

Local subgiants and time-scales of disc formation

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Accepted 2006 March 14. Received 2006 March 14; in original form 2006 February 8

ABSTRACT

Detailed evolutionary tracks and basic stellar parameters for the nearby subgiants 104 Tau and HD 168443 are presented and discussed. Both serve as invaluable key stars for accurate age-datings, especially as they possess the chemical signatures intermediate to the stars of the thick- and thin-disc population. We derive $\tau = 9.7_{+0.8}^{-0.6}$ Gyr for 104 Tau and $\tau = 9.8_{+1.0}^{-0.8}$ Gyr for HD 168443, very much in line with their local sibling HR 7569 at $\tau = 9.1 \pm 1.0$ Gyr that was formerly presented in Bernkopf, Fiedler & Fuhrmann. Both, 104 Tau and HD 168443, thus add to our local sample of the rare but very relevant subgiants for the disc formation time-scales and support the notion of a thick disc as an extremely old $\tau \geq 12$ Gyr single-burst population, and a thin disc that has a local age of $\tau \sim 8$ Gyr.

Key words: stars: evolution – stars: fundamental parameters – Galaxy: evolution – Galaxy: formation.

1 INTRODUCTION

Stars in the subgiant stage of evolution are extremely valuable targets for reliable age-datings. The prerequisite, an accurate knowledge of the absolute luminosities of local field stars, became however available only a decade ago with the precise *Hipparcos* astrometry. The enormous progress with these space-borne parallax data was soon hereafter demonstrated for, e.g. the closest subgiant β Hyi by Dravins, Lindegren & VandenBerg (1998; their fig. 1), who revised its age to $\tau \sim 6.7$ Gyr compared to that of the former $\tau \sim 9.5$ Gyr.

The important point to understand why subgiants play a key role for stellar ages is that a detailed knowledge of their effective temperatures is not required. This is because the evolution towards the red giant branch means a decrease in the effective temperature of a star by about a thousand degrees or more and this takes place on a comparatively short time-scale and mostly in the horizontal direction on the H–R diagram, with the consequence that temperature uncertainties have little impact on the inferred luminosities and ages. Hence, the principal advantage inherent to the subgiants is inevitably also their basic drawback, viz., that they must be a relatively rare species in comparison with main sequence or turnoff stars.

Thus, among the 300 northern F, G and early-K stars (FGK stars) down to $M_V = 6.0$ and within 25 pc only about a handful are actually subgiants, and none of them is a member of the old thick-disc population as demonstrated in Fuhrmann (2004, hereafter Paper III). Among the few subgiants of the local thin disc, it is 70 Vir that is

likely the oldest with an age $\tau = 8.1 \pm 0.6$ Gyr (cf. Bernkopf et al. 2001, hereafter BF²).

The understanding of whether a star belongs to the thick or the thin disc is herein guided by a chemical criterion, namely the appearance of the local FGK stars in the [Mg/H]–[Fe/Mg] abundance plane which shows a striking string-of-pearl-like distribution for the bulk of them, i.e. for its thin-disc population. An updated version of this diagram based on high-resolution spectroscopic analyses presented in Fuhrmann (1998, 2000, 2004) along with yet unpublished data (Fuhrmann, in preparation) for now more than 200 stars of the solar neighbourhood is given in Fig. 1. At the current state, it represents already a fairly complete account of the nearby FGK stars, north of $\delta = -15^\circ$ and down to $T_{\text{eff}} \geq 5300$ K on the main sequence. In addition to the easily identifiable thin-disc population in Fig. 1, there is also a separate group of iron-to-magnesium-deficient stars with abundance ratios in the range $-0.45 \leq [\text{Fe}/\text{Mg}] \leq -0.31$, which we identify as the local thick-disc members. One notices, however, as well a few objects with intermediate chemistry dubbed here as disc ‘transition stars’.

