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FREQUENCY OF MAUNDER MINIMUM EVENTS IN SOLAR-TYPE STARS INFERRED FROM ACTIVITY AND METALLICITY OBSERVATIONS

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ABSTRACT

We consider the common proposition that the fraction of chromospherically very inactive stars in a solar-type sample is analogous to the fraction of the Sun's main-sequence lifetime spent in a grand minimum state. In a new approach to this proposition, we examine chromospheric activity log R'_{HK} in a stellar sample having *Hipparcos* parallax measurements, and having spectroscopically determined metallicity close to solar ($-0.1 \leqslant$ [Fe/H] $\leqslant 0.1$). We evaluate height above the *Hipparcos* main sequence, and estimate age using isochrones, to identify the most Sun-like stars in this sample. As a threshold below which a star is labeled very inactive, we use the peak of the HK activity distribution mapped over the quiet Sun during the 1968 epoch. We estimate the fraction of Maunder Minimum (MM) analog candidates in our sample at 11.1%. Given the 70 yr duration of the historical MM, this suggests that in any given year there is a 1/630 chance of entering a similar grand minimum. There are three important cautions with this type of estimate. First, recent investigation using actual activity and photometric time series has suggested that very low activity may not be a necessary criterion for identifying a non-cycling MM analog candidate. Second, this type of estimate depends very strongly on the choice of very low activity threshold. Third, in instantaneous measurements of log R'_{HK}, it is not always clear whether a star is a viable MM analog candidate or merely an older star nearing the end of its main-sequence lifetime.

Key words: stars: activity – stars: solar-type – solar-terrestrial relations

1. INTRODUCTION

The Maunder Minimum (MM; ca. 1645–1715) was a dramatic shift in solar magnetic activity, and inferred reduction in extraterrestrial solar irradiance, that corresponded to a well-documented cooling of Earth's climate (Eddy 1976). Our evidence of the shift in solar magnetic activity consists primarily of (1) a near-total absence of sunspots for ∼45 yr and (2) cosmogenic radioisotope records. These point to a decline in activity to a level lower than present-day solar minimum, but firmly quantifying this decline has proven elusive. Nevertheless, the known Northern Hemisphere climatic responses to the MM have been successfully reproduced in global climate model simulations (Shindell et al. 2001; Rind et al. 2004; Song et al. 2010), and these simulations support the role of solar irradiance variability in altering major modes of dynamical variability in the terrestrial troposphere. Recent analysis of cosmogenic radioisotope records from Greenland ice cores (Abreu et al. 2008) and dendrochronology (Bonev et al. 2004) suggests that the current period of relatively high extraterrestrial solar irradiance may conceivably end sometime later this century. At the same time, solar "grand minimum" events as recorded in geophysical proxy data appear to be more stochastic than periodic (e.g., Usoskin et al. 2007).

An alternative path to estimating the prevalence of solar grand minima on 100–1000 yr timescales involves surveying the magnetic activity of solar-type stars. The fraction of solar-type stars showing evidence of very low activity is interpreted as an estimate of the fraction of the Sun's own lifetime spent in a grand minimum state. The rigorous way to make this type of estimate is to acquire multi-year time series of photometric variability and chromospheric activity determined from Ca II HK emission (Baliunas et al. 1995; Lockwood et al. 2007; Hall et al. 2009). Time series of this kind have revealed a plausible extrasolar MM candidate: HD 140538, a star showing four years of flat activity followed by a return to a cycle with a four-year period (Hall et al. 2007). However, target lists for these multi-year observations are not yet extensive enough to provide an estimate of grand minimum frequency that can be easily generalized to the Sun. Therefore, some studies have used instantaneous observations of Ca II HK activity, which comprise an order of magnitude more stars (Henry et al. 1996; Wright 2004). By instantaneous, we mean an observation or set of observations pertaining to essentially a single point in a decadal time series; for example, a monthly average or average over an observing run. The assumption here is that chromospheric activity below a given threshold (e.g., log $R'_{\mathrm{HK}} \leqslant -5.1$) indicates very low magnetic activity analogous to a grand minimum. Using instantaneous Ca II H and K flux measurements, the fraction of the Sun's lifetime spent in an MM state has been estimated in the range 10%–15% (Baliunas et al. 1995; Henry et al. 1996). Earlier, Baliunas & Jastrow (1990) had proposed an estimate of ∼30%, but Hall & Lockwood (2004) were unable to reproduce it.

