THE ASTROPHYSICAL JOURNAL, 200:392–394, 1975 September 1

PHOTOMETRY OF FG SAGITTAE

J. D. FERNIE
David Dunlap Observatory, University of Toronto, Richmond Hill, Ontario, Canada
Received 1975 January 27

ABSTRACT

BVRI photometry of FG Sge on seven consecutive nights in 1974 September is reported. The star was definitely variable, but the observations are too concentrated in time to allow suitable comparison with those of Papousek—although, if anything, the present results indicate more rapid variability than found by Papousek.

The mean $(B - V)$ of the star has now reached 1.41, which continues the linear trend of $(B - V)$ changes in recent years. The position of the star on the $(B - V)$ versus $(R - I)$ diagram is peculiar: dereddening the star in the usual way does not place it on the intrinsic sequence of supergiants in this diagram.

It is pointed out that the 60^d quasi-periodicity found by Papousek is in good agreement with the suggestion by Christy-Sackmann and Despain that FG Sge has $M_{bol} \simeq -5.5$ and $\mathfrak{M} \simeq 0.73\,\mathfrak{M}_\odot$.
Subject headings: luminous stars — stars, individual — stellar evolution

I. INTRODUCTION

The remarkable object FG Sge has recently been the subject of several major papers (Langer, Kraft, and Anderson 1974; Christy-Sackmann and Despain 1974; Ulrich 1974; the first two of these will hereafter be referred to as LKA and CSD, respectively.) An earlier seminal paper on the subject is that of Herbig and Boyarchuk (1968, hereafter HB).

Briefly, FG Sge is the central star of a small planetary nebula which apparently originated at least 6000 years ago. During the twentieth century the star seemingly has undergone another outburst, its B magnitude changing from 13.5 to 9.5 in 80 years. The most astounding aspect of the star, however, is that in the last 20 years it has been followed spectroscopically while changing from a B4 Ia star through an A supergiant to an F5 supergiant. In particular, recent spectrograms reveal a strong enhancement of *s*-process elements, which makes the star potentially of very great importance to theories of nucleosynthesis.

Various interpretations of these phenomena have been offered. HB suggested that the spectral changes were not those of a real star, but due to the expansion and cooling of an optically thick shell. With the discovery by LKA of the *s*-process element enhancement, this becomes improbable. LKA point out that the changes in the B magnitude can be understood in terms of a very early-type star cooling while maintaining a constant absolute bolometric magnitude. They, CSD, and Ulrich all accept the idea that the spectrum is that of a real star. They also suggest that the rapid change in spectral type is due to helium-flash instability, and proceed to consider models of various masses, luminosities, etc., which will explain the observations in general and the nucleosynthesis observations in particular.

Basically, LKA accept the conclusion (based on reddening versus distance considerations) of HB that FG Sge has $M_{bol} \simeq -4.2$, and prefer a model having $\mathfrak{M} \simeq 3\,\mathfrak{M}_\odot$. On the other hand, CSD suggest that better consistency can be obtained if $M_{bol} \simeq -5.5$ and $\mathfrak{M} \simeq 0.73\,\mathfrak{M}_\odot$. Ulrich offers two models, in one of which the envelope alone has a mass of 5–7 $\mathfrak{M}_\odot$, in the other of which the envelope mass is about 0.04 $\mathfrak{M}_\odot$. The latter case is to be preferred on grounds of the nucleosynthesis observations, and itself allows a dichotomy of models.

Since the star is now close to the Cepheid instability strip in the H-R diagram, it seemed to me that it would be worth looking for pulsational variability in FG Sge, in the hope that the period would allow a choice among some of the models arrived at by the above workers. Accordingly, the star was placed on a photometric program I undertook in Chile during 1974 September. Unfortunately, at the time I did not know that such a search had already been successfully undertaken by Papousek (1972).

