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The Semiregular Variable FS Comae—Evidence for Radial Oscillations

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ABSTRACT. We present newly obtained radial-velocity measurements of the semiregular variable FS Comae, together with available photoelectric data and visual brightness estimates. Both the light variations in the V band and the radial velocities show a similar periodicity of about 55 days, with a phase lag of approximately 40 days between the two. These observations strongly suggest radial pulsation as the mechanism driving the variations. There is evidence that both the photometric period and the spectroscopic period are variable over long time scales.

1. INTRODUCTION

A systematic search for periodic low-amplitude radial-velocity variations in a sample of late-type main-sequence stars has been in progress for more than six years at the Center for Astrophysics (Mazeh et al., in preparation). During this survey, it was noticed that one of the comparison stars, HD 113866 ($\alpha = 13^h06^m23^s$, $\delta = +22°37'.0$, J2000), displayed a slightly larger scatter around the mean value of the radial velocity than was expected from observational errors. As we continued to monitor this bright object ($V \simeq 5.6$) to investigate the nature of the scatter, we learned that it is a photometric variable known as FS Comae (also 40 Com=HR 4949 =Gls 499.1=SAO 82651). The *General Catalogue of Variable Stars* (Kholopov 1985) classifies it as a semiregular variable (SRb), with light variations exhibiting a total amplitude of 0.8 mag in the visual band (from 5.3 to 6.1) and a period of approximately 58 days. Percy et al. (1992) report on an unpublished study refining this value to 55.64 ± 0.17 days. As most variables of this class, FS Com is a late-type giant (spectral classification M4.8 III, according to Kenyon and Fernández-Castro 1987).

Semiregular variables are actually quite numerous in our Galaxy: more than 3300 of different subtypes are known (Kholopov 1985). They are typically intermediate and late-type giants or supergiants characterized by small-amplitude light variations generally not exceeding one or two magnitudes. The amplitude of the light curve is, by definition, the main difference between the semiregulars and the Mira variables, which usually vary by 5 mag or more in the visual band. The periodicity in the semiregular variables is not always well expressed, and can be at times replaced by intervals of irregular variation or even light constancy. Mean cycle lengths range from about 20 days to 2000 days. A typical case which is quite similar to FS Com was presented by Percy et al. (1989), who carried out a detailed photometric investigation of the semiregular variable EU Delphini. These are stars in an advanced stage of evolution, and are located in a region of the HR diagram where a large fraction of the objects seem to be variable. Comprehensive studies of the observational characteristics and evolutionary status of the semiregular variables have recently been published by Kerschbaum and Hron (1992), and also Jura and Kleinmann (1992).

As with the Miras, pulsational instability is believed to be the reason for light changes in the semiregular variables, and radial-velocity variations are also to be expected (e.g., Cox 1980), but have rarely been observed, probably due to their much lower amplitudes (Querci 1986, Querci et al. 1992). One such example, the bright M giant γ Crucis, was recently reported by Murdoch et al. (1992).

In this paper we report our radial-velocity measurements for FS Comae and we discuss also the available photometric observations which, together with the spectroscopic data, suggest that the star is undergoing radial oscillations, as is frequently the case for red giants.

2. OBSERVATIONS

2.1 Radial Velocities

FS Com has been monitored for five years with the Cassegrain echelle spectrographs operated by the Center for Astrophysics, mostly using the 1.5-m Wyeth Reflector at the Oak Ridge Observatory in Harvard, Massachusetts, and the 1.5-m Tillinghast Reflector at the Whipple Observatory on Mt. Hopkins, Arizona. At a reciprocal dispersion of approximately 2 Å mm^{-1} the spectral window is about 45 Å wide, and is centered at a wavelength of 5187

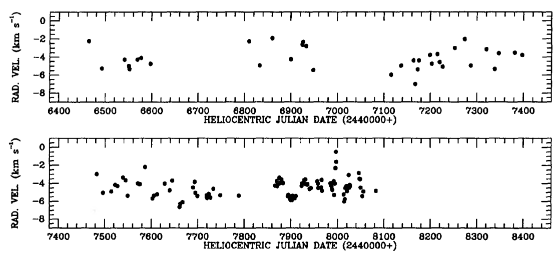

FIG. 1—Radial-velocity measurements of FS Com.

