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Stellar evolution of low and intermediate-mass stars

III. An application of evolutionary post-AGB models: the variable central star FG Sagittae

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Abstract. Based on a set of evolutionary calculations for thermally pulsating post-AGB models we introduce a robust method to measure FG Sge's mass which was found to be $0.61 M_{\odot}$. The corresponding evolutionary timescale is consistent with the expansion age of the planetary nebula. Assuming that FG Sge's surface was already enriched with heavy elements on the AGB we propose that during the central-star evolution these elements were removed from the superficial radiative layers due to, e.g., dust/gas separation, leaving the deeper convective layers unchanged. During the flash the outward moving envelope convection mixed the stored heavy elements back to the surface.

Key words: stars: evolution – stars: AGB, post-AGB – stars: abundances – stars: individual: FG Sge

1. Introduction

One of the most unique objects for the study of stellar evolution beyond the Asymptotic Giant Branch ever observed is without doubt the variable central-star of the planetary nebula He 1-5: FG Sge.

Its visual brightness increased by $\approx$ 5 mag from 1900 to 1970 (cf. Herbig & Boyarchuk 1968, Langer et al. 1974; see also van Genderen & Gautschy 1995) explicable by an increasing stellar radius and a decreasing effective temperature. The observed apparent magnitudes for 1900-1992.6 are shown in Fig. 1.

After 1967 dramatic abundance changes took place, too: s-process elements appeared at the surface. Langer et al. (1974) found that the strength of the corresponding absorption lines (like YII, ZrII, CeII, LaII) increased continuously during 1969-1972. In 1972 the s-process isotopes had become 25 times overabundant compared to solar values. The increase of these abundances continued during the next years and levelled out in the early 1980's (e.g. Wallerstein 1990, Kipper 1996).

At first, the carbon abundance stayed roughly normal during the above changes. However, Acker et al. (1982) found evidence for C_2 bands in a spectrum from 1980, and Iijima & Straffela (1993) clearly identified these bands in one taken in 1981. Since then FG Sge can be called a C star. Based on spectra taken in 1994, Kipper et al. (1995) estimated a carbon to oxygen ratio of $C/O \approx 4.5$ (for $T_{\rm eff}$ = 5500 K) with the assumption that the oxygen abundance had remained solar.

The existence of strong H_{α} lines in the spectra (Kipper & Kipper 1993, Kipper 1996) and the normal ratio of H to He equivalent widths (cf. Herbig & Boyarchuk 1968) leads to the conclusion that FG Sge is *not* a hydrogen-deficient star (as often assumed). This is in line with the presence of isotopic C_2 bands of the Swan system (Kipper 1996) and G bands (Iijima 1996) which are usually not detected in hydrogen-deficient stars.

During the eighties the cooling stopped ($T_{\rm eff}^{\rm min} \approx$ 5000…5500 K). Montesinos et al. (1990) stated that there seems to be evidence for a renewed increase of the effective temperature at the end of that decade. However, it should be noted that the estimations of the recent effective temperatures by different authors do not lead to a clear picture and, hence, only a temperature intervall can be deduced from observations (Kipper 1996).

In the fall of 1992 the optical brightness of FG Sge decreased drastically from V = 9.2 to 12.9 within only 40 days (Jurcsik 1992) followed by a slow recovery (Jurcsik 1993, Simon 1994). This temporary fading appears to be typical for R CrB stars leading often to the conclusion that FG Sge is a R CrB star in the making (e.g. Jurcsik 1993, Hinkle et al. 1995, Kipper et al. 1995, Iben et al. 1996). However, it is important to note that such erratic variations can also be observed in carbon-rich Mira stars, and are believed to be caused by newly formed carbon-based grains obscuring partially the stellar disc (Whitelock 1997). Therefore, one cannot conclude definitely from a light-curve pattern

