SOME INSIGHTS ON SOLAR VARIABILITY FROM PRECISION STELLAR ASTRONOMICAL PHOTOMETRY

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ABSTRACT

At Lowell Observatory, precision photoelectric photometry was directed toward the study of solar variability and the variability of sun-like stars beginning in 1949 and continuing until now. The ubiquity and range of low-level variability, including some that appears to be cyclic, among solar-type stars shows that recent solar variability may be unusual only in its present restraint.

SOLAR VARIABILITY STUDIES AT LOWELL OBSERVATORY

Astronomers at Lowell Observatory have been studying solar variability for more than forty years. A 1955 report, *The Study of the Variability of Solar Energy Output from 1949 to 1954 by Differential Methods,* describes the application of photoelectric photometry to the study of solar variability. The aim of the Lowell program was to measure solar variability indirectly by comparing the brightness of reflected sunlight from the planets Uranus and Neptune with that of nearby "constant" sun-like comparison stars. By working differentially, they hoped to avoid the well-known limitations of absolute solar radiometry that had plagued Charles Abbott in his pioneering long-term studies of the solar constant. Despite the limitations of their primitive equipment, the Lowell observers produced a significant early result: the Sun was constant to 1% or better over a five-year interval (1).

A 1966 report, *The Sun as a Variable Star,* was inconclusive: changes in the brightness of Neptune, less than 3% overall from 1950 to 1966, could have been caused by changes in Neptune's atmosphere, by solar variability, or by both (2). However, there was a significant by-product resulting from repeated measurements of a small group of sun-like stars, called the "10-year standards," from 1955 to 1966:

> *...this long series of photoelectric measurements has taught us more about the variations of solar-type stars than about the Sun itself. The observations of 15 stars of spectral types F and G in the years 1955–1966 indicate that for none of these stars does the standard deviation of the yearly mean magnitudes exceed 0.008 [0.8%] and for [three stars] this deviation is less than 0.004 [0.4%]. No evidence of variability in the stars which are similar to the Sun has been detected during this program.* ***If we assume the Sun acts in similar fashion to each of these stars, its variability over a fifteen-year period probably does not exceed one-half of one percent.***

RECENT SOLAR VARIABILITY

With the 1980 spacecraft measurements of small dips in the solar "constant" corresponding to the passage of large sunspot groups across the face of the Sun, the existence of solar variability was finally established (3) and led, incorrectly, to an irradiance variability model dominated by sunspot blockage (4). As solar minimum approached, however, the total irradiance decreased by 0.1% rather than increasing as expected, showing that the excess flux from bright faculae overcomes the flux deficits in sunspots to produce a long-term irradiance variation in phase with solar activity (5).

A new model of solar irradiance variations based on the observed variability in cycle 21 estimates the variation of the Sun's output back to 1874 (6). Surprisingly, because of the unusual ratio of sunspot area to sunspot number in cycle 21, that cycle produced the largest variation in the past 100 years. However, because of the uncertainties in the model, arising especially from the short timebase of the regressions upon which it was based, secular variations as large as 1%

over the last century are not ruled out.

We will show below that if the long-term variability of solar irradiance is always as small as the 0.1% amplitude recorded over the last decade, then the Sun is unusually stable compared with its stellar age, mass, and temperature cohort.

LONG-TERM STELLAR STUDIES

a) Variations of Young Solar-Type Stars in the Hyades Open Cluster

Nearly a decade ago, we began measuring the variability of ordinary F-, G-, and K-type dwarf stars similar to the Sun. Since the precision of stellar photoelectric photometry as commonly practiced is normally no better than 1% or so, extreme care was required to do much better. Using differential methods, we routinely attained a precision of 0.2–0.3% *rms* from night to night and, depending mainly on the intrinsic stability of comparison stars, sometimes as good as 0.1% from year to year.