In a discussion of the stellar magnesium and iron abundances as they come about in Fig. 1, the immediate question is: Is this chemical map displayed by the local FGK stars nothing but a manifestation of some other more basic parameter, for instance, age? We repeatedly advocated the answer as *yes*, and in particular in BF² we have presented the results of detailed stellar interior calculations for seven nearby subgiants: three of them with a thick-disc chemistry, another three with a thin-disc chemistry and one star, HR 7569, with an intermediate abundance mixture. Our result was that while 70 Vir at $\tau \sim 8$ Gyr is very likely a good representative for the oldest stars of the local thin disc, the three subgiants of the thick disc were all at least as old as $\tau \sim 12$ Gyr, and HR 7569 with its intermediate chemical signature turned out to be as well of intermediate age at

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[†]Based on observations collected at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck-Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC).

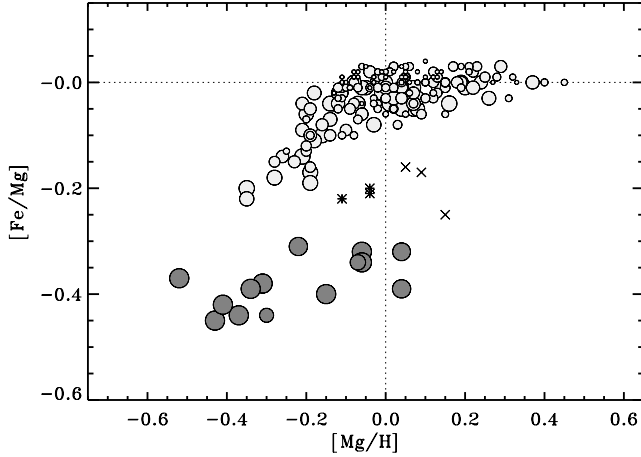


Figure 1. [Mg/H]–[Fe/Mg] abundance distribution of some 200 FGK stars within 25 pc, north of $\delta = -15^\circ$ and down to $T_{\text{eff}} \geq 5300$ K on the main sequence. Circle diameters are in proportion to the age estimates, i.e. with small diameters for young stars. Light and dark circles represent members of the thin disc and thick disc, respectively. Asterisks denote the three disc ‘transition stars’ of intermediate chemistry and age (including 104 Tau), whereas crosses mark three fairly cool and unclassifiable disc stars of intermediate chemistry and unknown age. Note that this presentation is already volume-complete for the thick-disc population and likewise for all disc transition stars. Note also that the most metal-poor thick-disc star of this unbiased sample has the same [Fe/Mg] abundance ratio as the most metal-rich object of this population.

$\tau = 9.1 \pm 1.0$ Gyr. In other words, there must have been a significant star formation gap between the thick and the thin disc and the distribution given in Fig. 1 is just the mirror of this circumstance.

Now, since even one of the rare disc transition stars in Fig. 1, 104 Tau is actually a subgiant, it is clear that it must play a key role among the nearby FGK stars and it is of utmost importance to know its age. Likewise, HD 168443, although somewhat more distant at 38 pc, came recently to our attention as another disc transition star. Since it is also in its subgiant stage of evolution, it is as well very relevant for our understanding of the time-scales of star formation in the Milky Way. In what follows, we will present detailed evolutionary tracks for both these objects and discuss some implications for the stellar disc populations.

2 TWO MOST RELEVANT NEARBY STARS

The stellar interior calculations presented in this section follow those given in BF², i.e. we explicitly take care of a different [Fe/ α] abundance mixture, but simply adopt the derived [Fe/Mg] ratio as representative to all other α -chain nuclei. For our stellar evolutionary tracks, we take the helium mass fraction $Y = 0.2723$ and the mixing-length parameter $\alpha = 0.883$, using the convection model of Canuto & Mazzitelli (1991). Both parameters were calibrated with a model for the present Sun. Also, helium diffusion is used in the calculations. For a more detailed reading, we refer here to BF² and in particular to Bernkopf (1998, 2001). Likewise, we mention only very briefly that the spectroscopic analyses follow exactly those of our previous work, e.g. that in Paper III.

