# CHEMICAL COMPOSITION AND EVOLUTION OF POST–AGB STARS

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**Abstract.** Analysis of the chemical compositions of post–AGB stars reveals the following abundance patterns: (*i*) Post–AGB stars which are extremely underabundant in Fe and other refractory elements, but which have nearly normal abundances of C, N, O, S, and Zn. The depleted refractory elements are locked up in circumstellar dust grains. Formation of dust close to the star, and dust–gas separation and dust-driven mass loss driving out mostly the dust may explain the abundances of these stars. (*ii*) High-latitude hot post–AGB stars which show an underabundance of carbon, indicating that they left the AGB before the third dredge-up occurred. (*iii*) Post–AGB stars with overabundances of carbon and *s*-process elements, indicating that they have gone through the third dredge-up and carbon-star phase on the AGB. The overabundance of Li, Al, C and *s*-process elements in some post–AGB stars indicate that they have gone through the dredge-up and Hot Bottom Burning nucleosynthesis at the base of the convective envelope. The observed characteristics of post–AGB stars indicate an evolutionary sequence in the transition region from the tip of the AGB into the young planetary nebula stage.

## 1. Introduction

The low- and intermediate-mass stars that initially have masses between 1 and 5 $M_\odot$ (perhaps up to 8 $M_\odot$) in the late stages of their evolution go through the AGB and planetary nebula stage and become white dwarfs with masses of $\sim 0.6 M_\odot$. These stars shed their massive outer envelopes during the mass loss on the AGB leaving a nuclear-processed white-dwarf-like core with a thin outer envelope. We do not know exactly where and when the strong AGB mass loss ceases. It is normally assumed that this happens when the envelope mass is in the range of 0.001 $M_\odot$, corresponding to an

*R.F. Wing (ed.), The Carbon Star Phenomenon*, 225-236.

effective temperature around 5000 K (Schönberner 1989). In practice the mass loss will cease when the mass of the hydrogen-rich envelope becomes so small that the pulsational amplitude decreases or the pulsation stops altogether. Stars close to the end of their AGB evolution are completely obscured by optically thick, relatively cool dust shells as a consequence of high mass-loss rates. The non-variable OH/IR stars most likely belong to the very early phases of post–AGB evolution (Bedijn 1987). With the advent of the IRAS a completely new class of stars was detected. These stars are found to be in rapid transition from the tip of the AGB into the planetary nebula region (Parthasarathy & Pottasch 1986). These stars often have cold detached circumstellar dust shells with far-infrared colors, flux distributions, dust temperatures and dust masses similar to the dust shells of planetary nebulae. They have supergiant-like spectra in the optical region extending from cool K,G,F supergiant types to hot A,B supergiant types (Parthasarathy & Pottasch 1986; Parthasarathy 1993a,b). Parthasarathy & Pottasch (1986) proposed that the dust shells around these stars are the result of severe mass loss during their AGB stage of evolution. It is likely that these objects are in a hitherto unseen post–AGB phase of the stellar evolution. The characteristics of molecular envelopes around these stars further confirms their post–AGB status (Likkel et al. 1987; Omont et al. 1993). Theoretical calculations through the AGB with inclusion of mass loss and also through the following evolutionary stages down to the white-dwarf sequence have become available (Schönberner 1989, 1993). These calculations predict evolutionary lifetimes of several thousand years in the transition region between the tip of the AGB and the planetary nebula region. Thus a direct comparison between theory and observation now appears possible in the very early phase of this post–AGB evolution.

Recent studies in the optical, infrared, millimeter and radio regions indicate that the following types of stars are in the post–AGB stage of evolution: (*i*) high galactic latitude supergiants, (*ii*) IRAS sources with far–IR colors similar to planetary nebulae and indentified with B, A, F, G, or K supergiants, (*iii*) RV Tauri and UU Her stars and Type II Cepheids like ST Pup, and (*iv*) UV–bright stars in globular clusters.