The first detection of variations came from measurements of young solar-type stars in the Hyades open cluster (7). With ten seasons of observation of the Hyades stars now completed, two at the Cloudcroft Observatory followed by eight at Lowell, we determined that nearly all the stars cooler than spectral type F8 are slightly variable from day to day and from year to year (8). Brightness variations, typically with amplitudes of 1% or more, result from the stars' rotation and have allowed us to determine rotation periods for 23 stars.

A comparison of the photometric time series with the near-simultaneous measurements of chromospheric emission in the Ca II H and K lines made by the Mount Wilson Observatory "HK project" showed that enhanced HK fluxes coincide with the temporary dimming of starlight caused by the disk transit of starspots. Thus, spots and active regions are associated, just like on the Sun. The amplitudes of the rotational lightcurves change from year to year, indicating evolution of the spot coverage. Larger rotational amplitudes correspond to fainter average magnitudes and vice versa. In young stars, the irradiance budget is evidently dominated by spots rather than by bright faculae.

Figure 1 shows the 10-year light curve of one of the Hyades stars, van Bueren 64, a G2 dwarf with a photometric rotation period of 8 days. This star, which is often cited as one of the best spectrophotometric solar analog stars known (9), may have a long-term cycle with an amplitude of about 3% as indicated by the smoothing spline fit to the data.

b) Luminosity Variations of Ordinary Solar-Type Stars

Olin Wilson began the renowned Mount Wilson "HK project" in 1966, using the 100-inch telescope to monitor chromospheric emission in 91 solar-type dwarf and subgiant stars. By the time he stopped observing in 1977, he had discovered stellar activity cycles reminiscent of the 11-year sunspot cycle (10). This program continued, using the 60-inch telescope, and showed nearly a decade ago that the younger stars display strong rotational modulation of the HK index indicating the presence of nonuniformly distributed active regions (11). Older, more slowly rotating stars, monitored for nearly 20 years now, tend to be fairly quiescent on rotational timescales but undergo sunlike activity cycles (12).

Since 1984 we have been monitoring the brightness variations of 33 of these "Wilson stars" using the *b* (472 nm) and *y* (551 nm) filters of the Strömgren photometric system. The goal of the photometry, as in the Lowell program a quarter century earlier, was to determine if ordinary field F-, G-, and K-type main-sequence stars, especially those of solar age, vary detectably, and if so, how that variability compares with solar irradiance variations. Parallel HK observations continue to be made at Mount Wilson.

To attain the highest possible photometric precision, the stars are observed differentially, grouped into trios and quartets containing nearby solar-type field comparison stars. Details of the methodology and complete results through the first four seasons are given in (13). The nightly *rms* dispersion of the differential magnitudes is typically 0.2–0.3%, depending mainly upon the stability of the comparison stars (whose constancy must, of course, be determined at the same time during the course of the program--a major complication). Over a single season the standard error of the mean approaches 0.1%. Thus, the observations are precise enough to show stellar variability not much larger than that observed for the Sun in cycle 21.

In the regime of photometric variation below 1%, now accessible through careful differential photometry, many stars previously thought to be stable turn out to vary slightly. As an unexpected by-product of the unusually high precision attained in this program, we have detected low-level brightness variations in several well-known photometric standard stars. Of the more than 100 F, G, and K type stars observed since 1984, including the 33 Wilson stars and their nearby comparison stars, one-third varies slightly from night to night with a median *rms* fluctuation of 0.5%. Two-thirds of the K stars are variable. Few exceed 1.0%. For individual stars, the amount of variability tends strongly to repeat consistently from season to season. There are also some--but not many--stars that are stable to 0.2% or so year after year (13).

For the program stars, the "chromospheric emission ratio," log R'_{HK}, an estimate of the fraction of the star's total luminosity originating in the chromosphere (14), turns out to be a good predictor of photometric variability as well as of chromospheric activity (13). Using log R'_{HK}, we can order the stars by increasing activity and compare the corresponding photometric and HK variations (15).