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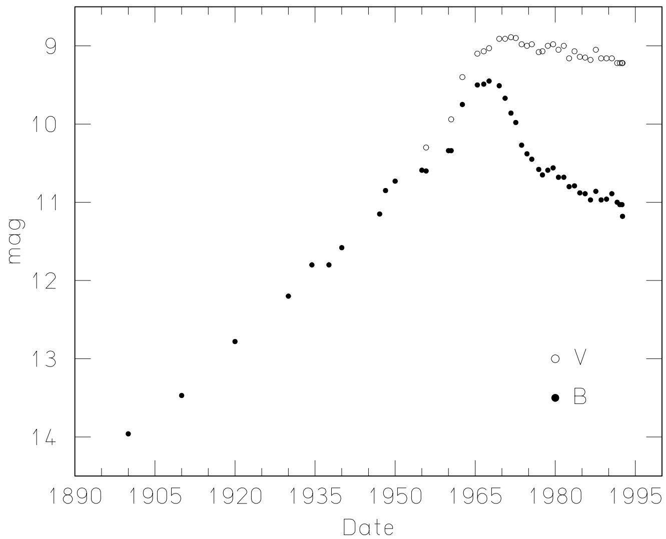

Fig. 1. Observed apparent magnitudes V and $B = m_{\rm pg}$ of FG Sge for 1900-1992.6 taken from van Genderen & Gautschy (1995).

reminiscent of that for (hydrogen-deficient) R CrB stars that the underlying star in question is also hydrogen-deficient.

For more details of the observational history see, e.g., the recent review of Kipper (1996), and references therein.

Due to its rapid evolution in the HR diagram and its surface enrichment with carbon and s-process isotopes, FG Sge is believed to have experienced a final thermal pulse during its post-AGB evolution roughly 100 yr ago (Paczynski 1971, Langer et al. 1974, Sackmann & Despain 1974, Schönberner 1979, Iben 1984) giving direct observational evidence for the existence of such helium-shell flashes.

Despite the various studies for FG Sge, the uncertainty concerning its mass is still large. For instance, Iben (1984) determined $0.65 M_\odot$ by means of evolutionary calculations whereas pulsational investigations suggest masses of $0.4 M_\odot$ (Whitney 1978), $0.65 M_\odot$ (Montesinos et al. 1990 with Iben 1984, van Genderen 1994 with Tuchman et al. 1993), $0.8 M_\odot$ (Fadeyev & Tutokov 1981, van Genderen & Gautschy 1995), or even $1.2 M_\odot$ (Mayor & Acker 1980).

The aim of this paper is to determine the mass of FG Sge by means of a *grid* of thermally pulsating post-AGB models, and to discuss the various consequences of helium-shell flashes for timescales and surface abundances during the central-star stage.

2. On the mass of FG Sge

2.1. Evolutionary models

During their evolution along the Asymptotic Giant Branch (AGB) stars of low and intermediate-mass suffer from mass loss and recurrent instabilities of the helium burning shell (thermal pulses). The strength of the stellar winds along the AGB determines the duration of the AGB evolution (i.e. the number of thermal pulses, the final mass, etc.) which is terminated when

