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THE SUN-LIKE ACTIVITY OF THE SOLAR TWIN 18 SCORPII

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ABSTRACT

We present the results of 10 yr of complementary spectroscopic and photometric observations of the solar twin 18 Scorpii. We show that over the course of its ∼7 yr chromospheric activity cycle, 18 Sco's brightness varies in the same manner as the Sun's and with a likely total brightness variation of 0.09%, similar to the 0.1% decadal variation in the total solar irradiance.

Key words: stars: activity — Sun: activity

1. INTRODUCTION

Since the advent of space-borne solar observatories, the Sun's total brightness has been found to vary directly with its activity level at a level of about 0.1% (Fröhlich & Lean 1998). It also appears to evolve on century (Lockwood & Stamper 1999) and longer (Rind 2002) timescales, although debate persists regarding the presence or absence of a secular increase between the 1986 and 1996 minima (Fröhlich & Lean 1998; Willson 1997). The decadal forcing of this observed total solar irradiance (TSI) variation appears unlikely to have been a dominant driver of global warming since 1970 (Wang et al. 2005), but longer term (and in some cases short-term) signals undeniably exist in the climate record (Rind 2002). The pronounced decadal variations of solar activity in the UV may have important effects on tropospheric conditions through modulation of ozone (Shindell et al. 1999; Haigh 2004).

To improve our perspective on our own star and its variability, we may turn to the most nearly Sun-like stars as additional examples of ostensibly typical stellar behavior. The Fraunhofer H and K lines of singly ionized calcium are well known as sensitive proxies for the chromospheric manifestations of the Sun's activity cycle (White & Livingston 1981; White et al. 1998), as well as the cycles of Sun-like stars (Wilson 1978; Baliunas et al. 1995). In addition to their chromospheric activity, true solar twins are required to be "nearly indistinguishable" from the Sun in their gross physical parameters (Cayrel de Strobel 1996), and they have been elusive. Only one star accessible to extant long-term programs, the 5th magnitude star 18 Scorpii, has met all the criteria (Porto de Mello & da Silva 1997), although additional good candidates have been proposed (Soubiran & Triaud 2004). We identified the likely presence of an activity cycle in 18 Sco after 4 yr of observations (Hall & Lockwood 2000), and our Ca II H and K data, combined with 1991–2001 observations from the Mount Wilson HK project kindly supplied by S. Baliunas (2005, private communication), yield a cycle length of 7.1 ± 0.2 yr (Hall et al. 2007).

To study the cyclic and irradiance behavior of Sun-like stars, long-term (i.e., decadal or longer), synoptic observations are necessary. Such studies have revealed important clues about the irradiance variability of Sun-like stars of different ages (Radick et al. 1998), but since concerted searches for solar analogs were simultaneous with (or postdated) the long-term studies, most of the resulting best candidates have not been observed in detail. To remedy this, we have been observing a large set of the closest solar analogs and twins both spectroscopically in Ca II H and K (Hall & Lockwood 1995; Hall et al. 2007) and photometrically in the *b* and *y* bandpasses of the Strömgren system (Henry 1999) for over 10 years. In this paper we demonstrate that the solar twin 18 Sco exhibits luminosity variations remarkably similar to those of the Sun over the course of its activity cycle, lending confidence—to the extent that this single data point permits—in the use of Sun-like stars as reliable proxies for the likely envelope of solar behavior on decadal to millennial timescales.

2. OBSERVATIONS AND DATA ANALYSIS

The spectroscopic observations presented herein were obtained with the Solar-Stellar Spectrograph (SSS), operated at a 1.1 m telescope at Lowell Observatory's dark-sky site near Flagstaff, Arizona. The spectrograph has been in regular operation for 12 yr and allows observations of Sun-like stars, as well as the unresolved Sun itself, via dual fiber optic feeds to the spectrograph input. We collect spectra of the Ca II H and K region (3860–4010 Å) on a charge-coupled device (CCD) detector and reduce the data with routines written in the Interactive Data Language (IDL). We measure the Ca II H and K emission in 1 Å rectangular bandpasses centered on the line cores, and we express our results in terms of the excess flux $\Delta F_{\rm HK}$, the fraction of the emission measured in the 1 Å bandpass arising from dynamo-related magnetic activity (see, e.g., Schrijver et al. 1989). Details of the SSS facility, the data reduction procedure, and how the measured emission in the H and K line cores is converted to $\Delta F_{\rm HK}$ have been presented by Hall et al. (2007).

