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On the new λ Bootis-type spectroscopic binary systems HD 84948 and HD 171948*

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Abstract. We report the discovery of two new λ Bootis-type spectroscopic binary systems (HD 84948 and HD 171948).

High resolution spectra were analyzed in order to derive abundances as well as astrophysical quantities. It resulted in extreme (HD 171948) and moderate (HD 84948) underabundances of Na, Mg, Si, Ca, Sc, Ti, Cr and Fe with respect to the Sun, thus establishing all four individual stars as true members of the λ Bootis group. These two systems are therefore the first spectroscopic binary systems where both components are λ Bootis-type stars. Furthermore, we have discovered δ Scuti type pulsation for one component of HD 84948 making this star particularly interesting for further observations.

Since many authors have used the rotational velocity for discriminating λ Bootis stars ($v \sin i > 50\,\mathrm{km s^{-1}}$), we note that both components of HD 171948 are the slowest ($v \sin i < 20\,\mathrm{km s^{-1}}$) rotating λ Bootis-type stars known so far.

Using the Hipparcos data, we are able to rule out the diffusion/mass-loss mechanism as origin for these two systems. Pre- as well as Main Sequence evolutionary tracks for the age determination yield consistent results with the predictions of the diffusion/accretion theory, establishing both systems as being *very close to the Main Sequence*. A determination of the orbital elements and/or an asteroseismological investigation of HD 84948 could provide an independent proof of our results.

Key words: binaries: spectroscopic – stars: chemically peculiar; early type; individual: HD 84948; HD 171948

1. Introduction

Up to now, observations and theoretical investigations were not able to clarify the λ Bootis phenomenon. The origin of these nonmagnetic, metal deficient (except of C, N, O and S) Population I, A to F-type stars remained unsolved. Two competing theories were developed in order to solve this problem. First, Michaud & Charland (1986) proposed a diffusion/mass-loss theory resulting in λ Bootis stars at the end of the Main Sequence. Venn & Lambert (1990) and Waters et al. (1992), on the other hand, argued that accretion of metal-depleted gas in early stages of the star formation causes the λ Bootis phenomenon. Turcotte & Charbonneau (1993) concluded from numerical simulations that λ Bootis stars are currently in an accreting phase or have ceased to accrete not later than 10^6 years ago. Circumstellar material (gas and dust) must therefore still be present and detectable (King 1994). As Gray & Corbally (1993) found one λ Bootis star in the young Orion OB1 association, the accretion theory was very much favoured. Recent results (Paunzen & Gray 1997) support the existence of young λ Bootis stars, but the question of whether evolved λ Bootis stars exist, still remains open.

Much effort was spent to further support the accretion theory as the explanation for the λ Bootis phenomenon. The first discussion about the evidence of gas and dust around λ Bootis stars is given by Gray (1988). Bohlender & Walker (1994) reported the detection of a shell for the mild λ Bootis-type star HD 38545. Holweger & Rentzsch-Holm (1995) presented a spectroscopic survey for circumstellar gas among ten λ Bootis stars resulting in one positive and three probable detections. However, their most prominent case with a varying gas component (HD 111786) recently turned out to be a candidate spectroscopic binary system (Faraggiana et al. 1997) consisting of one λ Bootis and one "normal" type component.

Age determinations by Iliev & Barzova (1995), based on Main Sequence evolutionary codes, on the other hand, indicated that λ Bootis stars are rather evolved and in the middle of the Main Sequence. The decision between the two theories remains, therefore, a matter of debate.

In this paper we present two spectroscopic binary systems for which each component belongs to the λ Bootis group. This

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* Based on observations obtained at the Osservatorio Astronomico di Padua-Asiago, McDonald Observatory, the Sierra Nevada Observatory and with the Hipparcos satellite

is proven by an abundance analysis for all four individual stars as described in Sect. 4.

We have used the Hipparcos data to derive exact luminosities in order to determine ages and masses via Pre- and Main Sequence models. It is immediately evident (Sect. 5) that HD 171948 is *very close to the Main Sequence*. Within limits, this is also true for HD 84948.

We suggest tests (e.g. an extensive investigation of the reported δ Scuti pulsation for one component of HD 84948) to prove our results.