II. OBSERVATIONS

The observations were made with the University of Toronto's 61-cm telescope at Las Campanas, Chile, using equipment described elsewhere (Fernie 1974). Most regrettably, a logistics problem resulted in a missing ultraviolet filter, so that no $(U - B)$ observations could be obtained. HD 191946, about 10′ away and of similar V magnitude, was also observed each night. The generally low internal errors of the observations can be gauged from the run of observations of HD 191946 shown in Table 1, but external errors in the transformations to the *BVRI* system will be larger, so that for comparison with other observers the present results should be rounded off to hundredths of a magnitude.

TABLE 1

PHOTOMETRIC OBSERVATIONS

JD 2,442,300+	FG Sge V	FG Sge $B-V$	FG Sge $V-R$	FG Sge $V-I$	HD 191946 V	HD 191946 $B-V$	HD 191946 $V-R$	HD 191946 $V-I$
5.574	8.933	1.383	0.823	1.338	8.554	−0.056	+0.030	+0.057
6.528	8.963	1.383	0.806	1.236	8.554	−0.050	+0.023	−0.055
7.577	8.972	1.416	0.810	1.303	8.556	−0.052	−0.003	−0.121
8.557	8.974	1.431	0.828	1.332	8.558	−0.033	+0.031	−0.025
9.535	9.040	1.417	0.806	1.299	8.552	−0.037	+0.037	−0.046
10.529	9.018	1.417	0.846	1.310	8.544	−0.032	...	−0.078
11.535	8.948	1.443	0.853	1.348	8.521	−0.029	+0.030	−0.048
Means	8.978	1.413	0.825	1.309	8.548	−0.041	+0.024	−0.046

III. DISCUSSION

Clearly FG Sge is variable on a time scale of days, as is shown in Figure 1. The variability is quite smooth in B and V, and possibly R, but the I values show considerable scatter. This kind of behavior is not unknown among even normal Cepheids, where mild stillstands on the visual light curve can become major secondary humps in I (cf. Eggen 1971), but it is not clear whether this is the same phenomenon here. The dotted curve shown below the V points represents the variation near minimum light found by Papousek (arbitrarily altered in zero point). The present results appear to show a more rapid variation than do Papousek's, but they are too concentrated in time for one to judge the significance of this difference. About all that can be said from the present results is that the period of variability is considerably longer than a week.

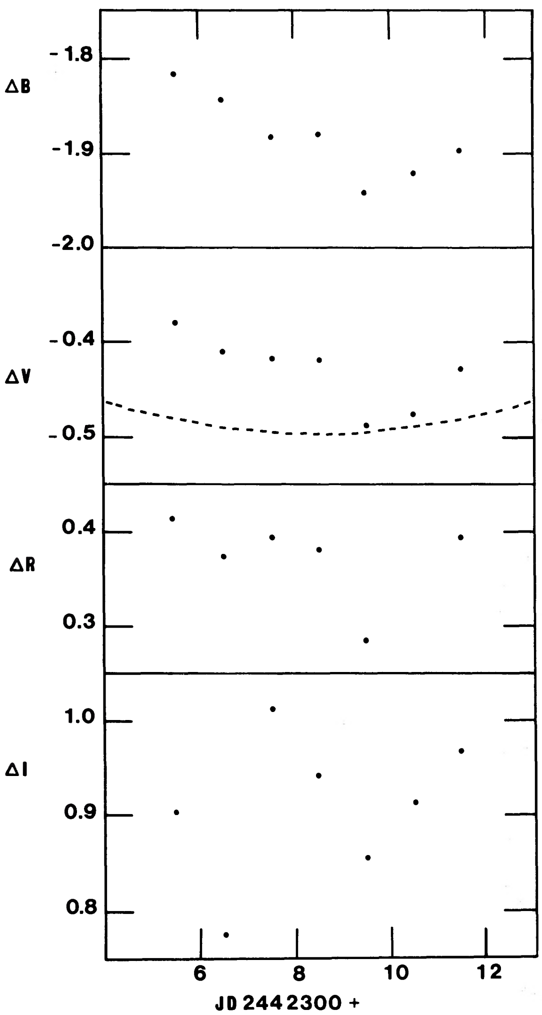

FIG. 1.—Light curves of FG Sge from present observations.