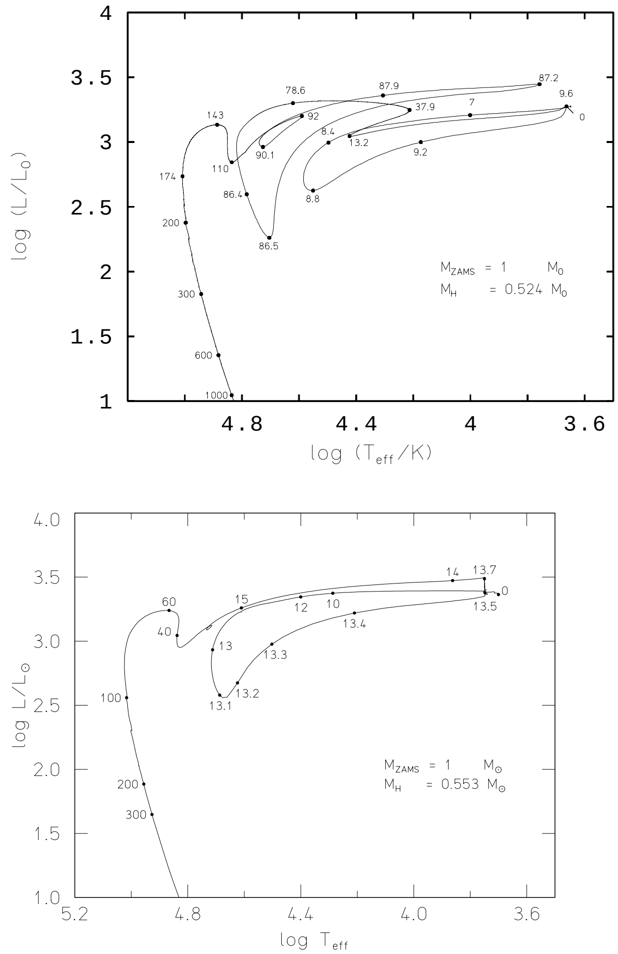

Fig. 2. Tracks for thermally pulsating post-AGB models with $M_{\rm H} = 0.524 M_\odot$ and $0.553 M_\odot$. Time marks are in units of 10^3 yr.

the envelope mass, $M_{\rm env}$, i.e. the mass above the hydrogen exhausted core, is reduced to the order of several percent of the total stellar mass ($\approx$ several $10^{-2} M_\odot$).

How the star evolves through the post-AGB stage depends on the thermal-pulse cycle-phase ϕ (fraction of the time span between two subsequent pulses) at which it moves off the AGB. For $0 \leq \phi \lesssim 0.15$ the evolution is dominated by helium burning. If $0.15 \lesssim \phi \lesssim 0.3$ the luminosity is determined both by the hydrogen and the helium shell-source, whereas in the case of $0.3 \lesssim \phi \leq 1.0$ hydrogen burning governs the nuclear energy production (Iben 1984). If the thermal-pulse cycle-phase is sufficiently large. i.e. $\phi \gtrsim 0.9$, a last thermal pulse can occur during the post-AGB evolution transforming a hydrogen burning into a helium burning remnant. The flash forces the model to expand rapidly to Red Giant dimensions, and the remnant quickly evolves back to the AGB ("born again"). There, it starts its post-AGB evolution again, but now as a helium burning object.

In contrast to previous efforts, we used a *grid* of thermally pulsating post-AGB models in order to determine FG Sge's mass (Blöcker & Schönberner 1996a). This grid consist of Pop.I

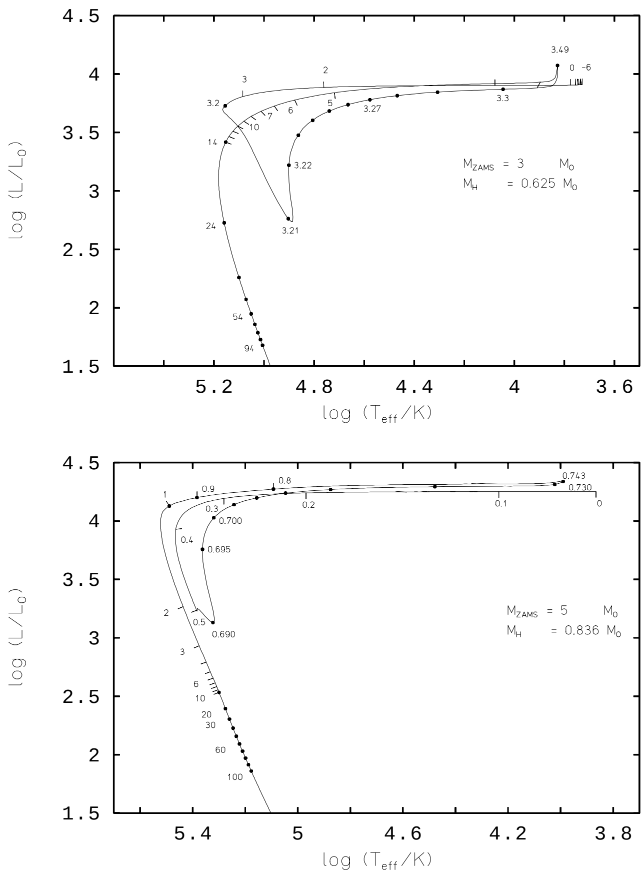

Fig. 3. Tracks for thermally pulsating post-AGB models with $M_{\rm H}$ = $0.625 M_\odot$ and $0.836 M_\odot$. Time marks are in units of 10^3 yr.