2.1 104 Tauri

The spectroscopy and basic atmospheric parameters of 104 Tau (=HR 1656, HD 32923) were already presented in Paper III. However, because of its central importance for the local disc stars, we

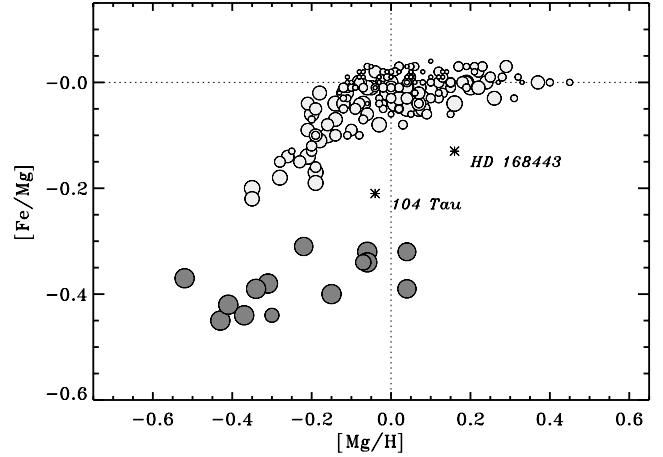


Figure 2. Same as Fig. 1, but with only 104 Tau and HD 168443 included among the disc transition stars. Note that at a distance of 38 pc HD 168443 is *not* a member of the volume-limited nearby star sample displayed in Fig. 1.

Table 1. Basic stellar parameters of 104 Tau and HD 168443. The entries ξ_t and ζ_{RT} denote the micro- and macroturbulence, respectively. d_{HIP} is the *Hipparcos* distance, d_{sp} the spectroscopic distance and Δd in the final row the difference of both scales.

| | 104 Tau | HD 168443 |
|------------------|------------------------------------|------------------------------------|
| T_{eff} | 5704 ± 60 K | 5546 ± 70 K |
| $\log g$ | 3.99 ± 0.10 cgs | 4.00 ± 0.10 cgs |
| [Fe/H] | -0.25 ± 0.06 dex | $+0.03 \pm 0.07$ dex |
| [Fe/Mg] | -0.21 ± 0.05 dex | -0.13 ± 0.05 dex |
| ξ_t | 1.11 ± 0.20 km s ⁻¹ | 1.01 ± 0.20 km s ⁻¹ |
| ζ_{RT} | (fixed) 3.7 km s ⁻¹ | (fixed) 3.9 km s ⁻¹ |
| $v \sin i$ | 1.00 ± 1.00 km s ⁻¹ | 1.00 ± 1.00 km s ⁻¹ |
| V | 4.908 ± 0.005 mag | 6.925 ± 0.005 mag |
| M_{bol} | 3.75 ± 0.06 mag | 3.86 ± 0.09 mag |
| BC_V | -0.15 ± 0.05 mag | -0.17 ± 0.05 mag |
| Radius | $1.63 \pm 0.06 R_{\odot}$ | $1.63 \pm 0.08 R_{\odot}$ |
| Mass | $1.00_{-0.04}^{+0.03} M_{\odot}$ | $1.06_{-0.05}^{+0.04} M_{\odot}$ |
| Age | $9.7_{+0.8}^{-0.6}$ Gyr | $9.8_{+1.0}^{-0.8}$ Gyr |
| d_{HIP} | 15.87 ± 0.24 pc | 37.88 ± 1.26 pc |
| d_{sp} | 16.38 ± 2.23 pc | 39.61 ± 5.42 pc |
| Δd | +3.2 per cent | +4.6 per cent |

re-observed 104 Tau in 2004 September, this time with a slightly increased resolution ($R \sim 65\,000$) and, in particular, at a much improved signal-to-noise ratio, $S/N \sim 400$ (the former observations of 2000 January were only exposed to $S/N \sim 200$). The result of our reanalysis is that it essentially confirms the earlier findings of Paper III with only minor revisions. Table 1 summarizes our updated stellar parameters for 104 Tau. We mention the good agreement of the derived spectroscopic distance with the *Hipparcos* distance in that table, which in turn gives not much credence for a putative secondary around 104 Tau.¹ Should it nevertheless exist, we do not expect that it can have significantly affected our spectroscopy.

¹ Such a companion was claimed to exist (e.g. Voronov 1934, Kuiper 1938, Eggen 1956), but in recent years rather disputed (e.g. Roberts et al. 2005). In particular, the case of an equal visual magnitude binary – as repeatedly maintained – is now excluded by virtue of the more than 40 per cent distance discrepancy that would follow for the spectroscopic versus astrometric parallax.

