HD 133656 a new high latitude supergiant *

Abstract. In the course of our study of post-Asymptotic Giant Branch objects, we discovered that the seventh magnitude A supergiant HD 133656 has an infrared excess emission due to circumstellar dust, and that its photospheric abundance pattern resembles that of population II stars. We present an abundance study of the object, and discuss its nature in terms of post-AGB evolution.

1 Introduction

In recent years interest has grown in the study of stars in transition between the Asymptotic Giant Branch (AGB) and planetary nebula stage (PN). AGB stars lose mass rapidly and eventually become obscured by their circumstellar dust. When a star leaves the AGB, its mass loss rate decreases significantly and the star may become sufficiently hot to create a PN. During the transition from the AGB to the PN stage, commonly called the post-AGB or proto-planetary nebula phase, the shell created during the AGB moves away from the central star and becomes optically thin after a few hundred years; hence the obscured star becomes visible again. The transition time from the AGB to a PN is believed to be a few thousand years.

Several searches for post-AGB stars have been reported in the literature (e.g. Parthasarathy and Pottasch, 1986; Hrivnak et al. 1989; van der Veen et al. 1989; Trams et al. 1991; Oudmaijer et al. 1992; Slijkhuis 1992). These searches yielded many post-AGB candidates of which most are stars with supergiant-type spectra, surrounded by dust shells. For recent reviews on the subject we refer to Waters et al. (1993) and Kwok (1993).

In order to extend the sample of post-AGB stars to objects that have evolved off the AGB longer ago than the objects studied so far, Oudmaijer (1995) conducted a search in the IRAS Point Source Catalog (PSC, 1985) for objects that were not detected at 12 μm. HD 133656 (A2Ib, 15°03′59.5″ -48°06′23″, 1950.0) was found in this selection. The star has a significant excess at infrared wavelengths, it is detected at 25 and 60 μm, while strong background radiation prevented a good measurement at 100 μm. Since Oudmaijer (1995) was the first to allow for an upper limit at 12 μm, it is clear why HD 133656 was

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missed in the above mentioned selections. HD 133656 is a bright object, with $m_V = 7.5$ and $E(B - V) = 0.34$. The galactic latitude of HD 133656 is $8^\circ$, which would place it more than 1500 pc above the plane if it were a true massive supergiant.

The structure of this paper is as follows. In Sec. 2 we present newly obtained photometry of the object, and fit the spectral energy distribution with an optically thin dust model. In Sec. 3 the spectroscopic and photometric variability are discussed. In Sec. 4 we describe the spectroscopical observations and the determination of the photospheric abundances. The results are discussed in Sec. 5, and we conclude in Sec. 6.

### 2 The spectral energy distribution of HD 133656

We have improved the PSC flux densities by making a co-add of all individual IRAS scans using the the IRAS-GIPSY software system developed at the Kapteyn Astronomical Institute, Groningen (Wesselius et al. 1992; Van der Hulst et al. 1992). It proved not possible to determine a flux density at 100 $\mu$m because the background at this wavelength is very strong. We are in the position however to significantly decrease the upper limit. We estimate the 100 $\mu$m flux density of HD 133656 to be less than 2-3 Jy, and it is certainly much less than 7.98 Jy, the upper limit listed in the PSC. The new flux densities are listed in Table 2.

Our set of observations in the Geneva photometric system is presented in Table 1 and was obtained during the ongoing photometric monitoring programme of optically bright post-AGB candidate stars by the Leuven group (e.g. Bogaert, 1994). The data were supplemented with observations from the Geneva archive that contains data taken ten years ago. From the tables of Cramer and Maeder (1979), we find a spectral type A4-5 Ib with a total reddening $E(B - V) = 0.32$

Further photometry for the object is taken from Humphreys (1975) and Olsen (1984). In addition we have obtained IUE short and long wavelength spectra (SWP50191 and LWP27563) taken on March 11, 1994. The integration times were 30 and 3 minutes re-
Table 2 Photometry of HD 133656