[initial composition: (Y, Z) = $(0.24, 0.021)$] models with core masses ($\approx$ total masses) of $0.553 M_\odot$ (Schönberner 1983), and 0.524, 0.625 and $0.836 M_\odot$ (Blöcker 1995). The corresponding initial masses range between 1 and $5 M_\odot$. Mass loss was taken into account by the Reimers (1975) rate and by an adaption to the radiation driven wind theory of Pauldrach et al. (1988), resp. Detailed descriptions of these post-AGB models are given in the respective publications.

The corresponding tracks are shown in Figs. 2-3. The $0.524 M_\odot$ remnant suffers even from two thermal pulses during its post-AGB evolution (see Blöcker (1995) for a discussion of multiple post-AGB shell flashes). Age zero refers to 5000 K in the case of the $0.553 M_\odot$ remnant, and to a pulsational period (fundamental mode) of P_0 = 50 d in the case of all other models (i.e. to 4580, 5970 and 7340 K). The time necessary to expand to Red Giant dimensions during the flash depends strongly on the thermal timescale of the envelope, and amounts to several hundred years for the low-mass models down to a few decades for the most massive remnant.

These "late" thermal pulses happen when the models still evolve with roughly constant luminosity from the AGB towards the white dwarf domain. In this central-star domain surface convection is absent as opposed to a position closer to or on the AGB. Only when the model, driven by the pulse, evolves back to its Hayashi limit, envelope convection sets in again and reaches its deepest penetration at minimum effective temperature and maximum luminosity. At this point the evolution reverses again (cf. Fig. 3). Due to the very small envelope mass this minimum effective temperature is substantially larger than typical AGB temperatures which, in turn, limits the depth penetration of the envelope convection. In this scenario one would not expect that the bottom of the envelope convection reaches layers enriched with carbon and s-process isotopes. Consequently, the envelope keeps virtually its original chemical composition. For instance, for our $0.625 M_\odot$ we got only a marginal helium enrichment of ΔY = 0.03, i.e. its surface stays *hydrogen rich*.

Another kind of post-AGB flash is the "very late" thermal pulse which occurs when the model is already on the white dwarf cooling track, i.e. after the cessation of hydrogen burning. This scenario also provides a rapid expansion towards Red Giant dimensions but differs substantially concerning the predicted mixing events and timescales. In this case the flash-driven convective pocket of the helium burning shell may reach and penetrate the hydrogen shell causing a considerable or even total burning of the envelope (Fujimoto 1977, Schönberner 1979, Iben 1984). Here, the envelopes can be expected to become hydrogen deficient, and to be enriched with carbon and s-process isotopes due to partial burning and mixing. The enrichment takes place immediately after the pulse, i.e. at high effective temperatures (above 20000 K), due to the pulse-driven convection. The brightening is extremely fast: calculations of Iben & Mc Donald (1995) for a $0.6 M_\odot$ model predicts in such a case an evolutionary speed of 5 mag/17 yr which is four times larger than the one observed for FG Sge. Note, however, that this is the only model available up to now for such a scenario.

2.2. *Comparison with the observations and determination of FG Sge's mass*

In order to compare the theoretical timescales with the observations one has to consider the brightness evolution during the pulse. For that purpose the luminosities were transformed into absolute magnitudes with the aid of fluxes taken from model atmospheres of Kurucz (1979) (LTE, $T_{\rm eff} < 40000$K) and Napiwotzki & Rauch (1994) (NLTE, $T_{\rm eff} > 40000$K). Furthermore, the timescales, Δt, and brightness variations, $\Delta m_{\rm v}$, have been normalized at maximum M_v. Concerning FG Sge this refers to the year 1973. Figure 4 shows the corresponding brightness changes of our thermally pulsating models in comparison with those observed for FG Sge indicating that its mass should be close to $0.6 M_\odot$.