Figure 2 shows the six-year range of variation of the program stars as a function of log R'_{HK}. The Sun is plotted on this figure, using a nominal cycle amplitude of 0.1% (0.001 mag) determined by its variability in cycle 21. In the lower panel of Figure 3 we show the corresponding range of variation of the most stable pair of stars (observed differentially) in the groups whose program stars are plotted above. If the star pair containing the program pair was the most quiescent pair of the group, there is no corresponding data point on the lower figure.

Photometric activity rises rapidly with increasing log R'_{HK} and begins to exceed 1% when the chromospheric emission ratio is about twice the solar value. The variation in b is consistently greater than in y, which is to be expected because of the relative positions of b and y on the stellar energy distribution. The dotted line at 0.5% (0.005 mag) is a plausible upper limit for the range of variation of the Sun's close neighbors on this figure; and since most of the corresponding comparison star pairs lie below this line with smaller ranges of variation, **we conclude that many of the program stars are demonstrably variable by much larger amounts than the Sun.**

c) A Sampler of Light Curves

Figures 3–7 are a sampler of differential light curves showing the individual nightly data points on the left-hand panels (b and y averaged) and the annual mean magnitudes on the right-hand panels. The six panels for a quartet of stars and three panels for a trio of stars display all the possible differential pairings of the stars (that is: star 1 minus star 2, 1–3, 1–4, 2–3, 2–4, and 3–4 for a quartet and 1–2, 1–3, and 2–3 for a trio). The error bars are 95% confidence intervals.

Pairs of light curves showing similar variation and sharing a star in common usually reveal unambiguously which star is varying. The sense of a brightness change (positive or negative) on the different panels depends on which star is varying (the first or the second named on the ordinate); so certain light curve pairs, for example (1–2) and (2–3), will show mirror-image variations if the star in common is variable.

Figure 3 shows a star with a small linear trend. Figure 4 shows the photometry of an unusually stable group with little or no variation. Figures 5 and 6 show cyclic variations, and Figure 7 shows a star that became very active during one season only.

CONCLUSIONS

Nearly 200 years of daily sunspot records teach us that the most visible manifestation of solar activity vary unpredictably. Every 11-year cycle is unique. The variation of the total solar output, measured only for slightly less than one 11-year solar cycle, leads us to think that long-term variations are quite small--only 0.1% or so. But to contain this miniscule variation requires the delicate and continual balancing between larger competing effects, the flux deficits associated with sunspots and the flux excesses associated with faculae. In addition, subtle temperature effects may add to whatever other variations occur. Secular trends may accompany the tendency of cycle amplitudes to rise and fall over many cycles. With less than 20 cycles elapsed since records began, there is little to guide us. It would be presumptious for us to assume that what we observed in cycle 21 is an accurate Rosetta stone to even the recent past.

Stellar photometry offers little assurance that the solar variability actually measured thus far provides an accurate long-term prognosis. Indeed, many stars quite similar to the Sun demonstrably vary by amounts much larger than the Sun has over the last decade. To be sure, these stars rotate faster than the Sun, but otherwise, in terms of age, mass, temperature, and chromospheric activity, they appear to be very much like the Sun. The observed stellar variations mostly appear to be "regular" in some sense: either they exhibit a linear trend, a curve with a single maximum or minimum, or what looks like a cycle. Rarely is the variation random, as would be the case if photometric errors dominated the long-term records. Thus we conclude, considering the Sun among the stars, that the present short record of solar variability is remarkable only in its present restraint.

