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The Suns of M67

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Abstract. We discuss the methodology and some preliminary results of a survey of the chromspheric Ca II H & K line strengths in a sample of solar-type stars in the galactic open cluster M67. We compare the distribution of H&K line strength among the solar counterparts in this cluster with that seen in the contemporary Sun during the course of its 11-year cycle.

1. Introduction

I present an update on a long-term study of the solar-type stars in the solar-age and solar-metallicity open cluster, M67. The primary objective of this program is to gain insight on the possible range of *solar* chromospheric activity and the associated, potential long-term variability of the Sun through the observation of stellar analogs of the Sun. In addition to the survey of Ca II chromospheric line strengths, I and my collaborators, J. Hall (Lowell Observatory), R. Radick (AFRL) and S. Baliunas (SAO), are in the process of conducting a monitoring program to confirm whether cycle-related variability of the chromospheric Ca II strength occurs in individual sun-like members of this cluster.

The working hypothesis of the survey portion of this program is that a single 'snap-shot' of a large sample of solar analogs will reveal the potential range of *solar* chromospheric activity. In this way, we immediately obtain information on the potential *long-term* variability of the Sun that would not otherwise be possible (or practically feasible) with the modern solar Ca II data-base of only three decades (e.g., White & Livingston 1978; Livingston 1994). This is especially important given that the amplitude of long-term, solar and stellar variations in *brightness* are correlated with cycle variations in *chromospheric* emission (Hudson 1988; Radick 1991). In view of the fact that the Sun is the engine that drives climate on the Earth, any variation in the solar 'constant' must be taken into account in the investigation of the long-term behavior of the global climate. The open cluster M67 itself is an especially appropriate target of observation since it is approximately the same age (about 5 Gyr $\pm$ 1 Gyr; Demarque, Guenther & Green 1992) and of the same metallicity as the Sun (Barry & Cromwell 1974).

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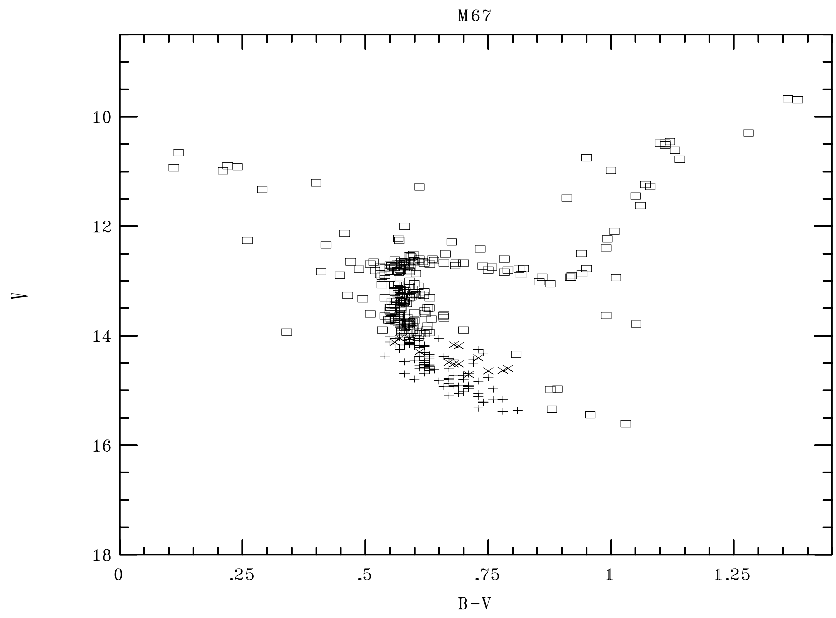

Figure 1. Color-magnitude diagram of M67 with proper-motion members. The plus (+) signs denote solar-type program stars that are not known to be binary while the crosses (x) represent known binaries among the WIYN/Hydra program stars.

2. Methodology

We utilized the 3.5-m WIYN telescope in conjunction with the Hydra multi-fiber positioner to perform multi-object spectroscopy over a 1 degree field. We use a bench-mounted spectrograph with the T2KC CCD, Simmons camera and the 1200 g mm^{-1} grating in second order. A $CuSO_4$ blocking filter was employed to suppress red leak. This configuration yields a spectral resolution of about 0.80 Å in the 3950 Å region between the Ca II K and H lines, as measured by the FWHMs of the CuAr comparison lines.

