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THE INFRARED TEMPORAL EVOLUTION OF FG SAGITTAE

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ABSTRACT

We present near- and mid-infrared photometry of the post-AGB star FG Sge obtained at two distinct epochs separated by a period of 10 years. Observations of FG Sge taken in 1983 suggest that the 1 to 12 μm energy distribution was produced at that time by a stellar photosphere, with a blackbody temperature of ≈ 5600 K. In late August of 1992, FG Sge exhibited a marked decline (≈ 3 mag in V) in its visible light curve. At the same time the 1 to 18.0 μm infrared energy distribution has evolved to become a ≈ 1000 K blackbody. We propose that this light decline partially is due to the ejection and condensation of a dust shell. We estimate the amount of dust condensed during this episode to be $\approx 3.3 \times 10^{-9}\ M_{\odot}$, with a covering factor (total visual depth) of ≈ 0.3.

Subject headings: circumstellar matter — stars: evolution — stars individual: (FG Sagittae)

1. INTRODUCTION

The post-asymptotic giant branch (AGB) star FG Sge in the core of the planetary nebula He 1 − 5 is unique because it is moving horizontally on the H-R diagram at a rapid rate. Stars in this region of the H-R diagram evolve rapidly in spectral type on time scales of $\leq 10^2$ yr at constant luminosity (Iben 1982). During the last 30 years the inferred spectral type of FG Sge has evolved from that of a hot B supergiant to that of a cool K supergiant. Prior to the most recent episode of activity, the reddest $B-V$ colors observed were ≈ 1.8 mag. Assuming a reddening of $E_{B-V} = 0.4$ mag toward the object (Herbig & Boyarchuk 1968), the intrinsic E_{B-V} color of ≈ 1.4 mag corresponds to that of a K0–K5 supergiant (Allen 1983).

Early observations of FG Sge, emphasizing the significant visual brightening of the object during the first two-thirds of this century, were summarized by Herbig & Boyarchuk (1968). A subsequent spectroscopic study of the source indicated that FG Sge was enveloped in a normal planetary nebula of radius 18″, with a mean nebular expansion velocity of ≈ 34 km s^{-1} (Flannery & Herbig 1973). At a distance of 2.5 kpc, this planetary nebula has an expansion age of 6000 yr. During the mid-1970s through the late-1980s the rate of brightening slowed, and a semi-regular, slow periodic ($p = 80$ to 130 days, $\Delta V \approx 0.2$ mag) variation in the visible brightness was observed (Jurcsik 1992; Guinan, McCook, & Thrash 1992). Because FG Sge lies in the instability strip in the H-R diagram, the visual variability has been attributed to Cepheid-like pulsations (Whitney 1978).

Langer, Kraft, & Anderson (1974) and Christy-Sackmann & Despain (1974) analyzed the chemical composition of the star, including the surrounding nebula, and noted that remarkable changes, including the dredge-up of *s*-process material (Y, Zr, Ce, La, and Ba) had taken place in the object on time scales of ≤ 2 yr. Temporal studies of the optical spectra (Hawley & Miller 1978; Acker, Jaschek, & Gleizes 1982) suggest that FG Sge is rapidly cooling after a thermal pulse (He shell flash) that occurred $\leq 10^2$ yr ago. Thermal pulses and convective mixing in the outer layers of the star cause a rapid expansion and cooling of a chemically enriched pseudophotosphere (Iben & Livio 1993).

At infrared wavelengths, FG Sge has been sporadically observed since 1973. Allen (1973), Arkhipova & Taranova (1990) and Montesinos et al. (1990) report near-infrared magnitudes that are consistent with radiation from a modestly reddened stellar photosphere. These data also suggest that the star was surrounded by a dust cloud of mass $\approx 10^{-10}\ M_{\odot}$. However, ground-based observations of FG Sge longward of 5 μm, where continuum thermal emission from warm dust will dominate the emergent energy distribution, are sparse.

In 1992 mid-August FG Sge suffered a sudden dimming at all optical wavelengths. By 1992 October 8, FG Sge had an observed brightness at V of ~ 12.1 mag and $B \sim 13.6$ mag, (Guinan et al. 1992), a decline of over ~ 3.1 mag from the previous mean brightness of $V \sim 9.1$ mag. During this same period, the infrared energy distribution of FG Sge showed remarkable changes similar to the temporal behavior of classical novae that eject dusty shells (Gehrz 1990). The infrared observations presented here suggest that an optically thin dust shell characterized by a blackbody temperature of ≈ 1000 K has recently condensed around FG Sge. We estimate that this shell has a mass in dust of $\approx 3.3 \times 10^{-9}\ M_{\odot}$. We suggest in the discussion below that the observed visible light decline is due partly to condensation of dust around the central star.

