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THE PHOTOMETRIC VARIABILITY OF SOLAR-TYPE STARS.
V. THE STANDARD STARS 10 AND 11 LEONIS MINORIS

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ABSTRACT

Light curves in Strömgren *b* and *y* for the 1985 season are presented for the *uvby* standard stars 10 LMi (HD 82635) and 11 LMi (HD 82885). The period of 10 LMi is 40.4 days, with an amplitude of 0.012 magnitude in *y*. The period of 11 LMi is 18.0 days, with an amplitude of 0.033 magnitude in *y*. The mechanism of the variability is interpreted as rotational modulation due to active regions on the stars. Observations of 11 LMi as a standard suggest the star was only weakly variable or constant during the interval from 1972 to 1984.

Key words: stellar rotation–photometric variability–solar-type stars–standard stars

I. Introduction

As part of a long-term study of activity on solar-type stars, we are making high-precision differential photoelectric measures of a representative sample of stars from Olin Wilson's (1978) classic survey of Ca II H + K emission. The purpose of these observations is to test for the presence of short-term rotational continuum brightness modulation, as well as long-term changes in mean brightness and activity level correlated with stellar cycles analogous to the solar sunspot cycle.

Included on our program are the Strömgren-Crawford four-color standard stars 10 Leonis Minoris (HD 82635 = HR 3800, V = 4.55, G8.5 III) and 11 Leonis Minoris (HD 82885 = HR 3815, V = 5.41, G8 IV–V) along with comparison stars 13 Leonis Minoris (HD 83591 = HR 3857, V = 6.14, F3 V) and HD 83525 (SAO 61620, V = 6.9: F5(HD)).

Both program stars have long observational histories, being among photometric standards on several systems and having been studied via narrow-band photometry, spectrophotometry, and polarimetry (see Cayrel *et al.* 1977, *et seq.*). Particularly germane to the present study is their inclusion in Wilson's (1978, 1982) surveys of chromospheric emission. 11 LMi was included in his decade-long survey of 91 solar-type stars. The chromospheric emission as measured by the flux from the cores of the Ca II H + K lines was about double that of the quiet Sun during the period of the survey. These measures showed nightly and year-to-year variations, indicative of both rotational and stellar-cycle variability. Though observed only twice by Wilson (1982) in a quick-look survey of late-type giants, the Ca II flux of 10 LMi was similar to that of 11 LMi and among the highest in a sample of 200 such stars. 10 LMi is included in a list of suspected variables by Fekel and Hall (1985), presumably only on the basis of its high chromospheric emission level, as no other information is given by them. Neither star has been suspected of variability based on photoelectric observations.

Chromospheric emission at similar levels is observed in solar-type stars of the Hyades (Duncan *et al.* 1984), many of which also show continuum rotational variability (Lockwood *et al.* 1984, Paper IV). Stars monitored in the Hyades program have been observed to change the character of their variability, becoming more or less active from year to year, or even during the course of one observing season. Photometric observations of the same kinds of stars in the general field are thus of interest.

II. Observations

Observations of the 10/11 LMi group stars are being made with the Lowell 53-cm photometric telescope in the *b* and *y* passbands of the Strömgren system. The two comparison stars are being observed with the same frequency as the program stars. The observing procedure is identical to that used for the concomitant survey of Hyades stars (Paper IV). Briefly, a single nightly observation of the quartet consists of two cycles of measurement in each color, the measurements being the mean of six 10-second integrations on "star" compensated by the mean of two integrations on "sky." The procedure takes about 35 minutes to complete.

III. Period Analysis

Measures made during the 1984 observing season (eleven nights) indicated that both 10 and 11 LMi were variable. The morphology of the differential "light curves" suggested that 13 LMi might also vary; consequently, HD 83525 was added to the group for the 1985 season.

Observations during this second year were made on 28 nights over the interval 1984 December 30 to 1985 May 11 (UT). The data points were sufficiently numerous that approximate periods could be estimated by eye from the light curves.

For each of the four light curves for each star (one with respect to the two comparison stars in each color) a period was found by making a series of least-squares cosine fits on the data string evaluated by chi-squared analysis. Periods were tested in 0.1-day increments bracketing the value estimated from the raw light curves; the paucity of data does not justify analysis at higher temporal resolution. We did, however, check for the presence of a double wave in the data.