Å. The detector is a photon-counting Reticon, and the radial velocities for our star were obtained by digital cross correlation against a standard template used for late-type stars (Latham 1985; 1992). The zero point was monitored each night by taking exposures of the dusk and dawn sky; typical errors for a single measurement are 0.4–0.5 km s^{-1}.

We have accumulated 135 observations of this star covering the period 1986–1990 (Fig. 1). The heliocentric Julian dates and heliocentric velocities in km s^{-1} are listed in Table 1. Measurements have been more intensive during the latter part of 1989 and 1990, and the standard deviation of all the observations around the mean is 1.1 km s^{-1}, about twice the value expected from instrumental errors.

TABLE 1
Radial-Velocity Observations of FS Com

HJD	RV	HJD	RV	HJD	RV
2446464.83	-2.23	2447585.87	-2.20	2447923.89	-4.00
6492.85	-5.25	7602.73	-5.67	7928.77	-3.61
6541.60	-4.30	7605.66	-5.38	7930.80	-3.53
6550.71	-4.99	7612.67	-5.19	7931.83	-4.09
6552.79	-5.32	7628.63	-3.99	7934.85	-4.14
6569.65	-4.29	7639.68	-4.77	7935.85	-4.08
6577.61	-4.10	7644.61	-3.70	7939.88	-4.61
6597.70	-4.76	7660.71	-6.64	7942.87	-4.51
6809.94	-2.26	7661.71	-6.31	7956.87	-3.78
6832.86	-4.93	7667.72	-6.08	7957.95	-4.01
6859.91	-1.92	7689.72	-4.42	7958.97	-4.51
6899.81	-4.27	7692.81	-3.82	7964.94	-4.45
6924.69	-2.67	7694.67	-5.03	7965.92	-3.61
6926.56	-2.32	7699.76	-5.43	7966.86	-4.80
6932.57	-2.79	7719.60	-5.54	7984.77	-3.97
6948.69	-5.45	7719.63	-5.34	7985.80	-4.25
7115.93	-5.97	7720.63	-5.63	7987.80	-4.42
7136.88	-4.97	7721.66	-5.39	7988.93	-4.73
7163.87	-4.39	7723.57	-5.18	7991.74	-3.76
7166.96	-7.01	7727.58	-5.57	7992.81	-5.29
7172.78	-5.36	7733.55	-4.60	7993.82	-4.00
7174.94	-4.39	7748.53	-5.30	7994.78	-2.30
7198.78	-3.79	7788.58	-5.37	7995.75	-2.30
7202.92	-4.78	7865.96	-4.25	7996.77	-0.51
7214.84	-3.68	7868.89	-4.21	7997.72	-1.62
7219.79	-4.58	7869.94	-3.74	8013.69	-5.21
7226.83	-5.09	7870.97	-4.28	8014.73	-6.01
7251.75	-3.02	7872.91	-4.06	8015.74	-5.79
7273.76	-2.03	7874.91	-3.35	8016.66	-4.51
7286.71	-4.97	7875.91	-3.95	8017.88	-4.40
7319.71	-3.14	7878.88	-3.88	8018.75	-4.30
7338.62	-5.34	7879.88	-3.55	8019.75	-4.32
7346.60	-3.60	7882.94	-3.92	8020.74	-4.85
7380.55	-3.53	7893.95	-5.44	8023.79	-3.09
7396.51	-3.81	7894.88	-5.28	8024.67	-4.49
7481.92	-2.97	7895.88	-5.40	8025.74	-4.20
7495.92	-5.03	7898.85	-5.78	8026.67	-4.32
7513.96	-4.90	7899.91	-5.86	8045.64	-2.85
7521.96	-4.17	7900.87	-5.57	8046.65	-3.50
7526.95	-4.28	7902.88	-5.86	8047.72	-3.52
7538.97	-3.36	7903.85	-5.39	8048.66	-3.52
7544.78	-3.65	7904.84	-5.53	8049.63	-4.48
7548.89	-5.37	7908.85	-5.62	8053.63	-5.43
7570.95	-3.97	7910.89	-5.43	8055.63	-4.89
2447574.87	-4.08	2447922.80	-4.27	2448082.66	-4.84