2. OBSERVATIONS

Infrared observations of FG Sge were conducted on several occasions during 1983 June through August and again in 1992 September and October subsequent to the report of Papousek (1992) that the visible light from the object had precipitously declined. Further monitoring observations were obtained in

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TABLE 1

OBSERVED INFRARED PHOTOMETRIC MAGNITUDES OF FG SAGITTAE

WAVELENGTH (μm)	UT OBSERVATION DATE AND APERTURE 1982 Jul 06.1 (5″0)	1983 Jun 30.0 (8″2)	1983 Aug 09.1 (6″6)	1983 Sep 11.2 (3″3)	1992 Sep 17.2 (5″2)	1992 Sep 19.1 (13″4)	1992 Oct 11.0 (5″2)	1992 Oct 22.0 (27″0)	1992 Oct 27.1 (9″0)	1993 Feb 05.8 (10″0)
1.25 (*J*)	...	...	6.98 ± 0.05	...	...	6.69 ± 0.12	...	8.75 ± 0.04	...	8.64 ± 0.10
1.65 (*H*)	...	...	6.68 ± 0.05	...	...	7.69 ± 0.05	7.58 ± 0.30	7.64 ± 0.04	...	8.07 ± 0.07
2.30 (*K*)	6.47 ± 0.05	...	6.52 ± 0.05	6.62 ± 0.05	...	6.26 ± 0.05	6.32 ± 0.01	6.29 ± 0.38	6.38 ± 0.06	6.59 ± 0.05
3.40 (*L″*)	...	...	6.42 ± 0.05	6.31 ± 0.07	...	4.08 ± 0.01	...	...	...	...
3.60 (*L*)	6.53 ± 0.05	...	6.45 ± 0.05	6.38 ± 0.07	...	...	4.34 ± 0.01	...	4.48 ± 0.05	4.87 ± 0.05
3.80 (*L′*)	...	...	...	...	...	...	...	4.30 ± 0.05	...	...
4.90 (*M*)	...	6.28 ± 0.15	...	...	3.64 ± 0.10	...	3.50 ± 0.02	3.46 ± 0.25	3.43 ± 0.10	3.40 ± 0.04
10.00 (*N*)	...	6.10 ± 0.20	...	...	2.91 ± 0.16	...	2.71 ± 0.09	...	2.70 ± 0.16	2.44 ± 0.11
7.80	...	...	...	...	...	...	2.77 ± 0.12	...	...	...
8.70	...	5.70 ± 0.20	...	...	...	...	2.91 ± 0.06	...	...	...
9.80	...	...	...	...	...	...	2.67 ± 0.12	...	...	...
10.30	...	...	...	...	...	...	2.61 ± 0.05	...	...	...
11.60	...	...	...	...	...	...	2.45 ± 0.16	...	...	...
12.50	...	4.80 ± 0.30	...	...	...	...	2.61 ± 0.16	...	...	...
18.00	...	...	...	...	...	...	1.61 ± 0.24	...	...	...

1993 February. All infrared observations were obtained using single detector, multifilter photometers on the Wyoming Infrared Observatory (WIRO) 2.34 m telescope and the University of Minnesota O'Brien Observatory (OBO) 0.76 m telescope. Data acquisition and telescope control (DA/TCS) functions on both telescopes were performed by a single 386PC running a FORTH$^{\rm tm}$ DA/TCS code in a DOS operating environment (Gehrz & Jones 1993). Operation, effective bandpasses and calibration of the photometers are described by Gehrz, Grasdalen, & Hackwell (1987). Beam switching, utilizing several apertures and beam separations (15″0 to 32″), was used to obtain data on the various nights listed in Table 1. The photometric uncertainty includes systematic errors in the extinction correction and absolute calibration, as well as statistical errors.

The extended nebulosity (≈36″ in diameter) surrounding FG Sge is not contained within the photometer apertures. Thus, our observations are not sensitive to emission from these regions. However, emission from the planetary nebula apparently is small. Only a 3 σ upper limit to the flux of FG Sge are found in the *IRAS* point source catalog for all wavelengths, except 60 μm. Furthermore, visual photographs of FG Sge (Herbig & Boyarchuk 1968) suggest that the gaseous material is centrally concentrated around the star. Thus, if the dust and gas are co-extensive, the observed infrared energy distribution will be dominated from material in the immediate vicinity of the star.