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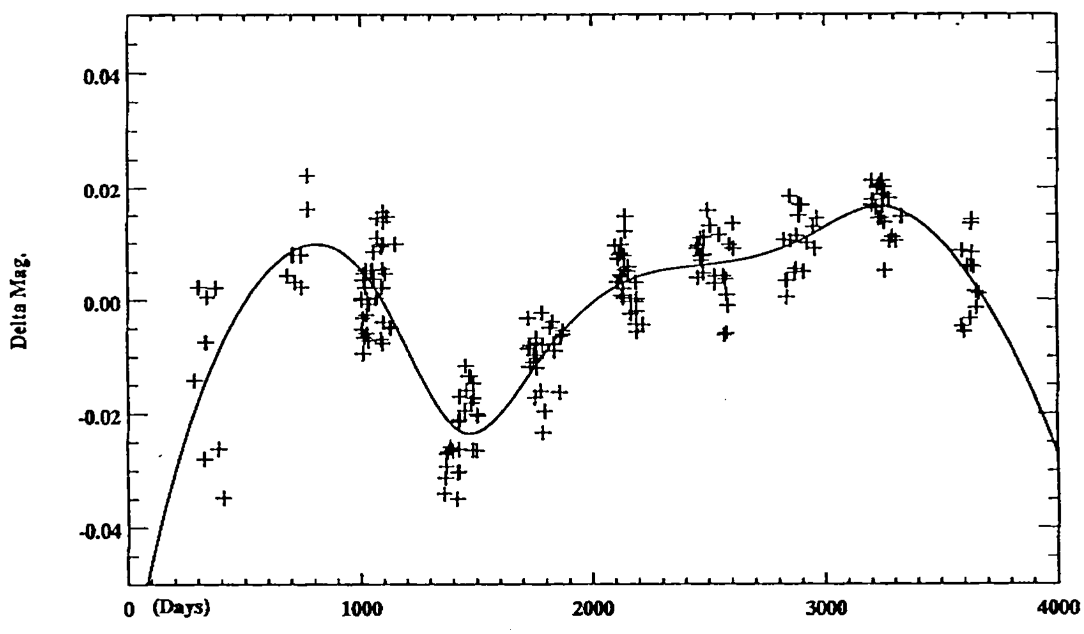

Figure 1. Long-term brightness variations of the young, solar analog, G2 V star, Van Bueren 64, in the Hyades open cluster. The first two seasons' data are from the Cloudcroft Observatory and the remainder are from the Lowell Observatory. vB64 has a rotation period of about 8.7 days based on the photometry. The smoothing spline fit through the data indicates an amplitude of about 0.03 mag and the possibile existence of a stellar luminosity cycle.