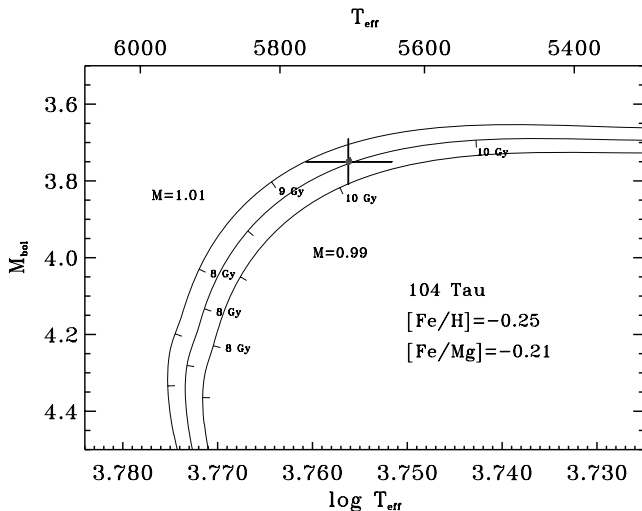


Figure 3. Evolutionary tracks for the nearby subgiant 104 Tau. The star has approximately solar magnesium abundance, but is deficient with respect to iron by almost a factor of 2, as given in the legend and Table 1. We derive an age $\tau = 9.7$ Gyr and a mass $M = 1.00 M_{\odot}$. Tick marks along the tracks are given in steps of 1 Gyr.

Table 2. Error budget for the mass and age of 104 Tau.

| | Mass | Age |
|------------------------------------|------------------------------|----------------------|
| $T_{\text{eff}} \& M_{\text{bol}}$ | -0.01 $+0.01 M_{\odot}$ | -0.5 $+0.5$ Gyr |
| [Fe/H] | -0.03 $+0.02 M_{\odot}$ | -0.3 $+0.5$ Gyr |
| [Fe/Mg] | -0.02 $+0.01 M_{\odot}$ | -0.2 $+0.3$ Gyr |

On account of the chemical similarities with HR 7569, a mass and age estimate of $M \sim 1.00 M_{\odot}$ and $\tau \sim 9$ Gyr was also proposed for 104 Tau in Paper III. This is now quantified in Fig. 3 to $M = 1.00_{-0.04}^{+0.03} M_{\odot}$ and $\tau = 9.7_{-0.6}^{+0.8}$ Gyr, where the given errors include that in ΔT_{eff} and ΔM_{bol} with $\Delta \tau = \pm 0.5$ Gyr, in $\Delta[\text{Fe}/\text{H}]$ with $\Delta \tau = \pm 0.3$ Gyr, and in $\Delta[\text{Fe}/\text{Mg}]$ with $\Delta \tau = \pm 0.3$ Gyr, according to complementary calculations, the results of which are also summarized in Table 2.

Thus, the only star² in our volume-complete sample of the nearby FGK stars, that is intermediate to both disc populations *and* for which a reliable age-dating is possible, turns out to be also intermediate in terms of age. This is an important result for the notion of whether the thick disc is a single-burst-like population with a duration of about 1 or 2 billion years as implied from the data in BF² or was instead formed on a considerably longer time-scale. We will come back to this point in the final section.

Before we proceed, however, with our second subgiant one more comment is required with respect to a former work on 104 Tau by Liu & Chaboyer (2000). From their own grid of stellar interior calculations, they have also presented a *Hipparcos*-based age-dating for 104 Tau and their result, $\tau = 10.0 \pm 0.5$ Gyr, agrees very well with that of ours. For a proper assessment of this finding, one must, however, know that Liu & Chaboyer interpolated between their $[\text{Fe}/\text{H}] = -0.24$ and $[\text{Fe}/\text{H}] = -0.10$ isochrones and adopted a slightly higher iron abundance $[\text{Fe}/\text{H}] = -0.20$ for 104 Tau, yet

² Note that HR 7569 is at a distance of 27 pc and hence slightly *beyond* the limits of the local FGK star sample. Like HD 168443, it does therefore not enter the chemical map of Fig. 1.

