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On the crossing mode of the long-period Cepheid SV Vulpeculae

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Abstract. The Cepheid SV Vul is demonstrated to be in the second crossing of the instability strip on the basis of its well-defined period decrease of -214.3 ± 5.5 s yr^{-1}. Recent arguments from its atmospheric abundance pattern that it is in the first crossing are not supported by the historical photometric data. Furthermore, an examination of atmospheric abundance patterns for other Cepheids in advanced strip crossing modes suggests that the presence of CNO-processed material in the atmospheres of intermediate-mass stars does not arise from red supergiant dredge-up phases but from meridional mixing during previous evolution as rapidly-rotating main-sequence B-type stars.

Key words. stars: variables: Cepheids – stars: abundances – stars: evolution

1. Introduction

When intermediate-mass main-sequence stars initiate hydrogen burning through CNO processing, the initial abundances of carbon (C), nitrogen (N), and oxygen (O) in a star's convective core gradually converge towards equilibrium values established by the different rates of the reactions in the nuclear chain (e.g., Clayton 1968). The sodium (Na) abundance also increases through a side chain involving neon isotopes (Wallerstein et al. 1984; Sasselov 1986; Luck 1994; Denissenkov 1994). By the end of the main sequence stage, the chemical composition of stellar cores is depleted noticeably in C and slightly in O, and enhanced in N and Na relative to the original values, the specific results depending upon the core temperatures of the stars and a variety of other factors. Such abundance anomalies have long been observed in the winds of Population I Wolf-Rayet stars (e.g., van der Hucht 2001) and the atmospheres of many O and B-type supergiants (McErlean et al. 1999), and more recently in the atmospheres of B-type main-sequence stars (Lyubimkov 1991; Gies & Lambert 1992; Hempel & Holweger 2003) and all rapidly-rotating OB stars (Herrero et al. 2000). Presumably turbulent diffusion and rapid rotation play an important role in bringing CNO-processed material to the stellar surface (Denissenkov 1994; Maeder 2001), although stellar winds and mass loss have long been recognized to be important for Wolf-Rayet stars.

In early computational models of post main-sequence evolution by Iben (1965) and Becker et al. (1977), similar enhancements in CNO-processed material were predicted for the atmospheres of intermediate mass stars of 3–9 $M_{\odot}$ after they became red supergiants, through deep convection in the outer layers of such stars dredging up nuclear-processed material from near the stellar core. Models of 3–9 $M_{\odot}$ stars by Iben (1965), Becker et al. (1977), and Becker (1985) predict extensive blue loops in the evolutionary tracks of most such stars following the onset of core helium burning and shell helium burning, and result in a variety of crossings of the Cepheid instability strip, up to five in some cases. In such circumstances a star might evolve through the red supergiant stage several times. During the first dredge-up at the beginning of core helium burning, one would expect CNO-processed material to appear at the stellar surface. Possible dredge-up stages occurring after a star has evolved through core and/or shell helium burning should produce a different chemical signature at the star's surface, since the triple-alpha process in a star's core increases the abundance of C, and later O, at the expense of elements like N and He. Of course, surface convection must dig deep enough into the core to produce noticeable effects.

Current evolutionary models for intermediate-mass stars of 3–15 $M_{\odot}$ from Meynet & Maeder (2000, 2002), Bono et al. (2000), and Salasnich et al. (2000) produce only one blue loop following the onset of core helium burning, with core dredge-up predicted for only limited ranges of stellar mass. Possible atmospheric contamination arising during evolutionary stages as red supergiants is therefore restricted to stars of specific mass according to the models. Such findings have important consequences for the study of Cepheid variables, the vast majority of which have evolved through earlier stages as red supergiants.

Direct evidence for enhanced CNO-processed material in the atmospheres of Cepheid variables and non-variable supergiants has been presented by Luck (1978, 1994), Luck & Lambert (1981, 1985, 1992), Luck & Wepfer (1981), Andrievsky & Kovtyukh (1996), Andrievsky et al. (1996), and Kovtyukh et al. (1996). One suggested link was to meridional mixing and rapid rotation during the main-sequence stage, but for Cepheids, in particular, it seems possible to use atmospheric abundance patterns as a means of identifying specific instability strip crossing modes for individual variables on the basis of whether or not there is evidence that a dredge-up phase has occurred.

