

ULTRAVIOLET AND INFRARED MONITORING OF FG SAGITTAE DURING 1982–1989: EVOLUTIONARY STATUS¹

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ABSTRACT

Ultraviolet *IUE* spectra and infrared *JHK*L photometry of FG Sge obtained over the period 1982–1989 indicate that the cooling rate of the star observed until ~ 1980 seems to have stopped and that an increase of the effective temperature may have occurred, this being a significant change in the evolutionary path traced so far. The current spectral type of FG Sge is F6–7 I as deduced from UV data. There is evidence of the existence of an envelope responsible for the infrared excesses observed at longer wavelengths. The short-term variation period is $\sim 100\text{--}110 \pm 15$ days, and it has remained stable since 1979, apart from small fluctuations of ± 15 days.

Subject headings: infrared: sources — stars: evolution — stars individual (FG sagittae) — ultraviolet: spectra

I. INTRODUCTION

FG Sge is, unquestionably, one of the most interesting and intriguing objects one can find when studying stellar astrophysics. Its rapid and special changes over time scales short in comparison with those normally expected in stellar evolution—with the exception of course, of cataclysmic variables, novae, supernovae, and luminous blue variables (LBV)—make it a very peculiar object. A great deal of effort has been put into the monitoring of FG Sge and into explaining the current evolutionary stage of the star from a theoretical viewpoint.

FG Sge is the nucleus of a planetary nebula ejected at least ~ 6000 yr ago. The star has undergone very rapid changes in the last century which will be reviewed in detail in § II. One of the most remarkable has been a well-monitored cooling rate observed until ~ 1980 during which the star has moved at nearly constant luminosity from the left to the right part of the H-R diagram, returning to the red supergiant region. There is evidence that the star is now ejecting material which could give rise eventually to a second planetary nebula.

In this work we present unpublished *International Ultraviolet Explorer* (*IUE*) spectra obtained in 1982 and over the interval 1986–1989, and infrared *JHK*L photometric observations taken in 1982 and 1986–1987. From these data, and trying to continue the recent intensive study and monitoring of FG Sge, we have estimated the effective temperature, spectral type, and short-term fluctuation period. The observations are presented in § III. The main results can be summarized as follows: (a) the cooling rate observed until ~ 1980 seems to have stopped and

even an increase in temperature could have occurred over the interval 1982–1989; (b) the current spectral type over this period *both at maximum and minimum* is F6–7 I; (c) the changes observed in the shape of the UV spectra can be attributed to changes in the gas density and emitting volume of the region where the UV radiation originates as the star pulsates (§ IV); (d) the characteristic time of the short-term fluctuations has stopped increasing, and it seems to have remained stationary since 1979 (§ V). These results seem to suggest that the star is finishing the expansion after a thermal pulse which has occurred during an instability in the helium-burning shell. We will discuss this point in § VI.

II. REVIEW OF PREVIOUS RESULTS

a) Long-Term Variability

The brightness of FG Sge rose in a nearly steady way from $m_{\text{pg}} \simeq 13.6$ in 1984 to $B = 9.6$ in 1965 (Herbig and Boyarchuk 1968; hereafter HB). According to these authors the spectral type of FG Sge changed from B4 I in 1955, when they took the first spectrum within their monitoring program, to A5 Ia in 1967. The planetary nebula around the star was discovered independently by Henize (1961) in 1955 and by Fürtig and Wenzel (1962).

HB proposed that the observed brightening could be explained by assuming that *an ejection of material is again taking place*. They observed different radial velocities for the absorption lines in the spectrum, indicating that, at that time, the material was being accelerated outward as it rose. Their model consisted of a very deep expanding atmosphere around a very hot star, and they assumed that the expansion began some time prior to 1900. The increase of ~ 4 mag over the above period can be explained on the basis of an *increase* of the radius accompanied by a *decrease* of the effective temperature. The results inferred from their observations, namely, spectral type B4 I, $T_{\text{eff}} \simeq 12,300$ K, and $R \simeq 10 R_{\odot}$ in 1955.8, and A5 I, ~ 8300 K, and $26 R_{\odot}$ for 1967.5, suggest that the same trend has held since the beginning of this century. HB derived a color excess $E(B-V) = 0.4$ and a distance $d = 2500$ pc. Although there are no significant differences between the adopted value of $E(B-V)$ used by several authors, the data for the distance are more uncertain. For example, Fadeyev and Tutukov (1981)

¹ Based on observations made with the *International Ultraviolet Explorer*, collected at the Villafranca Satellite Tracking Station of the European Space Agency, the Carlos Sánchez Magro telescope operated in the Observatory of Izaña (Tenerife) by the Instituto de Astrofísica de Canarias, and the 1.23 m telescope of the German-Spanish Observatory in Calar Alto (Almería).

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gave $d = 4200$ pc, Archipova *et al.* (1983) found $d = 4100$ pc, and Fadeyev (1984) estimated a value of 4830 pc. Since d enters in the computation of both the stellar radius and the age of the nebula, different results can be found depending on the choice of d . For example, Flannery and Herbig (1973) computed an expansion time for the nebula of ~ 6000 yr because they adopted the HB's determination for d ; if one takes $d = 4100$ pc, the age of the nebula is ~ 9800 yr.

Langer, Kraft, and Anderson (1974, hereafter LKA) continued the work of HB and studied the supergiant during the interval 1969–1972. Their determination of the effective temperature showed that the star was cooling down at a rate of ~ 250 K yr $^{-1}$, having an effective temperature of 6500 K in 1972. The authors detected the presence of abnormally strong absorption lines of Y II, Zr II, Ce II, La II, and other typical *s*-process species, which began to appear in the spectrum of the star after 1967. The strength of these lines increased, and the 1972 the abundances per gram of Y, Zr, Ce, La, and Ba reached ~ 25 times the solar value. On the other hand, the abundance of C and Fe relative to H remained roughly unchanged. By 1972 the rate of enrichment began to decrease. Ulrich (1974) gave two possible explanations for the *s*-process episode (a) the material in the region between the hydrogen and helium shells was irradiated by a weak neutron source over an extended period prior to the ejection of the planetary nebula, but the mixing with the gas at the stellar surface occurred after the event which caused the expansion of FG Sge; (b) iron-peak nuclei—Cr, Mn, Fe, Co, and Ni—captured neutrons from the strong source $^{12}\text{C}(p, \gamma) ^{13}\text{N}(\beta^+) ^{13}\text{C}(\alpha, n) ^{16}\text{O}$ during a brief recent mixing episode. It seems that the last alternative is the most likely since the weak-source theory cannot account for the small changes in carbon abundance. As for the evolutionary status, the authors proposed that (a) either the star is now in a postplanetary ejection phase associated with a helium-shell flash which occurs in all stars with masses near $\sim 1 M_{\odot}$, or (b) it is a more massive red giant which is now experiencing a post-helium-shell flash phenomenon preceding the transformation into a Ba or S-type star.