Optical CCD photometry in the Johnson *B* and *V*, and the Cousin-Krons *R* and *I* filters was obtained at OBO on 1992 October 28.1 UT. Image data were reduced using the IRAF/DAOphot package. Photometric calibration was achieved using the reference field NGC 7790 (Odewahn, Bryja, & Humphreys 1992) and Landolt standards. Because FG Sge is surrounded by diffuse nebulosity, a model point-spread function (generated from isolated field stars) was used to estimate the observed color magnitudes. We find $B = 15.49$, $V = 13.38$, $R = 12.19$ and $I = 11.37$, with an uncertainty of ±0.15 mag. Assuming $A_v = 1.3$ mag and adopting an extinction law (Rieke & Lebofsky 1985), we obtain dereddened magnitudes of: $B = 13.76$, $V = 12.08$, $R = 11.12$ and $I = 10.59$. These optical data are included in Figure 1.

The infrared coordinates of FG Sge ($l^{\rm II} = 60.^\circ 3$, $b^{\rm II} = -7.^\circ 4$) derived by offsetting the telescope from SAO 88276 and SAO 88299 are $\alpha_{1950} = 20^{\rm h}09^{\rm m}42.^{\rm s}98$; $\delta_{1950} = +20^\circ 11' 03.''9$ with an uncertainty of ±1″0. Distance estimates to FG Sge based on E_{B-V} colors of neighboring stars (Herbig & Boyarchuk 1968), integrated Hβ flux versus angular size of the nebula (Arkhipova 1973), and the strength and velocity of H and K line cores as compared to V Sge (Langer et al. 1974) range from 2.5 to 2.8 kpc. We adopt a distance of 2.5 kpc in the following discussion.

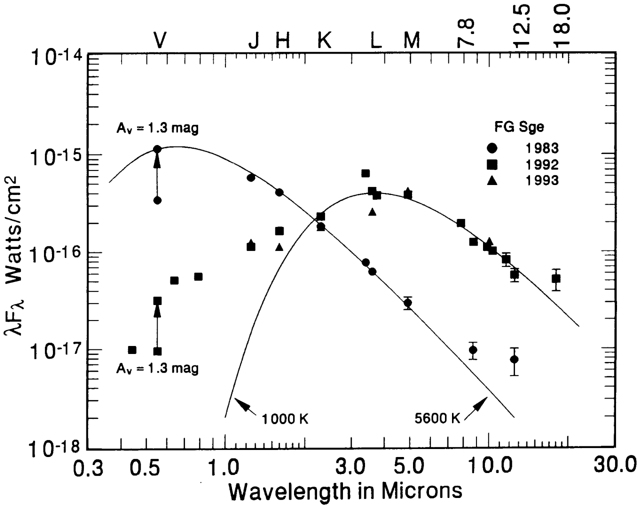

FIG. 1.—Infrared energy distribution of FG Sge. The solid curves represent the best-fit Planck function to the data points. The observed visible data at each epoch are dereddened assuming $A_v = 1.3$ mag and the reddening law of Rieke & Lebofsky (1985). *Filled circles:* in 1983 the infrared energy distribution (derived from the mean of the 1983 observations) is characterized by a temperature of ≈5600 K arising from the stellar photosphere. *Filled squares:* during the recent episode of mass loss in 1992 the emergent 1 to 18.0 μm infrared energy distribution (derived from the mean of the 1992 October observations) is that of a single ≈1000 K blackbody radiated by dust in the ejecta. *Filled triangle:* 6 months after the sudden light decline (1993 February) the infrared energy distribution is still dominated by a single ≈1000 K blackbody radiated by dust in the ejecta.

3. DISCUSSION

3.1. *Temporal Development*

The infrared energy distribution of FG Sge observed in 1983 and 1992 is presented in Figure 1. The 1983 energy distribution fits a blackbody spectrum with $T \sim 5600$ K. The infrared data show no evidence for an additional component (dust or a stellar secondary) to the source between visual wavelengths and 10 μm. Both the visible observations and the infrared energy distribution in 1983 are consistent with the interpretation that the V through 12 μm radiation was emitted from the photosphere of a G supergiant star. The mean visual magnitude of FG Sge at the time of the 1983 infrared observations derived from values tabulated in the literature is $m_v \sim 9.5$ mag, with $A_v \sim 1.3$ mag and $E_{B-V} = 0.4$ mag (Christy-Sackmann & Despain 1974; Whitney 1978; Herbig & Boyarchuk 1968). Using the near-infrared extinction curve of Rieke & Lebofsky (1985) to deredden the observed data, we find $m_K = 6.6$ mag and $(V-K)_0 \sim 1.6$ mag. These values are consistent with the colors of an early G-star (Johnson 1968), and in agreement with the spectral type of G1 ± 0.5 I deduced by Taranova (1987) during the same epoch.