A recent study by Luck et al. (2001) of the abundance patterns in the long-period Cepheid SV Vulpeculae led to their speculation that it might belong to the rare group of Cepheids that are crossing the instability strip for the first time. First crossings occur while the star is in the phase of shell hydrogen-burning, and takes place one or two orders of magnitude more rapidly than later crossings when the star is undergoing either core helium burning (second and third crossings) or possibly shell helium burning (fourth and fifth crossings?). According to Luck et al. (2001), the surface compositions of C, N, O, and Na in SV Vul identify it as having a nearly unmodified abundance pattern, as expected for a star that has not yet reached the first dredge-up stage and did not suffer atmospheric contamination during the main-sequence phase.

Luck et al. (2001) further note that there is no clear photometric criterion by which one can identify instability strip crossing modes of Cepheids confidently, and use that argument to demonstrate that their atmospheric study of SV Vul provides the only strong evidence regarding its crossing mode. That statement is no longer supported by the observational evidence. For several years now it has been recognized that rate of period change for specific Cepheids can provide a relatively clear diagnostic test of crossing mode for individual objects (Turner 1998; Turner et al. 1999; Turner & Berdnikov 2001; Turner et al. 2001). That is particularly true for SV Vul, which has a negative rate of period change entirely consistent with a Cepheid crossing the instability strip for the second time. As we demonstrate here, the atmospheric abundance patterns in SV Vul (Luck et al. 2001) and other Cepheids actually provide information about the effectiveness of main-sequence meridional mixing and possible dredge-up stages during post-main-sequence evolution of intermediate mass stars. But SV Vul is definitely not in the first crossing of the instability strip.

2. Crossing mode of SV Vul

Cepheids represent a mixture of intermediate to high mass stars that are crossing the instability strip at rates consistent with how they generate energy internally: shell hydrogen burning (first crossing), core helium burning (second and third crossings), and possibly shell helium burning (fourth and fifth crossings? – see later discussion). Each instability strip crossing for a Cepheid is also accompanied by gradual changes in overall size and pulsation period, P, as it evolves: increasing mean radius and P during evolution towards the cool side of the HR diagram (first, third, and fifth crossings), and decreasing mean radius and P during evolution towards the hot side of the HR diagram (second and fourth crossings). Since each crossing occurs at a different rate, which may itself be subject to small variations, and at a different luminosity, the rate of period change at a given period is fairly closely related to strip crossing mode, within possible constraints imposed by variations in chemical composition and pulsation mode, e.g. fundamental mode, first overtone, etc. (Berdnikov et al. 1997; Turner et al. 1999). The changes are revealed by parabolic trends in O–C data, where each datum represents the difference between Observed and Computed times of light maximum calculated from a linear ephemeris. The changes amount to mere seconds or minutes per year in pulsation periods of days to months, but the effects are cumulative. The observed offsets from established ephemerides are therefore significant and measurable as differences from the predicted epochs of light maximum amounting to several hours or more – in some cases as offsets of several days.

Two other mechanisms can generate systematic trends in O–C data: (i) binarity, which produces light travel time differences in epochs of light maximum resembling cyclical changes in pulsation period as a Cepheid orbits the system's center of mass, and (ii) random fluctuations in pulsation period, a meandering trend observed for a few Cepheids that apparently originates from minor fluctuations in their periods of pulsation. Of the three effects, evolution, light travel time effects, and period fluctuations, evolution is the most obvious over long time baselines, while light travel time effects are usually marginally detectable at best. Low-level random period fluctuations are conspicuous relative to evolutionary trends and observational scatter for a very small selection of Cepheids, e.g., S Vul, SV Vul, and SZ Tau (Berdnikov 1994; Berdnikov & Pastukhova 1995), but their origin is unexplained.

The case for SV Vul has been presented in some detail previously (Szabados 1981; Berdnikov 1994; Turner et al. 1999; Turner & Berdnikov 2001; Turner & Berdnikov 2003), but can be reiterated here. Table 1 summarizes the observable properties of the Cepheid for reference purposes. Figure 1 presents the O–C data compiled for SV Vul from literature data (Szabados 1981; Berdnikov 1994; Turner et al. 1999), obtained using a linear ephemeris for the star given by:

$$\mathrm{HJD}_{\max} = 2\,443\,723.525 + 45.082\,E, \quad (1)$$

Table 1. Representative parameters for SV Vulpeculae.