Stone (1979) studied the spectro- and *UBV* photometry of the star during the period 1968–1977. By comparing the dereddened and normalized continuum of FG Sge with a grid of MK standard supergiants he found that during this 10 yr period the mean cooling rate was ~ 310 K yr $^{-1}$, slightly larger than the value reported by LKA.

Whitney (1978) computed the angular diameter of the star from data taken from other authors prior to 1970 and using his own observations taken in 1977. He found (assuming $d = 2500$ pc) that the radius was $24 R_{\odot}$ in 1962, $46 R_{\odot}$ in 1970, and $70 R_{\odot}$ in 1977, concluding that the radius of FG Sge has been increasing almost steadily at a rate of $\sim 3 R_{\odot}$ yr $^{-1}$ since 1960.

Cohen and Phillips (1980) carried out spectroscopic monitoring of the star over the interval 1975–1978. Their study showed that the rare earth abundances had stopped increasing, and that the star cooled down ~ 500 K over 3 yr, which means that the cooling rate seemed to have decreased over that epoch.

Archipova, Zaitseva, and Noskova (1986) reported that the analysis of *UBV* photometry during 46 nights in 1985 showed that the prolonged reddening of the star was strongly reduced owing to the possible cessation of the cooling rate. Archipova *et al.* (1988) pointed out that the same behavior was observed during photometric monitoring over 1986–1987. Photoelectric observations taken during 1986–1987 (Jurcsik and Szabados

1989) still showed a slow reddening of the star, although Kipper and Kipper (1989) pointed out that there were no significant changes in the spectrum of FG Sge from 1980 to 1986.

Taranova (1987a) gives a temperature of ~ 5650 K for the star in 1985 on the basis of its spectral classification as $G1 \pm 0.5I$ according *UBVRJHKLM* observations and, assuming $d = 2500$ pc, finds a radius of $\sim 58 R_{\odot}$. Using the same method, she assigns $T_{\text{eff}} \approx 7500$ K in 1971 analyzing a similar set of observations obtained by Swings and Allen (1972).

b) Short-Term Variability

Superposed on the long-term variability, short-term fluctuations have also been detected in FG Sge. Both sets of information are fundamental to understand the present evolutionary status of the star.

As far as these short-term variations are concerned, Richter (1960) reported irregular fluctuations in the photographic brightness of ~ 0.3 mag during the period 1934–1959. The photographic brightness increased by 1.2 mag over that interval, but there was no evidence for a systematic change of the fluctuation amplitude. Wenzel and Fürtig (1967) carried out photoelectric measurements in 1962–1963 which showed an irregular fluctuation of ~ 0.3 mag in *B* with a characteristic time scale of 10–20 days. In 1971–1973 the variations were quite regular, with $\Delta V = 0.25$ and characteristic time scales of 60–80 days. Archipova and Noskova (1976) published a light curve for 1975, pointing out that although the reliable determination of the period was not possible, their result agreed with the 60-to-80 day time scale. Wenzel (1974) discovered a secular increase in the characteristic time of oscillation. This result was confirmed by Mayor and Acker (1980), who studied the radial velocity curve and radius of FG Sge during the period 1977–1979. They found a mean value of the radius of this period of $140 \pm 30 R_{\odot}$ and a mean period of 112.5 days, and from these data a stellar mass of $1.2 \pm 0.6 M_{\odot}$. Whitney (1978) computed a value of $M = 0.4 M_{\odot}$, and Sackmann and Despain (1974) suggested a current mass of $\sim 0.8 M_{\odot}$ for FG Sge, the main-sequence mass of the star being 3–5 $M_{\odot}$.

A good compilation of data and references concerning the fluctuation period from 1962 to 1979 can be found in the work by Jurcsik and Szabados (1979). They found a period of 108 days for 1979.7 and remarked on the almost linear variation from 15 days in 1962.6 to the reported value. The same authors (Jurcsik and Szabados 1989) detected, in addition to the continuous increase in the period, a quasi-periodic variation with an amplitude of about ± 15 days and a periodicity of 4–5 yr (see Fig. 1 of their paper).

Taranova (1987b) analyzed infrared photometric observations taken over the period 1985–1986, obtaining a value of the fluctuation period of ~ 115 days, and temperatures of ~ 5500 K at minimum and ~ 6800 K at maximum of brightness. Archipova *et al.* (1988) give a value of 100–120 days for the characteristic time of the fluctuations.

III. UV AND IR OBSERVATIONS

Here we present 15 observations of FG Sge taken with the *International Ultraviolet Explorer* (*IUE*) satellite, obtained with the aim of monitoring the changes in its ultraviolet spectrum. A general description of the instrument capabilities and spacecraft characteristics has been given by Boggess *et al.* (1978a, b). In Table 1 we give the image numbers, dates of observation, and exposure times. All the spectra were taken in

the long-wavelength region (1900–3200 Å) with low dispersion and using the large aperture. The first observation corresponds to 1982, and the remaining 14 cover the period 1986 October–1989 June. In Figure 1 we show a panel with all the spectra, not corrected for interstellar reddening, in the interval 2400–3200 Å where the signal-to-noise ratio reaches a significant value. The most remarkable feature in the spectrum is the doublet of Mg II in absorption at 2800 Å. The Mg I line in absorption at

2852 Å is also visible. These lines could have an interstellar component given the large distance to the star. The spectrum shows a jump at ~2630 Å which is caused by the strong effect of blocking by Fe II uv1 lines near this wavelength. The region 2630–3200 Å is full of absorption lines due to many Fe I and Fe II multiplets. The identification of individual lines in low-resolution spectra is very difficult, and the interpretation of Fe line formation in cool stars is complicated. The presence of all