Using *Hipparcos* parallax data, Wright (2004) demonstrated that many of the stars considered as MM analog candidates in earlier studies are slightly evolved, and not analogous to a late-type main-sequence star in a temporary grand minimum state; therefore, the frequency of MM analogs in nature may be much smaller than 10%. Judge & Saar (2007) subsequently argued that the arbitrary threshold log $R'_{\mathrm{HK}} \leqslant -5.1$ may be too restrictive because it does not account for variation with metallicity, and suggest that solar-metallicity stars having log $R'_{\mathrm{HK}} \approx -5.08$ or even slightly larger should be considered as possible MM analog candidates.

More recently, time series of both photometric and chromospheric (HK) flux variability from Lowell Observatory (Hall et al. 2007, 2009) call into question whether an instantaneous detection of very low log R'_{HK} is either a necessary or sufficient condition to identify an MM analog candidate. The flat portion of the time series for HD 140538 shows chromospheric activity higher than that of the present-day Sun, while other stars exhibit chromospheric activity and photometric brightness variations that do not correlate well. The validity of using very low instantaneous HK flux to identify an MM analog candidate therefore requires further clarification.

This brings us to the question of precisely defining an "activity level." In this context, very low log $R'_{\rm HK}$, i.e., significantly below the present-day solar minimum, is generally taken to mean low activity, and this is what we adopt in this study. However, Hall et al. (2009) raise the question of whether a star with log $R'_{\rm HK}$ even larger than present-day solar range, but showing little photometric variation, might also be considered an "inactive" star.

If we assume that there is some validity in using very low log $R'_{\rm HK}$ to identify possible grand minimum analogs, we can account for the complications arising from metallicity variation (Judge & Saar 2007) by choosing a sample of stars having near-solar metallicity. The purpose of this study is (1) to estimate the frequency of MM analog candidates in nearby field stars having spectroscopically determined metallicity close to solar, and (2) to determine how this estimate depends on the chosen threshold in log $R'_{\rm HK}$, which can vary depending on the magnetic structure approximation used to model the Sun during the MM (White et al. 1992; Judge & Saar 2007).

2. DATA SETS ANALYZED

We use spectroscopic detections of metallicity from two field star catalogs. The Spectroscopic Properties of Cool Stars catalog (SPOCS; Valenti & Fischer 2005) comprises 1040 stars surveyed with echelle spectrograph data for exoplanet searches. Synthetic spectra, generated from the ATLAS9 model atmospheres (Kurucz 1993), were fitted to the spectral data to simultaneously determine 12 stellar properties including [Fe/H]. The precision of the [Fe/H] detections is 0.03 dex. The catalog of 3356 FGK field stars by Cayrel de Strobel et al. (2001) compiles detections of [Fe/H] from several hundred references, but all are spectroscopically determined using methods similar to that of SPOCS, and all are tabulated with reference to the Sun. A subset of these two catalogs was chosen for which there were *Hipparcos* parallax measurements, and for which log $R'_{\rm HK}$ detections could be found in one of the seven references given in Table 2 of Lubin et al. (2010). This subset contains 494 stars in the near-solar metallicity range $-0.1 \leqslant$ [Fe/H] $\leqslant 0.1$, with 309 of them having $0.59 \leqslant B-V \leqslant 0.85$. This color index range corresponds to an approximate mass range $0.9 \leqslant M_\odot \leqslant 1.1$ on the main sequence, according to the isochrones of Girardi et al. (2000).

From the *Hipparcos* parallax measurements, we computed the height above the *Hipparcos* main sequence (HMS), ΔM_V, using the empirical expression of Wright (2005). Figure 1 shows ΔM_V as a function of log $R'_{\rm HK}$ for the near-solar metallicity and near-solar mass sample of 309 stars, and also for a metal-rich sample ($0.12 \leqslant$ [Fe/H] $\leqslant 0.32$) and a metal-poor sample ($-0.56 \leqslant$ [Fe/H] $\leqslant -0.20$) having the same mass range. Obvious giants with $\Delta M_V > 3.0$ have been omitted in these plots. In the near-solar metallicity sample, most stars with log $R'_{\rm HK} > -4.9$ lie slightly below the HMS, while ΔM_V increases rapidly for smaller log $R'_{\rm HK}$. This is consistent with stellar rotation slowing as stars evolve to and past the end of their main-sequence lifetimes. In the metal-rich sample, many stars with log $R'_{\rm HK} > -4.9$ lie slightly above the HMS. Two features in Figures 1(a) and (b) support the argument of Judge & Saar (2007) discussed above concerning metallicity variation: (1) the relative positions