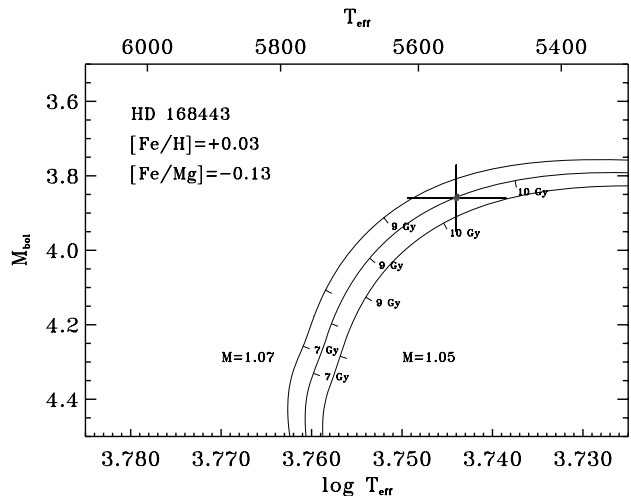


Figure 4. Evolutionary tracks for HD 168443. The subgiant has approximately solar iron abundance and a supersolar magnesium enrichment. The stellar interior calculations provide an age $\tau = 9.8$ Gyr and a mass $M = 1.06 M_{\odot}$. In comparison with the coeval 104 Tau in Fig. 3 note the ~ 150 K lower turnoff position for HD 168443, a consequence of its higher metal abundance. Because of a likewise lower effective temperature for HD 168443, both stars are, however, found in very similar positions of their subgiant evolution.

did not include any α -enhancement. It is clear, though, that both differences in the chemistry must work in opposite directions and therefore cancel to some extent. By virtue of the thin-disc-like kinematics that 104 Tau indeed possesses ($U/V/W = -16/-18/+36$ km s⁻¹, cf. e.g. fig. 47 in Paper III), Liu & Chaboyer (2000) state that it is one of the oldest nearby stars that appears to be a thin-disc member. In fact, it is only the chemical map of the fairly large volume-limited sample of local FGK stars in Fig. 1 that uncovers 104 Tau's *real* meaning in that context.

2.2 HD 168443

As opposed to HR 7569 and 104 Tau which come up with similar effective temperatures $T_{\text{eff}} \sim 5700$ K and abundances $[\text{Fe}/\text{H}] \sim [\text{Fe}/\text{Mg}] \sim -0.20$, HD 168443 is much cooler and less α -enhanced, but exhibits a solar iron abundance (cf. Table 1) and thereby represents the metal-rich end of the local disc transition stars.

This interesting aspect is most obvious from Figs 1 and 2 above, but also from a comparison with fig. 34 of Paper III, wherein one K dwarf, HD 38230, shares almost exactly the iron and magnesium abundance of HD 168443. However, while the age of HD 38230 remains unknown due to its low effective temperature, $T_{\text{eff}} = 5214 \pm 80$ K, and main-sequence status, we can get a fairly accurate age-dating of HD 168443. Even more, in Paper III some concerns about the existence of a faint companion to HD 38230 which could have affected the spectroscopic abundance analysis were put forward. This is, however, no issue for HD 168443: although it is known to harbour even two low-mass companions, both are likely substellar as outlined in Marcy et al. (2001).

The stellar interior calculations for HD 168443 are presented in Fig. 4 and the individual error estimates for its mass and age are summarized in Table 3. Because of its higher level of metal enrichment, HD 168443 possesses a slightly higher mass, $M = 1.06 M_{\odot}$, compared to 104 Tau. However, for the same reason its turnoff position is also shifted to $T_{\text{eff}} \sim 5750$ K, whereas the more metal-poor 104 Tau must have reached more than $T_{\text{eff}} \sim 5900$ K

Table 3. Error budget for the mass and age of HD 168443.