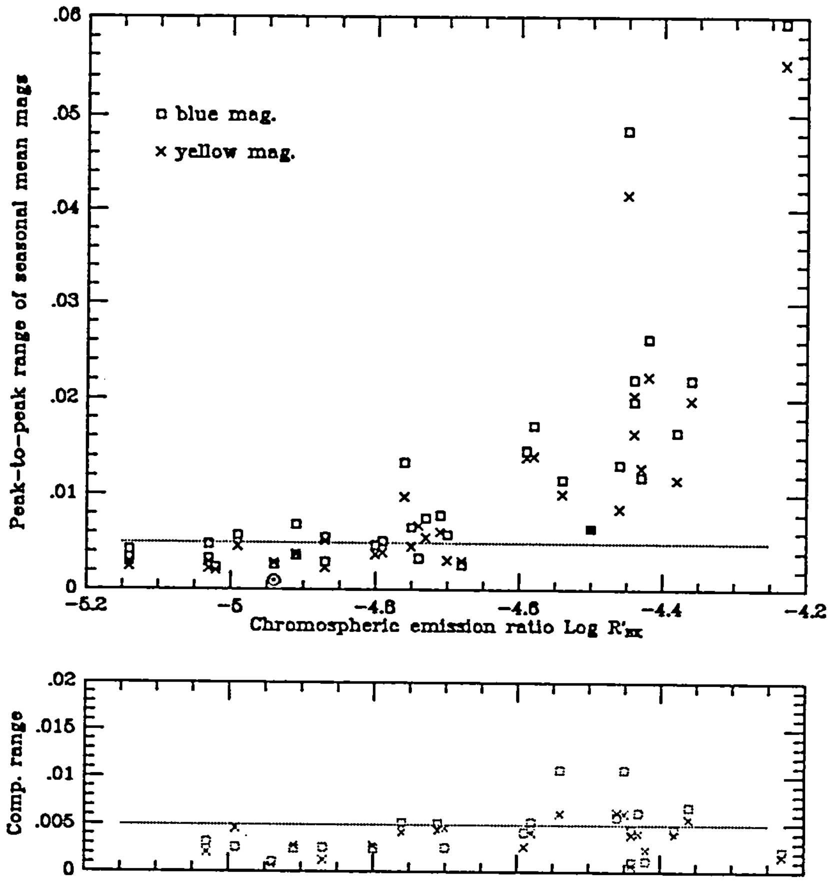

Figure 2. (*top*). The 6-year range of the annual mean *b* and *y* magnitudes of the program stars as a function of the chromospheric emission ratio, log R'_{HK}. Note the position of the Sun at (–4.94, 0.001). None of the Sun's neighbors on this figure vary by more than 0.5%, indicated by the dotted line at 0.005 mag. (*bottom*). The range of the least-variable pair of comparison stars in the groups corresponding to the program stars plotted above. Since the average variability of the comparison stars tends generally to be on the order of 0.0025 mag, the indicated variability of the corresponding program stars in excess of that amount is likely to be intrinsic rather than observational.

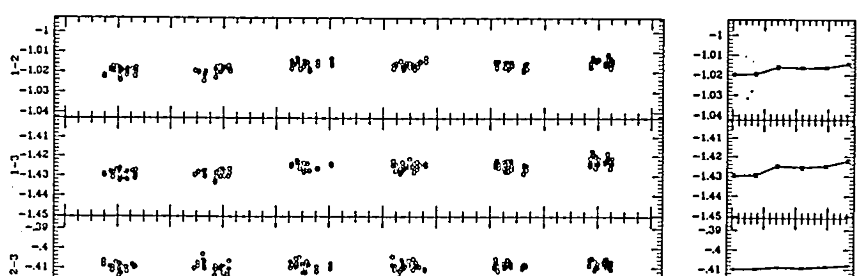

Figure 3. Differential light curves for a trio of stars comprising one program star and two comparison stars. The *b* and *y* magnitudes are averaged together. The left-hand panels show the individual nightly data points (two points per night, usually) for each of the pairwise combinations of stars; that is, star 1 minus star 2, star 1 minus star 3, etc. The right-hand panels show the yearly mean magnitudes and their 95% confidence intervals. Star 1 is HD10476 (K1V), log R'_{HK} =–4.87, close to the Sun's value of –4.94. This star has a 9-year HK activity cycle. The brightness has decreased by 0.0055 mag in *b* and 0.0052 mag in *y* over 6 years. The comparison star pair (star 2–star 3) is unusually stable, with a range of 0.0026 mag in *b* and 0.0013 mag in *y*.