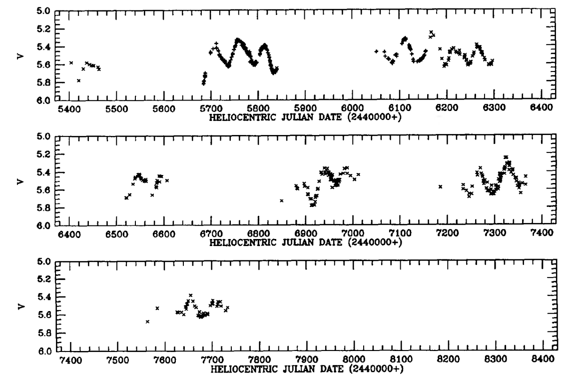

FIG. 2—Photoelectric observations of FS Com. Plus signs are APT observations and crosses are data from the AAVSO Photoelectric Program. Both are placed on the same absolute scale by adopting $V=5.94$ for the comparison star.

2.2 Photometry

FS Com has been known as a photometric variable for many decades. It was suspected to be variable by Müller and Kempf (1907), and also stated to be variable in the Henry Draper Catalogue (Cannon 1920). The semiregular character of the variation was first noted by Ljunggren and Oja (1964), who estimated a period of 58 days. These authors also noted that the star is bluer at minimum brightness.

More recently, photoelectric observations in the U, B, and V bands collected with the Automatic Photoelectric Telescope (APT) at Fairborn Observatory West in Arizona were reported by Boyd et al. (1990), and made available to us by Doug Hall. These are differential observations obtained mostly during 1984 and 1985, with average internal errors of about 0.005 mag (Hall et al. 1986). FS Com has also been observed as part of the Photoelectric Observing Program of the American Association of Variable Star Observers (AAVSO); this program provides photoelectric measurements made by amateurs with small telescopes in backyard observatories, with an estimated accuracy of 0.008 mag (Mattei 1992). These observations are only made in the V band, but they cover a longer period of time (1983–1989); they are also differential, and since the comparison star is the same one used in the APT observations, they can be easily placed on the same magnitude system. Combining these two sources there are a total of nearly 530 observations in the V band spread over a period of seven years (see Fig. 2), as well as $\sim$240 measurements of the $U-B$ and $B-V$ color indices made during 1984 and 1985.

Also available are the visual estimates of the brightness of FS Com collected through the regular AAVSO observing program, which were made by many different observers and are probably only accurate to about 0.2 or 0.3 mag. Although these data are admittedly of lower precision, the relatively large number of observations($\sim$470) and espe-

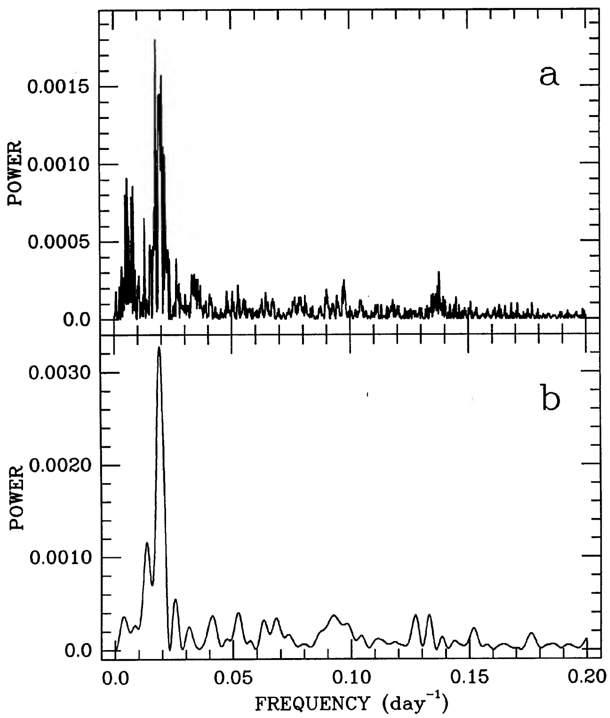

FIG. 3—Power spectra of the photoelectric observations: (a) entire data set (1983–1989); (b) 1985 season only.