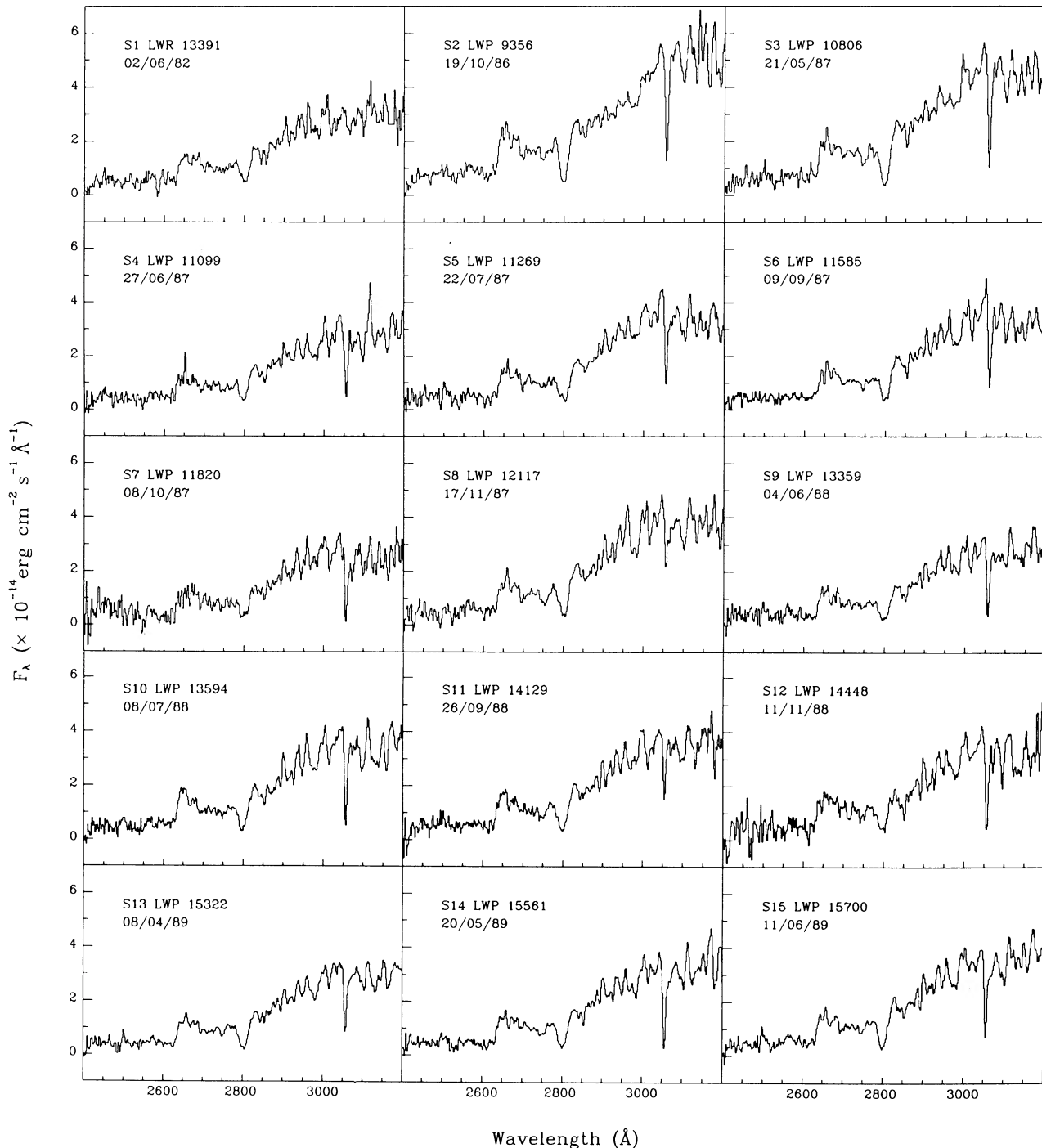


FIG. 1.—*IUE* UV spectra of FG Sge between 2400 and 3200 Å not corrected for interstellar reddening. The image number and date of observation are given for each spectrum.

these lines masks the appearance of the real continuum, so only the peak around 2650 Å and the peaks between the absorption lines in the region beyond 2850 Å can be considered as lower limits to the position of the continuum. An identification of the Fe I and Fe II multiplets which could be the origin of the strongest absorptions in the spectral range 2400–3200 Å and a qualitative study of the effects of Fe I and Fe II blocking on the spectrum of FG Sge have been carried out by Montesinos *et al.* (1990). The deep feature in absorption around 3050 Å is due to instrumental origin. We will use the notation S1, ..., S15 to denote the UV spectra, the number corresponding to their order in Table 1, and we add in the figures the indication "(dn)" if the spectrum has been dereddened and normalized. The noisy appearance of spectra S7 and S12 in comparison with the other spectra is due to their shorter exposure times.

We also present here two sets of infrared photometric observations. The first observing run was carried out in 1982 using the 1.23 m telescope at the German-Spanish Observatory in Calar Alto (Almeria, Spain). The second set, covering the period 1986–1987, was obtained with the 1.5 m Carlos Sánchez Magro telescope on the Observatorio de Izaña (Tenerife, Spain), using an IR single-channel photometer with an In-Sb detector. In Table 2 we give the *J*, *H*, *K*, and *L* magnitudes not corrected for interstellar reddening, with the corresponding errors and dates of observation. The UV fluxes and IR magnitudes have been dereddened by using a color excess $E(B-V) = 0.4$, according to the HB result, and the galactic interstellar extinction laws of Seaton (1979) for the ultraviolet and Howarth (1983) for the optical and infrared. The calibration by Wamsteker (1981) for infrared photometry has been used. When necessary, we will use for the infrared measurements the notation IR1, ..., IR12 in the same way as for the UV IUE observations.

IV. THE EFFECTIVE TEMPERATURE AND SPECTRAL TYPE

The estimates of the effective temperature, spectral type, and radius for each epoch obtained from the observational data presented here are very helpful tools for disentangling the problem of the current evolutionary status of FG Sge. A reliable determination of these parameters provides the opportunity of carrying out a comparative study with previous results, in spite of the inhomogeneous sets of data available

TABLE 1
SUMMARY OF IUE OBSERVATIONS

Image	Date	Ap	Res	Time (min)
LWR 13391.....	1982 Jun 2	L	L	160
LWP 9356.....	1986 Oct 19	L	L	180
LWP 10806.....	1987 May 21	L	L	144
LWP 11099.....	1987 Jun 27	L	L	100
LWP 11269.....	1987 Jul 22	L	L	100
LWP 11585.....	1987 Sep 9	L	L	100
LWP 11820.....	1987 Oct 8	L	L	42
LWP 12117.....	1987 Nov 17	L	L	100
LWP 13359.....	1988 Jun 4	L	L	110
LWP 13594.....	1988 Jul 8	L	L	110
LWP 14129.....	1988 Sep 26	L	L	97
LWP 14448.....	1988 Nov 11	L	L	40
LWP 15322.....	1989 Apr 8	L	L	110
LWP 15561.....	1989 May 20	L	L	110
LWP 15700.....	1989 Jun 11	L	L	120

TABLE 2
SUMMARY OF IR PHOTOMETRIC OBSERVATIONS

Date	<i>J</i>	<i>H</i>	<i>K</i>	<i>L</i>
1982 Jul 23	7.01 ± 0.04	6.72 ± 0.02	6.61 ± 0.04	6.57 ± 0.08
1982 Jul 25	7.04 ± 0.07	6.91 ± 0.04	6.61 ± 0.03	6.80 ± 0.11
1982 Jul 28	6.95 ± 0.04	6.72 ± 0.02	6.57 ± 0.02	6.51 ± 0.20
1986 Oct 20	6.96 ± 0.03	6.60 ± 0.02	6.43 ± 0.02	6.22 ± 0.05
1986 Oct 31	7.09 ± 0.01	6.70 ± 0.04	6.57 ± 0.03	6.51 ± 0.09
1987 Jul 20	7.00 ± 0.01	6.67 ± 0.04	6.50 ± 0.03	6.23 ± 0.18
1987 Aug 12	6.92 ± 0.03	6.56 ± 0.02	6.40 ± 0.02	6.14 ± 0.11
1987 Aug 13	6.88 ± 0.02	6.52 ± 0.02	6.39 ± 0.02	6.25 ± 0.06
1987 Aug 14	6.88 ± 0.02	6.55 ± 0.01	6.40 ± 0.01	6.19 ± 0.07
1987 Sep 1	6.99 ± 0.01	6.58 ± 0.02	6.45 ± 0.02	6.38 ± 0.02
1987 Sep 2	7.00 ± 0.02	6.63 ± 0.02	6.49 ± 0.01	6.30 ± 0.11
1987 Oct 8	7.10 ± 0.02	6.66 ± 0.02	6.50 ± 0.02	6.14 ± 0.14

and the very different ways in which the parameters have been computed.