Parameter	Value	Source
Period	$45^{\rm d}.0121$	Khurkarkin et al. (1985)
$\langle V\rangle$	7.209	Berdnikov (2002)
$\langle B\rangle - \langle V\rangle$	1.462	Berdnikov (2002)
Blue amplitude	1.63	Berdnikov (2002)
Reddening E_{B-V}	0.45 ± 0.01	Turner (1984)
Progenitor mass	$\sim 17\ M_\odot$	Turner (1996)
Mean radius	$201.0 \pm 6.0\ R_\odot$	Turner & Burke (2002)
Mean $T_{\rm eff}$	4830 K	Turner & Burke (2002)
Luminosity	$1.98 \times 10^4\ L_\odot$	Turner & Burke (2002)

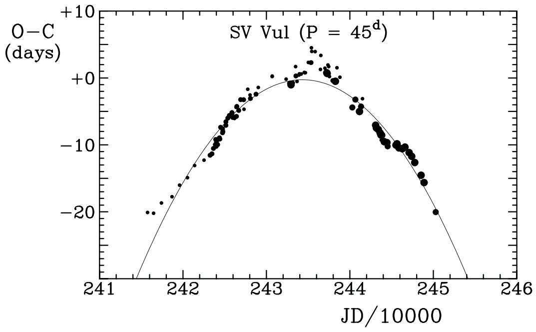

Fig. 1. O–C data for SV Vulpeculae are plotted as a function of the observed Heliocentric Julian Date of light maximum. The size of the symbol increases with increasing weight for the data set. The curve represents the best-fitting parabolic fit to the data.

where E is the number of elapsed cycles. The symbol size in Fig. 1 is scaled by the weight assigned each O–C determination, following the scheme established by Szabados (1977). The O–C data are matched reasonably closely by a parabola indicative of a regular period decrease described by:

$$\mathrm{HJD_{max}} = 2\,443\,722.544 + 45.061022\,E - 1.53 \times 10^{-4}\,E^2.$$

The inferred rate of period decrease for SV Vul, −214.3 ± 5.5 s yr^{-1}, is almost exactly what one predicts for a Cepheid in the second crossing of the instability strip, as demonstrated in Fig. 2. Plotted in the figure are rates of period change derived for a large selection of well-observed Cepheids (see Turner & Berdnikov 2001, 2003), along with computational predictions for various instability strip crossings derived from the stellar evolutionary models of Maeder & Meynet (1988) matched to the observational period-luminosity relation (Turner & Burke 2002) or modified empirically from the relationships published by Saitou (1989). The location of SV Vul in Fig. 2 is very close to what would be predicted for a Cepheid of its period lying near the center of the instability strip and crossing it for the second time. The star is definitely not in the first crossing of the instability strip. For that to be true, its rate of period change must be positive and at a rate two orders of magnitude greater than what is actually observed. Over the last century of observation for the star, its period would have increased by almost 4 days if it were in the first crossing! Such a possibility can be rejected categorically.

Residual trends in the O–C data of Fig. 1 can be attributed to random changes in the pulsation period of SV Vul (see Turner & Berdnikov 2001, for example). Our studies indicate that such fluctuations appear in relatively few Milky Way Cepheids. Most exhibit very regular trends in their O–C diagrams entirely consistent with evolution through the instability strip. Similar conclusions were reached by Pietrukowicz (2003) in a more restricted analysis of period changes in classical Cepheids.

The scattered location of observed rates of period change for Cepheids in Fig. 2 arises mainly from differences in location within the instability strip. Cepheids near the hot edge of the strip, for example, have larger masses and therefore evolve faster than Cepheids of identical period near the cool edge of the strip. Differences in rate of evolution produce a small spread