| | Mass | Age |
|------------------------------------|--|--------------------------|
| $T_{\text{eff}} \& M_{\text{bol}}$ | -0.01 M_{\odot} $+0.01$ M_{\odot} | -0.6 Gyr $+0.5$ Gyr |
| [Fe/H] | -0.04 M_{\odot} $+0.03$ M_{\odot} | -0.4 Gyr $+0.8$ Gyr |
| [Fe/Mg] | -0.02 M_{\odot} $+0.02$ M_{\odot} | -0.2 Gyr $+0.4$ Gyr |

at that stage (cf. Fig. 3). This in turn means that 104 Tau and HD 168443 occupy very similar positions on the subgiant branch in spite of their clearly different effective temperatures. At $\tau = 9.8$ Gyr for HD 168443 and $\tau = 9.7$ Gyr for 104 Tau, we do also emphasize that both stars are essentially coeval. Basically, on account of its larger distance (38 versus 16 pc) the uncertainty in M_{bol} for HD 168443 is increased to $\Delta M_{\text{bol}} = 0.09$ mag, as compared to $\Delta M_{\text{bol}} = 0.06$ mag for 104 Tau (cf. Table 1). Much of this difference in ΔM_{bol} for the more distant HD 168443 causes the somewhat larger error for its age; we recall, however, that without the precise *Hipparcos* parallaxes for both stars any age-dating would be meaningless at this point.³

3 DISCUSSION AND CONCLUSIONS

Investigations of the stars of the local disc populations are usually confronted with the basic issue of how to choose the *bona fide* members of each stellar component and a common approach is, for instance, to work on kinematically selected subsamples. Considering instead a volume-complete set of nearby FGK stars does not a priori aim at a particular stellar population, but rather tries to avoid any kind of selection from the outset. In that respect, the compact group of stars that emerge in the chemical map of Fig. 1 – and which is then identified as the local thin-disc population – is not what was intentionally searched for or aimed at. Since this figure implies, however, some basic agent for the observed peculiar distribution, and since age is certainly a prime candidate thereof, we have particularly focused on those stars that provide the most reliable age-datings, namely, the subgiants of the sample. As none of them from the thin disc ultimately turns out to be significantly older than 70 Vir, we corroborate our earlier finding of BF² that $\tau \sim 8$ Gyr must be the characteristic number for the local thin-disc formation epoch.

There is unfortunately no subgiant among the nearby stars of the thick disc in Fig. 1, but it was also demonstrated in BF² that alike subgiants which we found in the much larger volume out to 50 pc support ages in the relatively small interval $12.5 \leq \tau \leq 13.8$ Gyr. This is direct evidence for the thick disc as an extremely old population and a time-scale for its formation of about 1–2 Gyr.⁴ In

³ The spectroscopic distances as given in Table 1 do not constitute a useful absolute stellar luminosity substitute because of the much larger internal standard errors.

⁴ In this context, note also that the most metal-poor thick-disc star in the local but unbiased sample of Fig. 1 has essentially the same iron-to-magnesium deficiency, or, less correctly, the same ‘ α -enhancement’, as the most metal-rich thick-disc object presented in this figure.

addition, one chemically intermediate star, HR 7569, provided as well an age intermediate to that of the thick disc and the thin disc. With the present work, we add now two more such key subgiants, both also at an age somewhat above 9 Gyr and hence very similar to HR 7569.

Thus, we do confirm that it is basically the *age* that is the defining characteristic of the thick disc and the thin disc. And while both stellar populations display an overlapping chemistry with respect to iron as well as magnesium, it is the iron-to-magnesium abundance ratio that acts as a mirror of supernovae products driven from either massive or intermediate to low-mass stars, and which convincingly segregates the thick disc and the thin disc in Fig. 1. Hence, guided by the distribution of the stars in that diagram, as well as the detailed stellar interior calculations for a number of subgiants in BF² and the two stars discussed above, we learn from an individual comparison of the *UVW* space velocities of these local FGK stars that, as expected, its thick-disc members have a significantly hotter kinematics, but there is as well a non-negligible overlap with the numerous thin-disc stars.

As there is then no alike kinematical feature among the nearby stars that allows for a comparatively unambiguous identification of the thick disc and the thin disc as it is possible from the chemical signature revealed in Fig. 1, it follows that kinematically selected samples of local disc stars are mostly a convenient approach, but will inevitably introduce serious selection effects. This is particularly worrisome for the thick disc on account of the locally very different number densities of both disc populations. Thus, the distinct structures in age and chemistry that, we think, most likely exist for the thick disc and the thin disc are then prone to get reduced to rather insignificant conclusions about ‘average’ characteristics with ‘considerable overlap’ on almost every aspect. It is clear, though, that this kind of blurring is in effect counter-productive for a quantitative understanding of the stellar populations of disc stars in the Milky Way.

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