Two main sources of information, namely, the UV and IR observations, are available. In the next three subsections we analyze the information which it is possible to extract from the two sets of data, and we compare our results with previous determinations.

a) What Do the UV Data Tell Us?

When comparing the different UV observations, one would be tempted to state that, since the star seems to be pulsating as indicated by the short-term variations observed, the changes in the photospheric temperature due to the pulsation will affect the shape of the ultraviolet spectrum. Hence it should be possible to extract information on the variation of photospheric temperature—or even of the effective temperature—through the UV variations. In what follows we study the shape of the ultraviolet spectrum, attempting to carry out an estimate of the temperature at which the continuum is formed. The effective temperature and spectral type are obtained by comparing the spectra of FG Sge with the grid of LTE models computed by Kurucz (1979). As we pointed out in § III, the continuum is masked by the presence of many Fe I and Fe II absorption lines, so we will assume that the real continuum is indicated by the highest peaks around 2650 Å and in the region beyond 2850 Å.

i) The Shape of the UV Spectra

The UV continuum is essentially the hydrogen Balmer continuum which dominates the radiation in the interval $912 \leq \lambda \leq 3650$ Å. In cool stars—spectral types G, K—this continuum originates mainly in the chromosphere since its existence implies the presence of ionized hydrogen, but in hotter stars where the photospheric temperatures are higher, the region of formation could be placed in the photosphere. Strictly speaking, the continuum is emitted by free electrons interacting with positive ions, mostly H II, but the contribution of He II must be also taken into account. The emission coefficients for the H I and He I recombination continua, including bound-free and free-free contributions can be written (Osterbrock 1989)

$$j_{\nu}(\text{H I}) = \frac{1}{4\pi} N_p N_e \gamma_{\nu}(\text{H}^0, T), \quad (4.1)$$

$$j_{\nu}(\text{He I}) = \frac{1}{4\pi} N_{\text{He}^+} N_e \gamma_{\nu}(\text{He}^0, T),$$

where the functions γ_v involve atomic parameters and depend on the distribution of velocities of the free electrons.

A change in the shape of the spectrum from one epoch to another could be explained, to a first approximation, following the expressions (4.1), by two different causes, both of them realistic in a pulsating regime: first the region where the continuum originates experiences a very large change in temperature at constant density; second, this region experiences a change in density at constant temperature. A more complicated picture would involve both mechanisms at the same time.

In the first case one should observe changes in the *slope* of the spectra, even after a normalization of all them at a given wavelength, owing to the dependence of the slope of γ_v on T (see Tables 4.7–4.9 in Osterbrock 1989). In the second, the ratio between any two spectra should be proportional to the ratio between the corresponding values of $N_p N_e$, and the shapes of the spectra should match each other when normalized to the same wavelength.

To check which is the more likely explanation, we normalized all the spectra at $\lambda = 2700 \text{ \AA}$, and the result was that there are no changes in their *slope* but *all the spectra turn out to have the same global shape as they are normalized; i.e., the temperature of the region where the continuum is formed seems to be the same on all the dates, and what is varying is the density of that region and/or the emitting volume as a consequence of the pulsation*. The different appearance of the spectra as they are shown in Figure 1 is only the effect of a different multiplicative constant between them. Figure 2 shows spectra S1 and S2 corrected for interstellar reddening and normalized. S2 has been shifted one unit toward the top of the graph for clarity. A similar picture is obtained when plotting any other pair of spectra. As can be seen in Figure 1, both spectra—taken with a difference of more than 4 yr—have very different shapes, but they turn out to be very alike when the normalization procedure is applied. As we can see, the Fe II lines show different strengths; we will not attempt to analyze the formation conditions since they probably originate in many different regions and we are looking here for global changes rather than particular mechanisms of line formation.

We have computed, using the formalism presented by

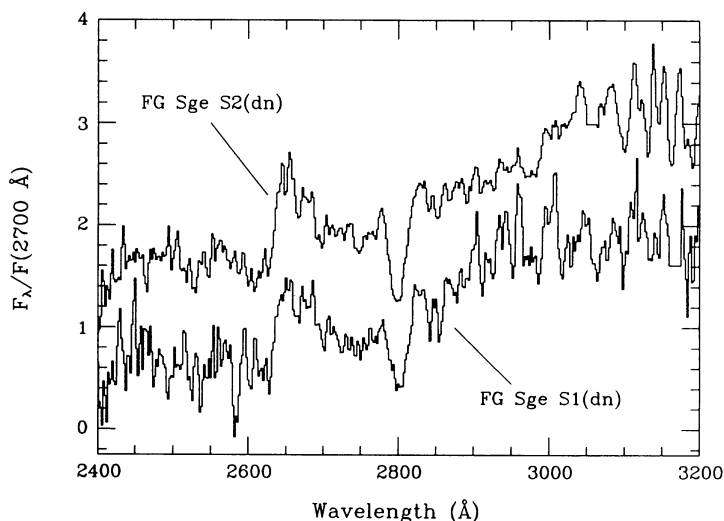


FIG. 2.—Ultraviolet spectra S1 and S2 of FG Sge corrected for interstellar reddening, assuming $E(B-V) = 0.4$, and normalized at $\lambda = 2700 \text{ \AA}$. S2 appears shifted one unit toward the top of the graph for clarity.

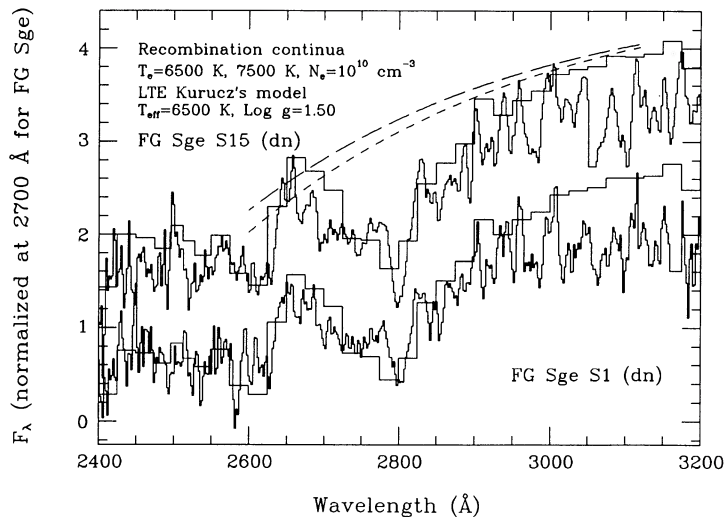


FIG. 3.—Spectra S1 and S15 of FG Sge dereddened and normalized compared with two H II and He II recombination continua, superposed on S15, computed assuming $X = 0.75$, $Y = 0.25$, $T_e = 6500 \text{ K}$ (short-dashed line), 7500 K (long-dashed line), $N_e = 10^{10} \text{ cm}^{-3}$, and LTE conditions. The Kurucz LTE model for $T_{\text{eff}} = 6500 \text{ K}$ and $\log g = 1.5$ appears superposed on both spectra. S15 appears shifted one unit toward the top of the graph.