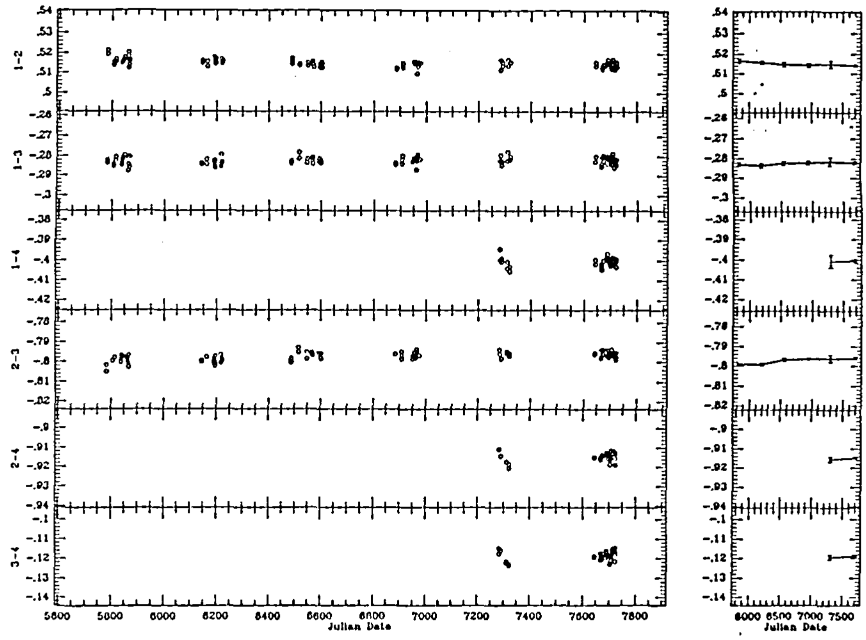

Figure 4. This group was observed as a trio for the first four seasons, but was promoted into a quartet by adding another comparison star when it became obvious that the identity of the "variable" star was unclear. Star 1 is HD143761 (G0V), a Mount Wilson HK standard and photometric standard star with a subsolar value of log R'_{HK}. The observed range (star 1–star 2) is 0.0024 mag in *b* and 0.0021 mag in *y*.

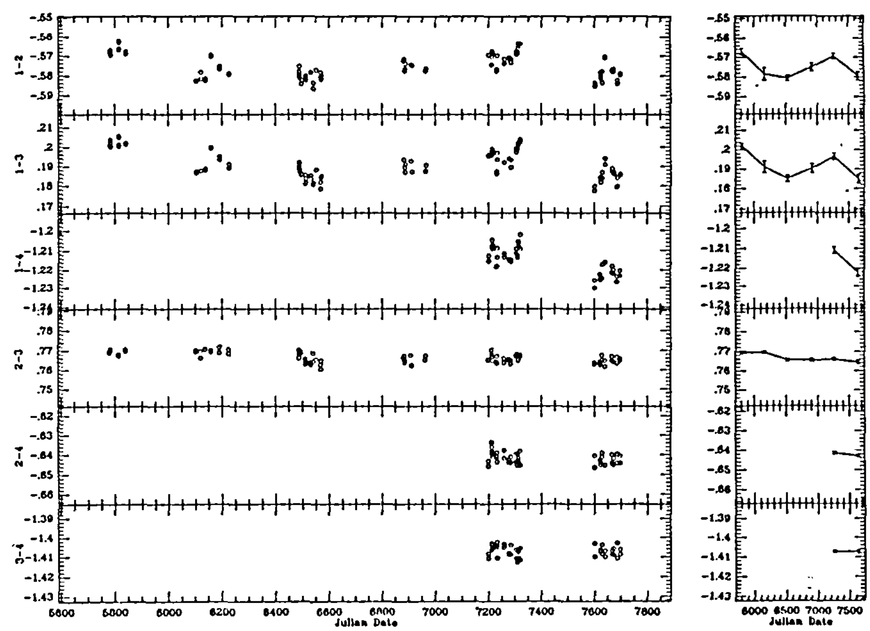

Figure 5. Star 1 is HD115383 (G0V), log $R'_{HK} = -4.43$, an active star. Although this star has long been used as a *uvby* standard, it shows a cyclic variation with an amplitude of 0.0119 mag in *b* and 0.0129 mag in *y* (1–2 and 1–3). The range of the comparison star pair (2–3) is 0.0063 mag in *b* and 0.0041 mag in *y*, large enough to indicate intrinsic variability, so we added another comparison star in the fifth season. We suspect star 2, a K0 giant, as the likely variable comparison star.