The stars are selected from the Girard et al. (1989) proper motion study combined with the CCD photometry given by Montgomery, Marschall & Janes (1993). For those objects from the Girard et al. study where photometry from Montgomery et al. is not available, we adopt the photometry given by Sanders (1989). We include only stars that have a membership probability of $\geq$ 90% as given by Girard et al. (1989). Our photometric criteria include stars in the range of apparent brightness of $14 \leq V \leq 15$ and intrinsic color of $+0.55 \leq (B-V) \leq +0.78$, where we adopt a value of $E(B-V) = +0.05$ for the color excess in M67 (Montgomery et al. 1993). The resulting spectral range of the entire sample is $\sim$ F8 - K0. In this way, we can ensure that we are observing stars that are very close to the Sun in their photospheric properties. A color-magnitude diagram of the cluster along with the survey objects is shown in Fig. 1.

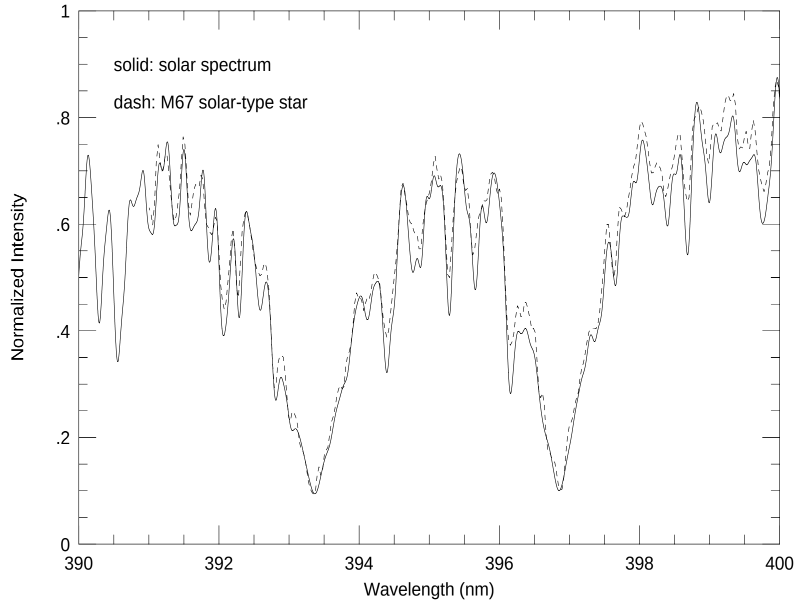

Figure 2. The solar spectrum degraded to the resolution of the stellar observations (solid) and the calibrated spectrum of a solar-type star in M67 (dash).

The calibration of the Hydra spectra to residual intensity and flux follows the relations given by Hall & Lockwood (1995) and Hall (1996), initially as functions of $(B-V)$ color. These relations give the residual intensities at pseudo-continuum points at 3912 Å and 4000 Å, respectively, along with the continuum flux at 3950 Å, each as a function of $(B-V)$ color. A comparison of the NSO solar atlas spectrum in the Ca II H&K line region with our calibration of the spectrum of a sun-like star observed in M67 is given in Fig. 2.

We then derive H+K index ("HK-index") values in 1 Å bandpasses centered at the H and K lines. From this index we can derive other relevant quantities such as the absolute surface flux and R_{HK} which is defined as the absolute surface flux in the H&K lines normalized by the stellar bolometric flux (σT^4_{eff}).

3. Discussion

A subset of our results from the WIYN/Hydra survey of chromospheric activity in 102 sun-like stars in the solar-age and solar-metallicity cluster M67 is encapsulated in the accompanying histogram (Fig. 3).

The abscissa of the histogram for the "solar twins", the HK-index, is the sum of the residual intensities in 1 Å bandpasses centered at the Ca II H and

