# A Giant Planet Around a Metal-poor Star of Extragalactic Origin

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**Stars in their late stage of evolution, such as Horizontal Branch stars, are still largely unexplored for planets. We report the detection of a planetary companion around HIP 13044, a very metal-poor star on the red Horizontal Branch, based on radial velocity observations with a high-resolution spectrograph at the 2.2-m MPG/ESO telescope. The star's periodic radial velocity variation of $P = 16.2$ days caused by the planet can be distinguished from the periods of the stellar activity indicators. The minimum mass of the planet is 1.25 $\mathrm{M_{jup}}$ and its orbital semi-major axis 0.116 AU. Because HIP 13044 belongs to a group of stars that have been accreted from a disrupted satellite galaxy of the Milky Way, the planet most likely has an extragalactic origin.**

In the last two decades, several hundred planets have been detected beyond our Solar-system. Most of these extra-solar planets orbit sun-like stars. A small number have been detected around stars that are in their late evolutionary state, such as Red Giant Branch (RGB) stars and pulsars. The phase directly after the RGB stage, the Horizontal Branch (HB), however, is still unexplored; therefore, there is no empirical evidence for whether close-in planets, i.e., those with semi-major axes less than 0.1 AU, survive the giant phase of their host stars.

Besides its evolutionary stage, a star's chemical composition appears to be a major indicator of its probability for hosting a planet. Previous studies, e.g., (*1*), showed that main-sequence (MS) stars that host giant planets are metal-rich. This finding is supported by the large exoplanet search surveys around MS stars reporting a connection between planet frequency and metallicity (*2*,*3*), and a survey of 160 metal-poor main-sequence stars finding no evidence for Jovian planets (*4*).

Until now, only very few planets have been detected around stars with metallicities as low as [Fe/H]= $-1$, i.e. 10% of the sun's metallicity. The detection of PSR B1620 b, a Jovian planet orbiting a pulsar in the core of the metal-poor globular cluster M4 ([Fe/H]=$-1.2$), suggests, however, that planets may form around metal-poor stars (*5, 6*), although the formation mechanism of this particular planet might be linked to the dense cluster environment (*7*).

We used the Fibre-fed Extended Range Optical Spectrograph (FEROS), a high-resolution spectrograph ($R = 48,000$) attached to the 2.2 meter Max-Planck Gesellschaft/European Southern Observatory (MPG/ESO) telescope (*8*), to observe the star HIP 13044. This star is classified as a red HB (RHB) star (Fig. 1) and its metal content is [Fe/H]$_{\mathrm{mean}} = -2.09$ (*9*–*12*), i.e. about 1% that of the Sun. So far, HIP 13044 is not known as a binary system. Detailed stellar parameters can be found in Supporting Online Material (SOM) text 1.

Previous radial velocity (RV) measurements of HIP 13044 showed a systematic velocity of about 300 $\mathrm{km\,s^{-1}}$ with respect to the Sun, indicating that the star belongs to the stellar halo (*13*). Indeed, the star has been connected to the Helmi stream (*14*), a group of stars that share similar orbital parameters that stand apart from those of the bulk of other stars in the solar neighborhood. The Helmi stream stars move on prograde eccentric orbits ($R_{\rm peri} \sim 7$ kpc, $R_{\rm apo} \sim 16$ kpc) that reach distances up to $|z|_{\rm max} \sim 13$ kpc above and below the galactic plane. From that, it has been concluded that these stars were once bound to a satellite galaxy of the Milky Way (*10, 14*) that was tidally disrupted 6–9 Ga ago (*15*).

The variation of the RV between our observations at different epochs has a semi-amplitude of 120 $\rm m\,s^{-1}$ (*16*) (Fig. 2). The Generalized Lomb Scargle (GLS) periodogram (*17*) reveals a significant RV periodicity at $P = 16.2$ days with a False Alarm Probability of $5.5 \times 10^{-6}$. Additional analysis, using a Bayesian algorithm (*18*), yields a similar period around 16 days. Such RV variation can be induced by an unseen orbiting companion, by moving/rotating surface inhomogeneities or by non-radial stellar pulsations. Exploring both stellar rotational modulation and pulsations is critical when probing the presence of a planetary companion, because they can produce a similar or even the same RV variation, mimicking a Keplerian motion.