<table>
<thead>
<tr>
<th>Wavelength ((\mu m))</th>
<th>Magnitude</th>
<th>Flux (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36 (U)</td>
<td>8.09</td>
<td>1.091</td>
</tr>
<tr>
<td>0.44 (B)</td>
<td>7.88</td>
<td>3.126</td>
</tr>
<tr>
<td>0.55 (V)</td>
<td>7.51</td>
<td>3.776</td>
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<tr>
<td>0.35 ((75\ \mu m))</td>
<td>9.32</td>
<td>0.248</td>
</tr>
<tr>
<td>0.411 ((v))</td>
<td>8.05</td>
<td>2.438</td>
</tr>
<tr>
<td>0.467 ((b))</td>
<td>7.78</td>
<td>3.257</td>
</tr>
<tr>
<td>0.547 ((y))</td>
<td>7.50</td>
<td>3.811</td>
</tr>
<tr>
<td>0.3463 (U)</td>
<td>8.94</td>
<td>0.611</td>
</tr>
<tr>
<td>0.4015 (B1)</td>
<td>7.84</td>
<td>2.675</td>
</tr>
<tr>
<td>0.4227 (B)</td>
<td>6.932</td>
<td>2.898</td>
</tr>
<tr>
<td>0.4476 (B2)</td>
<td>8.406</td>
<td>3.151</td>
</tr>
<tr>
<td>0.5395 (V1)</td>
<td>8.237</td>
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</tr>
<tr>
<td>0.5489 (V)</td>
<td>7.517</td>
<td>3.696</td>
</tr>
<tr>
<td>0.5807 (G)</td>
<td>8.619</td>
<td>3.817</td>
</tr>
<tr>
<td>12</td>
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<td>0.17</td>
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<td>60</td>
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</tr>
<tr>
<td>100</td>
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<td>&lt;3</td>
</tr>
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</table>

UBV photometry taken from Humphreys (1975), the Strömgren photometry is taken from Olsen (1984). The IRAS fluxes are determined from the raw data, and their errors, as determined from the signal-to-noise in the local background are 0.02, 0.03, and 0.13 Jy respectively.

spectively. These spectra are rebinned to pixels of 25Å and the resulting energy distribution is plotted in Fig. 1.

2.1 Fitting the energy distribution

The photospheric part of the spectral energy distribution (SED) is fitted with a Kurucz (1979) atmospheric model which will be used as input for the fit of the infrared part of the SED. We take the atmospheric parameters as derived from the abundance analysis (Sec. 4), \(T_{\text{eff}} = 8000\) K, and \(\log g = 1\). The interstellar reddening curve of Savage and Mathis (1979) was used to determine the total \(E(B - V)\) to the object. A value of \(E(B - V) = 0.34\) provides a very good fit to the optical photometry and the IUE spectra (Fig. 1). The extinction towards HD 133656 is likely to be interstellar, because the circumstellar dust is optically thin to the photospheric radiation (see below).

In order to fit the infrared excess of HD 133656 we employ the optically thin dust model, described by Waters et al. (1988). This model has been successfully applied to fit
the SEDs of post-AGB objects by Trams (1991), van der Veen et al. (1994) and Bogaert (1994). In the model the dust is optically thin and located in a spherically symmetric shell. The dust grain properties are taken from Hildebrand (1983) and are as follows: the density of the grains $\rho_d = 3 \, \text{g cm}^{-3}$, the dust emissivity law goes as $Q(\lambda) = Q_0 (\lambda/\lambda_0)^{-p}$, with $Q_0 = 7.5 \times 10^{-4}$ at $\lambda_0 = 125 \, \mu\text{m}$. The density is assumed to follow an $r^{-2}$ law, representing a constant mass loss with a constant outflow velocity. The dust emissivity parameter $p$ is set to 1 and the grain size is taken to be $0.1 \, \mu\text{m}$.