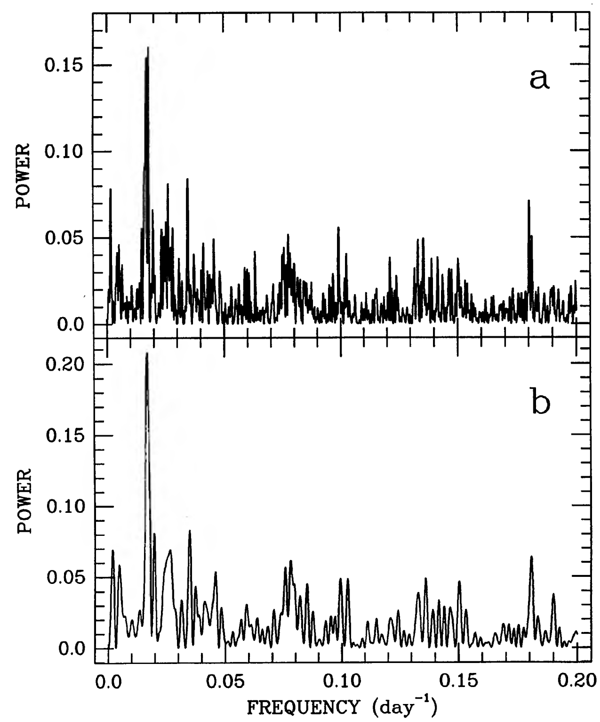

FIG. 4—Power spectra of the radial-velocity measurements: (a) entire data set (1986–1990); (b) restricted to the interval 1989–1990.

cially the longer time coverage (1971–1989) made us consider using it, for the information that may be contained on long-term photometric variations.

3. ANALYSIS OF THE OBSERVATIONS

As seen in Fig. 2, the light curve for FS Com clearly displays more or less cyclic variations with some irregularities that are characteristic of semiregular variables. The period, or perhaps more properly the "cycle length," is seen to lie between 50 and 60 days, but changes from cycle to cycle. The amplitude of the light curve also changes from about 0.2 to 0.4 mag, with a maximum variation of 0.55 mag over the seven-year interval covered by the photoelectric observations.

3.1 Period Analysis

In order to study the recurring character of the light curve and also of the radial-velocity modulations in a more systematic way, we begin by presenting in Fig. 3 (top panel) the power spectrum of the photoelectric data, computed as described by Mazeh et al. (1992). There is significant power at frequencies near 0.018 day^{-1} (corresponding to a period of roughly 55 days), although we note that the power is not concentrated at a single frequency. We have analyzed the effect of the window function (seasonal gaps in the photometry) by generating artificial data sets consisting of pure sinusoidal modulations imposed on the actual times of observation, and then computing the corresponding power spectra; by comparing these with that of the real data, we find that most of the structure in Fig. 3(a) is real. The appearance of the power spectrum changes considerably, however, when the observations are restricted to a shorter time interval, as shown in Fig. 3(b), which corresponds to the 1985 season alone. The structure near the main peak has largely disappeared.

A very similar situation is displayed in Fig. 4, this time corresponding to the radial-velocity measurements. The top panel shows the power spectrum of the entire data set. There is significant power at approximately the same frequencies as in Fig. 3(a), with some structure which is not due to the window function. This would seem to point toward a common underlying phenomenon causing the light variations as well as the radial-velocity changes. Once again, considering a shorter time interval reduces the structure and produces a much cleaner power spectrum, shown in the bottom panel [Fig. 4(b)], in this case for the 1989–1990 observations only.

The previous two figures strongly suggest that the mechanism causing the light variations and radial-velocity variations in FS Com is not strictly periodic over long time intervals, but is coherent only over periods of one or two years.

In Fig. 5(a) we show the power spectrum of the AAVSO visual brightness estimates. As opposed to what was found for the photoelectric observations and for the radial velocities, the visual data taken all together do not display any significant power at frequencies near 0.018 day^{-1}; instead, two very significant peaks appear at very low frequencies, corresponding to longer periods.