IV. Discussion

Statistical properties of the complete data set are summarized in Table I. Note that the differential magnitude of the two comparison stars (last column) was constant in both colors during the observing season to about 2.5 millimagnitudes (mmag).

The small amplitude of 10 LMi made period determination less certain than for 11 LMi, yet the total range of periods found in the four light curves was less than 1% of the mean. A representative light curve is shown in Figure 1a, which gives the data for 10 LMi minus 13 LMi in the y filter phased by a period of 40.4 days. Three complete cycles of the apparently smooth sinusoidal light curve are present in the data set. Light curves for the b filter are similar except that the amplitude is about 3 mmag greater. A similarly phased $(b-y)$ color-index curve for the same pair is shown in Figure 1b. An analysis of variance on the color curve was made on points centered on phases 0.0 and 1.0 against those centered on phase 0.5. The difference is significant at greater than the 99.9% level. The curve exhibits minimum $(b-y)$ at zero phase and a maximum at phase 0.5, anticorrelated with the light curve, and places limits on the size and temperature of starspots expected to cause the variability. Comparison of the 1984 and 1985 measures shows that the star became less active in 1985 and brightened by 4 mmag in y (Table I), in accordance with expectations based on our experience with stars whose activity changes.

A representative light curve for 11 LMi is shown in Figure 2a, which is for the pair 11 LMi minus HD 83525 in the y filter phased for a period of 18.0 days. This compares favorably with the rotational period of 18.1 days derived by Noyes *et al.* (1984) from chromospheric emission measurements. Again the amplitude in b is greater, by 4 mmag in this case. The color curve for the pair is shown in Figure 2b. The light curve here is distinctly nonsinusoidal, accounting for the larger residual in the cosine fit (see Table I). The curve exhibits a relatively rapid rise and more gradual decline after maximum. A simple starspot model to account for this would posit a starspot group of approximately triangular outline whose pointed end (containing smaller spots) leads in the sense of rotation. As the active region spins onto the visible surface, there is a gradual decline in brightness; the return to "normal" brightness is more rapid since the larger trailing spot(s) will be last to pass off the disk. Since the inclination of the star to our line of sight is unknown, the latitude and longitude of the spots cannot be uniquely determined. The light curve can be equally well modeled, for instance, by a pair of spots at high latitude on a

TABLE I

Summary of Differential Observations

			10 LMi minus		11 LMi minus		13 LMi minus
			13 LMi	HD 83525	13 LMi	HD 83525	HD 83525
Mean delta m (mag.)	1984	(y)	-1.5808	-	-0.7359	-	-
		(b)	-1.2952	-	-0.5266	-	-
	1985	(y)	-1.5849	-2.3601	-0.7269	-1.5020	-0.7748
		(b)	-1.3002	-2.1483	-0.5169	-1.3650	-0.8481
Std. dev. (mag.)	1984	(y)	0.0090	-	0.0060	-	-
		(b)	0.0101	-	0.0065	-	-
	1985	(y)	0.0047	0.0050	0.0120	0.0124	0.0026
		(b)	0.0060	0.0052	0.0138	0.0135	0.0023
Period (days)			40.4±0.2(σ)		18.0±0.1(σ)		
Epoch (JD) of maximum			2446032.8		2446009.1		
Amplitude (mag.)		(y)	0.0116		0.0325		
		(b)	0.0148		0.0365		
		(b-y)	0.0032		0.0040		
Mean residual of cosine fit (mag.)		(y)	0.0020		0.0038		
		(b)	0.0018		0.0040		
		(b-y)	0.0023		0.0023		