Using a minimization algorithm (AMOEBA, Press et al. 1986) the parameter space was searched for the best fit. The procedure was repeated several times and the results appeared to be stable. The error in the inner radius of the shell is less than 15%, and about a factor of two in the resulting mass loss rates. The outer radius of the circumstellar shell is less well determined, because the $100 \, \mu\text{m}$ flux density, that better traces the cool distant dust than the $60 \, \mu\text{m}$ flux density is not known.

The best fit is presented in Fig. 1. Note the large offset between the model $12 \, \mu\text{m}$ flux and the observed $12 \, \mu\text{m}$ flux. Since the $12 \, \mu\text{m}$ datapoint has a larger error than the 25 and 60 $\mu\text{m}$ points, the fit procedure put more weight on the other data points. Since the dust is optically thin, it is more likely that the discrepancy between the model $12 \, \mu\text{m}$ flux and the observed flux density is due to excess emission at 25 or 60 $\mu\text{m}$, than due to an absorption
feature at 12 μm. If the fit is forced through the 12 μm point, the model predicts too less flux at either the 25 or 60 μm points. In these cases, the inner radius of the shell increases by about 30%, while the mass loss rates remain within the same order of magnitude as the fit that we obtained now.

We find an inner radius of 11,000 R_⊙ and an outer radius of 15,500 R_⊙. The dust mass loss rate is then $5 \times 10^{-8} \, M_\odot/yr \frac{R_\odot}{kpc} \frac{v_{\text{exp}}}{100 \text{km s}^{-1}}$, where D is the distance to HD 133656 in kpc, and $v_{\text{exp}}$ the expansion velocity in km s$^{-1}$. From these values, the kinematic age of the inner radius of the shell is $\sim 1000$ years. This is a significantly larger age than found for most post-AGB objects that have been fitted with a dust model (e.g. Trams et al. 1991; van der Veen et al. 1994, Bogaert 1994), suggesting that older objects indeed tend to become too faint at 12 μm to be detected by IRAS.

### 3 Variability

In Fig. 3 we present several spectra around the Hβ line. The line exhibits a shell type profile, an emission profile that is found in almost all other optically bright post-AGB candidate stars (see e.g. Waters et al., 1993; Oudmaijer and Bakker, 1994). The Hβ line appears to be variable on timescales less than months. The variation of both emission components seems anti-correlated in the case of HD 133656; In Fig. 3 one can see that the red component of the line builds up strength in time while the blue component seems to decrease. The last date we observed the object in Hβ the situation seems to be reversed again, the blue component is strong, while the red component is hardly visible.

It is unclear which mechanism is responsible for the (variable) Hβ emission in the spectra of post-AGB. In the case of the post-AGB candidate star HR 4049, it is possibly due to mass loss, where the Hβ line-profile is influenced by the position of the supergiant in its orbit around its unseen binary companion, but also variability on a shorter timescale is observed (Waelkens et al. 1991a). We note that we could not find any significant radial velocity variations (pointing to a binary nature) during the observations of HD 133656.

Similar Hβ line-profile variability is observed in RV Tauri stars, where the emission arises due to a shock wave passing in the outer photospheric layers (e.g. Gillet et al. 1989; Lébre and Gilet, 1992 and references therein). Interestingly however, we do not find strong photometric variability, neither on short timescales nor on the long baseline of ten years; the photometric measurements vary around 0.01-0.02 magnitudes. Only the U band magnitude shows some minor variability with a total amplitude of 0.1 mag. Care should be taken, however, to interpret this as a real effect, as the amplitude is hardly larger that the estimated error of the individual U band measurements.

