Asymptotic Giant Branch Stars
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Dust formation events in the envelopes of the peculiar post-AGB stars FG Sge and V4334 Sgr (Sakurai's object)

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Abstract. Distinctive features of dust condensation events in the circumstellar shells of the born-again AGB stars FG Sge and V4334 Sgr are described together with updated optical, IR and bolometric light curves.

1. FG Sge

In August 1992 FG Sge entered a qualitatively new phase of its evolution. Suddenly, in ~ 50 days, its visual brightness dropped by $\sim 5^m$; during the summer of 1998 already a 5th deep decline has been observed. In Fig. 1 we display the recent light curves, for which the optical and IR data were taken from Arkhipova et al. (1996, references therein and private communication), and from Tatarnikov et al. (1998a, and references therein), respectively. All these deep declines in the visible were caused by the formation of dust grains around the star; in a sense, they all were unpredictable. The star itself did not change appreciably neither before the first deep decline nor since; it has the appearance of a late-F-type supergiant with rather strong Swan bands in its spectrum; it continues pulsating on a time scale of ~ 115 days.

The dust condensation events in FG Sge are very similar to those observed in R CrB type stars. An important advantage with FG Sge is that the recent declines started after a period when its circumstellar shell was dust free, so that the effects related to the dust formation events can be studied more clearly than in other cases.

The first condensation event in FG Sge, which does not differ markedly from the subsequent ones, is very similar to those observed in classical novae (Fig. 2). The nucleation and grain growth occur on a short timescale (about half a pulsation period for FG Sge) and result in a steep extinction of visible starlight.

The temperature of the newborn dust grains is $\sim 1\,000$ K, at least at the moment when their radiation begins to stand out against the background of the star or the old dust shell. Thus, the grains are located quite far from the star, at a distance corresponding to more than 200 days assuming an expansion velocity of 100 km s^{-1} for FG Sge. Possible hotter grains do not cause an observable near-IR excess.

The newborn IR excess is so large that it requires the dust clouds to cover an appreciable part of the star, not less than 50% for FG Sge. No significant reddening, as measured by the $B-V$ color, was observed in the visible during

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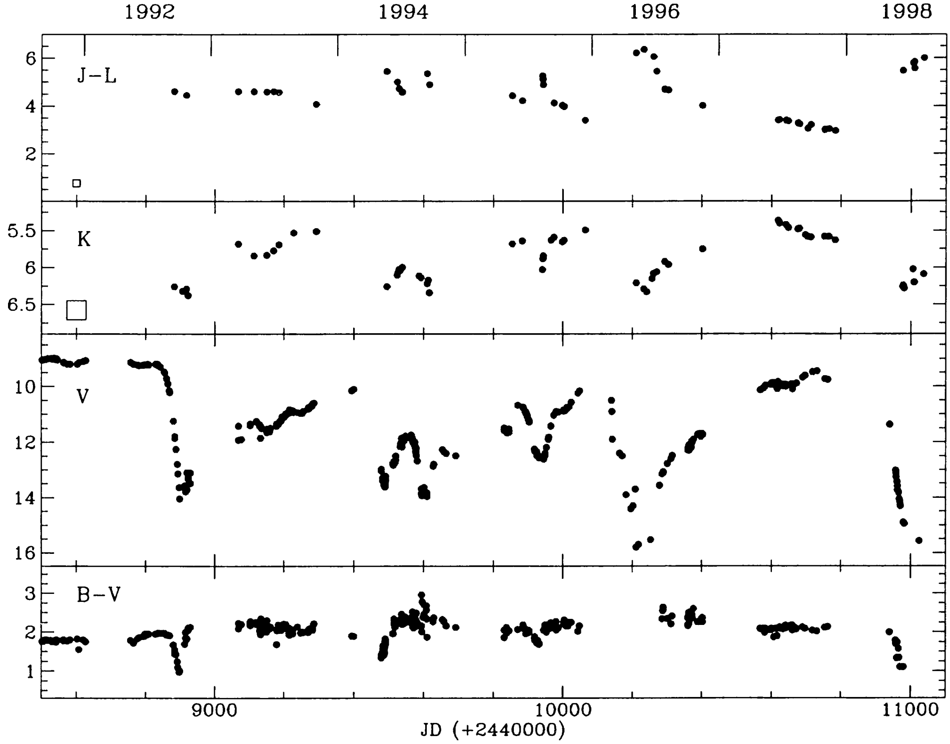

Figure 1. Optical and IR light curves of FG Sge in 1992-1998.

an overall cycle, i.e. between the start of the brightness decline and the recovery. This means that the optical depth of the dust layer from its formation to dispersal is governed by grains with a size of ~ 0.1 μm or larger and which by mass contain the bulk of the dust circumstellar matter. Comparing the dimming of the star in the *V* and *J* spectral bands, we come to the same conclusion.