The timescale for the fast evolution towards Red-Giant dimensions during the pulse depends steeply on the mass $M_{\rm env}$ of the expanding envelope. The correlation between the evolutionary speed $\Delta m_{\rm v}/\Delta t$ (averaged over the last 5 mag increase) and $M_{\rm env}$ taken at the onset of the flash (during the flash $M_{\rm env}$ remains practically constant) is demonstrated in Fig. 5 for the respective models. Taking for FG Sge

$$\Delta m_{\rm v}/\Delta t = 5{\rm mag}/70{\rm yr} \pm 15\%$$

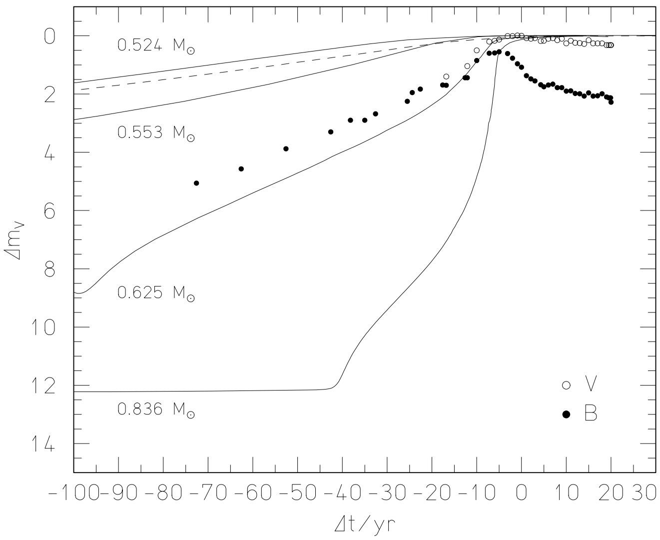

Fig. 4. Brightness variations of the post-AGB models shown in Fig. 2-3 as a function of time (normalized to maximun M_v). The dashed line refer to the first pulse of the $0.524 M_\odot$ model. The dots correspond to the observational data shown in Fig. 1 (t=0 refers to 1973) indicating $M_{\rm FG\,Sge} \approx 0.6 M_\odot$.

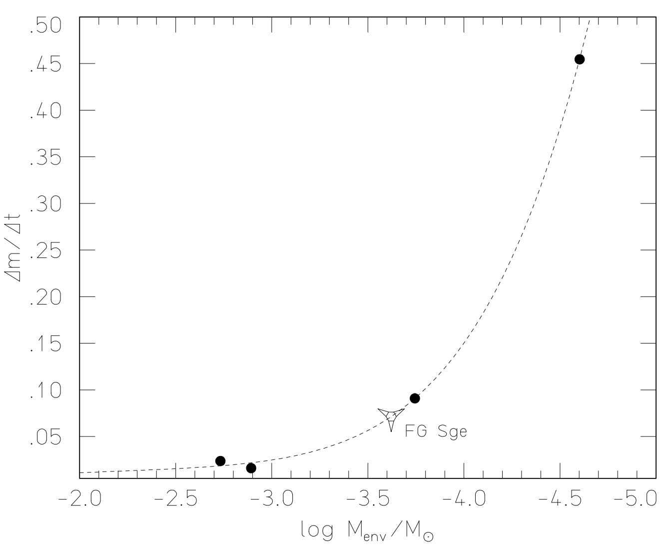

Fig. 5. Evolutionary speed $\Delta m_v/\Delta t$ (averaged over the last 5 mag increase) vs. $M_{\rm env}$.

yields

$$M_{\rm env} = 10^{-3.6\pm0.1} M_\odot.$$

On the other hand, $M_{\rm env}$, is also strongly correlated with the model's core ($\approx$ total) mass, $M_{\rm H}$, (Paczynski 1971, Schönberner 1979, Blöcker 1995). For example, the envelope mass decreases by $\approx$ 2 orders of magnitude if the core mass increases from 0.55 to $0.95 M_\odot$. Additionally, for a given core mass, $M_{\rm env}$ decreases up to a factor of 3 during the horizontal part of the evolution, i.e. prior to the pulse, due to hydrogen burning (and mass loss).