Osterbrock (1989), a grid of recombination continua and have compared them with the continuum of FG Sge. We assume a chemical composition $N_{\text{He}} = N_{\text{H}}/10$, and, after straightforward algebra, we have the following expression for the total emission coefficient per unit frequency interval per unit solid angle per unit time and per unit volume:

$$j_v = N_e N_p \left[\gamma_v(\text{H}^0, T) + \frac{F_2(N_e, T_e)}{10F_1(N_e, T_e)} \gamma_v(\text{He}^0, T) \right], \quad (4.2)$$

where the functions

$$F_1(N_e, T_e) = \frac{N_{\text{H II}}}{N_{\text{H I}} + N_{\text{H II}}},$$

$$F_2(N_e, T_e) = \frac{N_{\text{He II}}}{N_{\text{He I}} + N_{\text{He II}}},$$

are computed by using the Saha law, i.e., assuming LTE conditions.

After converting j_v to j_λ it is possible to estimate the temperature of the region where the continuum is emitted. In Figure 3 we show spectra S1 and S15—dereddened and normalized at $2700 \text{ \AA}$ —and two recombination continua computed for an electron density of 10^{10} cm^{-3} and electron temperatures 6500 K (short-dashed line) and 7500 K (long-dashed line) superposed on S15. We do not have any way to compute separately the factor $N_e N_p$ since the emitting volume is unknown, but normalized continua computed for a given temperature and densities two order of magnitudes larger have the same shape, so we can consider that a value of T_e around 7000 K is a good estimate for the temperature of formation of the continuum.

ii) The Spectral Type and Effective Temperature of FG Sge during 1982–1989

In order to obtain an estimate for the effective temperature and spectral type we have compared the spectra of FG Sge with the grid of LTE model photospheres computed by Kurucz (1979). The best fit was achieved for the model com-

puted with $T_{\text{eff}} = 6500$ K and $\log g = 1.5$, which corresponds to a F6–7 supergiant. This model has been plotted in Figure 3 superposed on spectra S1 and S15, which were taken 7 yr apart. The agreement is quite good, so we can conclude that those values for the effective temperature and spectral type are reasonably accurate.

The Kurucz models give absolute fluxes at every wavelength which allows the factor $(R/d)^2$ to be calculated in some cases (R is the stellar radius, and d is the distance to the star) after the normalization of a given spectrum to the chosen model. If the distance to the star is known, an estimate of the radius can be obtained. For our case this has not been possible, since, as we showed above, probably both the gas density and/or the emitting volume where the UV radiation originates change as the star pulsates. A normalization of each spectrum to the Kurucz model would not give a meaningful physical answer since the conditions of the emitting region are different from one observation to another and R is not the only parameter affecting the level of the UV emissivity level of each spectrum.

iii) The Visual Magnitude of FG Sge from FES Data

A calibration to convert the FES IUE count number into visual magnitude, provided the $B-V$ color of the object is known, was carried out by Imhoff and Wasatonic (1986). Barylak (1989) improved this calibration by analyzing the change of sensitivity with time of the FES photometer over the period 1978–1989. If one assumes that the value of $B-V$ for FG Sge is that corresponding to a star of spectral type F6–7 I, namely $B-V \simeq +0.44$ (Johnson 1966), it is possible to compute values of V using the FES counts collected in each observation. In Table 3 we give the FES counts for each observation, and the visual magnitudes computed in this way, *not corrected* for interstellar extinction. A comparison has been carried out, as an indirect test of the results extracted from the calibration, between our values for V and those given in the AAVSO (American Association of Variable Star Observers) circulars which are shown in the last column of the table. No precise dates are available for the AAVSO observations since the information contained in a circular is an average for the month prior to its publication. In spite of the inhomogeneity of the results, it is encouraging that both sets of values give answers within a few tenths of a magnitude, with some larger differences for particular dates. The mean values also agree with the V magnitudes given by Taranova (1987a) for 1985

(9.30–9.39) and the average V magnitudes reported by Jurcsik and Szabados (1989) for 1986 and 1987 (9.17 and 9.01.)

The V magnitude computed from the FES counts during the interval 1986–1989 oscillates between 9.08 and 9.36. After correcting for reddening, using $E(B-V) = 0.4$, these values lead to visual magnitudes from 7.84 to 8.12. Here the uncertainties in the distance become important, since taking an average magnitude $\bar{V} = 8.00$ and using $d = 2500$ pc, we obtain $\bar{M}_V = -3.99$, whereas the absolute visual magnitude for the standard F6–7 I is roughly -6.5 ; i.e., the star would be ~ 10 times fainter than it should if this distance is correct. Using $d = 4100$ pc, we obtain $\bar{M}_V = -5.06$, and, with $d = 4830$ pc, the result is $\bar{M}_V = -5.42$. In all cases the star seems to be fainter in the optical region than a normal supergiant, which could be explained by assuming the presence of a shell around the star. This is consistent with the proposal that FG Sge is now in the process of ejecting material.

It is worth noticing that the minimum V brightness obtained from FES counts corresponds to the first observation in 1982 ($V = 9.41$). This value is larger than the average magnitude over the period 1986–1989 ($\bar{V} = 9.20$). Since only one observation is available for that year, it is difficult to say whether this value corresponds to a minimum of luminosity, or it shows that the star was, on average, ~ 0.2 mag fainter in the V band in 1982. The results of Jurcsik and Szabados (1989) mentioned above and the mean values of the V magnitudes shown in Table 3 for 1987 and 1988–1989 (9.22 and 9.19) suggest that the increase in optical brightness might be real.

b) The Behavior of the Combined UV, Visual, and IR Data

In Figure 4 we show the variation with time of the J , H , K and L magnitudes for the set of data IR4–IR12. IR4 and IR5, on the one hand, and IR6–IR12 on the other, are connected by straight lines. We also show the variation of the visual magnitude V for the 14 last observations, derived from the FES counts as described in the previous subsection, and the UV observed flux between 2850 and 3000 Å converted to magnitudes, choosing an arbitrary constant to fit m_{uv} , the UV magnitude ($m_{uv} = C - 2.5 \log F[2850-3000 \text{ Å}]$) on the same scale as the infrared and FES magnitudes. We have added to this graph, which shows data unpublished so far, the IR observations of FG Sge carried out by Taranova in 1986 (Taranova 1987b); these points are not connected with straight lines to our observations. All the magnitudes shown in Figure 4 have been dereddened using $E(B-V) = 0.4$, and the K and L magnitudes have been shifted in the graph 0.1 and 0.2 units, respectively, toward the top for clarity.