## 2. Observed Characteristics

Most of the post–AGB stars are IRAS sources with warm and/or cold circumstellar dust shells. Their spatial distribution shows little concentration to the galactic plane, indicative of an older stellar population. Many are high galactic latitude, high-velocity, metal-poor and low-gravity stars. Their spectral types range from K I supergiants to B I supergiants. Observations of CO, OH, and HCN lines in the millimeter and radio regions have revealed molecular envelopes with expansion velocities and mass-loss rates similar to those of evolved stars. Also these observations show that some have oxygen-rich and some have carbon-rich envelopes (Omont et al. 1993). Several of these objects have been found to show unusual emission features at 3 $\mu$m and 21 $\mu$m which are probably due to PAH molecules. Most of them show H$\alpha$ emission or a peculiar H$\alpha$ profile. The hotter ones also show [N II], [S II] and several Balmer lines in emission indicating the presence of a very low excitation nebula.

From an analysis of the IRAS point-source catalogue a large number of post–AGB stars have been detected (Parthasarathy & Pottasch 1986, 1989; Lamers et al. 1986; Pottasch & Parthasarathy 1988; Hrivnak et al. 1989; Kwok 1993, and references therein). Detailed studies of these objects in wavelength regions from ultraviolet to radio are providing clues to understand the role of thermal pulses, nucleosynthesis, mixing, mass loss, and the transition from oxygen-rich to carbon-rich stars. The chemical composition analysis of several post–AGB stars in recent years reveals the following main abundance patterns: post–AGB stars which are extremely underabundant in Fe, high latitude hot post–AGB stars which are underabundant in carbon, and post–AGB stars with overabundances of carbon and *s*-process elements. An analysis and discussion of the chemical compositions of several post–AGB stars is presented in this paper.

## 3. Extremely Iron-Deficient Post–AGB stars

Recent studies have established the existence of a class of post–AGB candidates with extremely low iron-group abundances. HR 4049 ([Fe/H] = –4.8), HD 52961 ([Fe/H] = –4.8), HD 44179 ([Fe/H] = –3.1), and BD +39°4926 ([Fe/H] = –1.6) belong to this group. With [Fe/H] = –4.8, HR 4049 and HD 52961 are among the most iron-poor stars known so far in our Galaxy (Waelkens et al. 1991). The photospheric abundance patttern of these stars is similar to the gas-phase abundances of the interstellar medium. The refractory elements Fe, Mg, Si, Al, Ti, Ca etc. are depleted and the abundances of volatile elements C, N, O, S, and Zn are nearly normal. The photospheric abundances of these stars correlates with the grain condensation temperatures (Bond 1991; Van Winckel et al. 1992; Parthasarathy et al. 1992). Van Winckel et al. (1992) found a nearly normal abundance of Zn in the extremely Fe-poor post–AGB star HD 52961. S and Zn have very low condensation temperatures and therefore do not easily condense into dust grains. The detection of nearly normal amounts of Zn ([Zn/Fe] = +3.1) in HD 52961 is convincing evidence for the fractionation hypothesis. The presence of circumstellar dust around most of these stars lends strong support to the idea that the depleted refractory elements are locked up in circumstellar dust grains. Bond (1991) suggested that there is a selective removal of the metals from the photosphere through grain formation and mass loss.

Parthasarathy et al. (1992) suggested that during the AGB and/or post–AGB stage the outer atmospheres of these stars had expanded and cooled to the limit of the condensation temperature of refractory elements. Formation of cores of dust grains close to the stars and the resulting dust-driven mass loss, driving out mostly the dust, may be able to explain the photospheric abundances of the extremely iron-poor post–AGB stars.

Hoyle & Wickramasinghe (1962) were the first to suggest that dust grains tend to be formed in the atmospheres of cool red giants and supergiants at temperatures less than 2700 K. The dust grains thus formed have a significant effect on the photospheric opacity causing the photospheric density to decrease very markedly as the temperature falls towards 2000 K. It is this fall of density that allows the grains to be repelled outward by radiation pressure and to leave the star altogether.

Recently Van Winckel et al. (1995) found conclusive evidence that all the known extremely iron-deficient post–AGB A – F supergiants (HR 4049, HD 44179, HD 52961, HD 46703 and BD +39°4926) are single-lined spectroscopic binaries with periods of the order of one or two years. Post–AGB stars in binary systems with a narrow range of orbital periods and circumbinary disks resulting from mass loss and mass transfer processes may result in the separation of gas and dust, casusing the photosphere of the post–AGB supergiant companion to be depleted in refractory elements. In fact, Parthasarathy & Pottasch (1986) suggested that some of the post–AGB stars may be low-mass, long-period binaries with a circumbinary disk.