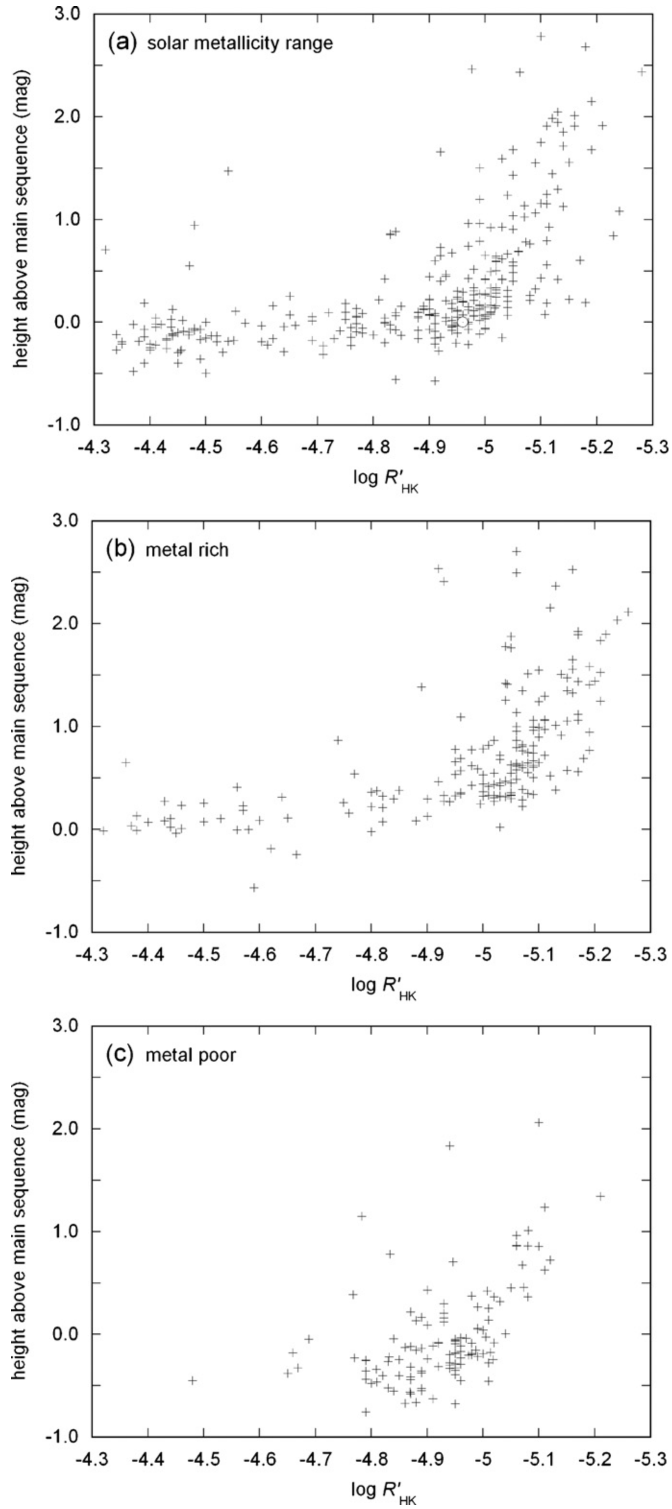

Figure 1. Height above the *Hipparcos* main-sequence ΔM_V as a function of chromospheric activity log $R'_{\rm HK}$ for a sample of stars with spectroscopically derived metallicity and *Hipparcos* parallax measurements available; (a) near-solar metallicity range, $-0.1 \leqslant$ [Fe/H] $\leqslant 0.1$; (b) metal rich, $0.12 \leqslant$ [Fe/H] $\leqslant 0.32$; and (c) metal poor, $-0.56 \leqslant$ [Fe/H] $\leqslant -0.20$. Based on the *Hipparcos* parallaxes, a typical uncertainty in ΔM_V is 0.07.

for the majority of the most active stars lie below and above the HMS, in the near-solar metallicity and metal-rich samples, respectively; and (2) the rapid rise in ΔM_V for inactive stars occurs around a slightly lower value of log $R'_{\rm HK}$ in the metal-rich sample, compared with the near-solar metallicity sample.

The sample used by Wright (2004) to derive the HMS appears to have a slight metal-rich bias, and adoption of a slightly larger threshold in log R'_{HK} than −5.1, as suggested by Judge & Saar (2007), appears to be warranted by Figures 1(a) and (b). In the metal-poor sample (Figure 1(c)), the narrower range of log R'_{HK}, biased toward lower values, is consistent with the advanced ages of these stars.