Although in § V we describe in detail the current value for the period of the short-term variations, it is interesting to notice the different behavior of the four infrared bands compared with the variations of the visual and UV data. As the star experiences a maximum in optical and UV brightness, all the IR fluxes increase, whereas, as the star decreases its visual and UV brightness, the J , H and K fluxes also decrease—the last two not in the same proportion as the first one—but the flux in the L band tends to increase again (see also the behavior of the infrared bands, J , H , and K in comparison with the L band in the left part of the diagram). This fact means that at the minimum of UV, optical, and J , H , and K fluxes there is an infrared excess at longer wavelengths, confirming the presence of a cool envelope around the star responsible for the extreme infrared radiation.

TABLE 3
FES-IUE COUNTS AND VISUAL MAGNITUDES

Image	Date	FES(cts)	V(FES)	V(AAVSO)
LWR 13391.....	1982 Jun 2	581	9.41	9.10
LWP 9356.....	1986 Oct 19	634	9.10	9.06
LWP 10806.....	1987 May 21	627	9.08	9.15
LWP 11099.....	1987 Jun 27	483	9.36	9.36
LWP 11269.....	1987 Jul 22	584	9.15	9.17
LWP 11585.....	1987 Sep 9	553	9.20	9.13
LWP 11820.....	1987 Oct 8	482	9.35	9.16
LWP 12117.....	1987 Nov 17	571	9.16	9.22
LWP 13359.....	1988 Jun 4	515	9.24	9.18
LWP 13594.....	1988 Jul 8	579	9.11	9.10
LWP 14129.....	1988 Sep 26	573	9.11	9.18
LWP 14448.....	1988 Nov 11	545	9.16	9.19
LWP 15322.....	1989 Apr 8	509	9.22	9.30
LWP 15561.....	1989 May 20	480	9.28	9.30
LWP 15700.....	1989 Jun 11	514	9.21	9.30

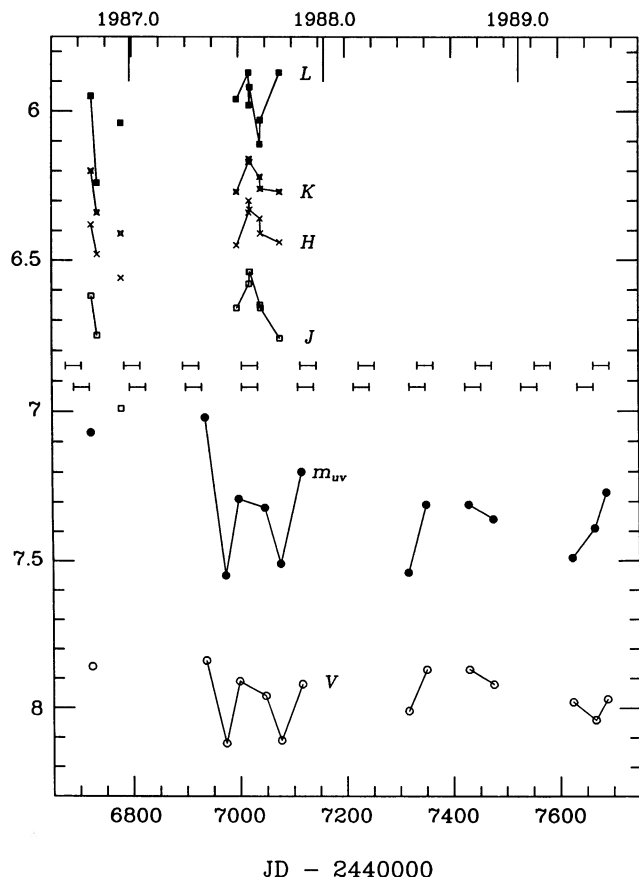


FIG. 4.—Variation with time over the period 1986–1989 of the J , H , K , and L magnitudes, the V magnitude as computed from the FES IUE counts, and an “ultraviolet” magnitude ($m_{uv} = C - 2.5 \log F[2850-3000 \text{ \AA}]$). The infrared observations for 1986 by Taranova (1987b) are also included. All the data shown in this figure have been dereddened, and the points corresponding to the K and L magnitudes have been shifted 0.1 and 0.2 units toward the top of the graph.

c) What Do the IR Data Tell Us?

To obtain results from the available infrared photometry we have compared our data with the standard values of infrared magnitudes for supergiants given by Koornneef (1983). We have plotted in Figures 5a and 5b the color diagrams $J-H$ versus $J-K$ and $J-H$ versus $J-L$ obtained from the dereddened magnitudes of FG Sge (solid circles). We have also included supergiants of spectral types from F0 to G3 (open squares).

In Figure 5a it can be seen that apart from IR2, whose color $J-H$ shows an anomalous behavior due to the odd value of H (see Table 2), colours corresponding to observations IR1 and IR3 (taken in 1982) are close to those of a supergiant of spectral type $\sim F0$, whereas the colors corresponding to sets IR4–IR11 (taken in 1986–1987) lie in a band around $\sim F5$ – $F8$. IR12 appears to match with a cooler spectral type. The agreement between the observations and the standard colors is quite remarkable within the uncertainties. An assignation of effective temperature according to this diagram gives $T_{\text{eff}} > 7200 \text{ K}$ in 1982, which is too high in comparison with other estimates made for the period 1979–1980 (e.g., Acker *et al.* 1982 give $\sim 5000 \text{ K}$), and 6100–6900 K for 1987–1989, which are in agreement with the results given by Taranova (1987b) for the

temperature at a maximum of luminosity, and also with our result from UV data.

In Figure 5b the points spread out when a comparison with a color containing the L magnitude is introduced. This is partly because of the errors in the determination of the L magnitudes (see Table 2) and partly because of the infrared variability of the star. As we pointed out in the previous subsection, the L brightness increases both when the fluxes in the other bands reach a minimum and when they are near a maximum. Observations IR7–IR9 correspond to a maximum of all the fluxes, while IR12 is near a minimum for the ultraviolet, V , and J fluxes—and probably for H and K but it corresponds again to a maximum of L brightness. This infrared excess appears as a shift of the color $J-L$ toward the right-hand side of the diagram. An estimate of the temperature in this case is unreliable since it is very likely that the infrared flux at the longer wavelengths is formed in a different region from that observed at shorter wavelengths.