A well-established technique to detect stellar rotational modulation is to investigate the line profile asymmetry or bisector (*19*) and Ca II lines (SOM text 3). Surface inhomogeneities, such as starspots and large granulation cells, produce asymmetry in the spectral line profiles. When a spotted star rotates, the barycenter of the line profiles moves periodically and the variation can mimic a RV variation caused by an orbiting companion. Instead of measuring the bisectors, one can equivalently use the bisector velocity spans (BVS) to search for rotational modulation (*20*). Adopting this technique, we have measured BVS from the stellar spectra. There is only a weak correlation between BVS and RV (correlation coefficient $=-0.13$), but the BVS variation shows a clear periodicity with $P$ =5.02 days (SOM text 3.1.1). No period around 16 days is found in the BVS variation.

In addition to the BVS analysis, we investigated the variation of the Ca II $\lambda$849.8 line, which is one of the Ca II infrared triplet lines. From the observed Ca II 849.8 equivalent-width variations we computed a mean period of 6.05 days (SOM text 3.1.2), which is in the same order of the period of the BVS variation. We adopted the mean period of both stellar activity indicators, $P_{\rm rot} = 5.53 \pm 0.73$ days, as the stellar rotation period of HIP 13044 and then calculated the inclination angle of the stellar rotation axis, which follows from $P_{\rm rot}/\sin i = 2\pi R_{*}/v \sin i$. With a stellar radius $R_{*} = 6.7\,{\rm R}_{\odot}$ (*21*) and our adopted value for the projected rotational velocity, $v \sin i$=10.25 $\rm km\,s^{-1}$, which was derived from the observed line broadening (SOM text 1), we obtained an inclination angle $i = 9.7 \pm 1.3$ deg. Thus, the real stellar rotation velocity is $\sim$62 $\rm km\,s^{-1}$, which is typical for an early F type MS-star but relatively high for HB stars.

An explanation for this high rotation velocity is the assumption that HIP 13044 has engulfed its close-in planets during the red giant phase. Infalling planets are able to spin-up their host star (*22–24*), and this mechanism has been suggested to explain the high $v \sin i$ values observed for many RGB and HB stars (*25*).

We observed variations of HIP 13044 in the photometric data from the Hipparcos satellite (*26*) and SuperWASP (*27*) (SOM text 3.2.4). While the Hipparcos data shows only a marginal significant periodicity of 7.1 hours (FAP=1.8%), the SuperWASP data shows few intra-day periodicities with FAP$\sim$1% and two significant periodicities at 1.39 (FAP=$5 \times 10^{-4}$) and 3.53 days (FAP=$2 \times 10^{-4}$). These two periods, however, are most likely harmonic to each other ($1.4^{-1} + 3.5^{-1} = 1$). It is expected that HIP 13044 oscillates only at pulsationally unstable overtones of high order (*28*). Observations of one RHB star in the metal-poor globular cluster NGC 6397 (*29*) as well as theoretical predictions (*28*) set these periods in the range of a few hours to a day or so. No clear theoretical predictions for a star with parameters similar to HIP 13044 exist, hence it is possible that some high-order oscillations are able to explain the 1.4 or 3.5 day signal. What is important, however, is that there is no signal of a period around 16.2 d in the photometric data.

The arguments above show that neither stellar rotational modulation nor pulsations are plausible sources of the observed periodic RV variation. Therefore, the best explanation for the ~16 days period is the presence of an unseen companion. We computed its orbital solution (Table 1). Its minimum mass lies securely in the planetary mass domain, even with a plausible $\sin i$ uncertainty. With an eccentricity of 0.25 and a semi-major axis of 0.116 AU, the planet has a periastron distance of about 0.087 AU which is ≈2.8 times the present stellar radius. The periastron is ~0.06 AU away from the stellar surface.