3. ISOCHRONE AGES

Isochrone age determination is generally very challenging, as the functions of absolute magnitude versus effective temperature are extremely nonlinear, sometimes not single valued, and involve ranges with insufficient dependence of magnitude and temperature upon age. Our task is simplified by our pre-selecting 374 stars within a narrow range of metallicity (near solar, $-0.1 \leqslant [\mathrm{Fe/H}] \leqslant 0.1$), and a narrow range in evolutionary state ($-0.56 < \Delta M_V < 1.3$). In the solar-composition isochrones of Girardi et al. (2000), we make an initial estimate graphically following Soderblom et al. (1991). We then iterate upon this estimate using the weighted, χ^2 minimization defined by Ng & Bertelli (1998),

$$\chi^2 = \frac{\sqrt{(M_{V,O} - M_{V,S})^2 + 16(\log T_{\mathrm{eff},O} - \log T_{\mathrm{eff},S})^2}}{\sigma(M_{V,O})},$$

where the subscripts O and S refer to the observed and synthetic quantities, respectively. This minimization provides a final estimate of both age t and mass $m/m_\odot$.

The specific procedure for this minimization involves computing χ^2 for the observed $M_{V,O}$ and $\log T_{\mathrm{eff}}$, and also propagating the uncertainties for $M_{V,O}$ and $\log T_{\mathrm{eff}}$ {i.e., $[M_{V,O}, \log T_{\mathrm{eff}}]$, $[M_{V,O} + \sigma(M_{V,O}), \log T_{\mathrm{eff}}]$, …, $[M_{V,O} - \sigma(M_{V,O}), \log T_{\mathrm{eff}} - \sigma(\log T_{\mathrm{eff}})]$}. The uncertainty in $M_{V,O}$ is computed from the *Hipparcos* parallax standard error. The uncertainty in $\log T_{\mathrm{eff}}$ is set at 0.01 dex, as suggested by Nordström et al. (2004). The nine solutions for t and $m/m_\odot$ are then averaged to yield the final estimates. As mentioned above, the narrow range in metallicity and evolutionary state favors stable solutions in the isochrones. However, we noticed a tendency for spuriously young ages (<1 Gyr) when χ^2 was noticeably larger than average. Some behavior of this kind is unavoidable when working in a range where these nonlinear functions tend to converge. We therefore omitted any of the nine solutions for a given star if $\chi^2 \geqslant 1.0$. Ng & Bertelli (1998) used a similar approach, in omitting obviously spurious solutions.

We express age both in (1) Gyr and (2) as the fraction f_{MS} of the star's time already spent on the main sequence. To evaluate this fraction, we obtain the main-sequence turn-off ages as a function of initial mass, t_{TO}, from the Girardi et al. (2000) solar-metallicity isochrones, and fit a ninth-order polynomial,

$$t_{\mathrm{TO}} = a_0 + a_1 x + a_2 x^2 + \cdots + a_9 x^9,$$

where $x = m/m_\odot$, t_{TO} is in Gyr, and the constants a_0 through a_9 have values +488.66, −1511.10, +2026.90, −1540.80, +731.12, −224.75, +44.827, −5.6034, +0.39903, and -1.2355×10^{-2}, respectively. From this,

$$f_{\mathrm{MS}} = \frac{t}{t_{\mathrm{TO}}}.$$

The estimated ages and f_{MS} for all near-solar-metallicity stars are shown as a function of $B - V$ in Figure 2. Figure 2(a) illustrates the consistency in estimated f_{MS} with height above