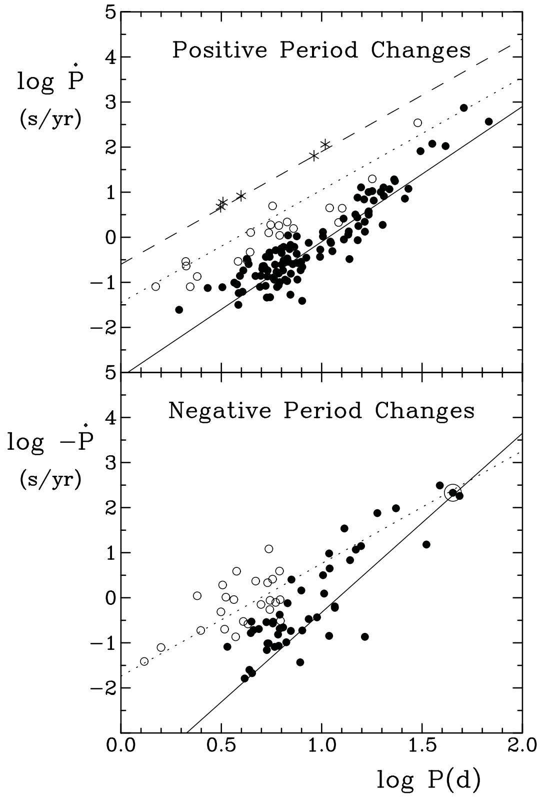

Fig. 2. Observed rates of period change for Cepheids are compared with model and semi-empirical predictions for stars lying in the center of the observed instability strip. From top to bottom the lines in the upper plot (period increases) correspond to first (dashed), possible fifth (dotted), and third (solid) crossings; those in the lower plot (period decreases) correspond to possible fourth (dotted) and second (solid) crossings. Filled circles indicate Cepheids likely to be in the second or third crossing of the instability strip, open circles Cepheids identified as in potential fourth or fifth crossings, and asterisks Cepheids in the first crossing. SV Vul is the circled point in the lower plot.

at constant pulsation period in the rates of evolutionary period change, which can be linked, albeit in preliminary fashion, to location within the instability strip. Current work on Cepheid period changes suggests that pulsation amplitude can be used as a diagnostic for such traits (e.g., Turner 2001), which is how ambiguous cases in Fig. 2 were resolved. Since the work is still in a preliminary stage, however, one should not try to glean too much detail from the diagram. It turns out that any unresolved problems associated with distinguishing between, say, third or fifth (?) crossing, or second or fourth (?) crossing, for individual Cepheids are unimportant here.

An interesting feature of Fig. 2 for the observed rates of Cepheid period change is the spread in $\dot{P}$ for pulsation periods of less than 8 days. It is primarily in that range of periods where the available observational data suggest the existence of Cepheids in what seems likely to be fourth or fifth crossings of the instability strip, despite the negative predictions for such a possibility from current stellar evolutionary models of solar composition stars (Sect. 1). Cepheids pulsating with periods of less than 8 days had main-sequence progenitors of less than ~7 $M_{\odot}$ (Turner 1996), which is close to the threshold for core carbon ignition in evolved stars. Perhaps stars that do not undergo core carbon ignition can pass through intervals crossing the Cepheid instability strip beyond those predicted for core helium burning, at least according to the observational data on Cepheid period changes.

3. Chemical signatures in cepheids

If SV Vul is in the second crossing of the instability strip, why does its atmospheric chemical composition so closely resemble that of a star uncontaminated by CNO-processed elements? The simplest answer is because SV Vul evolved from a slowly rotating main-sequence star and its surface composition was relatively unaffected during an earlier stage as a red supergiant. Presently available from studies by Andrievsky et al. (2002a,b), Luck et al. (2003), and Usenko (2002) is a large selection of atmospheric abundance data for Cepheids, a large proportion of which also have O–C data that allow one to identify likely strip crossing mode from rate of period change. Such data reveal interesting empirical information about the nature of chemical anomalies in Cepheids and how they relate to prior stages as main-sequence stars or as red supergiants subject to possible dredge-up.