However, since 1955, FG Sge has evolved rapidly to later spectral type. The inferred effective temperature has cooled from $T_{\rm eff} \approx 12{,}300$ K in 1955 to $T_{\rm eff} \approx 5600$ K in 1985 (Montesinos et al. 1990). The decrease in the effective temperature over this period and the increase of ≈ 4 mag in the visual since 1900 has been attributed to an increase in the stellar radius of FG Sge (Arkhipova & Taranova 1990). Adopting a distance of 2.5 kpc, the bolometric luminosity of FG Sge in 1983 at the epoch of our infrared observations (Fig. 1) is $\approx 3.15 \times 10^3\ L_\odot$.

The evolution of the infrared energy distribution of FG Sge observed in 1992 is remarkable. Our 1 to 18.0 μm observations during the recent period of marked visible decline show no evidence for emission from a hot stellar photosphere. The observed, featureless infrared energy distribution (Fig. 1) can be fitted by a single blackbody with a temperature ≈ 1000 K. We interpret this energy distribution as arising from thermal emission from dust recently condensed out of material surrounding the central star. The appearance of this dust suggests either: (1) normal mass-loss mechanisms in the supergiant envelope have been restablished after the period of hydrogen shell burning in a convective outer shell (Iben & Livio 1993); or (2) FG Sge has undergone a episode of rapid mass loss akin to that which occur in fast novae (Gehrz 1990) events or outbursts of Wolf-Rayet stars such as HD 193793 (Hackwell, Gehrz, & Grasdalen 1979; Ney & Hatfield 1978).

The infrared data obtained during the period from 1973 to 1983 indicate that FG Sge brightened by 0.6 ± 0.1 mag at broad-band K. The magnitude change is consistent with the spectroscopic changes noted for the star during this epoch. However, from 1983 to the present epoch, the mean K-magnitude has remained stable, $\langle K_{\rm mean}\rangle = 6.46 \pm 0.15$ mag, while the broad-band L-magnitude has increased in brightness ≈ 2 mag. The variation of the near-infrared brightness of FG Sge during this later period is presented in Figure 2. The dramatic variation in the L band is consistent with the hypothesis that dust condensation has occurred.

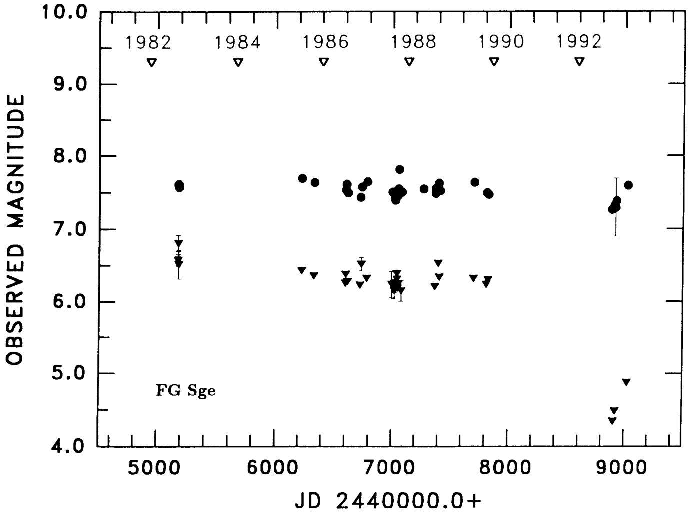

FIG. 2.—Temporal variation in the observed infrared broad-band magnitudes of FG Sge during the period from 1982 to 1993. *Filled circles:* the K observations. The observed K-magnitudes have been shifted by +1.0 mag for clarity. *Filled triangles:* the L observations. Data from Montesinos et al. (1990) and Arkhipova & Taranova (1990) also are included in this figure for completeness.