2. Target stars

HD 84948 was classified by Abt (1984) as F0Vwl (met: A3); Strömgren photometry supports the metal deficiency. Andrillat et al. (1995) investigated this star in the infrared and reported an asymmetry for the Paschen as well as for Ca and O lines with a shift of 45 kms^{-1}. They interpreted this shift as a shell feature, which is probably incorrect.

HD 171948 is known as a visual binary system (Δm = 5 mag and d = 20″). It was classified as A0Vp (λ Boo) by Abt (1985). Paunzen & Gray (1997) recently confirmed its membership to the λ Bootis group. HD 171948 was one program star for our photometric survey to detect pulsation of λ Bootis stars. Observations yielded a null result with an upper limit of 2.6 mmag in Strömgren b (Paunzen et al. 1997b). No further photometric or spectroscopic data are published in the literature.

3. Observations and reductions

HD 84948 was observed in the night of 17/18.03.1995 on the 1.82 m telescope at the Osservatorio Astronomico di Padua-Asiago. With the Echelle-spectrograph and the 300 lines/mm grating, a resolution of 0.15 Å pixel^{-1} in the range from 4000 to 5700 Å was achieved.

The photometric observations of HD 84948 were obtained on the 0.9 m telescope at the Sierra Nevada Observatory (Granada, Spain) during the nights of 19/20 and 20/21.02.1997. The telescope is equipped with a six channel $uvby\beta$ photometer for simultaneous measurements in $uvby$ and in the narrow and wide Hβ channels, respectively (Grönbech & Olsen 1977). An integration time of 30 seconds and a circular diaphragm of 45″ were chosen. HD 84526 (A3; V = 8.5 mag) and HD 85783 (A2; V = 7.9 mag) were used as comparison stars for the observations.

The spectrum in the range from 4290 to 4730 Å for HD 171948 was obtained in the night of 01/02.04.1996 on the 2.1 m telescope at the McDonald Observatory with the Sandiford Cassegrain Echelle spectrograph resulting in a resolution of 0.035 Å pixel^{-1}.

The Echelle spectra were reduced (bias-subtracting and flatfielding) and normalized with standard IRAF routines. All photometric data were analyzed using standard techniques (Sterken & Manfroid 1992). The differential data were calculated by subtracting one data set from the other. We interpolated linearly between two data points of the comparison star for a given time.

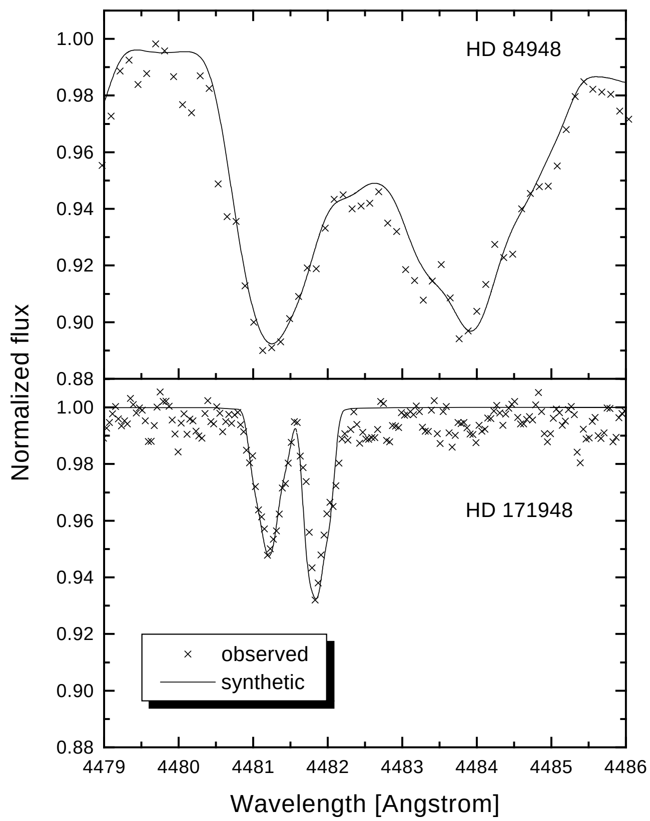

Fig. 1. Observed and synthetic spectra for HD 84948 (upper panel) and HD 171948 (lower panel) around Mg II 4481Å. The synthetic spectra were calculated with the quantities listed in Table 1

4. Model atmospheres and abundance analysis

All hydrogen line profile and model calculations were carried out with Kurucz's ATLAS9 and BALMER9 (Kurucz 1993). The program AAP (Gelbmann et al. 1997) was used to compute and analyze the synthetic as well as the reduced observed spectra.