The average V magnitude found here is 8.98, which may be compared with the range of 9.07 to 8.91 found by Wentzel and Fürtig (1971) between the years 1966 and 1970, and an average of about 8.88 found by Papousek in 1971. There has been no very significant change.

On the other hand, there has been a quite spectacular change in $(B-V)$. The average of the present measures is 1.41, almost a magnitude redder than the value of 0.42 listed by Wentzel and Fürtig for 1966. Figure 2 shows how $(B-V)$ has continued to increase; the trend is linear at about 0.16 mag yr^{-1}. If interpreted purely as a temperature effect this would correspond to 400 K yr^{-1} (Johnson 1966), whereas LKA, on the basis of changing spectral type, find a cooling of 250 K yr^{-1}. This, as well as the anomalous location of the star on color–color plots discussed below, makes it

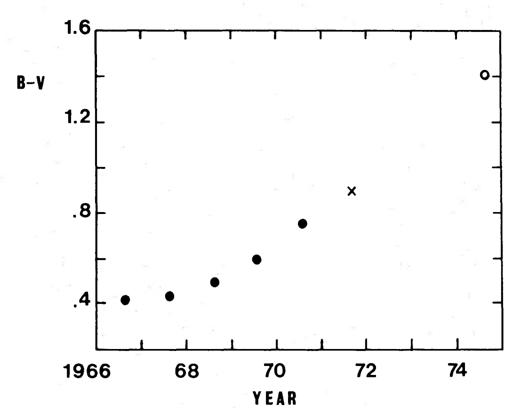

FIG. 2.—Change in $(B-V)$ of FG Sge 1966–1974. *Solid circles*, from Wentzel and Fürtig (1971); *cross*, Papousek (1972); *open circle*, the present result.

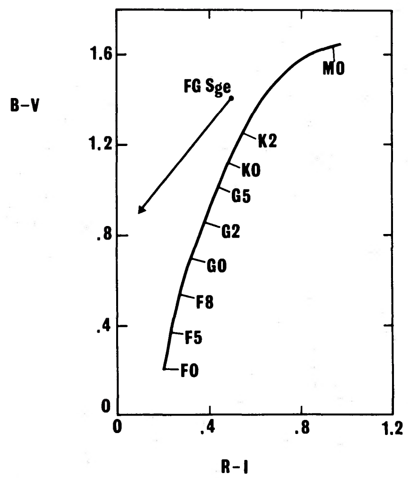

FIG. 3.—Location of FG Sge on the $(B - V)$ versus $(R - I)$ diagram. The intrinsic sequence of supergiants is shown, and the slope of the reddening line is denoted by an arrow.

seem likely that the increasing color index is due to more than just a temperature effect. One thinks of circumstellar reddening increasing as a consequence of the recent P Cygni phase (described by LKA), but then the V magnitude has remained nearly constant. A more likely possibility is the effect of increasing line blanketing caused by the enhancement of the s-process elements.

Figure 3 shows the location of FG Sge on the $(B - V)$ versus $(R - I)$ plot, based on the present observations. The intrinsic sequence of supergiants (Johnson 1966) is shown, and the arrow indicates the slope of the reddening line. This has the value 0.76 ± 0.09, based on a number of intermediate-type supergiants listed by Fernie (1972); the Whitford interstellar absorption curve gives 0.74. Clearly FG Sge has anomalous colors, in that no amount of dereddening will place it on the intrinsic sequence of colors. A similar situation prevails in the $(U - B)$ versus $(B - V)$ diagram. Wentzel and Fürtig (1971) found that while FG Sge in the mid-1960's mimicked the colors of normal supergiants with a constant reddening of $E_{B-V} = 0.40$, it had begun to depart rather sharply from this sequence by 1970. Even in the 1960's the star may have shown an anomalous ratio of color excesses: $E_{U-B}/E_{B-V} = 0.40$ (HB), all of which casts considerable doubt on the conclusion that the color excess really is 0.40.