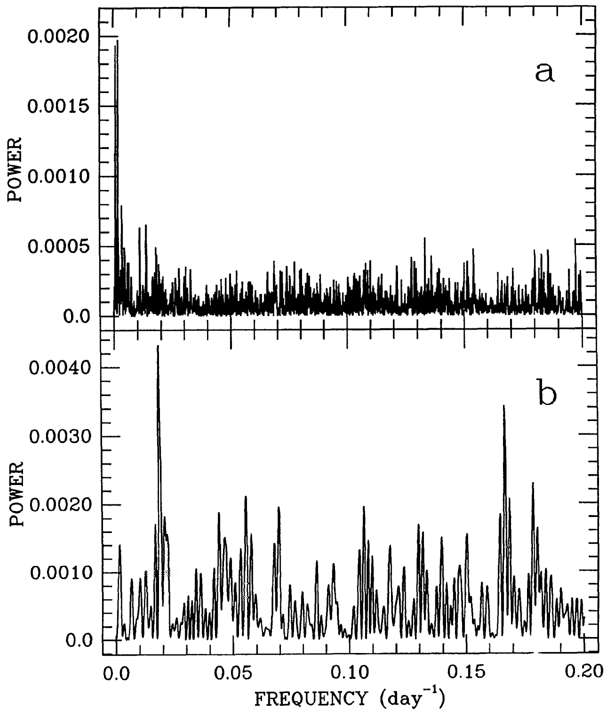

FIG. 5—Power spectra of the AAVSO visual brightness estimates: (a) entire data set (1971–1989); (b) restricted to the interval 1985–1986.

Whereas the radial-velocity measurements and the photoelectric data cover time intervals of five and seven years, respectively, the visual observations are spread over a much longer interval of 19 years. Since the main periodicity seems to be rather unstable, this long time span in the visual data has evidently smeared out any peaks at this frequency in the power spectrum. To illustrate this, we have again restricted the time interval to only two years (1985–1986), and plotted the resulting power spectrum in Fig. 5(b). A single peak at a period of about 55 days reappears, lending further support to the conclusion that the cycle length changes significantly over time scales longer than a few years. Different intervals of time in the visual data do not always show this periodicity as clearly, which may be another sign that it is changing.

To test this hypothesis we have divided the photoelectric data and the radial-velocity measurements into one-year subsets, and fitted sine curves separately in each group to derive average cycle lengths. A sine curve is admittedly not the appropriate model for the light curve (even over short time scales) since it will not reproduce the irregularities apparent in Fig. 2, but it does provide a useful estimate of the typical "period" over the interval considered. For the photoelectric data we excluded the 1983 observations, which are too sparse to be useful, and analyzed each of the seasons from 1984 to 1989 separately. For the spectroscopic data we considered the 1988, 1989, and 1990 subsets, and excluded 1986 and 1987 for the same reason as above.

The cycle lengths derived in this way are shown in Fig.

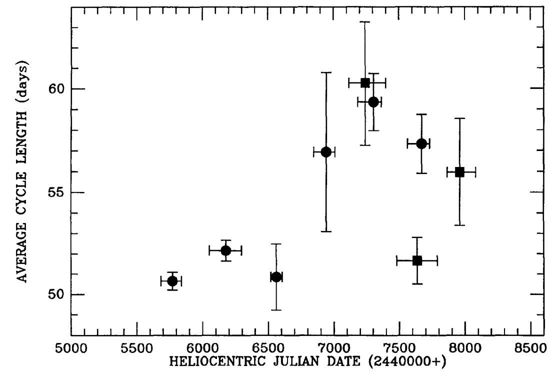

FIG. 6—Average cycle length as a function of time, from sine curve fits to restricted intervals of time. Circles represent photometric determinations, and squares correspond to estimates from the radial-velocity data. Horizontal error bars indicate the range in time considered for each separate fit, and the vertical bars correspond to formal 1σ errors from the χ^2 fits (see text).

6, where filled circles indicate photometric estimates and the squares are the spectroscopic estimates. The time intervals spanned by the observations in each group are indicated by the horizontal error bars. Meaningful uncertainties for the cycle lengths are difficult to determine in this case because the star behaves somewhat irregularly even on a time scale of one year, and therefore does not quite conform to the simple model we have adopted. Formal 1σ errors from the χ^2 fits using the observational uncertainties given in Secs. 2.1 and 2.2 are unrealistically small. For the purpose of providing a more useful indication, we have adopted instead the rms residual from each of the χ^2 fits as the measurement uncertainty, which therefore includes the deviations from the model. While we do not claim any statistical rigor in this approach (see e.g., Press et al. 1989, Chap. 14), the error estimates for the cycle lengths computed in this way seem more reasonable, and are represented in the figure by the vertical error bars. Figure 6 suggests there are significant variations in the cycle length of FS Com from one season to the next, confirming the impression given by the power spectrum analysis above.