Starting values for an effective temperature and surface gravity for HD 171948 were based on hydrogen line profiles (Hγ and Hδ). Since the hydrogen line profiles are not sensitive to the surface gravity in the range from 6000 to 8000 K (the relevant temperature range for HD 84948), we additionally have used photometric calibrations (Napiwotzki et al. 1993; Künzli et al. 1997) to derive starting values for log g. The continuum flux was calculated with the program SYNTH (Piskunov 1992). In order to derive a "composite" spectrum, the individual spectrum of each component was shifted by the relative radial velocity, weighted by the continuum flux ratios (almost equal for HD 84948 A+B and HD 171948 A+B) and added. The notation A and B is arbitrary and not related to visual binarity (HD 171948, see Sect. 2). Finally, the spectra were convolved with the instrumental profiles.

The final effective temperatures, surface gravities and microturbulent velocities (Table 1) were obtained from the analysis (a detailed description of the used method including an error determination is given in Kupka et al. 1996) of Fe I

Table 1. Some fundamental parameters of HD 84948 and HD 171948. The notation A and B is arbitrary and not related to visual binarity (HD 171948)

	HD 84948		HD 171948	
	A	B	A	B
$T_{\rm eff}$ (±200 K)	6600	6800	9000	9000
$\log g$ (±0.2)	3.3	3.7	4.0	4.0
$v \sin i$ (±5 kms^{-1})	45	55	15	10
$v_{\rm micro}$ (±0.5 kms^{-1})	3.5	3.5	2	2
Δv (±1 kms^{-1})	77		21	
at HJD	2449794.4399		2450174.9944	

and Fe II lines (HD 84948 A: 54 lines; HD 84948 B: 56 lines; HD 171948 A+B: 15 lines). The chosen lines are almost free of blends and have accurate experimental oscillator strengths (taken from the Vienna Atomic Line Database, VALD; Piskunov et al. 1995). Using these final model atmospheres, the abundances values of the considered elements are given in Table 2 with respect to the Sun as: [X] = log X - log $X_{\odot}$.

The abundance of a particular chemical element and of an individual spectral line was derived by fitting the synthetic to the observed line profile using a least-squares method. The mean abundance resulted from averaging of all individual line abundances. The error was estimated by calculating the standard deviation of the mean (Table 2).

The values for $v \sin i$ (Table 1) were determined with ROTATE (Piskunov 1992). This program compares synthetic spectra convolved with kernels representing various broadening mechanisms with observations.

Fig. 1 shows the observed and synthetic spectra around Mg II 4481Å for both stars. The observations are in very good agreement with the theoretical spectra.

The radial velocity differences (Δv) between the components of each system for a given epoch are also listed in Table 1.

With the abundances listed in Table 2, HD 171948 A + B seem to be two of the most extreme λ Bootis stars observed by now whereas HD 84948 A + B show only moderate underabundances but still in the range of λ Bootis stars (Fig. 2).

Since many authors have used the "rotational velocity criterion" ($v \sin i_{\lambda\,\rm Boo} > 50$ kms^{-1}) for distinguishing λ Bootis stars (see Paunzen et al. 1997a for a review and discussion), we note that HD 171948 A + B are the slowest rotating λ Bootis-type stars known so far.

5. Evolutionary status of both systems

In order to determine the evolutionary status (ages and masses) for both systems, we have used the Hipparcos data as well as the astrophysical quantities from Table 1. The evolutionary tracks for the Pre-Main Sequence were taken from Palla & Stahler (1993), whereas the Main Sequence models are from Claret (1995). The latter have initial parameters X = 0.7, Z = 0.02 (solar abundance) and $\alpha = 1.52$. These values (especially the used solar abundance) are appropriate for the study of (chemically peculiar) λ Bootis stars because the main contribution to the overall metallicity is due to C, N and O (solar abundant in λ Bootis stars). Furthermore, there are strong indications that the λ Bootis phenomenon is restricted to the stellar surface (Holweger & Rentzsch-Holm 1995).