Recently Gonzalez & Wallerstein (1996) found the Type II Cepheid ST Pup ($[Fe/H] = -1.47$) to be a binary ($P = 410$ d) with a chemical composition similar to that of very iron-poor post–AGB stars. A few carbon-rich RV Tauri stars — IW Car (Giridhar et al. 1994), DY Ori, EP Lyr, AR Pup, and R Sge (Gonzalez et al. 1997) — show chemical compositions simliar to those of very iron-poor post–AGB A – F supergiants. It is likely that the RV Tau stars depleted of refractory elements are all binary stars with periods of the order of one to two years similar to those of high-latitude metal-depleted post–AGB stars. These results show that some of the RV Tau stars are not intricsically metal-poor. The metals are depleted due to fractionation and all these stars are IRAS sources with warm dust shells. The presence of circumstellar dust shells and the similarity in chemical compostion of RV Tau stars to the extremely iron-deficient post–AGB A and F supergiants indicates that RV Tau stars and Type II Cepheids like ST Pup are most likely in the post–AGB stage of evolution.

The processes that produce photospheres with depleted refractory elements in $\lambda$ Boo stars and in post–AGB A – F supergiants may be the same. Formation of dust close to the star (during the pre-main-sequence phase in the case of $\lambda$ Boo stars, and during the AGB and/or post–AGB mass-loss phase in the case of post–AGB stars) and subsequent gas and dust separation and dust-driven mass loss (driving out mostly the dust) may have taken place resulting in the depletion of refractory elements in the photospheres of these stars (Parthasarathy 1994). The presence of a companion and/or disk may help in the separation of gas and dust.

The depletion of Fe and other refractory elements seems to range from extremely Fe–depleted stars like HR 4049 and HD 52961 ([Fe/H] = –4.8) to stars with mild depletions. Recently Reddy (1996) found HD 70379 to be an F6 I post–AGB supergiant with a cold detached dust shell and far-infrared colors similar to those of planetary nebulae and high-latitude F supergiants like HD 161796. An analysis of the spectrum of HD 70379 shows that [Fe/H] = –0.4 and the abundances of S and Zn are almost solar (Reddy 1996).

Recently Hambly et al. (1996) have found a high latitude B–type star ($T_{\rm eff}$ = 25,000 K) to be a binary with an abundance pattern similar to that of stars with depleted refractory elements. They find normal He, marginally enhanced C, N, and O, and a deficiency of 0.4 to 0.6 dex in Mg, Si, Fe, etc. The abundance of sulphur is normal.

In a few high-latitude low-gravity B stars, Ca seems to be very underabundant compared to Mg and Fe. In ROA 24, a post–AGB star in $\omega$ Cen, Gonzalez & Wallerstein (1992) found an extreme deficiency of Al. The condensation chemistry is quite complicated. The depletions of various refractory elements may depend on many factors and on the physical conditions in the grain-forming regions of these stars.

## 4. Carbon-Rich Post–AGB Stars

Post–AGB stars which have gone through the carbon-star stage on the AGB are expected to show the products of the triple-alpha process, CN and ON cycling, and the *s*-process on the surface as a result of thermally-pulsing AGB evolution and the third dredge-up phenomenon. Recent chemical composition analysis of several post–AGB stars reveals that they are overabundant in carbon and *s*-process elements, indicating that the triple-alpha products have been brought to the surface. The chemical compositions of the following post–AGB stars show that they are carbon-rich and overabundant in *s*-process elements:

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| – HD 56126 | (F5 I) | (Parthasarathy et al. 1992; Klochkova 1995) |
| – HD 179821 | (G5 I) | (Parthasarathy et al. 1998) |
| – HD 187885 | (F3 I) | (Van Winckel 1996; Parthasarathy et al. 1998) |
| – SAO 34504 | | (Začs et al. 1995) |

- IRAS 05341+0852 (Reddy et al. 1997)
- IRAS 18095+2704 (Klochkova 1995; Reddy 1996)

The iron abundance in most of these stars is around [Fe/H] = –1.0. The low iron abundance in these stars is intrinsic and not due to fractionation. Some of these stars are at high latitudes and have high radial velocities. All of them are IRAS sources with far-infrared colors similar to planetary nebulae. The CO and HCN data and infrared spectra indicate that the dust shells around these stars are also carbon-rich. These results indicate that they are low-mass metal-poor stars which have gone through the carbon-star stage on the AGB.