Papousek (1972) found a moderately well-defined periodicity to the star's variability of $60^d \pm 1^d$, and it is interesting to see whether this offers any distinction between the various models proposed for FG Sge.

Böhm-Vitense *et al.* (1974) have found a period-radius-mass relation that appears to give good results for Population II Cepheids, i.e., intermediate, low-mass supergiants. They state that the relation is essentially independent of composition, and it is in any case similar to other such relations found empirically for variables in general (see, for example, Fernie 1965). Their relation may be written

$$\log P = -1.65 + 1.72 \log R - 0.72 \log \mathfrak{M} ,$$

with R and $\mathfrak{M}$ in solar units, and P in days. If this is combined with the usual relation

$$L \approx R^2 T_e^{\,4} ,$$

we obtain

$$\log P = 12.92 - 0.34\, M_{\rm bol} - 3.44 \log T_e - 0.72 \log \mathfrak{M} .$$

The effective temperature may be taken from the statement by LKA, based on spectral type, that in 1972.5 FG Sge had the temperature of α Per (6500 K) with a diminution of 250 K yr^{-1}. Thus in 1971.7, when Papousek's observations were made, $T_e \simeq 6700$ K. With this temperature and the model suggested by LKA, *viz.* $M_{\rm bol} = -4.2, \mathfrak{M} = 3\, \mathfrak{M}_\odot$, the above relation predicts $P = 7^{d}.0$. On the other hand, the CSD model of $M_{\rm bol} = -5.5$ and $\mathfrak{M} = 0.73\, \mathfrak{M}_\odot$, gives $P = 53^{d}.6$, which is in much better agreement with the observed $P = 60^d$. Likewise, one of Ulrich's models, the one in which the stellar envelope alone contains 5–$7\, \mathfrak{M}_\odot$, could likely also be ruled out on the grounds of the period it would predict; it is, in any case, unfavored on nucleosynthesis grounds.

Finally, attention is drawn to the fact that the rapidity with which FG Sge is changing spectral type should induce a relatively enormous rate of period change in the variability. The above relation predicts a period change of the order of a week per year, or over one day per cycle! This, indeed, may be why Papousek's results appear to be only quasi-periodic. Given the sensitivity of period changes as a diagnostic for motion on the H–R diagram, as well as the unique opportunity provided by FG Sge for studies in stellar pulsation generally, a continuing thorough photometric examination of this star in the future would be very worthwhile.

This research was supported in part by an operating grant from the National Research Council of Canada. I thank Miss Susan Clarke for assistance with the photometric reductions.

REFERENCES

Böhm-Vitense, E., Szkody, P., Wallerstein, G., and Iben, I. 1974, *Ap. J.*, **194**, 125.
Christy-Sackmann, I. J., and Despain, K. H. 1974, *Ap. J.*, **189**, 523.
Eggen, O. J. 1971, *Ap. J.*, **163**, 313.
Fernie, J. D. 1965, *Ap. J.*, **142**, 1072.
———. 1972, *A.J.*, **77**, 150.
———. 1974, *Pub. A.S.P.*, **86**, 837.
Herbig, G. H., and Boyarchuk, A. A. 1968, *Ap. J.*, **153**, 397.
Johnson, H. L. 1966, *Ann. Rev. Astr. and Ap.*, **4**, 193.
Langer, G. E., Kraft, R. P., and Anderson, K. S. 1974, *Ap. J.*, **189**, 509.
Papousek, J. 1972, *Contr. Astr. Inst. Univ. Brno*, **2**, No. 18.
Ulrich, R. K. 1974, *Ap. J.*, **192**, 507.
Wentzel, W., and Fürtig, W. 1971, *Mitt. Veröff. Sterne*, **5**, 165.

J. DONALD FERNIE: David Dunlap Observatory, Richmond Hill, Ontario L4C 4Y6, Canada