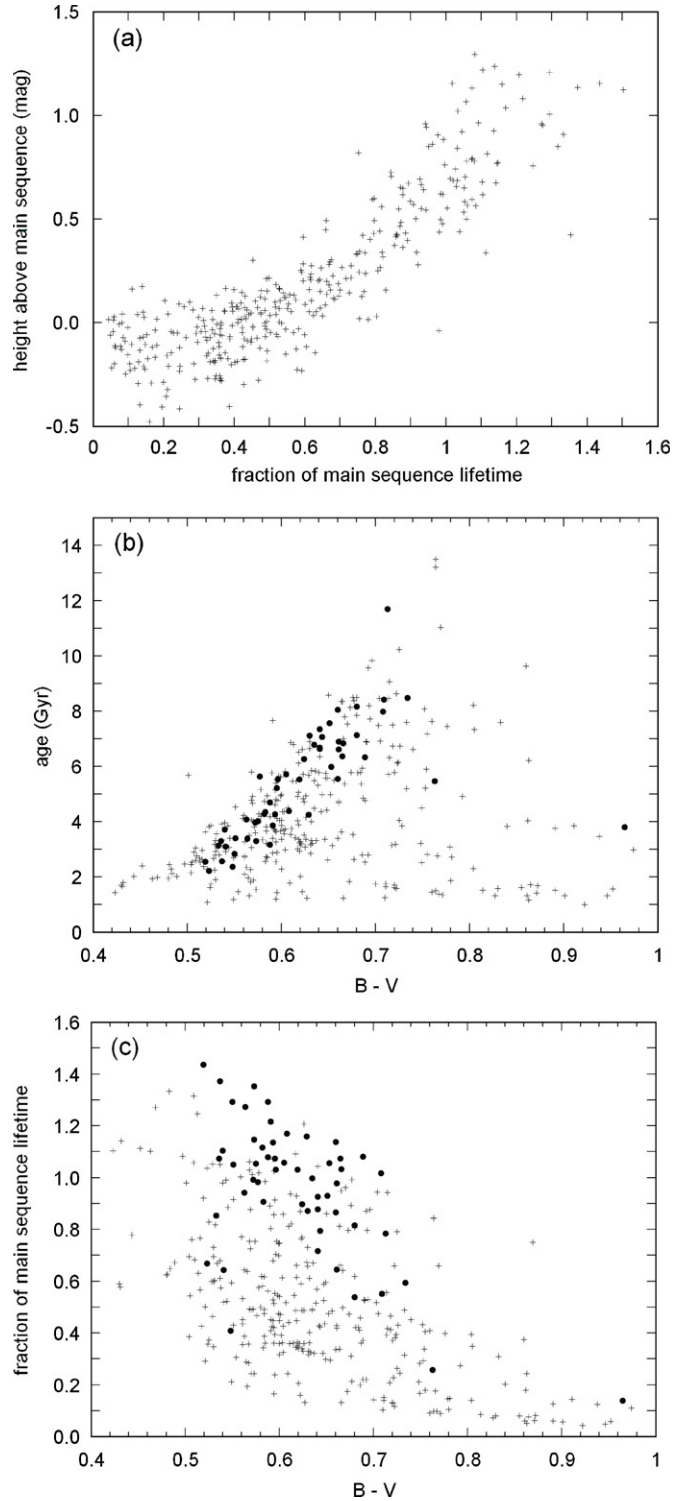

Figure 2. Isochrone ages derived for the near-solar-metallicity sample with $-0.56 < \Delta M_V < 1.3$: (a) as fraction of time already spent on the main-sequence f_{MS} plotted against ΔM_V; (b) in Gyr vs. $B - V$; and (c) as f_{MS} vs. $B - V$. Circles depict inactive stars with log $R'_{HK} < -5.02$; crosses depict all others.

the HMS. A parabolic regression through this scatter diagram yields a correlation of $R = 0.893$. In these isochrone estimates, the median uncertainty in derived age is 1.83 Gyr, or 51%. The median uncertainty in derived f_{MS} is 0.185, or 38%.

Figures 2(b) and (c) show the isochrone ages as a function of $B - V$. In these figures, we differentiate between inactive stars having log $R'_{HK} < -5.02$ and the rest of the sample. The very inactive stars tend to have more advanced ages for their color index, and most are in the second half of their main-sequence lifetime, if not already evolving off the main sequence. This figure emphasizes the most important caution when using HK flux to identify a possible MM analog candidate: many stars with very low activity, even if on the main sequence, may just be older stars, per the well-known age–activity relation originally reported by Skumanich (1972).

4. DISCUSSION

If we proceed with the assumption that any of our stars that are on the main sequence might be considered as MM analog candidates if their activity is low enough, then the next task is to choose an appropriate threshold for classification as "very inactive." Here we consider two possibilities. Judge & Saar (2007) suggest that the stringent threshold used by Wright (2004) should be modified to $\log R'_{\rm HK} \leqslant -5.08$ for stars with near-solar metallicity. Alternatively, White et al. (1992) estimate the HK activity level for an inactive Sun with magnetic network removed and contributions only from the supergranulation cells. This is analogous to the peak of the Skumanich et al. (1975) distribution in the Ca^{+} K core brightness, mapped over the quiet Sun. White et al. (1992) give a Mt. Wilson S-value (Duncan et al. 1991) of 0.156 ± 0.007, which corresponds to $\log R'_{\rm HK} = -5.02$ at solar $B - V = 0.656$, following the conversion procedure described by Henry et al. (1996), Wright (2004), and references therein. In $\log R'_{\rm HK}$ units, this threshold of $S = 0.156$ actually varies between -5.002 ($B - V = 0.59$) and -5.073 ($B - V = 0.85$). The dependence of this threshold $\log R'_{\rm HK}$ on $B - V$ described by Henry et al. (1996) and Wright (2004) is well represented by a third-order polynomial,

$$\log R_{\rm HK} = -3.6069 - 5.3981\,(B - V) + 7.0141\,(B - V)^2 - 3.1689\,(B - V)^3\,,$$

with regression coefficient $R = 0.99986$.