In the same way as happens to the V magnitude, the values of J , H , K , and L corresponding to observations IR1, IR2, and IR3 are somewhat larger than those for the other 12 observations, but not by the same amount: $\sim 0.2 \text{ mag}$. This global infra-

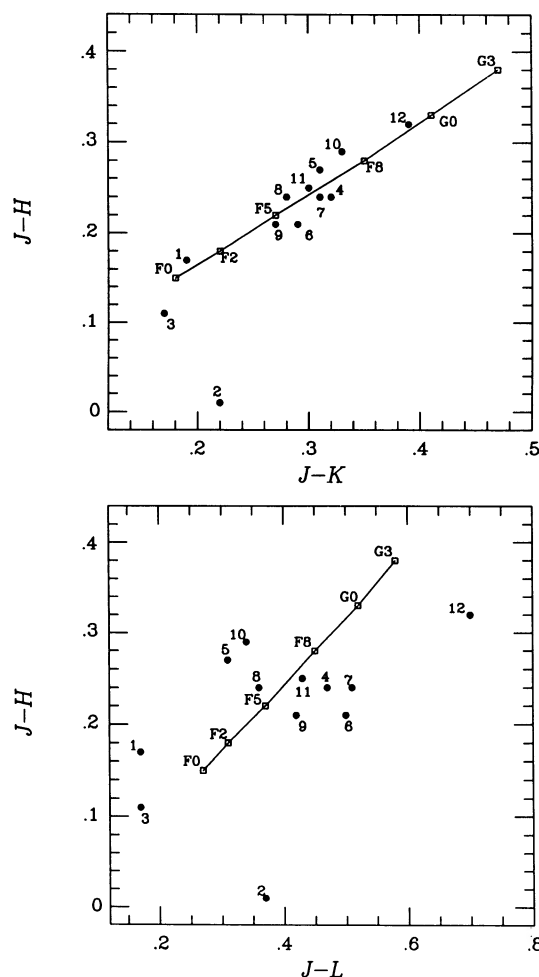


FIG. 5.—Color-color diagrams $J-H$ vs. $J-K$ (top) and $J-H$ vs. $J-L$ (bottom) for FG Sge (solid circles). Numbers correspond to the order of the infrared observations in Table 2. Colors for standard supergiants taken from Koornneef (1983) are also included (empty squares).

red excess in comparison with the optical output from 1982 to the period 5 yr later might imply a more active episode of ejection of material, but it does not explain why the spectral type found from IR1 and IR3 is so early.

V. THE PERIOD OF THE SHORT-TERM VARIATIONS

As mentioned in the Introduction, the existence of short-term fluctuations in the brightness of FG Sge superposed on its secular variation is well established.

As far as the IR observations are concerned, the existence of a maximum in brightness at JD 2,447,020 is very clear (see Fig. 4). The shape of the change and values of the magnitudes for our two 1986 observations, plus those taken by Taranova (Fig. 4, *left*) in comparison with those seen after the maximum, suggest the presence of another maximum before or around JD 2,446,725. On the other hand, the variation of UV and optical fluxes also shows a maximum around JD 2,447,020, in coincidence with the one detected from IR observations, and two other points of high brightness, at both sides of the central maximum separated by ~ 180 days.

In addition to our data we have recent information from other authors which allow us to determine an estimate of the current fluctuation period. Archipova, Zaitseva, and Noskova (1985) report the occurrence of a *minimum* in the optical brightness at JD 2,446,026. If we assume a fluctuation period of ~ 115 days for that epoch (Taranova 1987b), this would imply the presence of a maximum in optical brightness around JD 2,446,084. Taranova (1987b) also reports another maximum in the IR brightness at $\sim$ JD 2,446,618, but her observations do not cover dates before and after that day; furthermore, this information should be regarded only as approximate. The separations between these two maxima and the one observed by us at JD 2,447,020 are ~ 936 and ~ 402 days, respectively.

It must be stressed that the results concerning the short-term variation period which one can infer from the available information must be taken with caution, partly because of the lack of observations and partly because of the existence of a sort of erratic nature of the variation during short intervals of time, pointed out by several authors. For example, Taranova (1987b) notes that the infrared minimum corresponding to the optical one at JD 2,446,026 was observed with a 15 day delay, and Jurcsik and Szabados (1989) also show the existence of a fluctuation of roughly ± 15 days, superposed on the average increasing trend, among determinations of the short-term period close in time. Although a consistent picture accounting for the observed fluctuations can be reached if we assume a period of ~ 100 – 110 days, an error bar of ± 15 days must be added to this result to account for all the uncertainties.

We have drawn in the middle of the figure, for the purposes of illustration only, two groups of 10 small horizontal bins which correspond to the expected position of maxima in brightness, assuming a period of 105 days (*lower row*) and 110 days (*upper row*) and allowing for a delay of ± 15 days in their appearance. The observed variation matches reasonably well with the expected position of the maxima. Unfortunately the UV observations taken in 1988 and 1989 do not provide enough information to obtain the position of another maximum to minimum.⁹

⁹ Note that the lines joining the points representing the “UV” and *V* magnitudes obtained from the 1988 and 1989 observations should not be regarded as the true behavior of the star between two observations. For example, a maximum in brightness between the last two observations obtained in 1988 might have occurred in the same way as the one observed in the IR at JD 2,447,020 which occurred between two *IUE* observations.

Our result is consistent with the ~ 115 day period observed in 1985–1986 by Taranova (1987b) and the 100-to-120 day “quasi-period” found by Archipova *et al.* (1988) over 1986–1987. It does not differ very much from the 108 day period for 1979.7 given by Jurcsik and Szabados (1979), and it agrees with the trend shown by Jurcsik and Szabados (1989) in the sense that the average increase in the fluctuation period has slowed down since ~ 1980 .

Finally, we shall make a brief comment on the type of variability of FG Sge. Although some authors (Whitney 1978; Taranova 1987b) claim some of similarity between FG Sge and δ Cep variables, Mayor and Acker (1980) observed FG Sge during 1978–1979 and pointed out that the phase difference between luminosity and velocity variations was $\sim \pi/2$ for FG Sge, while this difference is $\sim \pi$ for classical Cepheids. So, if the variation in brightness for FG Sge is due to pulsation, the phenomena involved must differ from those governing the pulsation of a Cepheid. Unfortunately no data on radial velocity simultaneous with our observations are available to check this point.

VI. EVOLUTIONARY STATUS

As we mentioned in § II, the observed evolution of FG Sge during this century, and until 1982, has consisted of a relatively fast increase of the radius and a decrease of the effective temperature accompanied by short-term fluctuations in luminosity whose characteristic time has increased since the first detections in the early 1960s. We will try in this section to show how FG Sge has evolved since ~ 1965 and to pose the problems raised by its behavior.