Two other periodicities are indicated in the power spectrum of the visual data [Fig. 5(a)], corresponding to periods of roughly 530 and 1150 days. These are not seen, however, in the available photoelectric photometry, and only the shortest of the two is marginally present in the radial-velocity measurements. In Figure 7 we show the AAVSO visual data folded with each of these two periods and binned. The error bars are mean errors in each bin. The total amplitudes of these tentative light variations are seen to be a little under two tenths of a magnitude. We note that the 530 day period was found independently by Percy et al. (1992) through an autocorrelation analysis; these authors also find evidence for periodicities of 170 and 920 days, which do not appear to be present in our data.

3.2 Correlation Analysis

To gain further insight into the nature of the variations described in the preceding section, we have investigated the

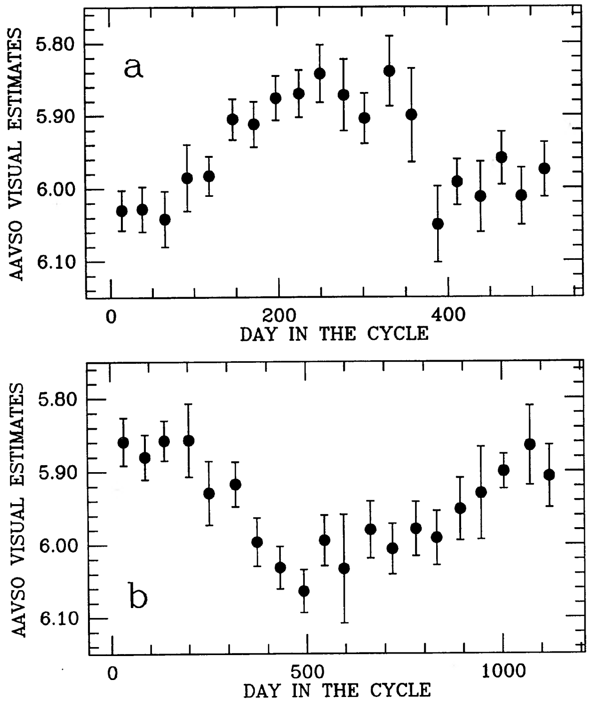

FIG. 7—AAVSO visual data folded with two different periods suggested by Fig. 5(a), and binned; error bars represent mean errors in each bin. (a) Folded with a period of 530 days; (b) Folded with a period of 1150 days.

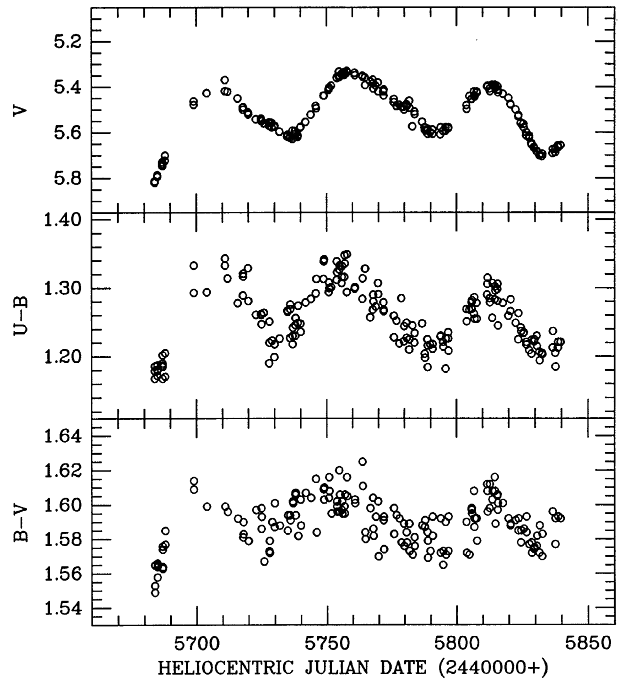

FIG. 9—Variations in V, $U-B$, and $B-V$ during 1984. The color indices are seen to vary in phase with the light curve, so that the star appears bluer at minimum brightness.

extent to which the light changes are correlated with the radial-velocity changes by performing a cross-correlation analysis of the two data sets (Mazeh et al., in preparation). The result is shown in Fig. 8. The two modulations are clearly correlated, and the phase difference is such that the radial-velocity maximum occurs approximately 40 days before maximum magnitude (minimum brightness), as indicated by the position of the first peak in the figure. This peak repeats itself at intervals of 50–60 days, again corresponding to the main cycle length in the data.