Figure 3(a) shows the activity distribution in Mt. Wilson S-units for all near-solar-metallicity stars with $f_{\rm MS} < 1.0$. Many of these stars are very active, and therefore should not be regarded as analogs of the present-day Sun for purposes of MM frequency estimation (cf. Baliunas & Jastrow 1990). According to White et al. (1992), the largest activity value measured by Skumanich et al. (1975) on the disk of the quiet Sun is equivalent to $S = 0.263$. Therefore, we consider only stars with S-value below this limit in our estimation of MM frequency. Figures 3(b) and (c) show the distributions of our isochrone ages $f_{\rm MS}$, for all $f_{\rm MS} < 1.0$, in solar range ($0.156 \leqslant S < 0.263$), active ($S \geqslant 0.263$), and very inactive ($S < 0.156$) categories. This figure demonstrates overall consistency in our isochrone age estimates with the age–activity relation (Skumanich 1972), in that most of the active stars are considerably younger than the present-day Sun.

Of our 206 stars with age estimates $f_{\rm MS} < 1.0$, and $0.59 < B - V < 0.85$, 155 have $S < 0.263$. For an estimation of MM frequency, we should include only stars with $\Delta M_V < 0.5$, for additional confidence that they are on the main sequence (Figure 2(a)). This leaves 135 stars. From this subsample, the numbers of stars with $S < 0.156$ and $\log R'_{\rm HK} \leqslant -5.08$ are 15 (11.1%), and 4 (3.0%), respectively. If we follow the common paradigm that the fraction of very inactive solar-type stars in a given sample is analogous to the fraction of the Sun's lifetime spent in a grand minimum state, then this fraction depends very strongly on the threshold chosen for labeling a star as very inactive. If we use the quiet-Sun threshold $S < 0.156$, then the canonical 70 yr duration of this historical MM suggests a 1/630 chance in any given year of entering an equivalent new grand minimum. We are now ∼300 yr after the end of the