In Figure 6 we show a compilation of results for temperatures and fluctuation periods found over the past 25 yr. Empty circles represent the values for T_{eff} compiled by Acker, Jaschek, and Gleizes (1982) from different authors plus their determinations, solid circles are results by Stone (1979), empty squares

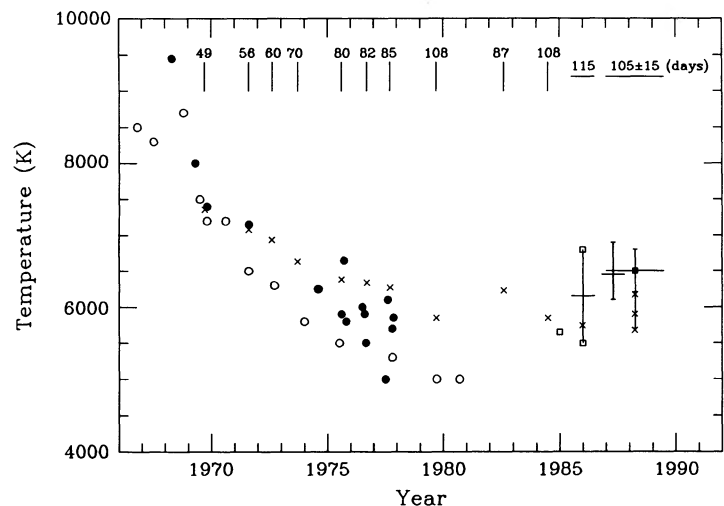


FIG. 6.—The variation of the effective temperature of FG Sge with time. Empty and solid circles and empty squares are determinations from other authors. The solid square in the right part of the diagram is our result from UV data, and the vertical bar to its left is the estimate obtained from IR photometry. At the top of the graph some values for the fluctuation period—in days—are given. The value of 105 ± 15 days has been obtained from the data presented in this work. The crosses show the temperatures computed for the periods given at the top, assuming a mass of $0.66 M_{\odot}$ for FG Sge (Iben 1984) and that both the theory of PNN evolution and linear pulsation theory hold for this star. The three crosses placed at 1988.25 and connected with a vertical line correspond to the temperatures predicted assuming pulsation periods of 90 (*upper cross*), 105 (*middle*), and 120 (*lower*) days, respectively.

show Taranova's (1987*a, b*) results, and the solid square is our determination from UV measurements; the vertical bar to its left is the estimate obtained from IR photometry and the meaning of the crosses will be explained later. At the top of the graph we show some values for the fluctuation period—in days—taken from Jurcsik and Szabados (1979, 1989) (*vertical ticks*), as well as the value given by Taranova (1987*b*) and our estimate. The horizontal bars mean that values are given over an interval of time.

If the results shown in this graph are accurate, it seems that from ~ 1980 an *increase* in the effective temperature of FG Sge has occurred, accompanied by the stabilization of the short-term oscillation period. The cooling rate of $\sim 250\text{--}310\text{ K yr}^{-1}$ observed during 1968–1980 has stopped, and the star appears to have the same spectral type in 1982 and 1986–1989, as found from UV data. Unfortunately a determination of the radius has not been possible from our data, so the set of the current physical parameters of FG Sge is not complete.

One of the most realistic scenarios to explain the current evolutionary stage of FG Sge could be the one suggested by HB, LKA, and Paczyński (1971, 1975) which has been discussed in the Introduction. These authors pointed out that the star is now returning to the red supergiant region after the occurrence of a thermal pulse in its interior as a result of the thermal instability in the helium-burning shell.

We do not intend to review here the theory of the Asymptotic Giant Branch (AGB) evolution, but a very detailed description of all the physical processes involved can be found in the works by Paczyński (1971, 1975), Reimers (1975) Iben (1981*a, b*, 1982), and Renzini (1981). It is worth recalling that the central star of a planetary nebula can undergo a second planetary ejection event *after* the star leaves the AGB. During the post-AGB evolution it is possible for the star to experience a new helium-shell flash which carries it from left to the right part of the H-R diagram. A new ejection of material is possible as the star reaches again the AGB.

Although the qualitative behavior of FG Sge during this century matches with some of the planetary nebula nuclei (PNNs) evolutionary models presented by Iben (1984) (see, e.g., Figures 10 and 11 of his paper), he claims that the cooling rates observed in the past are not consistent with the rate at which theoretical models evolve to the red after a flash. Iben estimates a mass of $\sim 0.66 M_{\odot}$ for FG Sge using arguments based on PNNs evolution. From linear pulsation theory, he gives the following expression for M :

$$\frac{M}{M_{\odot}} \sim 0.5 + 0.0010P^{1.16} \left(\frac{M}{M_{\odot}} \right)^{0.84} \left(\frac{T_{\text{eff}}}{T_{\text{eff}\odot}} \right)^4, \quad (6.1)$$

where P is the pulsation period in days and T_{eff} the effective temperature of the star. Introducing $M = 0.66 M_{\odot}$ in both sides of this equation, one finds, *assuming that this mass is the correct one*, that the effective temperature of the star as a function of the pulsation period is given by

$$T_{\text{eff}} \sim 22747/P^{0.29} \text{ K}, \quad (6.2)$$

where $T_{\text{eff}\odot} = 5860\text{ K}$ has been used. Equation (6.2) predicts the effective temperature that FG Sge should have, under the hypothesis that linear pulsation theory holds for this star. The crosses in Figure 6 show the temperatures computed using the periods given at the top of the graph. It can be seen that the agreement over the period 1970–1980 is remarkable, within the errors, although the cooling rate of FG Sge is somewhat steeper than it should be if both the theory of PNN evolution

and linear pulsation theory hold for this star. The agreement is also good for the period 1985–1989, so if the rise in temperature is real, this is an indication that FG Sge must be now undergoing some phenomena different from those observed prior to 1980. Fadeyev and Tutukov (1981), Fadeyev (1982), and Aikawa (1985) remarked that the pulsational models of FG Sge do not account for the observed amplitudes, and that the pulsation modes so far remain unidentified. Therefore, the explanation of the noncomplete agreement between theories and observations is still an open question.

Iben (1984) also proposed some alternative explanations of the apparent abundance changes, attributed to an *s*-process episode by other authors. He suggested that the presence of a strong wind, responsible for the formation of an envelope which partially hides the “real” photosphere, might explain the abundance changes. We have evidence from the IR data of the presence of an envelope cooler than the star, which is responsible for the infrared excesses observed in the *L* band. We do not have enough information to show that this envelope is the cause of the abundance changes, but its existence might explain why the *V* magnitude is always larger than that corresponding to a standard supergiant of the spectral type deduced from UV data.

Although a picture of the evolutionary stage qualitatively similar to that proposed at the beginning of this section is very likely to be accurate, there are still many problems to be solved, such as the determination of the current luminosity, radius, and mass, which would allow the position of the star in the H-R diagram to be found and hence its evolution to be compared with other nuclei of planetary nebulae. Estimates of the effective temperature carried out following independent methods would also be desirable.

VII. FINAL REMARKS

UV and IR observations of the variable star FG Sge in 1982 and over the interval 1986–1989 suggest that the star has undergone a change in the evolutionary path traced with reliable measurements since 1955. The spectral type, as deduced from UV *IUE* observations, is around F6–7 I, which corresponds to an effective temperature of $\sim 6500\text{ K}$. This result is somewhat higher than the previous determinations and indicates that a rise in temperature has occurred. The current pulsation period is $\sim 100\text{--}110$ days, and its value has remained more or less constant, with fluctuations of $\sim 10\text{--}15$ days over the interval 1979–1989. An envelope around the star radiates in the infrared and probably hides the photosphere, confirming the presence of ejection of material which could give rise eventually to a second planetary nebula.

Finally, we stress the importance of carrying out an intensive monitoring of FG Sge over the next few years to investigate whether its further behavior will follow the predicted trends. This would allow the collection of a unique and invaluable observational data set concerning physical changes over a time interval extremely short compared with normal evolutionary scales and during which a number of complex structural changes might occur.

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