Table 1: Orbital parameters of HIP 13044 b

| | | |
|---|---|---|
| $P$ | 16.2 ± 0.3 | days |
| $K_1$ | 119.9 ± 9.8 | $\mathrm{m\,s^{-1}}$ |
| $e$ | 0.25 ± 0.05 | |
| $\omega$ | 219.8 ± 1.8 | deg |
| $JD_0 - 2450000$ | 5109.78 ± 0.02 | days |
| $\chi^2$ | 32.35 | $\mathrm{m\,s^{-1}}$ |
| $rms$ | 50.86 | $\mathrm{m\,s^{-1}}$ |
| $m_2 sini$ | 1.25 ± 0.05 | $\mathrm{M_{Jup}}$ |
| $a$ | 0.116 ± 0.01 | AU |

Because a large number of known exoplanets have orbital semi-major axes between 0.01 and 0.06 AU, the distance between the periastron and the star HIP 13044 itself is not unusual. The non-circular orbit ($e$ =0.25), however, is not expected for a close-in giant planet around a post RGB star.

In the case of HIP 13044, the original orbit could have been disturbed or changed during the evolution of the star-planet-system, in particular during the RGB phase (*22*). Interestingly, the orbital period of HIP 13044 b is close to three times the stellar rotation period. There are a number of known planetary systems which also have such a “coupling” between the stellar rotation and orbital periods, e.g. Tau Boo (1:1), HD 168433 (1:2), HD 90156 (1:2) and HD 93083 (1:3). Such planetary systems are particularly interesting to study star-planet interactions (*30*).

So far, there are only very few planet or brown dwarf detections around post RGB stars besides the pulsar planets, namely V391 Peg (*31*), HW Vir (*32*) and HD 149382 (*33*) (Fig. 1). These are, however, substellar companions around subdwarf-B or Extreme Horizontal Branch (EHB) stars, i.e., the nature of their host stars differs from that of HIP 13044, an RHB star. Contrary to RGB stars, such as G and K giants (*34–37*) and subgiants, e.g. (*38*), HB stars have not been yet extensively surveyed for planets.

While at least 150 main-sequence stars are known to bear close-in ($a = 0.1$ AU) giant planets, so far no such planets have been reported around RGB stars. A possible explanation is that the inner planets have been engulfed by the star when the stellar atmosphere expanded during the giant phase. The survival of HIP 13044 b during that phase is theoretically possible under certain circumstances (*22, 39, 40*). It is also possible that the planet's orbit decayed through tidal interaction with the stellar envelope. However, a prerequisite to survival is then that the mass loss of the star stops before the planet would have been evaporated or accreted. Assuming asymmetric mass loss, velocity kicks could have increased the eccentricity of HIP 13044 b to its current, somewhat high value (*41*). The same could be achieved by interaction with a third body in the system.

Interestingly, a survey to characterize the multiplicity of EHB stars showed that more than 60% of the sample are close binaries (*42*). Their orbital radii are much smaller than the stellar radius in the RGB phase. This could be explained by the high friction in the interstellar medium, which wold move a distant companion towards the primary. Such spiral-in mechanism could also take place in the RGB-to-RHB transition phase. Similar to the binary case, a distant giant planet in the RGB phase can move towards the primary into a smaller orbit. Consequently, the resulting close orbiting planets will be engulfed when the stellar envelope expands again in the next giant phase. HIP 13044 b could be a planet that is just about to be engulfed by its star.

HIP 13044, with a mean metallicity estimate of [Fe/H]=-2.1, is far more metal-poor than any previously known exoplanet hosting star (Fig. 3). For the existing theories of hot giant planet formation, metallicity is an important parameter: in particular, it is fundamental for the core-accretion planet formation model (*43*). It might be that initially, in the planet formation phase, HIP 13044 had a higher metallicity, and that during its subsequent evolution, it lost its heavier elements. For example, during the giant phase, heavy elements could have had been incorporated into dust grains and then separated from the star's atmosphere (*44*). However, given the star's membership to the Helmi stream, in which the most metal-rich sub-dwarfs known so far have [Fe/H]$\sim -1.5$ (*45*), we do not expect its initial Fe abundance to exceed this value.