All of these stars show overabundances of *s*-process elemets. SAO 34504 and IRAS 05341+0852 show overabundances of lithium also. In the above list of stars HD 56126, SAO 34504 and IRAS 05341+0852 show the 21 $\mu$m emission feature. The large ratio of HCN/CO millimeter emission, the presence of $C_2$, $C_3$, and CN molecular absorption features in their optical spectra, and the overabundance of *s*-procees elements indicate that these stars have evolved from the carbon-star phase on the AGB. Recently Webster (1995) suggested that the 21 $\mu$m emission observed in these carbon-rich post–AGB stars is due to fulleranes $C_{60}H_m$ ($m = 1$ to 60).

IRAS 18095+2704 (F3 Ib) is a high latitude post–AGB F supergiant. The iron and carbon abundances are found to be [Fe/H] = –1.0 and [C/Fe] = +0.5, respectively (Klochkova 1995; Reddy 1996). However, the *s*-process elements are more underabundant. A similar abundance pattern is also observed in the high-latitude post–AGB star HD 133656 (Van Winckel et al. 1996): [Fe/H] = –1.0 and [C/Fe] = +0.3. However, in another high latitude A supergiant, HD 105262, Reddy, Parthasarathy & Sivarani (1996) find C/O = 1.2 and [Fe/H]= –2.2. It had previously been classified as a Field Horizontal Branch (FHB) star. The hydrogen line profiles suggest a lower surface gravity and higher luminosity. Its very high galactic latitude (+72°) and large proper motion ($0.''057\ \mathrm{yr}^{-1}$), as well as its overabundance of carbon, makes this star an important one for further study.

### 4.1. IRAS 05341+0852 (F6 I)

Recently Reddy et al. (1997) derived the photospheric abundances of the F–type post–AGB supergiant IRAS 05341+0852. This object shows the 3.3 and 21 $\mu$m emission features which are attributed to carbon-rich molecules such as PAHs and fullerenes, indicating that the circumstellar dust is carbon rich. From an analysis of high-resolution spectra we find that the star is carbon-rich (C/O = 2.2) and metal-poor ([Fe/H] = –1.0). Lithium is overabundant (log Li = 2.5) by a factor of about 100 relative to that observed in normal giants and supergiants. Carbon, nitrogen, oxygen, aluminum and silicon are found to be overabundant. Most importantly we find large overabundance of *s*-process elements: [Y/Fe] = 1.8, [Ba/Fe] = 2.58, [La/Fe] = 2.86, [Ce/Fe] = 2.95, [Pr/Fe] = 2.27, [Nd/Fe] = 1.97 and [Sm/Fe] = 0.86. The result that [S/Fe] = 0.07 indicates that the low Fe abundance is intrinsic and is not due to fractionation in this case. The overabundance of Li, CNO, and *s*-process elements and the large C/O ratio, high galactic latitude, detached cold dust shell, and supergiant-type spectrum indicate that IRAS 05341+0852 evolved from the carbon-rich AGB phase and is now in the post–AGB phase of evolution.

So far IRAS 05341+0852 is the only post–AGB star showing overabundances of Li, C, Al and *s*-process elements which are all in general agreement with the predictions of the third dredge-up and Hot Bottom Burning (HBB) AGB evolutionary models (Lattanzio 1993; Lattanzio et al. 2000). However, these theoretical models suggest that Li and Al are produced in significant amounts during HBB in massive AGB stars. The low iron abundance and high galactic latitude suggest that IRAS 05341+0852 is a low-mass star. The overabundance of Li, Al, C, and *s*-process elements in IRAS 05341+0852 suggests that HBB and third dredge-up occurs in low-mass stars also.