It is also interesting to point out that the light variations and color variations ($U-B$ and $B-V$) are strongly correlated in the sense that the star is redder at maximum brightness. This can be seen directly from the data with no need for a more sophisticated analysis, as illustrated in Fig. 9. The amplitude of the $U-B$ curve is seen to be about a factor of three or four larger than the variations in $B-V$.

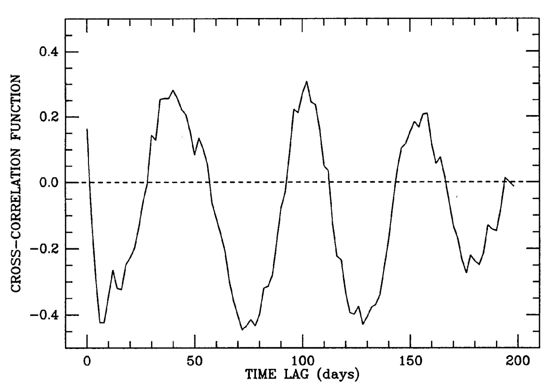

FIG. 8—Cross correlation of the radial-velocity data against the photoelectric observations of FS Com. The phase difference is seen to be approximately 40 days, as indicated by the position of the first peak.

4. DISCUSSION

One of the main observational features in FS Com displayed by the photometric material at hand is the quasi-periodic nature of the brightness changes and of the color changes. The spectroscopic measurements reported here reveal radial-velocity variations for the first time, with a total amplitude of about 2 km s^{-1} and essentially the same period. These variations are also found to be somewhat irregular, as shown in the previous section. This supports the idea that the star is undergoing radial oscillations, a phenomenon that is quite common among late-type giants.

The fact that the light changes and the radial-velocity changes are correlated with each other is an important additional piece of information. The phase difference we determine indicates that the radial velocities peak about 40 days before light minimum, and this pattern is maintained throughout the entire time series. We note in passing that this phase lag is in excellent agreement with the simple-minded model of radial pulsation in which the star is at its maximum brightness at the state of maximum contraction. In this case, and if the variation is sinusoidal, the peak in the radial-velocity curve is expected to occur 0.75 cycle before minimum light, or about 41 days for a mean cycle length of 55 days, just as observed.

As is the case for other late-type variables, the color curves for FS Com are reversed, that is, the star appears bluer when it is at minimum brightness, contrary to what is expected from pure thermal variations driven by pulsation. This is known to be the effect of atmospheric molecular condensation of (mainly) titanium oxide, which changes considerably over one cycle following the temperature variations. It affects the B band and especially the V band, but not the ultraviolet, so that as the star expands and cools molecular absorption increases dramatically, making the star appear bluer. In fact, one of the bands of the α system of TiO with a bandhead at $\sim$5167 Å occupies the entire spectral window in our echelle observations. Thus, the observed $U-B$ and $B-V$ colors in this star are molecular absorption indices, rather than temperature indicators.

The photometric properties of late-type giants, and in particular, variable red giants, have been well studied by various authors (e.g., Smak 1964; Celis 1978, 1982). Through an empirical approach it is possible to disentangle the effect of differential TiO absorption upon the color indices from that of direct temperature variations (Smak 1964). In addition, the effect of the change in surface area in FS Com under the assumption of radial oscillations can be computed, since the change in absolute radius can be determined directly from the radial-velocity data. We estimate the change in radius over one cycle to be $3R_\odot$, from a total observed amplitude of 2 km s^{-1}, a projection and limb-darkening factor of 1.37, and an average period of 55 days. Using this information, we have tested a very simple model to see whether the observed amplitudes in V ($\approx$0.30, cf. Fig. 9) and in $U-B$ and $B-V$ (approximately 0.12 and 0.03) are consistent with the idea of the star alternately expanding and contracting. The model takes into account the geometric effect plus the empirical TiO corrections by Smak (1964), reanalyzed to incorporate an improved effective temperature scale (Ridgway et al. 1980), and restricted to the semiregular variables. Brightness and color changes along the cycle are assumed to follow those of a blackbody. We find that we can obtain values for the V amplitude and color changes in reasonably good correspondence with the observations, for a total temperature change of the order of 50–100 K and an adopted effective temperature of 3450 K, derived from the spectral type (M4.8 III). The results are only mildly dependent on the mean radius of the star, as long as it is a giant. The idea of radial pulsation seems reinforced by this consistency check, which even accounts for the observed $U-B$ and $B-V$ color reversal in FS Com.