3.2. *Dust Emission*

The primary motivation for our 1983 observations of FG Sge was to determine whether or not this highly evolved object had an infrared energy distribution dominated by thermal emission from dust. No infrared excess was evident along the line of sight to the central object in our 8".2 aperture (Fig. 1), suggesting that no substantial warm dust component was present. The lack of an infrared excess was surprising because thermal continuum emission from dust at wavelengths ≥5 μm is common in many proto-planetary and planetary nebula. Emission from a cool dust component was not detected by *IRAS*.

In late August of 1992 both the optical brightness and infrared energy distribution of FG Sge changed dramatically (Fig. 1). The infrared energy distribution presently observed is a 1000 K blackbody which we attribute to thermal continuum from dust. The observed energy distribution is smooth and lacks strong features near 9.7, 11.3, or 18 μm which are signatures of silicate dust (Gehrz et al. 1984). This suggests that the emitting material is dominated by carbon or iron grains (Hackwell et al. 1979). If the visible decline is due to dust extinction, the line-of-sight optical depth to the star through this material {deduced from the ratio of the integrated infrared to visible flux $[\lambda F_\lambda(\max)]$} is quite large ($\tau = 4.4$). While the extinction along the line of sight may be heavy, 70% of the energy is leaking out suggesting that the shell is clumpy and/or asymmetric. The maximum infrared luminosity emitted by this material is $\approx 30\%$ of the average optical luminosity of the star observed in 1983 if the bolometric luminosity has remained constant.

The observed infrared continuum energy distribution of FG Sge (Table 1) allows us to estimate the mass of dust condensed in the ejecta during this recent episode of activity. The mass of grains can be estimated from the observed infrared emission maximum, $\lambda F_\lambda[({\rm IR})]_{\max}$, assuming that the dust shell is optically thin in the infrared. The infrared luminosity of N grains of radius a and characterized by a blackbody temperature $T_{\rm BB}$ is

$$L_{\rm IR} = N 4\pi a^2 Q_e \sigma T_{\rm BB}^4 = 4\pi D^2\{1.3586\lambda F_\lambda[({\rm IR})]_{\max}\}\,, \qquad (1)$$

where Q_e is the Planck mean-emission cross section for a grain of radius a, σ is the Stephan-Boltzmann constant (5.67×10^{-5} ergs cm^{-2} deg^{-4} s^{-1}), and D is the distance to the source

(Gehrz & Ney 1992). The total dust mass in this shell is $M_{\rm dust} = (4\pi/3)N\rho a^3$, where ρ is the grain density. If we assume that the emitting material is dominated by carbon grains of $a \leq 1$ μm with a temperature $T_{\rm BB} \leq 10^3$ K, Q_e can be approximated as $10^{-2}a({\rm cm})T_{\rm BB}^2$ (Draine & Lee 1984; Gilman 1974). Adopting a density of ≈ 2.25 g cm^{-3} for condensed carbon grains yields

$$M_{\rm dust} = 1.1 \times 10^6 \{\lambda F_\lambda[({\rm IR})]_{\rm max}\} D^2/T_{\rm BB}^6 \text{ in } M_\odot , \qquad (2)$$

where $\lambda F_\lambda[({\rm IR})]_{\rm max}$ is in W cm^{-2}, D in kpc, and $T_{\rm BB}^6$ in units of 10^3 K. On 1992 October 11.0 UT, $T_{\rm dust}$ is ≈ 1000 K and $\lambda F_\lambda[({\rm IR})]_{\rm max}$ is 4.8×10^{-16} W cm^{-2} (Fig. 1). Thus, we find $M_{\rm dust} \approx 3.3 \times 10^{-9}$ $M_\odot$.

4. CONCLUSION

Our infrared observations of FG Sge in 1983 show that the energy distribution was a 5600 K blackbody. This agrees with the temperature determination deduced from visual data obtained at the same epoch and suggests that the star was a G supergiant. Recent infrared observations show that the infrared energy distribution is now that of a 1000 K blackbody, dominated by thermal continuum emission dust in an ejected shell. This material is distributed asymmetrically or in clumps about the central star, with a total mass of $\approx 10^{-9}$ $M_\odot$. The sudden appearance of *s*-process materials and rapid horizontal evolution of FG Sge on the H-R diagram suggests that this object is a highly evolved post-AGB star, undergoing shell flashes (Iben & Livio 1993; Schoenberner & Weidemann 1983; Langer et al. 1974). If the preceding model for the evolutionary stage of FG Sge is valid, our infrared observations suggest that ejection of optically thick dust shells can occur rapidly as a result of post-AGB processes.

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