It is likely that the photospheric shockwave does not contain much energy. The shock is then observable in variations in the strong Hβ line, but not strongly in the photometry.
4 Abundance analysis

We performed a detailed standard LTE abundance analysis on the basis of high signal-to-noise (S/N > 100), high resolution (\(\lambda/\Delta\lambda \approx 50,000\)) optical spectra. The spectra were obtained with the CES spectrometer mounted on the 1.4m CAT telescope of the ESO La Silla observatory during several runs in 1993. A detailed description of the obtained data and reduction processes can be found in Van Winckel (1995) and will be published elsewhere.

4.1 Model parameters

One of the main problems in determining the chemical composition of a star is that an accurate knowledge of the temperature and gravity of the object is required. Unfortunately, quantitative model parameter estimates from photometric data alone is hampered by
the uncertainty in the calibration of photometric systems for supergiants. We therefore combined several photometric and spectroscopic indicators.

The photometry given in the previous section definitely points towards a low gravity. We derived the parameters for an appropriate model atmosphere by the requirement that Fe I and Fe II lines should yield the same abundance. This method determines a line in the $\log g$–$T_{\text{eff}}$ diagram in the sense that a higher temperature requires a higher gravity in order to fulfill the ionisation balance. We find the most likely values to range between $(T_{\text{eff}} = 7800, \log g = 1)$ and $(T_{\text{eff}} = 8200, \log g = 1.5)$. A higher temperature would yield a sub-solar helium content which is rather unlikely, a lower temperature would imply even more extreme abundances and a large supersolar helium content. The best agreement for the other species for which we have neutral and singly ionised lines (Mg, Cr) is found for the cooler model. A micro-turbulent velocity of 3 km/s was found by minimizing the scatter of the abundances of the Fe lines. The $H\gamma$ and $H\beta$ line-profiles were compared with the theoretical profiles computed by Kurucz (1979) and agreement was found to be good in the above range of model parameters.

4.2 Abundances

The chemical abundances were computed in local thermodynamic equilibrium (LTE) using a standard model atmosphere analysis technique. The abundance of a certain element was computed by matching the measured equivalent width and the equivalent width computed by integration through a model atmosphere with the abundance as a free parameter. The model atmospheres were interpolated from the grid of Kurucz (1979) or computed using the ATLAS8 code of Kurucz as described by Castelli (1988).

In order to minimize the influence of the error in the microturbulent velocity and unprecise damping parameters, we limited our abundance analysis to lines with an equivalent width smaller than 115 mÅ. In doing so, we focus on lines formed in deeper layers where the non-LTE effects are known to be smaller as well. Moreover, the non-LTE effects are not thought to be very large for Ib supergiants (e.g. Venn, 1993).

In Table 3 we list the computed abundances for the two models mentioned above. For every element, the abundance is given in the usual manner: the logarithm of the number of atoms of that element scaled to hydrogen with $\log(N_H) = 12.00$. A good indicator for the internal consistency is given by the line-to-line scatter in the abundances for elements for which many lines were observed. In Table 3 we list the number of lines ($n$) used in the analysis and the standard deviation ($\sigma$) around the unweighted mean of the abundance calculations for every ion. The influence of errors on the model parameters are given by the difference in abundances for the two models.

From Table 3 one can clearly see that the abundances of the iron-peak elements are significantly underabundant relative to the solar values. This is a strong indication that HD 133656 is indeed an old and thus a low-mass object. The main chemical indicators that probe the yields of stellar evolution are the abundances of C, N, O and s-process elements. The evolved nature of the object is confirmed by the C and N photospheric
Table 3 Abundances of HD 133656