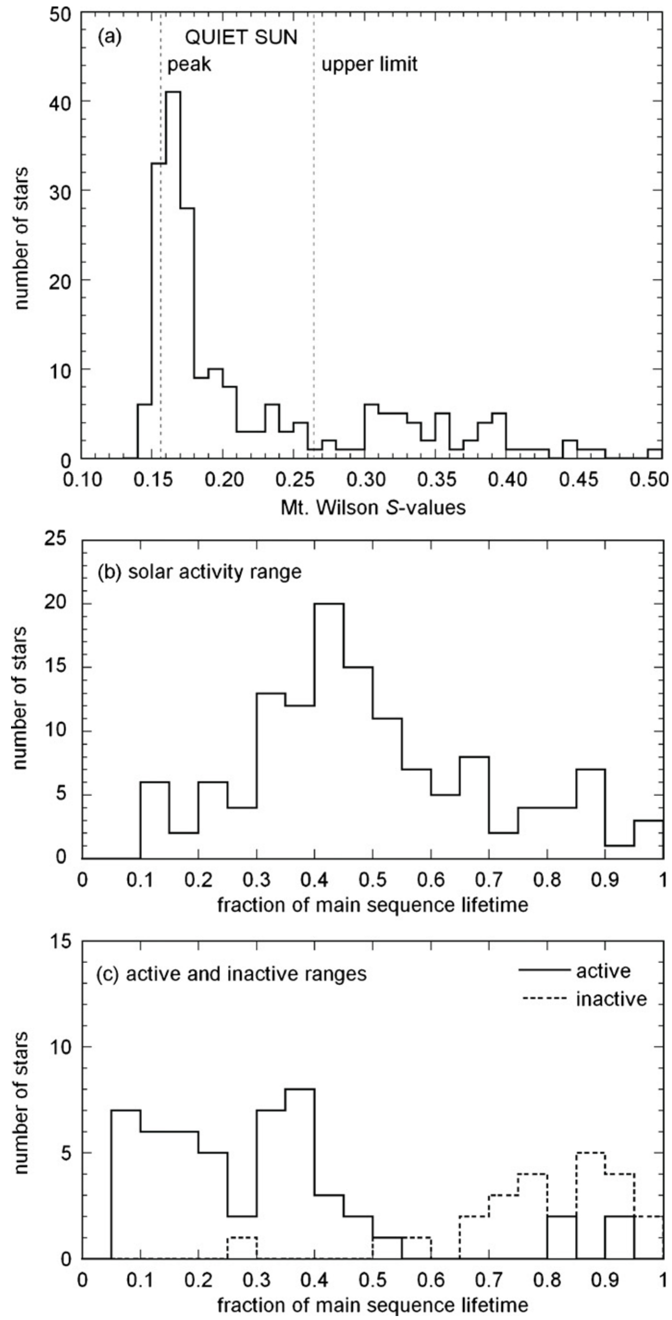

Figure 3. (a) The distribution of chromospheric activity, in Mt. Wilson S-values, for the near-solar-metallicity sample with isochrone ages $f_{\rm MS} < 1.0$. Bins are of width 0.01 and begin vertically at their lower bound. The vertical dashed line at $S = 0.156$ indicates the peak of the quiet-Sun activity distribution (Skumanich et al. 1975) used herein as one possible threshold below which a star might be considered very inactive. The vertical dashed line at $S = 0.263$ indicates the maximum value in HK flux distribution observed on the surface of the quiet Sun (White et al. 1992). In our estimate of the fraction of the Sun's lifetime spent in MM-like states, stars with $S > 0.263$ are considered too active (young) to be analogs of the present-day Sun and are omitted from consideration. (b) Distribution in isochrone-derived $f_{\rm MS}$ for the most Sun-like stars in the near-solar-metallicity sample, having $0.156 < S \leqslant 0.263$. (c) Distribution in isochrone-derived $f_{\rm MS}$ for both active ($S > 0.263$) and very inactive ($S \leqslant 0.156$) stars in the near-solar-metallicity sample. Bins in (b) and (c) are of width 0.05 and begin vertically at their lower bound.

Table 1
Stars from the Near-solar-metallicity Sample Identified as Possible Maunder Minimum Analog Candidates Based on Chromospheric Activity below Either of the Thresholds Described in the Text

Identifier		Observed Properties			Isochrone Estimates		
HD	HIP	$B-V$	ΔM_V	$\log R'_{\rm HK}$	$m/m_\odot$	Age (Gyr)	$f_{\rm MS}$
10307	7918	0.618	0.137	−5.02	1.02	6.13	0.662
34411	24813	0.630	0.485	−5.05	1.04	7.13	0.872
49736	32874	0.600	0.334	−5.01	1.09	4.98	0.749
93385	52676	0.595	0.091	−5.01	1.07	4.13	0.553
95128	53721	0.624	0.339	−5.02	1.04	6.26	0.771
97037	54582	0.613	0.318	−5.02	1.04	6.80	0.821
115617	64924	0.709	0.068	−5.04	0.92	8.43	0.551
135204	74537	0.763	0.078	−5.11	0.91	5.48	0.258
157347	85042	0.680	0.145	−5.04	0.96	7.14	0.539
166553	89269	0.599	0.332	−5.01	1.09	4.94	0.746
168009	89474	0.641	0.214	−5.08	1.00	7.36	0.717
168746	90004	0.713	0.402	−5.05	0.92	11.71	0.784
186408	96895	0.643	0.432	−5.10	1.03	7.07	0.796
186427	96901	0.661	0.265	−5.08	0.99	6.91	0.646
218133	114028	0.597	0.244	−5.02	1.07	5.66	0.754

last MM, and the probability of not entering another MM at present is 0.62. This probability decreases to 0.58 by the year 2050 and to 0.54 by 2100. The "core" of the historical MM—the period with consistently near-zero sunspot number—lasted from approximately 1655–1700. Using this duration with the quiet-Sun threshold, the chance of entering a new grand minimum in any given year becomes 1/405. If we use the more strict threshold fixed at $\log R'_{\rm HK} \leqslant -5.08$, then grand minimum events remain nearly as infrequent as suggested by Wright (2004). We suggest adopting the quiet-Sun threshold $S < 0.156$ of White et al. (1992), as it appears to have a rigorous physical basis in direct mapping of solar magnetic activity. However, the issue remains unresolved and may be difficult to resolve given the limited data available from the historical MM.