Finally, as a member of the Helmi stream, HIP 13044 most probably has an extragalactic origin. This implies that its history is likely different from those of the majority of known planet-hosting stars. HIP 13044 was probably attracted to the Milky Way several Gyr ago. Before that, it could have had belonged to a satellite galaxy of the Milky Way similar to Fornax or the Sagittarius dwarf spheroidal galaxy (*14*). Because of the long galactic relaxation timescale, it is extremely unlikely that HIP 13044 b joined its host star through exchange with some Milky Way star, after the former had been tidally stripped. The planet HIP 13044 b could thus have a non-Galactic origin.

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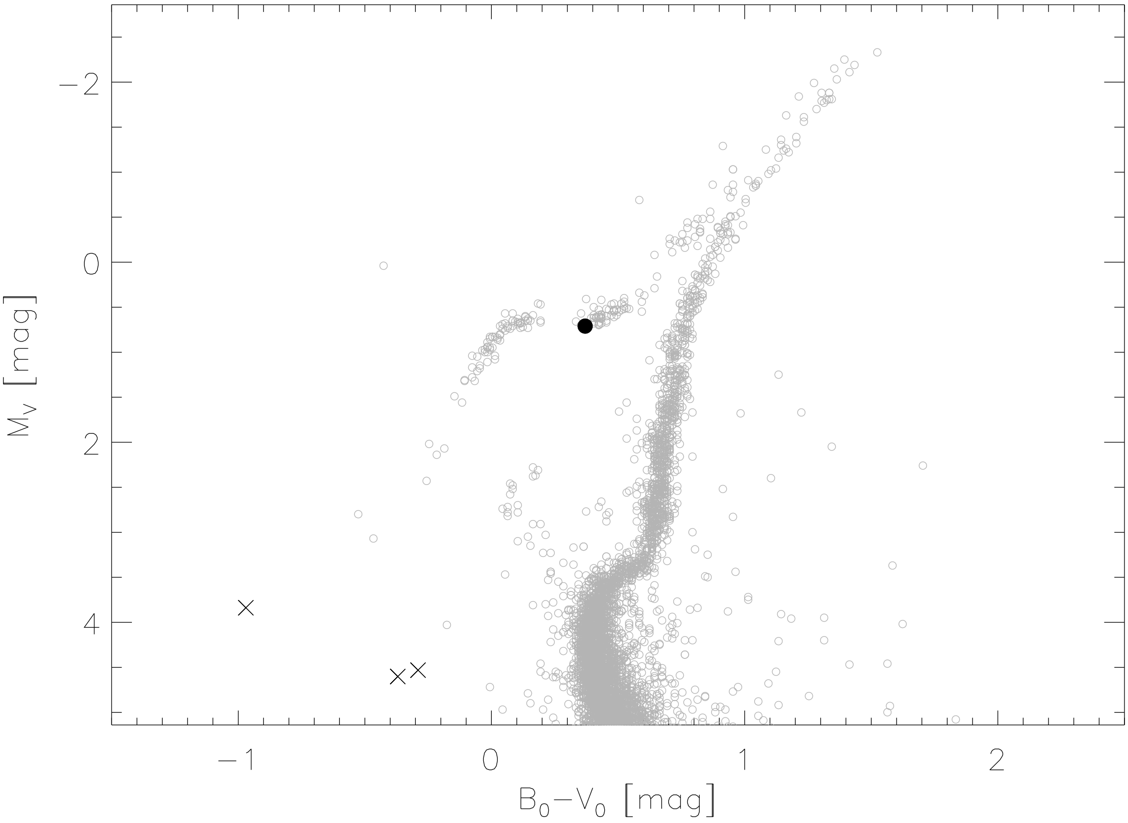

Figure 1: Location of HIP 13044 in a M$_V$ vs. $B-V$ color-magnitude diagram (CMD) shown as a black dot superimposed to the CMD of Messier 3 (grey open circles) based on the photometry by (*46*). Apparent magnitudes have been converted to absolute magnitudes by considering the distance modulus and extinction given by Harris (*47*). The gap separating the blue and red Horizontal Branch (HB) is due to RR Lyrae instability strip. The CMD location of HIP 13044 implies that it is a core He-burning star, located a the blue edge of the RHB. Further candidates for post RGB stars hosting planets/brown dwarf, V391 Peg, HW Vir and HD 149382 (*31–33*) are displayed as crosses.

