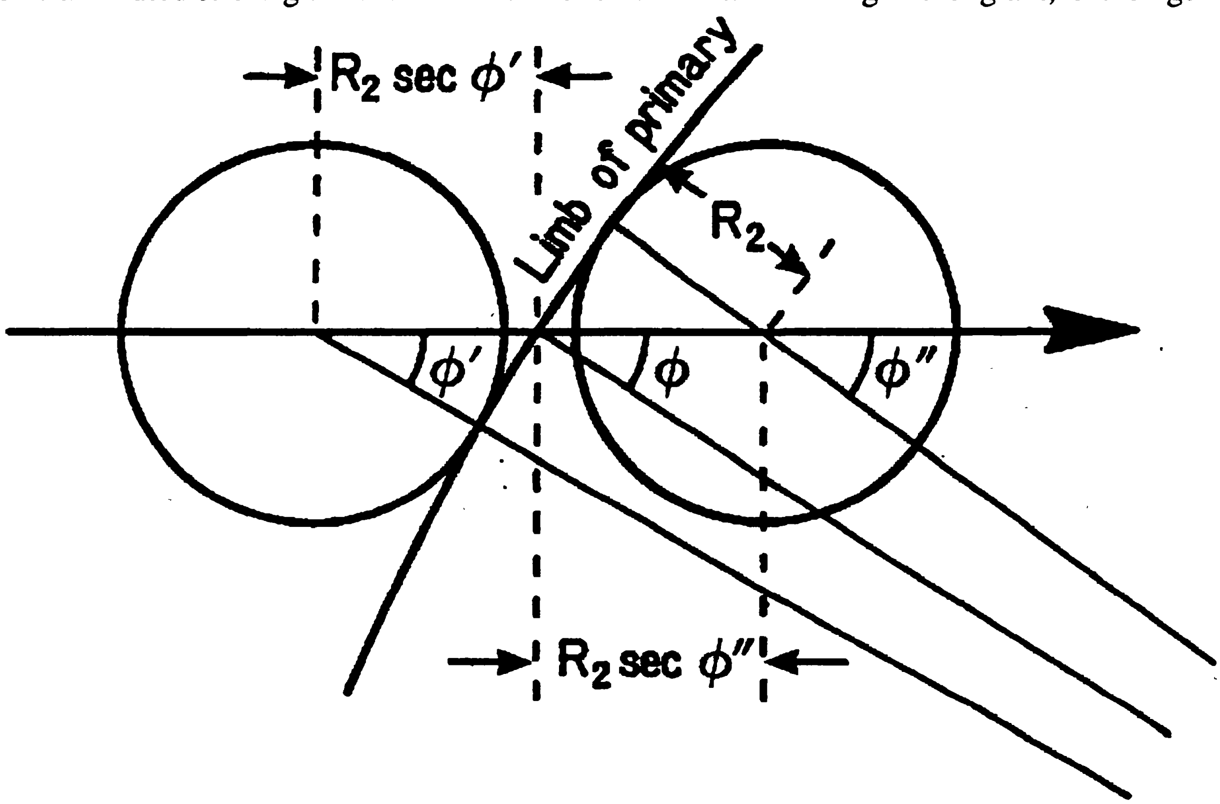

FIGURE 3. Geometry of the partial phase of the eclipse. The length of the partial-eclipse chord, between the external and internal contacts as shown, is V_1 (1 + q) d, where d is the duration of the partial phase. It is also R_2 sec ϕ'' + R_2 sec ϕ' , as the diagram attempts to show. When the latitude ϕ of the eclipse is low, $\phi'' \approx \phi \approx \phi'$ and the secants of all three angles are close to unity, so the length of the partial-eclipse chord is approximately $2R_2$; that is the case with γ Per.

TABLE 4.
Magnitudes of γ Per with respect to τ Per

Date (1991)		m(γ)-m(τ) V	m(γ)-m(τ) B	Observer
July	22.410	-0.994		Clark
	26.417	-0.996		Clark
	28.422	-1.011		Clark
	31.386	-1.009		Clark
Aug	2.406	-0.981		Clark
	3.461	-1.005	-1.050	Snyder
	7.460	-0.997	-1.045	Snyder
	9.472	-0.993	-1.039	Snyder
	11.400	-0.986		Clark
	16.417	-1.006		Clark
	18.353	-1.006		Clark

the impact parameter and the higher the latitude of the chord. The duration of partial eclipse can be adjusted merely by altering the radius attributed to the dwarf star; the higher the latitude of the eclipse chord the smaller must be the dwarf. Thus the family of solutions that provide satisfactory modeling of the photometry has increasing giant radii matched by decreasing dwarf radii. The solution that is most nearly compatible with the conclusions of Popper & McAlister (1987), which were of course based on criteria entirely independent of the eclipse photometry, is one in which the eclipse occurs along a diameter of the giant— or, to put it more accurately, it occurs at an indeterminately low latitude where the length of the eclipse chord is not distinguishable from the giant's diameter. The radii required for the stars are then 22.2 $R_\odot$ for the giant and 3.9 $R_\odot$ for the dwarf; Popper & McAlister give 21 and 3.9 $R_\odot$ respectively. An impact parameter that required a significantly increased radius for the giant, necessitating a correspondingly decreased radius for the dwarf, would worsen the agreement for both stars. Ultimately— perhaps soon— it will be possible by optical interferometry to determine the impact parameter independently; when thus constrained, the eclipse photometry together with an accurate double-lined radial-velocity orbit will determine the sizes of both stars uniquely.

The photometric solution provides the date of the mid-time of the eclipse as 1990 September 16.67, to an accuracy of the order of 0.01 day. Within a couple of cycles of the 15-year orbit the period ought to be known to one part in a million.

IV. THE SECONDARY ECLIPSE

The radial-velocity orbit showed that a secondary eclipse, in which the hot dwarf star would transit across the disk of the giant, would occur in 1991, about the end of July. It could be expected to last a little longer than the primary eclipse, since it would occur somewhat further from periastron when the stars were therefore not moving quite so quickly past one another. Observationally it would be an inconspicuous phenomenon, because the disparity in the sizes of the stars implies that only about 1/30 of the disk of the giant would be occulted: the depth of the eclipse would be hardly $0^m.03$ in V, and even less in B and U, where a more substantial part of the light of the binary system is contributed by the secondary star itself and is unaffected by the eclipse. Nevertheless, such an event is in principle of great interest: not only would its timing refine the determination of the orbit, but if a meaningful light-curve could be obtained it would give direct information on the limb-darkening of the giant star as the transiting secondary star occulted successively a series of equal areas of the giant's disk from the limb practically to the center and out again.

Unfortunately, an event which is of only marginal observability and which, moreover, takes place in the pre-dawn sky is not the most popular type of event for observers. Nevertheless, two of the present authors did attempt to observe the secondary eclipse; the photometry is presented in Table 4. It is difficult to draw any firm conclusion from those data. The very consistent measures by L.F.S. provide reasonable assurance that the eclipse did not begin or end between August 3 and 9; the two faintest measures by W.E.C. are those of August 2 and 11, suggesting that the eclipse may have bracketed those dates. But the evidence is uncomfortably marginal, and we cannot safely base any discussion upon it.

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