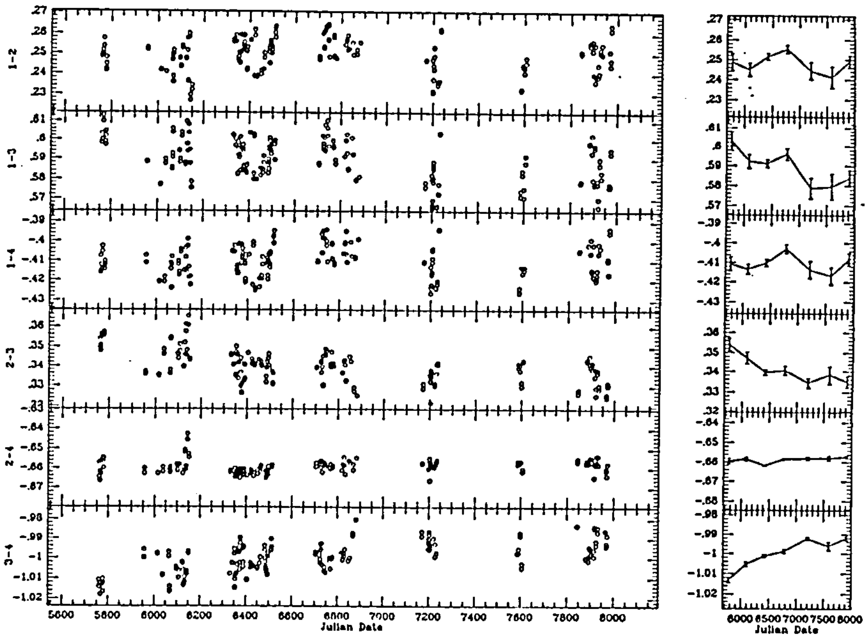

Figure 6. Star 1 is HD35296 (F8V), log $R'_{HK} = -4.38$, an active star showing a trend in its HK index and cyclic brightness variation with an amplitude of 0.0165 in *b* and 0.0116 in *y*. Star 3, HD39587 (G0V), log $R'_{HK} = -4.44$, displays a linear brightness decrease with a range of 0.0221 mag in *b* and 0.0204 mag in *y*. The comparison star pair (2–4) is fairly stable, with a range of about 0.004 mag.

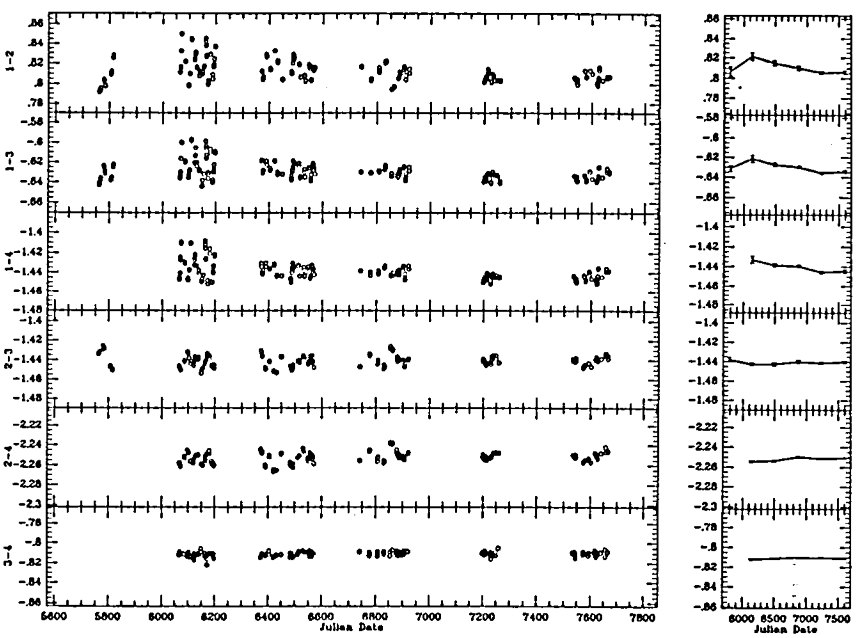

Figure 7. Star 1 is HD82885 (G8IV-V), another variable *uvby* standard star, with log $R'_{HK} = -4.58$. The HK data showed a noisy trend with no apparent cycle. During the second observing season, the star was on average fainter by 0.01 mag than in the previous 13 years, during which we observed it as a *uvby* standard. During this season we determined a photometric rotation period of 18 days and an amplitude of 0.033 mag indicating the presence of large starspots. Star 2 in this group is HD82635 (G8.5III), another *uvby* standard that turned out to be slightly variable on rotational timescales. Over the long term it is quite steady. In the second season, it showed a rotational modulation with an amplitude of 0.012 mag and a period of 40 days (16). Note that variability, when it occurs, scatters the points toward fainter magnitudes (upwards on the light curves) from an essentially unblemished level maximum.