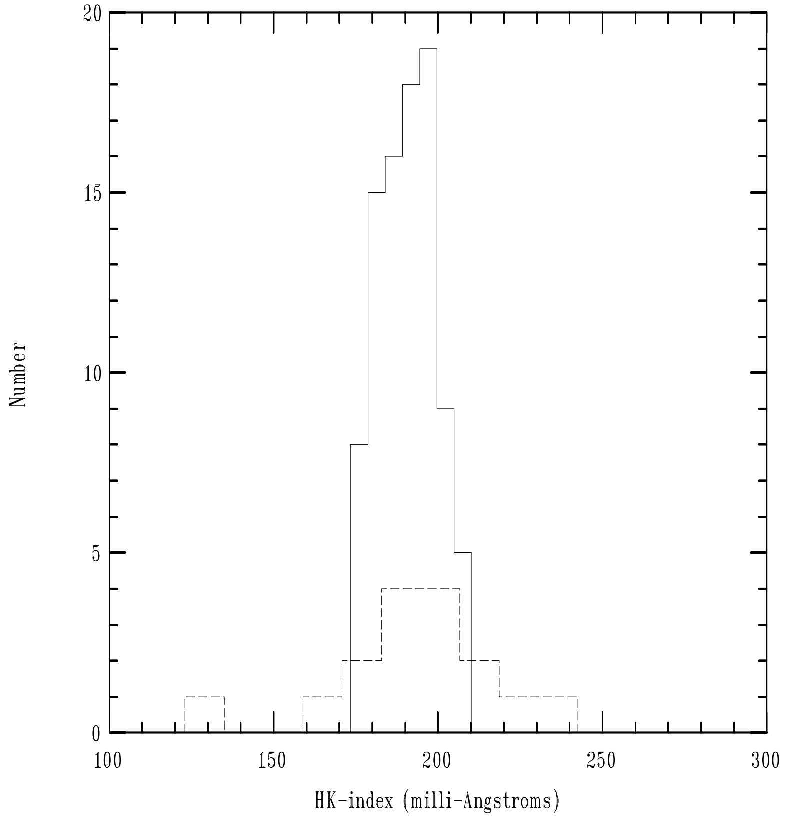

Figure 3. The distribution of the HK-index for the solar cycle (solid line) and "solar twins" (dashed line). This index is identical to that defined by W. Livingston for his Sun-as-a-star synoptic observations at the NSO McMath-Pierce telescope on Kitt Peak. About 10% of the stars have HK-index values that are exceptionally quiescent, reminiscent of Maunder-minimum levels. About 20% exhibit HK-index values that exceed the value of solar maximum, at least as recorded from 1976-1994.

K lines. The solar twins are defined as those stars in M67 with unreddened colors in the range of $0.63 \leq B-V \leq 0.67$. This is the range of colors that has been quoted in the literature for the Sun (VandenBerg & Bridges 1984, see their Table 2). There are 20 stars in this subsample. The solar cycle in HK-index is also shown, based on data obtained by W. C. Livingston (NSO/Kitt Peak) at the McMath-Pierce Solar Telescope facility on Kitt Peak since 1976.

The broader distribution in chromospheric Ca II strength for the solar twins, compared to that of the Sun during the contemporary solar cycle, suggests that the potential excursion in the amplitude of the solar cycle is greater than what we have seen so far. The stars with HK values noticeably less than solar minimum may be in a prolonged state of quiescence analogous to the Maunder-minimum episode of the Sun during A. D. 1645-1715 when visible manifestations of solar activity vanished. This period corresponds to a time of reduced average global temperatures on the Earth known as the "Little Ice Age" (Foukal & Lean 1990).

Among the solar twins we find that 10% have HK-index values less than that estimated for the Maunder Minimum while 20% exhibit HK-indices which exceed that observed at solar maximum. Thus, these preliminary results (based only on the solar twins) would indicate that the Sun can be in a state of activity outside of the envelope defined by the contemporary solar cycle at least 30% of the time. In view of the positive correlation between magnetic activity and brightness changes, our results suggest that the total solar irradiance could change by more than the 0.1% currently observed! This could, in turn, have significant implications for climate change over century-long time scales. Conversely, the results in Fig. 3 imply that the Sun and solar-type stars are more similar than they are different in terms of their level of chromospheric activity. From this perspective, the Sun is a "normal" star.

A lingering question remains, however, as to whether the enhanced activity, compared to solar maximum, in some of the sun-like stars in M67 is due to an excursion in their cycles or to more rapid rotation. An approved program to measure *vsini* values for these stars will be implemented at the 9-m HET telescope in conjunction with the High Resolution Spectrograph (HRS) to address this issue.

4. Future Work

These intriguing results pose crucial questions. In particular, is the stellar distribution in the figures really the result of the modulation of activity by cycles analogous to the solar cycle, or are the *relative amplitudes* of the cycles actually similar with the differences due only to differences in the *mean level* of activity among solar-type stars? Even more fundamentally, is the distribution of chromospheric H&K emission strength arising from solar-like cycles at all? The only way to address these critical issues is to obtain regular observations of a well-defined subsample of M67 "Suns" over a period of several years. We have therefore implemented a long-term program of WIYN/Hydra observations during each bright Hydra run during the M67 observing season (about December - April).

The results of this long-term program will provide fundamental empirical data on the cycle characteristics of unarguably solar-like stars. Of equal importance, they will provide valuable input for the construction of global climate change models.

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