Figure 3 illustrates the carbon and oxygen abundances in Cepheids, scaled to iron and to the Sun, relative to similarly scaled sodium abundances. The data were taken from the above sources, and the abundances for SV Vul are indicated. Different symbols distinguish Cepheids that seem likely to be in second and third crossings from stars that seem likely to be in possible fourth and fifth crossings. The cited uncertainties in the abundances are typically ±0.01 to ±0.02 dex, which is roughly the size of the plotted symbols, so the observed scatter in the data is presumably intrinsic in origin rather than the result of observational scatter. There appears to be no difference in the distribution of the data in Fig. 3 arising from the distinction between strip crossing modes, which suggests that second dredge-up stages do not occur for stars in the mass range of Cepheids. It can also be noted that, if sodium abundance is taken as an indicator of the efficiency of the mechanism that brings CNO-processed material to the stellar surface, the mechanism must operate at different levels of effectiveness from one star to another. It is conceivable that the observed chemical signatures of CNO processing (primarily reduced carbon and enhanced sodium abundances) arise mainly from turbulent diffusion during each Cepheid's main-sequence lifetime, with very little change, if any, arising when the star became a red supergiant.

In most Cepheids there is an overall depletion in carbon abundance of about [C/H] = −0.3, which is consistent with what a meridional mixing mechanism would produce during a rapidly-rotating star's main-sequence lifetime (Maeder 2001). The variation from one star to another may reflect differences in mass for the Cepheid progenitors or different rates of rotation while on the main sequence. The two Cepheids that appear to exhibit relatively unmodified carbon abundances are SV Vul and BD Cas (a possible fourth crosser?). Both Cepheids exhibit decreasing pulsation periods, so must have passed through the first red supergiant phase previously.

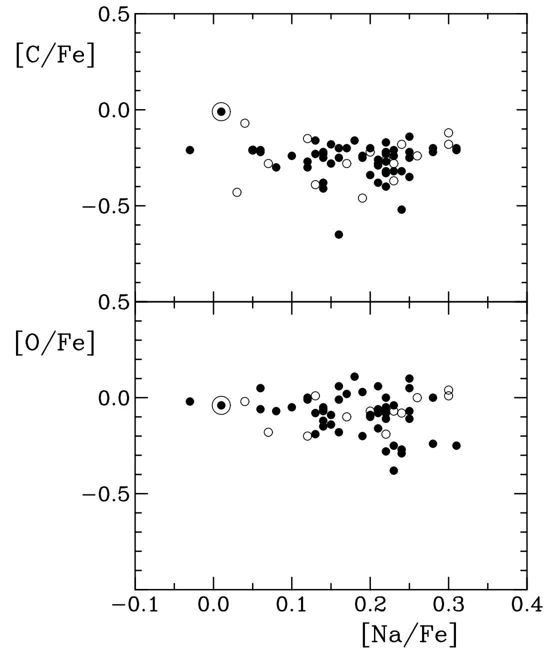

Fig. 3. Carbon (C) and oxygen (O) abundances relative to iron (Fe) are plotted relative to sodium (Na) abundance, scaled to iron, for Cepheids that have both a recent atmospheric abundance study and O–C data to distinguish crossing mode. Filled circles represent Cepheids likely to be in the second or third crossing of the instability strip, open circles to Cepheids in possible fourth or fifth crossings of the strip. SV Vul is the circled point.

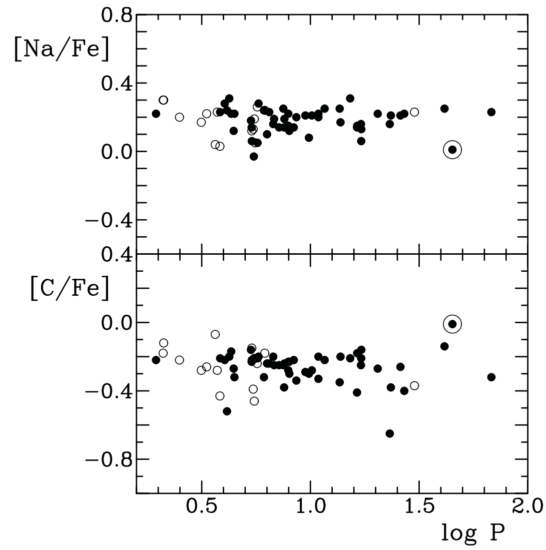

Fig. 4. The abundances of sodium relative to iron ([Na/Fe]) and carbon relative to iron ([C/Fe]) are plotted as a function of the logarithm of pulsation period for each Cepheid. Symbols are as in Fig. 3.