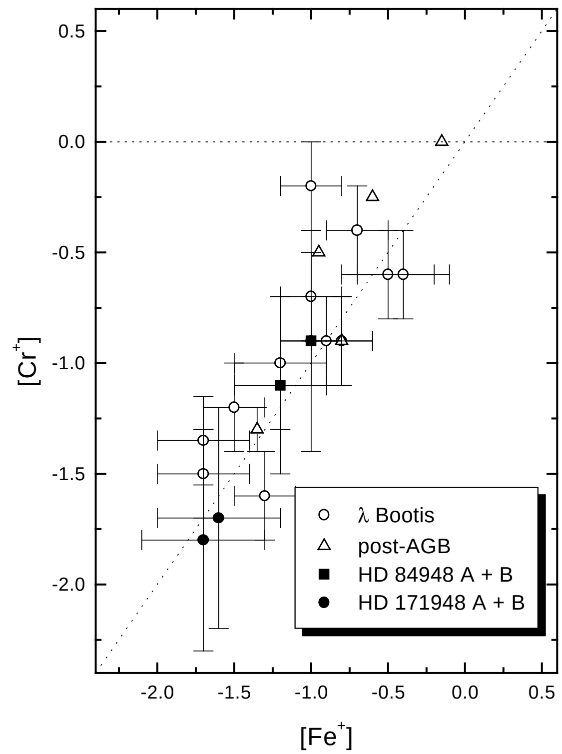

Fig. 2. The abundance of [Fe$^+$] *vs.* [Cr$^+$] for well established λ Bootis stars (Stürenburg 1993), post-AGB stars (Van Winckel 1997), HD 84948 and HD 171948. There is a continuous transition between "normal" and metal-deficient stars.

First, the program stars have to be located in a $\log T_{\rm eff}$ (taken from Table 1) versus $\log L/L_{\odot}$ diagram within the stellar evolutionary tracks. The determination of $\log L/L_{\odot}$ for HD 171948 A+B is straightforward. Since both components are very similar (in terms of the effective temperature and surface gravity), the observed $m_{\rm V}$ value was corrected for the binary nature. With the Hipparcos parallax, the $M_{\rm V}$ values have been determined and the bolometric corrections (derived with the $T_{\rm eff}$ values from Table 1 and the relevant formula given by Balona 1994) was added. With $M_{\rm bol}(\odot) = 4.75$ given by Cayrel de Strobel (1996), we have calculated $\log L/L_{\odot}$ as listed in Table 3.

Due to the small parallax of HD 84948 A+B (and thus the large error), we had to determine $\log L/L_{\odot}$ from evolutionary calculations. The used Pre- and Main Sequence (Palla & Stahler 1993; Claret 1995) models also list $\log g$ to corresponding $\log L/L_{\odot}$ values. We, therefore, have calibrated HD 84948 A+B in a $\log T_{\rm eff}$, $\log g$ plane (equal to $\log T_{\rm eff}$ and $\log L/L_{\odot}$) and derived $\log L/L_{\odot}$. This method is much more uncertain than using "observed" luminosities (as for HD 171948). Furthermore we have to stress that no proof using the Hipparcos parallaxes can be given (although the found values are within the large error boxes of the Hipparcos measurements). Nevertheless, both models give consistent luminosities (Table 3).

It is immediately evident from Table 3 that HD 171948 is *very close to the Main Sequence* (age $\approx 10^7$ years). Since the errors for the estimated masses and ages for HD 84948 A+B are quite large, we are able to present only preliminary conclusions for this system based on the following brief review of the two competing theories explaining the λ Bootis phenomenon:

Diffusion/mass-loss: Michaud & Charland (1986) found that after 10^9 years underabundances of up to 0.5 dex with respect to the Sun are predicted by this theory. But Charbonneau (1993) showed that even an equatorial rotational velocity of 50 $\mathrm{km s^{-1}}$ suppresses the appearance, at any epoch of Main Sequence evolution, of the characteristic λ Bootis underabundance pattern because of the effects of turbulent mixing and meridional circulation. The abundance for all program stars (e.g. HD 171948A:[Mg] = -2.4) are therefore not consistent with this theory. Furthermore, the rotational velocities for HD 84948 A+B are too high to avoid the effects of mixing. But more important, the determined ages (especially for HD 171948) clearly contradict these predictions.