### 4.2. HD 179821 (= AFGL 2343) (G5 Ia)

HD 179821 is an IRAS source with a cold detached dust shell and far–IR colors similar to planetary nebulae. Pottasch & Parthasarathy (1988) concluded that HD 179821 is a post–AGB star. Recently Hawkins et al. (1995) have found that HD 179821 is surrounded by a dusty nebula 4–5″ in diameter at 10.5 and 12.5 $\mu$m. Hawkins et al. (1995) conclude that HD 179821 is an extremely massive star at a distance of about 6 kpc. They estimate the dust-shell mass to be 8 $M_\odot$. Kastner & Weintraub (1995) also conclude that HD 179821 is a massive post–red-supergiant with a dust-shell mass of 5 $M_\odot$. They infer that it is evolving towards the LBV or W–R stage.

Recently we have determined the chemical composition of HD 179821. We find it to be metal-poor ([Fe/H] = –1.0) and overabundant in carbon and *s*-process elements. Its high radial velocity (+100 km s$^{-1}$), underabundance of metals, overabundance of carbon and *s*-process elements, cold detached dust shell, and CO, OH molecular envelope indicate that HD 179821 is a low-mass high-velocity star in the post–AGB stage of evolution.

## 5. Hot Post–AGB Stars

Not all high galactic latitude OB stars have compositions similar to those of Pop. I stars. Several metal-poor high galactic latitude B stars have now been found and identified as post–AGB stars. Conlon et al. (1991), McCausland et al. (1992), Kendal et al. (1994), and Hambly et al. (1996) have determined the chemical compositions of several high-latitude B stars. These high latitude hot post–AGB stars do not have the compositions of Population II dwarfs and red giants. The high latitude hot post–AGB stars are found to be metal-poor and also significantly underabundant in carbon. The chemical composition of these stars indicates that they left the AGB before the third dredge-up occurred. They left the AGB before or at the beginning of the thermal pulsing stage.

Hambly et al. find that the high-latitude B star CPD –61°455 is a hotter analogue of very metal-poor post–AGB stars like HR 4049. CPD –61°455 shows normal He, marginally enhanced CNO, a metal deficiency of 0.4 to 0.6 dex and normal abundance of sulphur. Several hot post–AGB stars have been found by Parthasarathy & Pottasch (1989), Parthasarathy (1994), and Oudmaijer (1996). Chemical composition analysis of all these stars is clearly important.

## 6. Post–AGB Stars in Globular Clusters

The chemical composition of Barnard 29 in M13 ($V = 13$, $T_{\rm eff} = 20{,}000\,$K, $\log g = 0.3$, [Fe/H] = –1.46, $\log L = 3.25\ L_\odot$) has been determined by Conlon et al. (1994). Barnard 29 shows a severe carbon deficiency of more than 2 dex which has also been observed in a number of high-latitude low-gravity B–type stars. This implies that these stars left the AGB before undergoing the third dredge-up. The derived CNO abundances are compatible with the products of hydrogen burning having been brought to the surface during the first and second dredge-ups. Carbon is depleted and nitrogen is enhanced. Oxygen, magnesium and silicon are not enhanced, indicating no evidence of $\alpha$-capture processing. Low-mass stars (0.8 to 1 $M_\odot$) may lose their envelopes and evolve blueward before thermal pulsing begins.

The chemical composition of star No. 1412 in M4 ($V = 10.1$, $T_{\rm eff} = 4125\,$K, $\log g = 0.5$, [Fe/H] = –1.45) was determined by Brown et al. (1990) and Whitmer et al. (1995). It is grossly deficient in carbon and overabundant in nitrogen compared to other stars in M4. It lies about 1 mag above the AGB in M4. It is a late-type analogue of Barnard 29. These results indicate that globular clusters contain low-mass post–AGB stars which left the AGB before undergoing the third dredge-up.

The chemical composition of ROA 24 (= HD 116745), an F0 Ibp star in $\omega$ Cen ($V = 10.82$, $T_{\rm eff} = 6950\,$K, $\log g = 1.15$, [Fe/H] = –1.77, $M_V = -3.66$), was determined by Gonzalez & Wallerstein (1992). In ROA 24 the C, N, O, Na and *s*-process elements are significantly enhanced relative to the other giants in $\omega$ Cen. The large C abundance implies that triple-alpha products have been brought to the surface. The abundance pattern indicates that material that has experienced the triple-alpha process, *s*-process, and possibly Ne–Na, CN and ON cycles has reached the surface.