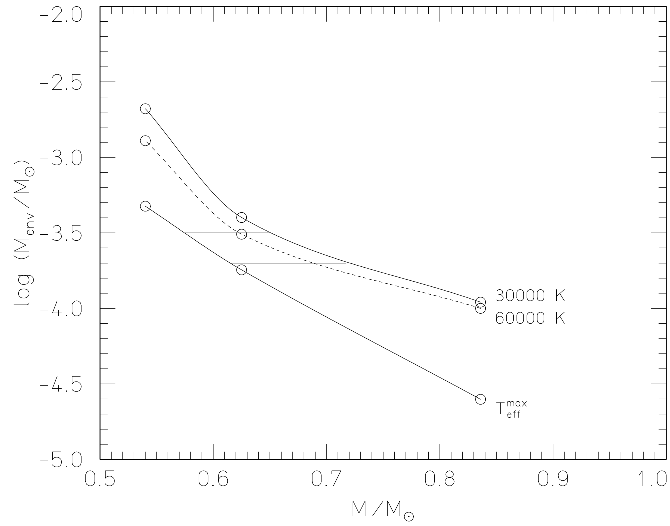

Fig. 6. Envelope mass $M_{\rm env}$ vs. core ($\approx$ total) mass at maximum $T_{\rm eff}$ ($\geq$ 100000K), 60000 and 30000 K for our models (bottom to top, indicated by open circles). The horizontal lines correspond to the range of estimated envelope masses of FG Sge ($10^{-3.6\pm0.1} M_\odot$).

Now, FG Sge's mass can be limited by means of these correlations, even under consideration of different starting points for the thermal pulse. Figure 6 shows $M_{\rm env}$ vs. $M_{\rm H}$ at maximum $T_{\rm eff}$ ($\geq$ 100000K) as well as at 60000 and 30000 K (bottom to top). Because one observes a planetary nebula, 30000 K is certainly the lower limit for the onset of the pulse. In this case we get with $M_{\rm env} = 10^{-3.6\pm0.1} M_\odot$:

$$0.57 M_\odot \leq M_{\rm FG\,Sge} \leq 0.71 M_\odot$$

On the other hand, model calculations for the planetary nebula have shown that the onset of the thermal pulse could not have occurred at an effective temperature lower than 50000 K in order to account for the observations (Harrington & Marionni 1976, Hawley & Miller 1978, Tylenda 1980). This temperature constraint reduces FG Sge's upper mass limit to $0.69 M_\odot$ (see Fig. 6).

The question arises how the evolutionary timescale given by the mass of the central star compares with the expansion age, $t_{\rm ex}$, of the planetary nebula. Based on a distance of d = 2.5 kpc (Herbig & Boyarchuk 1968) and the known expansion velocity (34 km/s), an expansion age of 6000 yr can be derived (Flannery & Herbig 1973).

However, several authors suggest a larger distance (e.g. Fadeyev & Tutokov (1981): 4200 pc, Archipova et al. (1983): 4100 pc, Fadeyev (1984): 4830 pc, van Genderen & Gautschy (1995): 3900 pc). Assuming, for instance, d = 4.1 kpc leads to $t_{\rm ex}$ = 9800 yr.

Considering the distance and age uncertainties we assume 6000 yr $\lesssim t_{\rm ex} \lesssim$ 10000 yr being consistent with the evolutionary timescales belonging to the derived mass range of FG Sge. Moreover, these expansion ages suggest a mass close to $0.6 M_\odot$ and rule out values below $0.55 M_\odot$ and above $0.65 M_\odot$. For instance, the $0.625 M_\odot$ model completes its horizontal evolution within about 3000 yr. This time drops to 800 and 400 yr for $0.7 M_\odot$ and $0.84 M_\odot$, resp.