It should be noted that even in such a case fine graphite grains could produce a 2200 Å absorption band. Moreover, if the important blueing of FG Sge in the visible, appearing on the descent to the deep minimum, is attributed to reflection of the direct star light by graphite grains, the most suitable grain size for creating such an effect is ~ 0.05 μm.

Paying attention to the similarity between the dust condensation episodes observed in classical novae and FG Sge, we recall that also in the former objects the grain nucleation takes place quite far from the star. Thus, the photometric behavior of FG Sge is fully consistent with a far-from-the-star model for dust formation.

Correcting for the blueing of the starlight in the visible, the spectral energy distribution of FG Sge in the range 0.36-10 μm can be fitted with a model with a spherically symmetric dust layer composed of 0.05, 0.1 and 0.25 μm graphite grains. Such a set of grains of different sizes is necessary and sufficient for a

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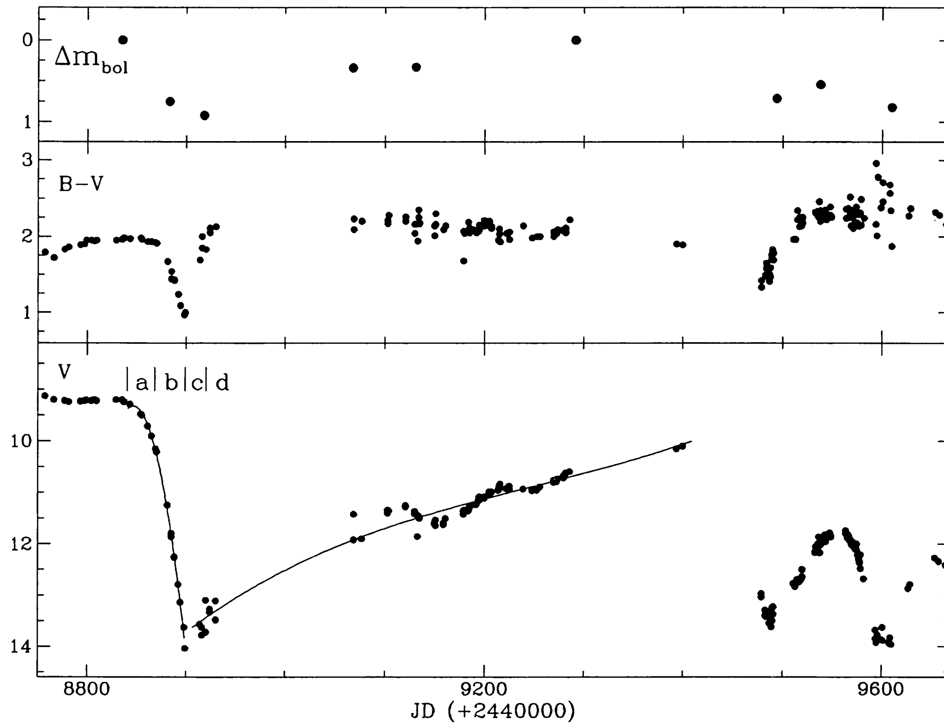

Figure 2. The first deep decline in the visual brightness of FG Sge.
a - initial decline (ΔV≈ 1 for 25 days), no change of $B - V$ color.
b - final decline (ΔV≈ 3.5 for 30 days), decrease of $B - V$ color.
c - short minimum (ΔV≈ 0 for 20 days), recovery of $B - V$ color.
d - recovery (ΔV≈ −3.5 for 500 days), no change of $B - V$ color.

good fit (Tatarnikov et al. 1998a). The spherically symmetric model reproduces also the case when the dust clouds cover the entire star.

During the deep decline the bolometric luminosity of FG Sge dropped by a factor $\sim$ 2.5 relative to its mean value prior to this event. This factor could be compatible with the value of $\sim$ 1.8 observed during the strongest pulsation episode in the 1980s, by accounting for holes in the dust cloud coverage then. However we cannot conclude that the deep decline was not accompanied by a decrease of the star's bolometric luminosity. It is also important to compare the IR excess before, during and after deep decline. For example, during the first deep decline the IR excess was smaller by a factor $\sim$ 2.1 than after brightness recovery in 1993, although the optical depth of the dust shell had decreased noticeably by this time. The observed correlation between apparent bolometric magnitude and L-band magnitude suggests a connection between deep decline and decrease of the stellar bolometric luminosity.