Diffusion/accretion: Waters et al. (1992) suggested that accretion of circumstellar material (remnant of the proto-stellar cloud) as in post-AGB stars causes the λ Bootis phenomenon. This model requires that λ Bootis stars are unevolved and very close to the Main Sequence. Observational results from the young Orion OB1 association and NGC 2264 (Paunzen & Gray 1997) seem to support such age estimates. The evolutionary status of HD 171948 A+B further strengthens this model. A recent paper (Crifo et al. 1997) determined the age of β Pictoris (the prototype of "dusty" young low-mass stars) to at least $8{\cdot}10^6$ years, which is comparable to the predictions of the accretion theory.

We, therefore, suggest the explanation that HD 84948 is indeed close to the Main Sequence (age $\approx 2{\cdot}10^6$ years; Table 3). This might be proven by the determination of orbital elements for this system (note the significantly different masses derived by the Pre- and Main Sequence models in Table 3) as well as by the results of an asteroseismological investigation (Sect. 6).

It is interesting to note that the link between binarity and metal-deficiency is a key to understand a possible gas-dust separation for post-AGB stars (Van Winckel et al. 1995). They presented five extremely Fe deficient post-AGB binary systems with orbital periods from one to a few years, suggesting that mass transfer has occurred in these systems leading to the present circum-system disk. This might also be an additional mechanism which has to be considered for the λ Bootis phenomenon. However, it shows that close binarity and accretion does not exclude each other.

6. Pulsation of HD 84948

Pulsation of HD 84948 was discovered during two nights of observations. In total, more than five hours of differential data were collected. From a time series analysis, we derived a formal numerical solution of $P_{\mathrm{obs}} = 113$ min and $A(v) = 15$ mmag. Figure 3 shows the amplitude spectra of the differential data for HD 84948 and both comparison stars (HD 84526 and HD 85783) as well as the spectral window. The mean noise level is about 3 mmag resulting in a significance level of 5σ for the detected pulsation. The period and amplitude are very similar to those for another cool, pulsating λ Bootis star, HD 83041 ($T_{\mathrm{eff}} = 6900$ K, $\log g = 3.3$; Paunzen & Handler 1996). Both stars are in the same region of the H-R diagram at the cool border of the Instability Strip.

The period and the values of the physical parameters given in Table 1 and 3 can be used to estimate the pulsation constant according to López de Coca et al. (1990):

$$\log Q = -6.456 + \log P + 0.5 \log g + 0.1 M_{\mathrm{bol}} + \log T_{\mathrm{eff}}$$

This results in $Q = 0.009$ and $Q = 0.019$ d for the A and B component, respectively. These preliminary results seem to indicate that HD 84948 B is actually pulsating whereas the Q-value for HD 84948 A seems too small for a typical δ Scuti like pulsation (Stellingwerf 1979). Furthermore, we are able to conclude that the excited modes are not the fundamental and first overtone modes, a fact which is also found for some other δ Scuti stars in this region of the H-R diagram. However, only further photometric observations would allow to determine whether HD 84948 is really a single or a multiple periodic pulsating star and to estimate accurate values for the mass, luminosity and age. This would provide an independent test for the "Pre-Main Sequence hypothesis".

Table 2. Results of an abundance analysis for HD 84948 and HD 171948 with respect to the Sun; in parentheses are the estimated errors of the means (in units of 0.1 dex); # denotes the number of used neutral and ionized lines

Element	HD 84948		HD 171948	
	A	B	A	B
[Na]	-0.3(3)	0.0(3)		
#	2	2		
[Mg]	-1.2(5)	-1.0(4)	-2.4(4)	-2.4(4)
#	6	8	3	3
[Si]	-1.3(6)	-1.2(7)		
#	5	3		
[Ca]	-1.3(5)	-0.8(4)		
#	11	9		
[Sc]	-1.4(4)	-0.7(5)		
#	6	6		
[Ti]	-1.3(5)	-0.5(4)	<-3(5)	<-3(5)
#	14	21	2	2
[Cr]	-1.1(4)	-0.9(5)	-1.7(5)	-1.8(5)
#	13	10	2	2
[Fe]	-1.2(3)	-1.0(2)	-1.6(4)	-1.7(4)
#	54	56	15	15