Due to these constraints we finally adopt for FG Sge:

$$M_{\rm FG\,Sge} = (0.61 \pm 0.04) M_\odot .$$

3. Discussion of the surface composition

At the tip of AGB, the models' envelope convection extends from the surface down to the immeadiate vicinity of the hydrogen burning shell (it is always separated from the nuclear shell by a radiative layer even in the case of massive AGB models suffering normally from hot bottom burning since the envelope mass has dropped to a few $10^{-2} M_\odot$ in this phase). Moving off the AGB towards larger effective temperatures, the envelope convection shrinks in both directions: its depth decreases, and it becomes separated from the surface by a thin radiative layer (see e.g. van Genderen & Gautschy 1995). During the flash – on the model's way back to the AGB – the envelope convection both moves outwards and inwards finally reaching the surface and penetrating into deeper layers again.

The flash models discussed in the previous section show that the maximum extent in depth of envelope convection (and an additional small dredge up of helium) occurs at minimum effective temperature and maximum luminosity. The increase in the s-process abundances reported in the literature (Langer et al. 1974) occurs, however, already before that phase is reached, namely at ≈ 8000 K (cf. Fig. 4 in van Genderen 1994). A concomitant increase of carbon has not been observed (Langer et al. 1974).

This fact conflicts the typical dredge-up scenario where the s-process elements were formed in a carbon-rich helium environment immediately beneath the hydrogen-burning shell. Thus, dredge up of these elements occurs always together with carbon (see also discussion in Iben 1984).

Inspection of the models indicates that this temperature nearly coincides with the one when the surface layers become convectively unstable again (see also van Genderen & Gautschy 1995). At this temperature the total mass of the convectively unstable regions is only 20% of that at maximum depth (i.e. at minimum temperature). This rather low downward extension indicates that s-process elements as well as carbon must have already been present before in the deeper parts of the envelope and generated by previous thermal pulses (on the AGB).

Concerning carbon, it should be emphasized that both its abundance and the carbon to oxygen ratio are not available with sufficient precision: The oxygen abundance given by Herbig & Boyarckuk (1968) is based on one line only, and Langer et al. (1974) assigned "low weights" for their carbon abundances. From the appearence of C_2 and the analyses of Kipper & Kipper (1993) follows that FG Sge is carbon rich at present though the carbon to oxygen ratio depends on the effective temperature and the assumed oxygen abundance. It is evident from Fig. 4 of van Genderen (1994) that the appearence of the C_2 feature coincides with FG Sge's approach to its minimum surface temperature. Thus, it seems not unreasonable to assume that the presently observed carbon abundance has been already present at the end of the AGB evolution.

This assumption would be in agreement with recent spectroscopic analysis of post-AGB objects by Hrivnak (1995), Klochkova (1995), Zacs et al. (1996) and van Winckel et al. (1996a), which show molecular carbon features and strong absorption lines due to s-process elements. These properties were found to be in full accordance with what one would expect in a post-AGB star in which carbon-rich materials formed in thermal pulses is dredged up to the surface of a mass-losing object (Hrivnak 1995).

The abundances of FG Sge and these post-AGB objects (which are found at comparable effective temperatures) are very simliar. For instance, Fig. 7 compares the metal abundances of FG Sge (Kipper & Kipper 1993) with those of SAO 34504 = IRAS 22272+5435 (Zacs et al. 1995) and HD 187885 (van Winckel et al. 1996a). According to Zacs et al. (1995) SAO 34504 is with C/O ≈ 12 even more carbon rich than FG Sge. Both FG Sge and SAO 34504 show on the average an enrichment of s-process elements (from La to Gd) of ≈ 1.8 dex, whereas HD 187885 is enhanced by 0.9 dex. Similiar examples are HD 56126 (Klochkova 1995) and HD 158616 (van Winckel 1997). Note that the uncertainties of the individual values can be quite large (up to 0.3...0.5 dex, cf. Wallerstein 1990, Kipper 1996) depending, e.g., on the number of spectral lines observed for the respective element, on the chosen reference lines (e.g. Fe II lines) or on the assumed effective temperature. It should be noted that many post-AGB candidates, like HD 133656 (van Winckel et al. 1996b), do not exhibit any enhancements in the s-process elements (cf. Bond 1991).