We acquired the brightness measurements of 18 Sco with the T8 0.8 m automatic photometric telescope (APT) at Fairborn Observatory, located in the Patagonia Mountains of southern Arizona (Henry 1999). The T8 APT is equipped with a two-channel precision photometer employing two EMI 9124QB bi-alkali photomultiplier tubes to make simultaneous measurements in the Strömgren *b* and *y* passbands. The APT measures the difference in brightness between a program star and a nearby constant comparison star or stars with a typical precision of 0.13% rms for bright stars ($V < 8.0$). We observed three comparison stars along with 18 Sco: HD 143841 ($V = 7.12, B - V = 0.43$), HD 144892 ($V = 6.69$, $B - V = 0.51$), and HD 141128 ($V = 7.00$, $B - V = 0.47$). Intercomparison of the various differential brightnesses between the three comparison stars showed that HD 143841 and HD 144892 exhibited the greatest constancy; the standard deviation of their night-to-night differential brightnesses averaged

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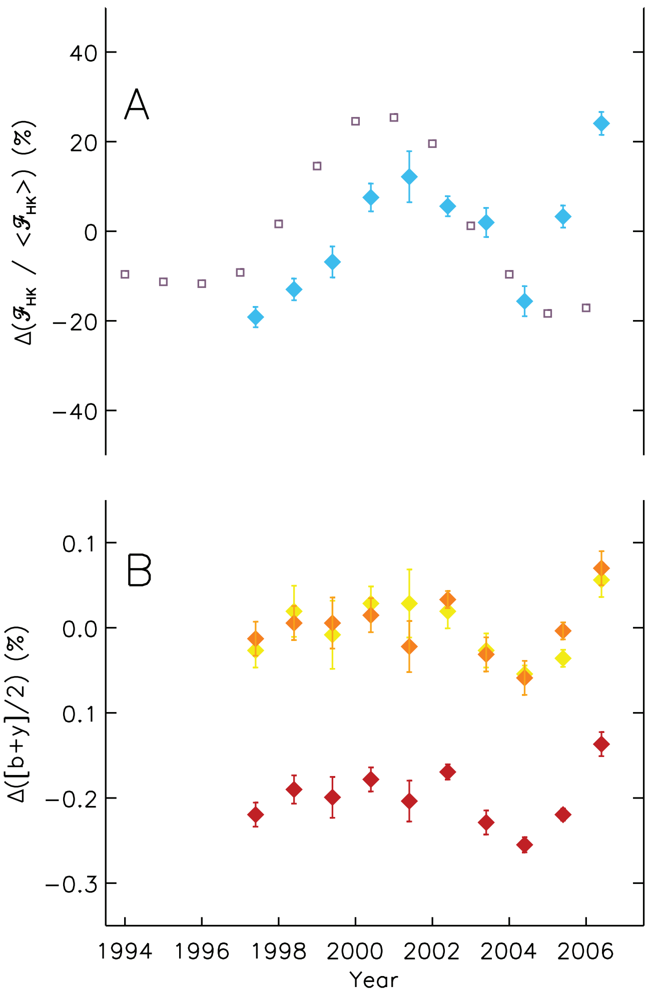

Fig. 1.—Photometric and spectroscopic behavior of 18 Sco, 1997–2006. (*a*) Variation of the Ca II H and K magnetic flux about its mean (*blue diamonds*). Our 13 yr of observations of the solar HK variation (*purple squares*) are shown for comparison, scaled the same way. (*b*) Photometric light curves. Brightness increases upward. Orange and yellow diamonds show the individual variations relative to two different comparison stars. The red series is the weighted mean of the first two and is offset by 0.2% for clarity.

only 0.12% over the 10 yr time span of the observations. Seasonal means of the HD 143841 versus HD 144892 differential brightnesses scattered about their grand mean by only 0.02%. To maximize the precision of our 18 Sco differential brightnesses, we chose to combine the Strömgren *b* and *y* differential brightnesses into a single $(b + y)/2$ passband and to compute 18 Sco's differential brightnesses with respect to the *mean* of the two best comparison stars. As shown below, this allowed us to resolve subtle brightness variations in 18 Sco above the combination of measurement errors and any low-level intrinsic variability in the two comparison stars. Additional information on the operation of the telescope and photometer, observing procedures, and data reduction techniques can be found in Henry (1999).

3. RESULTS

In Figure 1 and Table 1 we present the spectroscopic and photometric behavior of 18 Sco from 1997 through 2006. All data points are seasonal means of typically ∼60 APT observations and ∼20 SSS observations per season; error bars show the standard deviation of the mean. For ease of comparison with the familiar 0.1% TSI variation over the solar activity cycle, we have converted all flux measurements and photometric magnitudes to percent variations about their respective means.

TABLE 1

Spectroscopic and Photometric Variations in 18 Scorpii from 1997 through 2006

Year (1)	$\Delta F_{\rm HK}/\langle\Delta F_{\rm HK}\rangle$ (%) (2)	$\Delta([b+y]/2)$ (%) (3)
1997	−19 ± 2	−0.018 ± 0.001
1998	−13 ± 2	0.009 ± 0.002
1999	−7 ± 3	0.000 ± 0.003
2000	7 ± 3	0.018 ± 0.002
2001	12 ± 6	0.000 ± 0.003
2002	5 ± 2	0.028 ± 0.001
2003	1 ± 3	−0.028 ± 0.002
2004	−16 ± 3	−0.055 ± 0.001
2005	3 ± 2	−0.018 ± 0.001
2006	24 ± 2	0.064 ± 0.002

Notes.—For each year we show the seasonal mean and the standard deviation of the mean for the Ca II H and K flux relative to its 10 yr mean (col. [2]) and the brightness of 18 Sco relative to its 10 yr photometric mean (col. [3]). The Ca II H and K variations in col. (2) correspond to the blue diamonds in Fig. 1, and the $(b + y/2)$ variations in col. (3) correspond to the red diamonds, which are the weighted mean of the two individual series shown in yellow and orange.