We note that it is possible to fit the observed spectral energy distribution also with a nonspherical model in a way which is not worse than in the spherically symmetric case, by changing the grain size distribution. Thus, it is not possible to find out whether the extinction by dust clouds is homogeneous or clumpy from energy distribution fitting only. However, after even partial brightness recovery in the visible, the apparent bolometric magnitude returns to its mean value observed before the first deep decline (Fig. 2). Thus, it might be that by this time the dust clouds spread over the entire sphere. Before the second deep decline, which occurred during the spring of 1994, the optical depth of the dust shell was ~ 1.3, and it was caused mainly by large grains, with a size of $\sim 0.1\ \mu$m or larger. Such a dust shell is a very efficient scatterer. However, the obscuration by such a cloud of the direct starlight would have reduced the visual brightness of FG Sge by $\leq 1.^m5$, while the observed decrease during the second deep decline was by $\geq 3^m$. Hence, it cannot have been caused by a single dust cloud in the line of sight towards the star.

Usually, on the descent to deep minimum one observes important blueing of the optical starlight (Fig. 2); the decrease of the $B - V$ color index can reach $\sim 0.^m7$. If the blueing is due to scattering by dust, such a large value means that the scattered component of the light accounts for almost the entire starlight in the visible and it should be produced by Rayleigh scatterers. As in scattered light the star's spectrum is not altered, the emission lines and emission Swan bands, which appear on the descent to the deep minimum, should originate in the shell. To avoid this conclusion we should reject dust scattering as the cause of the blueing effect.

We could fit the spectral energy distribution of FG Sge, observed at the moment when the object was bluest, only with a model in which the optically thin dust clouds (with visual optical depth ranging from 0.2 to 0.3) cover about a half of sphere around the star. These clouds consist of $\sim 0.05\ \mu$m graphite grains and provide the visible brightness of FG Sge. The observed IR excess is created by the optically thick dust clouds composed of $\sim 0.1\ \mu$m graphite grains which do not cause the reddening. On the line of sight to the star their optical depth is ~ 5.2 (Tatarnikov & Yudin 1998b). If silicate grains are used as the scatterers the range for the possible values of model parameters becomes wider.

2. Sakurai's object

In February 1996 Sakurai discovered a nova-like object in Sagittarius with an outburst amplitude of $\sim 10^m$. Subsequent photometric and spectroscopic observations have shown that it is surrounded by a faint old planetary nebula and that it looks like an early-F supergiant with noticeably faint Balmer lines. Thus, it turned out that Sakurai had discovered a new "born-again AGB star". Apparently, the star underwent the final helium flash in late 1994 (Fig. 3).

The evolution of Sakurai's object after its discovery is characterized by a gradual decrease of the stellar surface temperature and increase of the stellar apparent bolometric magnitude (Arkhipova et al. 1998 and references therein; Whitelock & Feast 1998). The bolometric flux was derived by the integration of the spectral energy distribution from U to M bands of Johnson photometric system, and corrected for radiation out of this spectral range. This correction does not exceed 20%; since the dust shell formation it came mainly from radiation at wavelengths longer than 5 μm. From early 1996 to today the apparent

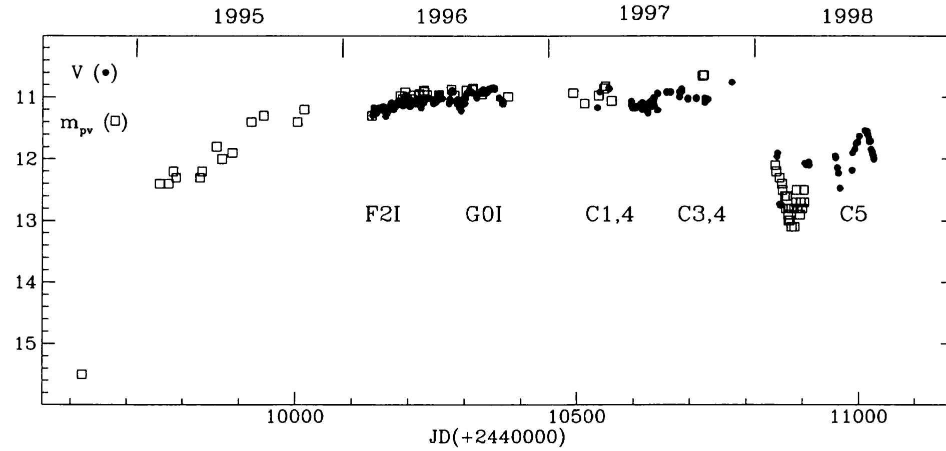

Figure 3. Visual light curve of Sakurai's object.

bolometric flux increased by more than a factor 4. During this time the stellar surface cooled down from $\sim 8\,000$ K to $\sim 4\,000$ K.