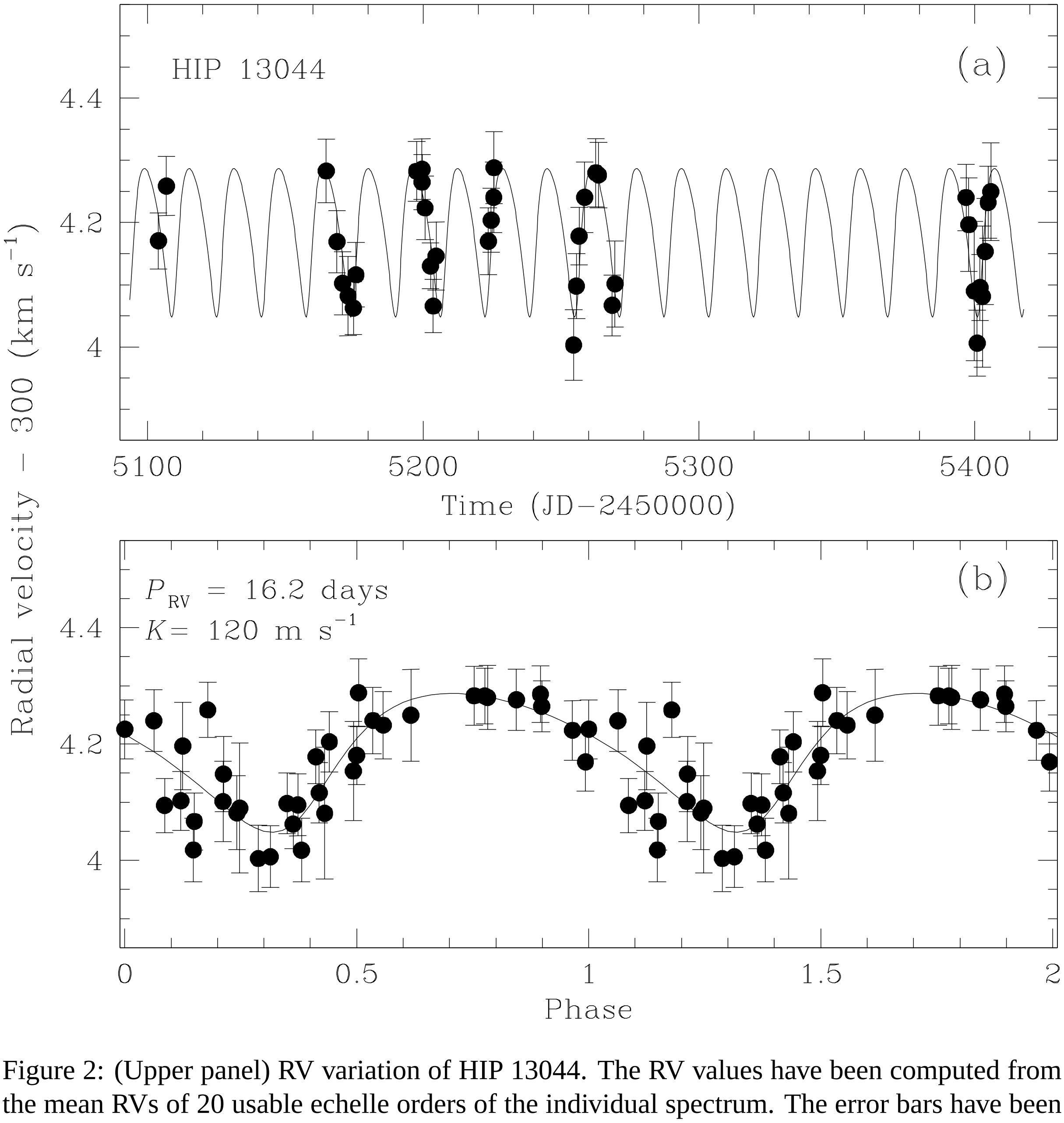

Figure 2: (Upper panel) RV variation of HIP 13044. The RV values have been computed from the mean RVs of 20 usable echelle orders of the individual spectrum. The error bars have been calculated from the standard error of the mean RV of each order. (Lower panel) RV variation phase-folded with $P$ =16.2 days.