The SSS observations of 18 Sco are shown in Figure 1*a* (*blue diamonds*), wherein we show the variation of each seasonal mean about the grand mean of the means. For comparison, the SSS seasonal mean $\Delta F_{\rm HK}$ for the Sun from 1994 through 2006 is also shown (*purple squares*). The Fairborn differential photometric data appear in Figure 1*b*, shown as the difference in brightness between each seasonal mean and the grand mean. The orange and yellow data points are the individual series for 18 Sco relative to the comparison stars HD 143841 and HD 144892, respectively. The red data series is the weighted mean of these two and is offset by 0.2% for clarity.

The data in Figure 1*a* show that 18 Sco exhibits a clear chromospheric activity cycle that peaked in 2001 and reached a pronounced minimum in 2004. In the 2005 and 2006 observing seasons, the SSS observations showed a surprisingly sharp rise in 18 Sco's activity, exceeding the full amplitude of the previous cycle in just 2 yr. As is demonstrated by the overlaid solar data, the amplitude of the most recent cycle in 18 Sco relative to its mean is comparable (so far) to that of the Sun. Its absolute level of chromospheric activity, however, is somewhat greater than the Sun's; in terms of the dimensionless index *S* used by the Mount Wilson program to characterize stellar activity (Baliunas et al. 1995), our mean derived value for the Sun is 0.171, while for 18 Sco it is 0.182.

The photometric data for 18 Sco also vary directly with its activity cycle, with an amplitude in $(b + y)/2$ of 0.12%. A Spearman rank order test applied to the 10 yr data set yields $\rho = 0.620$, which for 10 data pairs rejects the null hypothesis of noncorrelated data sets at the ∼95% confidence level. This relatively strong correlation is obtained despite what appears to be elevated variability in the records for the comparison stars from 1999 to 2001 (evident in the increased variability and significantly larger errors on the seasonal means in the individual and weighted time series in Fig. 1*b*, particularly in 1999 and 2001). Possibly as a result of this comparison star variability, we find no significant correlation between the spectroscopy and photometry for the seasons between 1997 and 2000. However, since 2001, the two comparison stars appear to have been extremely stable, and for the six seasonal means between 2001 and 2006, we obtain $\rho = 0.943$, rejecting the null hypothesis at a confidence level of 99.5%.

We now must relate the observed variability in the Strömgren b and y passbands to the probable total brightness variation for 18 Sco over the course of its cycle. As Radick et al. (1998) have discussed in detail, the variability in the $(b + y)/2$ passband is not expected to simply equal the variations in a star's total brightness. Those authors assumed that the Sun's brightness variations arise from small changes in $T_{\rm eff}$ and that the Sun radiates like a blackbody to deduce the necessary factor to convert a change in $(b + y)/2$ into a change in bolometric flux, finding that $(b + y)/2$ variability should be larger than bolometric variability by a factor of 1.34. Fligge et al. (1998a, 1998b) have also examined the problem of converting spectral variability in the passbands of the VIRGO package aboard the *SOHO* spacecraft to total variability. For the VIRGO "green" channel at 5000 Å, comparable to the passband of our $(b + y)/2$ data, they obtain a similar conversion factor of 1.39. Reducing the 0.12% amplitude in $(b + y)/2$ for 18 Sco by the mean of these two estimates yields a likely total brightness variation for 18 Sco over its present cyclic variations of $\sim$0.09%, very similar to that observed for the Sun.

4. CONCLUSIONS

Reconstructions of the evolution of solar luminosity, especially in regard to its behavior during grand minima, can be usefully guided by these stellar observations, and this has led to numerous efforts to characterize the nature of Sun-like stars, in terms of both their general parameters (e.g., Henry et al. 1996; Gray et al. 2003) and their long-term variability (e.g., Baliunas et al. 1995; Radick et al. 1998). Chromospheric proxies such as Ca II H and K have been fruitful, since they are easily observed and display a marked variation for cycles comparable to the Sun's. It is essential, however, to also observe the brightness cycles, which are more closely tied to a star's climate-forcing ability on such planets as it may have than are the evanescent H and K variations. We know that the direct variation of TSI with Ca H and K emission observed for the Sun holds in general for solar-age stars (Radick et al. 1998), but the targets in that study are generally not "nearly indistinguishable" from the Sun. The present results demonstrate for the one star that does seem to fit the criterion that both the chromospheric activity cycle and the brightness variations very closely mimic those of the Sun for the 10 yr span of observations accumulated thus far.

As we begin to observe a few stars that appear to have made significant transitions between cycling and noncycling states (Hall et al. 2007), analysis of their complementary photometric behavior should further constrain our understanding of the likely envelope of luminosity excursions of Sun-like stars; these results are in preparation. The next two to three observing seasons will also likely reveal the full amplitude of the newly emerging and rather abruptly rising cycle in 18 Sco, which already exceeds that of the 1996–2004 cycle.

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