Table 1 contains the 15 stars from our sample that may be very inactive, ranked in priority order as MM analog candidates based on isochrone age $f_{\rm MS}$. Three of these stars are reported in the study of Hall et al. (2009), and the activity and photometric time series from their data are shown in Figure 4. In these plots, the scale of the right vertical axis spans a typical range for a photometrically active star, and the scale of the left vertical axis spans a typical range for a star varying from very inactive to slightly above present-day solar activity levels. The time series for HD 95128 is short and shows no evidence of deviation from a very inactive and photometrically quiet star. Both HD 10307 and HD 168009 remain photometrically quiet over ten years, but also show chromospheric excursions from very inactive into the normal solar active range. Hall et al. (2009) specifically discuss HD 168009 in this respect. The photometric data for these two stars may be consistent with a transient, weakly cycling and lower luminosity state analogous to a grand minimum, but the activity time series are not. This suggests that instantaneous activity measurements might be useful for identifying stars that deserve longer-term study (particularly photometric observation), as opposed to conclusively identifying MM analog candidates.

Hall et al. (2007, 2009) have questioned the validity of using instantaneous measurements of very low Ca HK flux as conclusive indicators of grand minima in solar-type stars, based on the range of mean activity levels they observe in non-cycling stars, and the general lack of correlation between activity and photometric variation in their sample. Here we reach a similar conclusion, but for two additional reasons. First, even if a star's main-sequence membership and metallicity can be determined, the threshold for "very inactive" classification is still uncertain. Second, as illustrated by Figure 2, a star appearing "very inactive" may just be an older star nearing the end of its main-sequence lifetime. This is an important consideration given the typical measurement uncertainty in $\log R'_{\rm HK}$ of ∼0.09 in this type of stellar sample (Judge & Saar 2007).

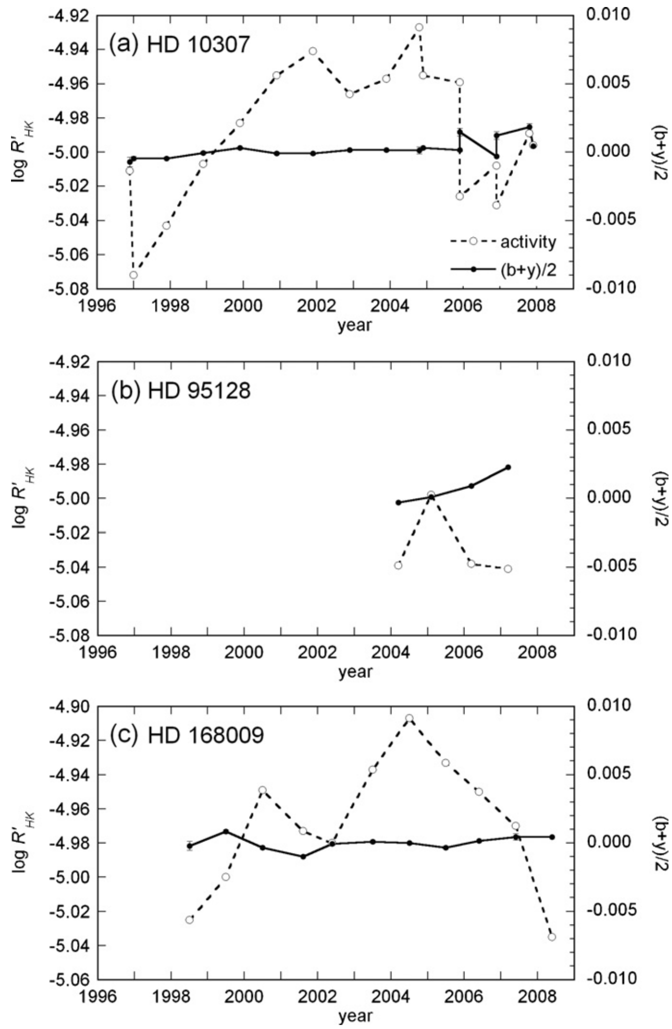

Figure 4. Time series of $\log R'_{\rm HK}$ and photometric variability from Hall et al. (2009), for three stars in Table 1 monitored by the Lowell and Fairborn Observatory programs. In the photometric data, error bars (1σ) that do not appear are within the diameter of the symbols.

We therefore recommend that the best use of instantaneous chromospheric activity measurement is to identify stars that might be profitably added to target lists for long-term monitoring, to increase the chances of finding plausible MM analog candidates via cycling versus non-cycling time series. The historical MM was an example of very low stellar magnetic activity, with sunspot number near zero and weaker cycling than the present-day Sun. Despite the above-mentioned difficulties, very low activity in a solar-type star can still be considered suggestive of MM-like behavior, even if not entirely conclusive.

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