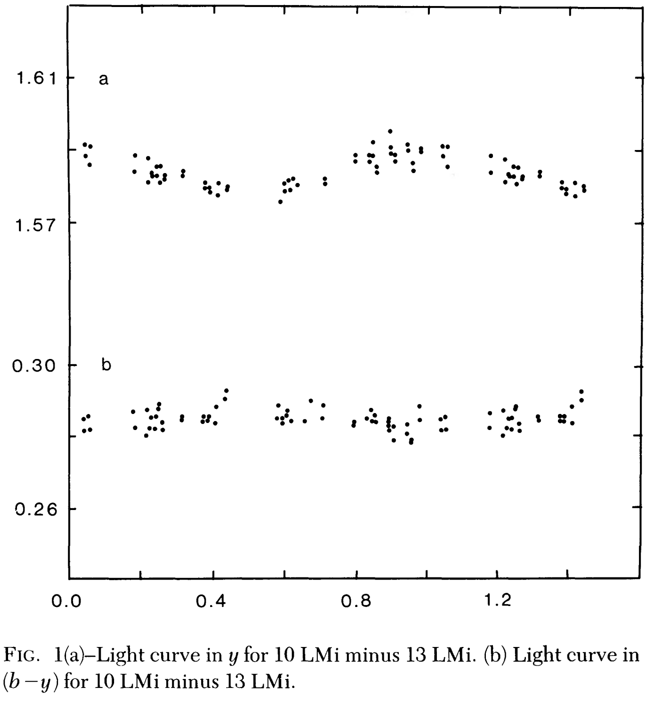

FIG. 1(a)–Light curve in y for 10 LMi minus 13 LMi. (b) Light curve in $(b-y)$ for 10 LMi minus 13 LMi.

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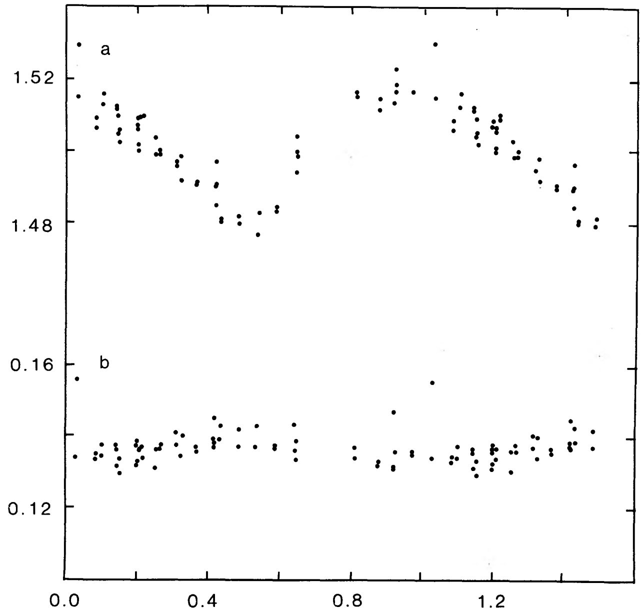

FIG. 2(a)–Light curve in y for 11 LMi minus HD 83525. (b) Light curve in $(b-y)$ for 11 LMi minus HD 83525.

star of moderate inclination. In any case, the continuously variable light of the star implies that spots are always present on the Earth-facing hemisphere.

Using a nominal effective temperature of 5000 K for 11 LMi and the observed amplitudes of 0.033 ± 0.004 mag in y and 0.004 ± 0.002 mag in $(b-y)$, we have made some elementary calculations to constrain the spot area and temperature responsible for the light curve. Limb darkening and geometrical factors have been ignored in this effort to account simply for the observed amplitudes. The error box centers on a 4500 K spot covering 7% of the visible hemisphere, but it includes a 4000 K spot covering 4% of the visible hemisphere. Warmer spots (i.e., less than 500 K cooler than the photosphere) are included within the formal errors; but, if present, they must cover an increasingly large (> 15%) fraction of the surface.

11 LMi has been extensively observed for over 30 years at Lowell Observatory as both a zero-point and extinction star on both the *UBV* and *uvby* systems with the same telescope used for the present work (Johnson and Iriarte 1959; Serkowski 1961; Jerzykiewicz and Serkowski 1966; and Lockwood and Thompson, unpublished extinction measures 1972–85, continuing). From analysis of the early (1951–66) *UBV* measures, we conclude that random errors in the data mask any low-level intrinsic variability that may have been present.

Table II gives a summary of the four-color y measures of 11 LMi made for zero-point and extinction determinations since 1972 in a program conducted by Lockwood and Thompson. Importantly, the same EMI 6256S photomultiplier and filters have been used for all these observations (including the present differential series), though the data-recording equipment has changed. These observations were always made together with at least five (usually more) other standard stars, so variations in 11 LMi should not greatly influence the final zero-point offset on any given night. The mean air mass of the observations is about 1.8, though they are usually made at very low (~ 1.0) or very high (~ 2.3) air mass. Seasonal mean y (reduced to the standard system) is listed along with the number of measures and the standard deviation for the mean. The means are plotted in Figure 3; the error bars represent the size of the 95% confidence interval. This interval is large for the 1985 season not only because of the relatively small number of measures, but also because σ is large as a result of the star's variability. Nevertheless, the drop during the 1985 season is obvious, amounting to 14 mmag from the mean of the previous 13 years. The independent differential measures (11 LMi minus 13 LMi) between 1984 and 1985 show a drop of 9 mmag. Similar data for $(b-y)$ show no significant variations.