<table>
<thead>
<tr>
<th>Ion</th>
<th>A (Sun)</th>
<th>σ</th>
<th>A (Sun)</th>
<th>σ</th>
<th># lines</th>
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<td>HeI</td>
<td>11.09</td>
<td></td>
<td>10.83</td>
<td></td>
<td>11.00</td>
</tr>
<tr>
<td>C I</td>
<td>7.87</td>
<td>0.31</td>
<td>8.02</td>
<td>0.31</td>
<td>8.56</td>
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<td>N I</td>
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<td>0.22</td>
<td>7.80</td>
<td>0.22</td>
<td>8.05</td>
</tr>
<tr>
<td>O I</td>
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<td>0.09</td>
<td>8.80</td>
<td>0.10</td>
<td>8.93</td>
</tr>
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<td>0.00</td>
<td>6.84</td>
<td>0.00</td>
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<tr>
<td>AlI</td>
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</tr>
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<td>0.07</td>
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<tr>
<td>Si</td>
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<td>0.09</td>
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<td>CrII</td>
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<td>4.93</td>
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<td>FeI</td>
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<td>6.95</td>
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<td>FeII</td>
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<td>BaII</td>
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<td></td>
<td>0.91</td>
<td></td>
<td>2.13</td>
</tr>
</tbody>
</table>

* taken from Grevesse (1989), ** Identification is not sure

abundance with [C/Fe] = +0.3, [N/Fe] = +0.7 which is distinctly different from the C and N abundances found in unevolved objects with the same metallicity (Wheeler et al. 1989). There is however no evidence for evolutionary photospherical enrichment of oxygen. With [O/Fe] = +0.5, the oxygen abundance is similar to the oxygen abundance of unevolved stars with [Fe/H] = −1.0. Also the light α-elements (Mg, Si, S) yield [α/Fe] = +0.45, a value that is predicted by the chemical evolution of our Galaxy. The heavier α-element Ca seems to follow the Fe deficiency, and so do the Fe-peak elements Sc, Ti, Cr and Ni. The one observed suitable He I line at 5876 Å indicates a solar He content.

Surprisingly the s-process elements are apparently deficient relative to Fe: [Sr/Fe] = −0.8 and [Ba/Fe] = −0.6. Both values are only based on one line, so the internal errors cannot be estimated.
5 Discussion

HD 133656 appeared during our study of objects in the IRAS Point Source Catalog with an upper limit at 12 μm. Its supergiant spectral type, its infrared excess, the apparently high galactic latitude and low metal content are indicators that the star is in a post-AGB evolutionary stage of a low mass star.

So far, several abundance analyses of post-AGB stars have been reported in the literature, and it appears that several different classes can be distinguished. One class consists of extremely metal deficient post-AGB candidate stars that have rather peculiar photospheric abundance patterns. This group consists of HD 52961 (Waelkens et al. 1991b), HR 4049 (Lambert et al. 1988), BD +39 4926 (Kodaira et al. 1970), and the central star of the well known Red Rectangle nebula (HD 44179, Waelkens et al. 1992). These objects share photospheric abundance patterns similar to the composition of the gaseous component of the interstellar medium (Van Winckel et al. 1992; Trams et al. 1993). In particular the abundances of C, N, O, but also S and Zn (for HD 52961 and HD 44179) are about solar, while Fe is orders of magnitudes less abundant. In order to explain these peculiar abundances, it has been suggested that the outflowing wind has been stripped of its metals that condensed onto grains (Lambert et al. 1988; Bond, 1991; Van Winckel et al. 1992, Mathis and Lamers, 1992; Waters et al. 1992). The ‘cleaned’ wind then has reaccreted onto the stellar photosphere. Obviously, the photospheric abundance pattern is not of use to investigate the nucleosynthetic processes that occur during the thermal-pulsing AGB phase in these cases. Recently Van Winckel et al. (1995) found all those objects to be binaries with a period in the order of one year. HD 133656 does not show similar abundance patterns to this class of objects, and we can conclude that it is not a less extreme candidate of this group.