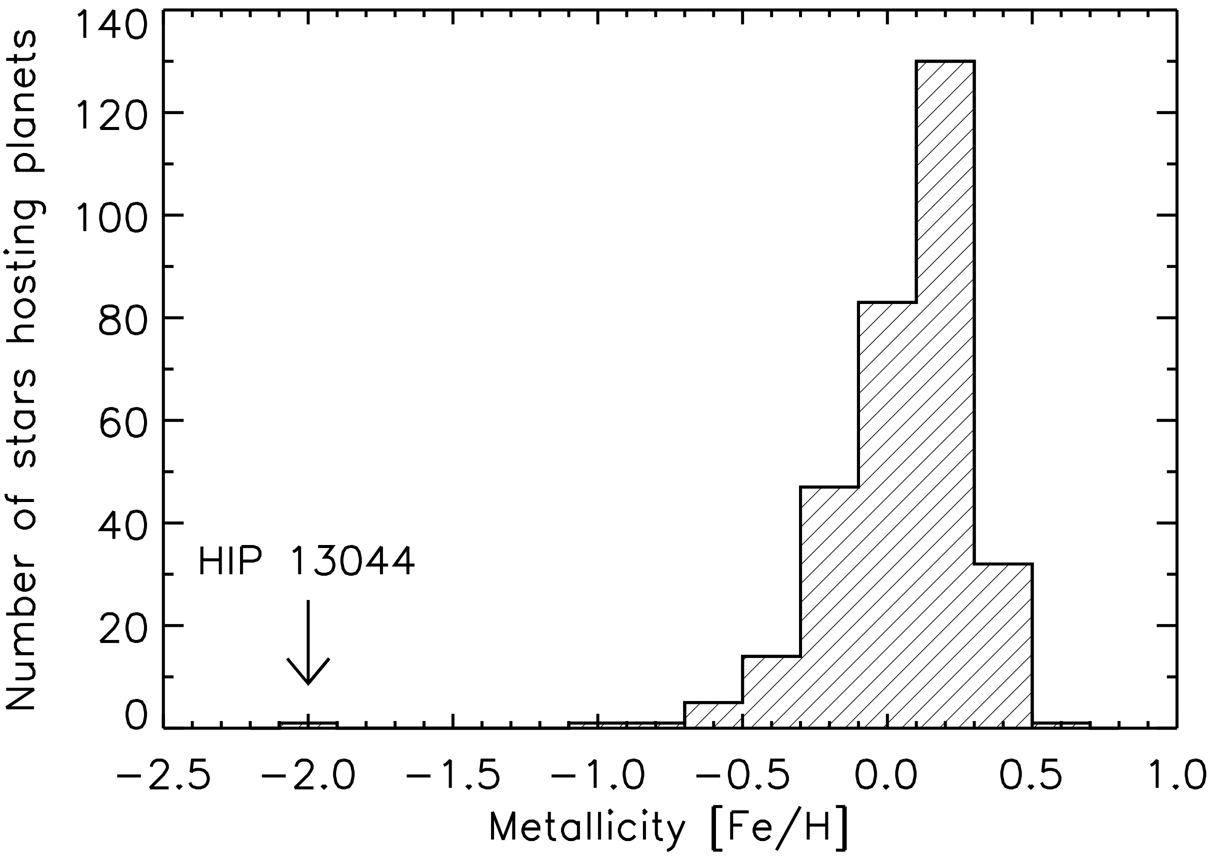

Figure 3: Distribution of the metallicity [Fe/H] of planet-hosting stars.

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