During the autumn of 1996 Sakurai's object looked still as a yellow supergiant with a dust-free circumstellar envelope. However, during the winter of 1997 the Swan bands and an IR excess appeared (Fig. 3, Fig. 4). Thus, during the spring of 1997 it became a carbon star surrounded by an optically thick dust shell (Arkhipova et al. 1998). However, in the visible there were not yet any indications for the dust shell formation. The visual brightness was essentially constant (Fig. 2) and the increase of $B - V$ color, observed at that time, could be attributed entirely to the cooling of the star. Hence, without IR observations we could not suspect the existence of the dust shell and could have missed the remarkable increase of the bolometric magnitude of Sakurai's object.

Without noticeable changes in the visual brightness in reply to the dust condensation, we could suggest that in 1997 there was still a hole in the blanket of dust clouds in the line of sight towards the star, although, judging the value of the IR excess, there should only be few such holes. With such a dust shell structure we could connect the sudden decline in visual brightness of Sakurai's object discovered in February 1998 (Liller et al. 1998) with the appearance of a dust cloud in the line of sight. Accordingly, after this event the apparent bolometric flux can not exceed the one of the star itself, and we can safely conclude that its bolometric luminosity has increased by more than a factor 4 during the last 3 years.

There are two main differences in the dust condensation events observed on Sakurai's object and on FG Sge. The first one is that in the former the transition from a dust-free shell to a one crowded with cool dust grains was much smoother than in the latter, though more IR photometric observations of FG Sge in 1992 but before the first deep decline would be useful to verify this conclusion. The second one is that the profound fading of Sakurai's object in the visible was not accompanied by the noticeable changes in bolometric flux that were observed in the case of FG Sge (Fig. 2, Fig. 4). These usually are

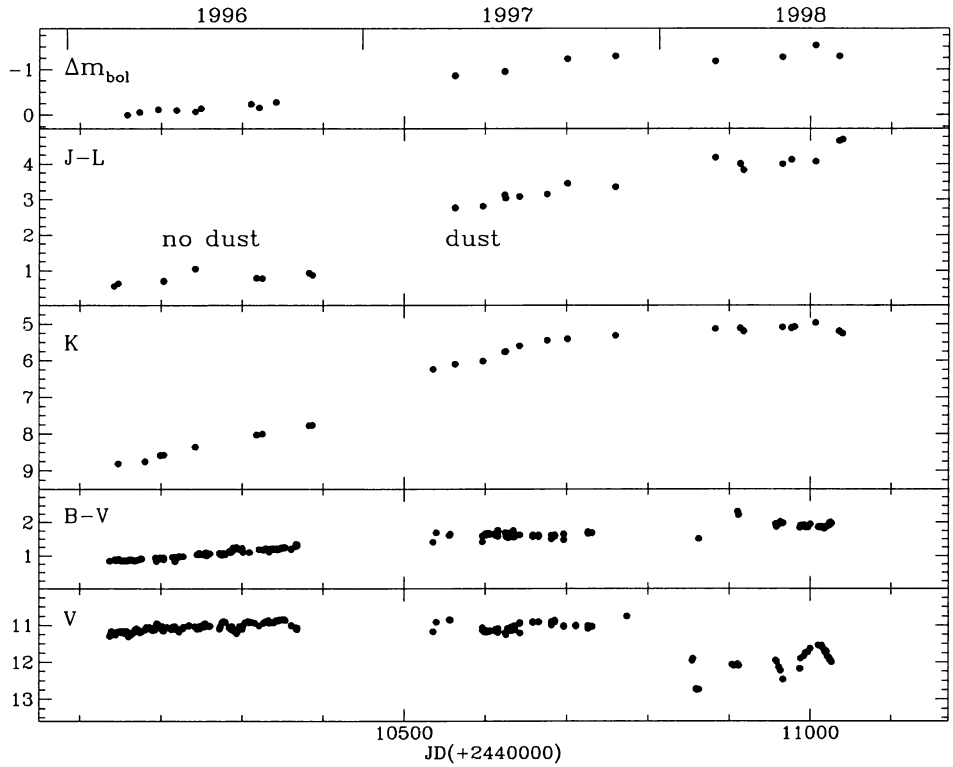

Figure 4. Optical, IR and bolometric light curves of Sakurai's object in 1996-1998.

considered as an argument in favor of spherically symmetric dust condensation around the star. The presence or absence of blueing during the descent to the minimum could clarify this point but it occurred in the dead season for Sakurai's object observations.

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