Another group of objects has been discussed by e.g. Luck et al. (1983, 1990) and Van Winckel (1995), and also consists of optically bright F type post-AGB objects. A similar object is the F type post-AGB star HD 116745 in the globular cluster ω Cen (Gonzalez and Wallerstein, 1991). Most of these objects are moderately metal deficient. The C, N and O abundances show that N is enhanced with respect to C and O. The iron deficiencies in these stars reflect the primordial abundances, confirming the population II nature of the objects. The solar values of C, N, and O indicate that processing has occurred during their evolution. The lack of s-processed elements may mean that these stars have undergone not many thermal pulses, or that the third dredge-up was not very efficient (Van Winckel, 1995). In fact, based on the surface abundances, only three objects are beyond doubt post-AGB stars. These are HD 187885, HD 158616 (Van Winckel, 1995), and HD 56126 (Klochkova, 1995). They are all carbon-rich and show a wealth of lines from the s-process elements.

How does HD 133656 compare with the group of optically bright post-AGB stars with moderate metal deficiencies? First of all, like most objects, HD 133656 shows an enhancement of C and N with respect to Fe. Secondly, N seems to be more overabundant than C or O, and finally, no enhancement of s-process elements is found. From the above
comparison we conclude that HD 133656 strongly resembles these lower temperature objects.

Interestingly, over the last years the group of post-AGB candidate stars has been extended to hotter objects by the Belfast group (e.g. McCausland et al. 1992). This group of objects consists of high latitude B stars with abundances that are not expected from a young population. Their iron content is very small, and although the N and O abundances are enhanced with respect to the iron group elements, the C abundance is surprisingly low compared to N and O. These objects have no observed infrared excess, with the exception of LS IV -12.111 (Conlon et al. 1993), that shows an observable PN.

The question that arises here is whether HD 133656 can be considered an intermediate case between the cool F-G type post-AGB objects and the B stars discussed by Conlon et al.. The appearance of the infrared excess due to the circumstellar dust indicates that HD 133656 could be an intermediate case. In Sec. 2.1 it is shown that the far-infrared excess of HD 133656 is cool, and the fitting results imply that the inner radius of the shell has a dynamical age of order 1000 years. This is significantly larger than those objects for which dust fitting has been performed (Trams 1991; Van der Veen et al. 1994; Bogaert 1994). Moreover, HD 133656 is not strongly photometric variable, in contrast to the cooler objects. The B stars however do not have excess emission in the infrared implying that if these objects are post-AGB stars, the dust shell must have dispersed in the interstellar medium. McCausland et al. (1992) already speculated that these objects must be of low mass, and thus slowly evolving, because they are located on the lower mass Schönberner (1983) tracks in the temperature-gravity plane.

The abundance patterns leave open some questions. In particular the extreme carbon deficiency in the hot stars is contrary to that observed in the cooler objects and HD 133656. The iron deficient B-stars all show an extreme low carbon content and if the third dredge-up indeed took place in these objects, one has to invoke scenarios where the C abundance becomes low (such as Hot Bottom Burning, that should destroy the newly synthesized carbon, or carbon-poor progenitor stars, McCausland et al. 1992). This is apparently not the case for HD 133656. Although the stellar temperature, iron deficiency and IR-excess of HD 133656 are consistent with an evolutionary stage in between the cooler F-supergiants and the B type post-AGB objects, the large difference in the carbon abundance remains to be explained.

6 Summary

In this paper we have presented a study of the post-AGB candidate star HD 133656. The object was discovered in a selection conducted by Oudmaijer (1995) who searched for bright stars listed the IRAS Point Source Catalog with an upper limit at 12 μm.

From fitting the infrared excess we find that the kinematic age of the circumstellar shell is of order 1000 years, and that the dust mass loss rate is relatively low \(5 \times 10^{-8} \text{ M}_{\odot}/\text{yr}\). The large kinematic age and the low mass loss rates imply that the object may be a low mass object. This is supported by an abundance analysis. The significant underabundance
of the iron-peak elements with respect to the solar values imply an old age and thus low mass for the object. Other results from the analysis are the presence of a photospheric enhancement of N and to a lesser extent C abundances. The absence of any enhancements in O or the s-process elements implies that the third dredge-up was not so efficient in this object, or has not happened at all.

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