While there is a fair amount of evidence that the $\sim$55-day cycle is produced by radial oscillations, the nature of the longer 530- and 1150-day periods detected in the observations is unclear. If these variations are confirmed (as appears to be the case for the shortest of the two), several mechanisms such as nonradial oscillations, modulation by giant convective cells, or rotational modulation by surface features could be considered as plausible explanations. We note that the presence of a longer secondary periodicity is not at all uncommon in semiregular variables. In fact, it was discovered several decades ago that the ratio P_2/P_1 is roughly the same for all long-period variables of a given spectral type (Gaposchkin 1954, Houk 1963, see also Wood 1981). These statistical studies indicate that M-type variables cluster around a ratio of $P_2/P_1 \approx 10$, which is incidently the same value shown by FS Com in regard to the 530 and 55 day cycles.

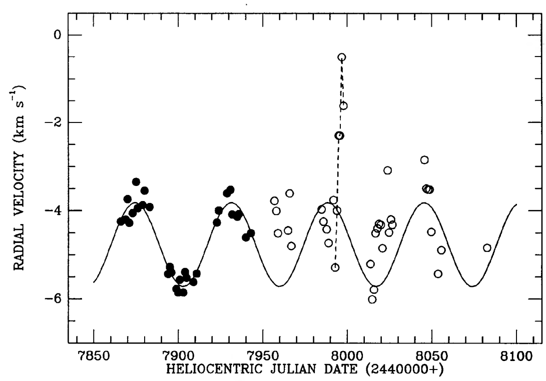

FIG. 10—Radial-velocity measurements for the interval December 1989–July 1990. The sine curve is a fit to the data for the first three months (represented by filled circles), extrapolated forward for reference. Subsequent observations (open circles) are out of phase, and the dashed line indicates a collapse suffered by the star in April 1990.

From the observed radial-velocity and light curves we obtain a ratio of light (V) to velocity amplitude for the $\sim$55-day period of about 0.15 ($\Delta V \approx 0.3$, $\Delta RV \approx 2$ km s^{-1}), and approximately the same ratio for the 530-day period ($\Delta V \approx 0.15$, $\Delta RV \approx 1$ km s^{-1}).

4.1 FS Com during 1990

Our intensive spectroscopic observations of FS Com during the latter part of 1989 and beginning of 1990 allow the radial-velocity variations to be seen clearly, with no need for a power spectrum analysis. Figure 10 shows a plot of the data, where the first three months are represented in filled circles and are observed to display quite regular oscillations. Solely for the purpose of providing a reference, a sine curve was fit to this data and extrapolated forward. The radial velocities for March 1990 are apparently out of phase with the previous data, and in April the star suffered a collapse, as evidenced by the sharp increase in the radial velocity. The contraction rate increased roughly by a factor of five compared to average, reducing the radius from its mean value by 1.5 $R_\odot$ in about four days. After this, the star appears to have resumed its normal oscillations, perhaps with a slightly larger radial-velocity amplitude, at least for the following cycle. This episode is just another example of the kind of irregularities that occur in stars of this class. Due to their relatively low amplitude and unpredictable nature, it is likely that many such events are missed in other similar stars, emphasizing the need for continuous monitoring of both the radial velocities and the light curves in semiregular and irregular variables.

5. CONCLUSIONS

We have presented an analysis of the photoelectric data and the visual observations available for FS Com which clearly show the quasiperiodic character of the light variations in the visual band as well as $U-B$ and $B-V$ color changes in this semiregular late-type variable star. Our newly reported spectroscopic observations also display a modulation in the radial velocities with a total amplitude of only 2 km s^{-1} and a similar cycle length of approximately 55 days. These observations suggest radial pulsation as the most likely explanation for this star. The constant phase difference between the radial-velocity variations and the brightness changes supports this idea, and in this case is such that the radial velocity is at its maximum value about 40 days before the star is faintest.

No doubt many of the details about the processes taking place in this star are not yet known, as is the case with most other semiregular and irregular variables of low amplitude, and further progress towards an understanding of the nature of the variability would greatly benefit from long-term simultaneous radial-velocity and photometric observing programs. Photoelectric monitoring of these relatively bright stars is ideally suited to backyard telescopes such as those used to obtain the AAVSO photoelectric photometry, as well as to remotely accessed robotic telescopes of the kind that provided some of the observations used here.

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