A further complication is that very often the abundances of elements with high condensation temperatures are obviously depleted in the superficial layers to various degrees. The most likely process seems to be the separation between the grains containing the condensable elements and the gas phase (Bond 1991, Lambert 1991, Mathis & Lamers 1992). For instance, Giridhar et al. (1994) and Gonzales et al. (1997) performed abundance analyses for five field RV Tauri stars which are supposed to be in the post-AGB evolutionary stage. They showed that the atmospheres of these stars (IW Car, Ep Lyr, Dy Ori, AR Pup, and R Sge) are depleted from elements with high condensation temperatures.

4. Conclusions

Concerning the peculiar variable star FG Sge we arrive at the following conclusions:

- Based on a grid of thermally pulsating post-AGB models we introduced a method to determine FG Sge's mass. With these models and constraints from its planetary we found its mass to be $(0.61 \pm 0.04) M_\odot$.
- Since s-process elements appear at the surface *before* the deepest penetration of envelope convection, they cannot have been made during this late pulse. In any case, in all regular thermal-pulses on the AGB s-process elements are only produced either well after the present pulse (radiative

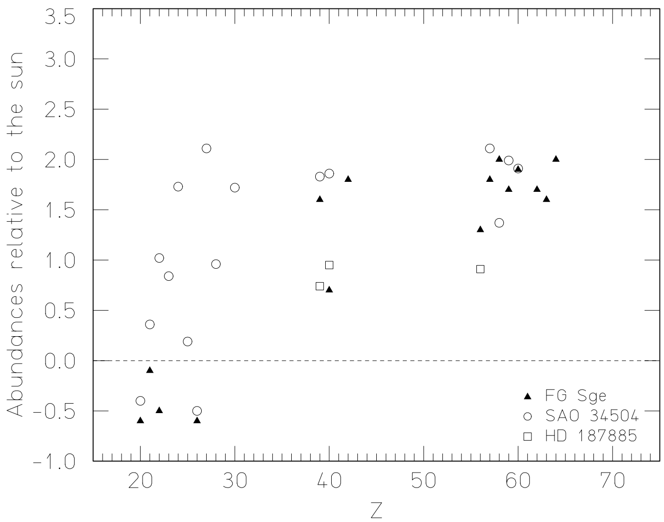

Fig. 7. Metal abundances relative to the sun vs. atomic number for FG Sge (filled triangles, $T_{\rm eff}$ = 5500 K, Kipper & Kipper 1993) and SAO 34504 (open circles, $T_{\rm eff}$ = 5600 K, Zacs et al. 1995). The squares denote the corresponding s-process abundances of HD 187885 ($T_{\rm eff}$ = 8000 K, van Winckel et al. 1996a) which has a larger effective temperature and show milder but also clear overabundances (0.9 dex). Note, that the uncertainties can be quite large (up to 0.3...0.5 dex).

^{13}C burning, see Straniero et al. 1995, Blöcker et al. 1997) or during the next pulse (convective ^{13}C burning, e.g. Hollowell & Iben 1990, Gallino et al. 1993). Thus, it appears reasonable to conclude that FG Sge's surface was enriched with carbon and s-process elements already on the AGB.

- Consequently, at least the s-process elements must have disappeared from the surface layers after the convection had ceased during the evolution towards higher effective temperatures. The abundances, however, remain unchanged in the deeper layers, and are restored by convection at the surface when the star expands to Red Giant dimensions as a consequence of a thermal pulse (Blöcker & Schönberner 1996b).
- This transitory "cleaning" from metals might be caused by multicomponent mass outflows (cf. Hunger et al. 1996, Babel 1996) or, more likely, by fractionation processes, i.e. the decoupling of gas and dust, as discussed above and observed in several post-AGB objects (cf. Lambert 1996).
- However, *quantitative* conclusions concerning the observed evolution of FG Sge's surface metal-abundances cannot be drawn up to now. Further theoretical work on thermally pulsing post-AGB models including mass loss, fractionation processes, etc. is badly needed.

If one accept these conclusions, then FG Sge is unique in one further aspect: It should be an ideal object for studying the interplay between mass loss, diffusion, convection, and surface abundance changes during the post-AGB evolution.

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