TABLE II

Summary of Observations of
11 LMi as a Standard Star

Season	n	Mean y	σ
1972	6	5.377	0.008
1973	4	5.374	0.003
1974	5	5.374	0.003
1975	6	5.374	0.011
1976	12	5.379	0.012
1977	16	5.378	0.005
1978	15	5.375	0.005
1979	10	5.373	0.004
1980	15	5.378	0.005
1981	11	5.374	0.011
1982	26	5.375	0.014
1983	20	5.378	0.006
1984	13	5.376	0.008
1985	5	5.390	0.017
	164	5.377	0.009

Using the same data set, we tested further for a correlation between mean y and σ. Other stars in the program have been observed to fade slightly (~ 0.01 mag) when they become actively variable and to brighten during

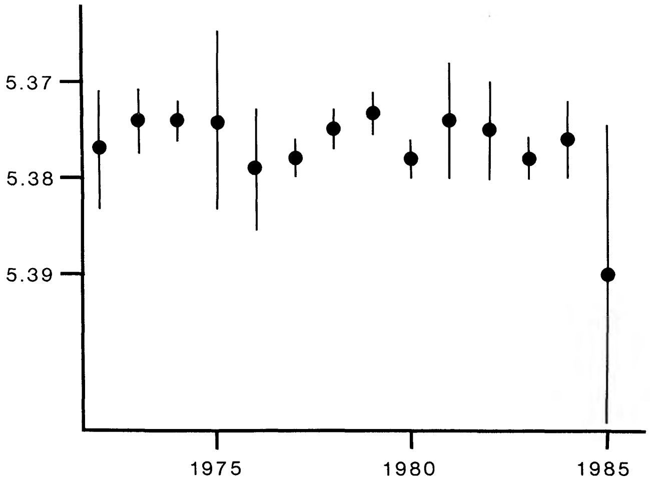

FIG. 3–Seasonal mean y magnitudes and 95% confidence intervals for 11 LMi observed as a standard star for the interval 1972 to 1985.

more stable episodes. Thus if large σ is due to variability caused by spots, then we expect $\langle y \rangle$ to be fainter, as demonstrated above. We find, however, that the years with $\sigma > 0.01$ (*viz*. 1975–76 and 1981–82) do not have $\langle y \rangle$ significantly different from the remaining years 1972 to 1984. This suggests that 11 LMi has not been observed to vary in the last 14 years because variations were very small or absent prior to 1985. Indeed, the more precise differential measures in 1984 and 1985 show that the range of variation in the star roughly doubled between the two seasons.

A more intensive set of data in the four-color system was obtained by Radick *et al.* (1983, Paper II) at Cloudcroft Observatory. They also found no variations during the period December 1978 through April 1979, though the photometric errors (about 6 mmag in b and y) were small enough to permit detection of the variations shown here, had they been present.

Like many chromospherically active stars, the character of the variability of these two stars is likely to change from year to year in both phase and amplitude. 11 LMi may be of special interest in this respect, since the H + K rotational signal (from R. W. Noyes, private communication) appears to have been in phase for a decade. Long-term monitoring of these and other such stars is recommended over a longer wavelength baseline and in spectral regions diagnostic of changes at various depths in the stellar atmosphere.

V. Conclusion

Strongly periodic variability has been observed in 10 and 11 LMi, both chromospherically active stars. The variability is consistent with being due to rotational modulation by stellar active regions. The drop in mean brightness of 11 LMi in 1985 relative to extensive measures during 1972–84, amounting to 14 mmag, suggests that periodic variability has not been detected in prior years.

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Note added in proof: Ca II data provided by Laura Woodard at Mount Wilson show a slight increase in the mean H + K flux from the 1983/84 season to 1984/85. The 18.0-day period is present in the 1984/85 data only, and the phase of Ca II maximum flux corresponds to light minimum.