Figure 4 illustrates the data in slightly different fashion, and plots the relative sodium and carbon abundances as a function of Cepheid pulsation period, which is related directly to the star's mass. Again it appears that the efficiency of the mechanism that brings CNO-processed material to the stellar surface is highly variable from one star to another. There is no obvious dependence on pulsation period, for example, which is surprising given predictions for a red supergiant dredge-up phase (e.g., Bono et al. 2000) only for low-mass Cepheid progenitors (pulsation periods less than $\sim 10^{d}$). There may be a slight trend in the data consistent with the expected increase in surface abundance of CNO-processed material with increasing stellar mass (longer pulsation period) predicted by evolutionary models for rotating stars (Maeder 2001). Otherwise, it appears that Cepheids at nearly all periods exhibit similar variations in Na and C abundance, i.e. similar variations in the process by which CNO-processed material is brought to the surface. Presumably there are sufficient differences in main-sequence rotation rate from one star to another to reproduce the observations. The overall scatter in the data and the lack of any distinction between Cepheids in the second and third crossing of the instability strip and those possibly in the fourth and fifth crossing suggests that dredge-up as a red supergiant is relatively unimportant in establishing a Cepheid's atmospheric composition.

The older models of Cepheid evolution published by Becker et al. (1977) and Becker (1985) provide surprisingly good predictions regarding the expected frequency of stars of different pulsational period and crossing mode in the instability strip. For example, only three strip crossings are predicted for stars of 9−20 $M_{\odot}$, and only one strip crossing for more massive objects. The corresponding pulsation periods are 12^{d}–60^{d} and $>60^{d}$, respectively (Turner 1996), which is consistent with the distribution observed in Fig. 2 for Cepheids with well-studied period changes. Contemporary models for 4−20 $M_{\odot}$ stars (e.g., Meynet & Maeder 2002; Bono et al. 2000) appear to generate different predictions that seem to be inconsistent with the present data for period changes in classical Cepheids. The models of Meynet & Maeder (2000) do imply that some high mass stars may terminate their redward evolution in the H-R diagram before their surface temperatures become as low as those of red supergiants, for which there may be observational examples. The O–C data for the 23^{d} Cepheid WZ Car, for example, suggest that it may have switched from a redward crossing of the instability strip to a blueward crossing while still in the strip, as recently as 1972 (Turner et al. 2003). Its rate of period increase during the first three-quarters of the twentieth century was consistent with a third crossing, however, so its more recent period decrease is difficult to explain using current stellar evolutionary models, which do not produce second blue loops. The apparent reversal in period change for WZ Car might also be a short-lived phenomenon, of course.

4. Discussion

Although the available O–C data for the long period Cepheid SV Vul contradict the claim of Luck et al. (2001) that it may be crossing the instability strip for the first time, the existing data base for Cepheid period changes is presently large enough that it can be used with published data for Cepheid atmospheric abundances to investigate the observational effects of stellar evolution on surface composition during post red supergiant stages. As noted here, such data provide interesting insights into the post-main-sequence evolution of intermediate-mass stars, and suggest that peculiar surface abundance distributions in such stars indicative of CNO processing are imprinted during the main-sequence phase, presumably as a consequence of meridional mixing in rapidly rotating stars. Red supergiant dredge-up phases appear to have negligible effects on stellar surface compositions, if indeed they even occur for individual Cepheids. The 45^{d} pulsation period for SV Vul implies a mass of ~ 17 $M_{\odot}$ (Turner 1996), where red supergiant dredge-up is unlikely to occur (Bono et al. 2000). The Cepheid's relatively unaltered atmospheric chemical signature is therefore not surprising, yet a comparison with the results for other long-period Cepheids implies that not even meridional mixing has affected it to any marked extent. Presumably SV Vul was a relatively slow rotator during its prior stages as a B-type main-sequence star, so its atmosphere has remained uncontaminated by CNO biproducts.

The scenario inferred from stellar atmosphere observations suggests that the observed chemical peculiarities in Cepheids and late-type supergiants were imprinted during their main-sequence lifetimes, with little modification, if any, during subsequent red supergiant phases. By extension it can be predicted that true first-crossers of the instability strip will display atmospheric CNO contaminations no different from those exhibited by other Cepheids. Polaris, for example, displays a rapid rate of period change consistent with a first crossing of the instability strip, yet it also displays the sodium enhancement and carbon depletion typical of other Cepheids (Andrievsky et al. 1996).

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