Thus chemical composition analysis of post–AGB stars in globular clusters is important. Often these are called UV–bright stars (Zinn 1974). There are at least half a dozen luminous non-variable F supergiants known in globular clusters (Harris et al. 1983). Recent surveys have revealed the presence of several hot post–AGB stars in several different globular clusters. The deatiled study of these stars will enable us to better understand the post–AGB evolution of low-mass stars.

## 7. Evolution

Zuckerman & Aller (1986) find that 62 % of planetary nebulae are carbon-rich. They find that a clear majority (62 %) of planeatry nebulae with reasonably reliably determined C/O ratios have $C/O > 1$. This result suggests that more than half of all intermediate and low mass main-sequence stars go through the carbon-rich phase during their AGB and post–AGB evolutionary stage. The percentage of carbon-rich planetary nebulae is in agreement with the relative numbers of carbon-rich and oxygen-rich red giant stars with large mass-loss rates. The planetary nebulae with [WC] central stars are carbon-rich. However, IC 4997 and SwSt 1 show oxygen-rich nebulae and carbon-rich central stars. A similar phenomenon is observed in the post–AGB star Roberts 22. More recently Zijlstra et al. (1991) have found the young planetary nebula IRAS 07027–7934 with a [WC11] central star to show a strong 1612 MHz OH maser as well as weak CO emission. PAH features suggest that the ionized region is carbon-rich, and the outer region where the OH maser is situated is oxygen-rich. This star appears to have transformed from an OH/IR star to a carbon star within the last few hundred years. Parthasarathy (1993a) suggested that the [WC11] central stars of planetary nebulae are the hotter analogues of carbon-rich post–AGB supergiants. The carbon-rich post–AGB supergiants during their evolution to higher temperatures may turn into [WC11] central stars. The carbon-rich post–AGB supergiants with 21 $\mu$m emission and the planetary nebulae with [WC11] nuclei show similar PAH and UIR emission features between 3 and 12 $\mu$m. The characteristics of the circumstellar dust around both these types of objects are similar. It is likely that the carbon-rich post–AGB supergiants may evolve into planetary nebulae with [WC11] nuclei.

### 7.1. SAO 244567 (= Hen 1357)

SAO 244567 (= Hen 1357) is an IRAS source with far–IR colors similar to planetary nebulae. The optical spectrum of this star obtained by Henize around 1950 shows only the H$\alpha$ line in emission. The optical specrum obtained by Kilkenny in 1971 shows that it was a B1 supergiant at that time. Optical spectra obtained since 1990 show strong forbidden emission lines corresponding to a low-excitation and young planetary nebula. It has turned into a planetary nebula within the last 20 years (Parthasarathy et al. 1993, 1995).

HST planetary camera imaging in H$\beta$ and [O III] 5007 Å revealed a 2″ nebula around the central star (Bobrowsky 1994). The IUE ultraviolet spectra obtained during the last seven years show that the central star is rapidly evolving. It is found that the central star of this young planetary has faded by a factor of 2.83 within the last seven years. The terminal velocity of the stellar wind has decreased from $-3500$ km s$^{-1}$ in 1988 to almost zero in 1994.

We derive the parameters of the nebula and the central star to be the following: radius of the nebula 0.02 pc, expansion age 2700 years, luminosity $= 3000\ L_\odot$, core mass $= 0.55\ M_\odot$. The B–type supergiant spectrum in 1971 suggests the effective temperature of the star was around 20,000 K at that time. However, the 1995 IUE high-resolution spectrum of this star and the nebular emission lines indicate that the effective temperature of the central star is now around 50,000 K. The time scale of evolution appears to be very rapid. For such a fast evolution a core mass of 0.8 $M_\odot$ or even higher is required. However, the observed luminosity of the central star does not suggest a high core mass. The estimated distance to SAO 244567 may be uncertain. Further observations of this young planetary nebula may shed new light on the evolution of post–AGB stars.

The B1 supergiant-like spectrum of SAO 244567 in 1971 shows that post–AGB stars, before they turn into planetary nebulae, have extended atmospheres and may mimic the spectra of supergiants. It also confirms the evolutionary sequence of post–AGB supergiants from cooler to hotter and into young planetary nebulae.

I am thankful to Prof. Robert F. Wing for his kind encouragement and support which enabled me to participate in this conference. I also thank the IAU for partial travel support.

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