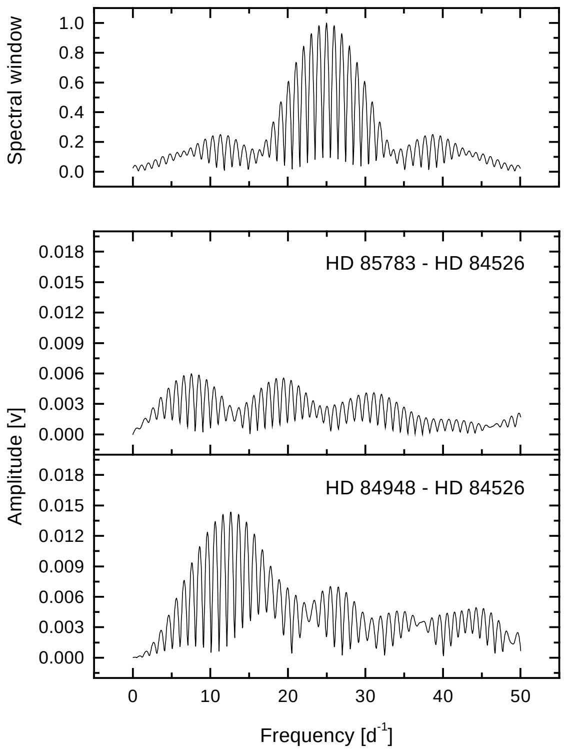

Fig. 3. Amplitude spectra for the merged differential data of both nights for HD 84948 and both comparison stars in Strömgren v

Table 3. Pre-Main Sequence ("PMS"; Palla & Stahler 1993) and Main Sequence ("MS"; Claret 1995) models together with Hipparcos data were used to derive masses and ages for our program stars

	HD 84948		HD 171948	
	A	B	A	B
r [pc]	201.2 ± 46.2		130.5 ± 12.3	
V [mag]	8.15		6.71	
$M_{\rm bol}$ [mag]	0.50 ± 0.30	1.50 ± 0.30	1.76 ± 0.18	
$\log L/L_{\odot}$	1.70 ± 0.16	1.30 ± 0.16	1.20 ± 0.08	
$\mathscr{M}_{\rm PMS}$ [M$_{\odot}$]	2.9 ± 0.2	2.1 ± 0.2	2.0 ± 0.1	
$\log t_{\rm PMS}$	6.0 ± 0.4	6.6 ± 0.4	7.0 ± 0.1	
$\mathscr{M}_{\rm MS}$ [M$_{\odot}$]	2.4 ± 0.2	1.9 ± 0.2	2.0 ± 0.1	
$\log t_{\rm MS}$	9.0 ± 0.2	8.9 ± 0.2	7.0 ± 0.1	

7. Conclusion

For each component of two spectroscopic binary systems (HD 84948 and HD 171948) we have established the membership to the λ Bootis group. These are the first two λ Bootis-type systems discovered so far. An abundance analysis resulted in extreme (HD 171948) and moderate (HD 84948) underabundances of Na, Mg, Si, Ca, Sc, Ti, Cr and Fe with respect to the Sun.

Using the Hipparcos parallax for HD 171948 and comparing ages as well as masses from Pre- and Main Sequence evolutionary tracks, we conclude that this system is *very close to the Main Sequence*. Due to the large distance and the resulting large error in the parallax, a similar conclusion for HD 84948 is less evident. Since the properties of this system contradict the predictions of the diffusion/mass-loss theory (e.g. too high rotational velocities, too prominent underabundances), we tend to suggest an unevolved nature, too. This might be proven by an estimation of the orbital elements and/or an asteroseismological investigation (the discovery of δ Scuti like pulsation for HD 84948 is also reported).

Furthermore, many authors have used the rotational velocity to distinguish λ Bootis stars (defined as stars with $v \sin i > 50\,{\rm kms}^{-1}$; Paunzen et al. 1997a) from other objects. Since HD 171948 A+B are both sharp lined ($v \sin i < 20\,{\rm kms}^{-1}$) this criterion has to be refuted.

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