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HD 166620: Portrait of a Star Entering a Grand Magnetic Minimum

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Abstract

HD 166620 was recently identified as a Maunder minimum candidate based on nearly 50 years of Ca II H and K activity data from Mount Wilson and Keck HIRES. These data showed clear cyclic behavior on a 17 yr timescale during the Mount Wilson survey that became flat when picked up later with Keck HIRES planet-search observations. Unfortunately, the transition between these two data sets—and therefore the transition into the candidate Maunder minimum phase—contained little to no data. Here, we present additional Mount Wilson data not present in Baum et al., along with photometry over a nearly 30 yr baseline that definitively traces the transition from cyclic activity to a prolonged phase of flat activity. We present this as conclusive evidence of the star entering a grand magnetic minimum and therefore the first true Maunder minimum analog. We further show that neither the overall brightness nor the chromospheric activity level (as measured by S_{HK}) is significantly lower during the grand magnetic minimum than its activity cycle minimum, implying that an anomalously low mean or instantaneous activity levels are not a good diagnostic or criterion for identifying additional Maunder minimum candidates. Intraseasonal variability in S_{HK}, however, *is* lower in the star's grand minimum; this may prove a useful symptom of the phenomenon.

Unified Astronomy Thesaurus concepts: Stellar activity (1580); Maunder minimum (1015); Solar cycle (1487)

Supporting material: machine-readable tables

1. Introduction

The Maunder minimum was a period of extraordinarily low sunspot levels from roughly 1645–1715 (Eddy 1976). The nature of this apparent pause in the Sun's 11 yr sunspot cycle has implications for the nature of the solar dynamo and for our interpretations of sunspot records in other stars.

Data from the Mount Wilson HK survey (Baliunas et al. 1995) and later surveys revealed a population of apparently Sun-like stars with low and constant levels of activity, interpreted by Baliunas & Jastrow (1990), Saar & Baliunas (1992), Henry et al. (1996), and others as ordinarily cycling stars caught in a Maunder minimum–like state, or a "grand magnetic minimum" (Saar & Testa 2012).

Wright (2004), however, showed that most of these stars are actually slightly evolved, implying that they are not in extraordinary states of low activity in between normal cycling behavior, but old stars that have stopped cycling entirely as their dynamos die out.

In the model of Metcalfe & van Saders (2017), stars with mean activity levels near a threshold $\log R'_{\mathrm{HK}}$ value of −4.95 (Brandenburg et al. 2017) will episodically experience grand minima, a behavior that increases in frequency as the star's mean activity level drops, until it eventually becomes permanent.

Saar & Testa (2012) have a good discussion of the difficulties in identifying true Maunder minimum analog stars and show efforts to overcome these difficulties by studying the activity level, activity variability, and evolutionary state of stars. Donahue et al. (1995) identified HD 3651 as a candidate, based on the apparent weakening of its activity cycle, perhaps toward an extended long state.

Shah et al. (2018b) showed that the weakening of the cycle of HD 3651 had not continued into the 2010s but identified another star, HD 4915, that might be a better candidate because it showed three consecutively weaker activity maxima across 12 yr of data.

In the opposite vein, Mittag et al. (2019) observed an increasing trend in the activity-cycle amplitude in HD 140538. Mittag et al. (2019) point to this (and the slightly decreasing trend in the final years of data) as evidence of a longer ∼30 yr activity cycle on top of the 3.88 yr cycle. However, the earliest few observations from the Solar-Stellar Spectrograph (SSS) fall below the expected cycle maximum. Therefore, another plausible interpretation of the SSS data, which otherwise shows good agreement with other contemporaneous data sets, is that of a star caught *exiting* a magnetic grand minimum state.

More recently, Baum et al. (2022), hereafter B22, combined Mount Wilson HK project measurements with two sets of Keck HIRES planet search measurements to show that HD 166620 (stellar parameters given in Table 1) was once a strongly cycling star but since 2004 has low and constant levels of activity, a stark and dramatic change in behavior that would seem to be unambiguous evidence that it was in a Maunder minimum–like state.

Table 1
HD 166620 Stellar Parameters

Parameter	Value
$T_{\rm eff}$	4970 K
$\log g$	4.51
[Fe/H]	−0.16
$M_\star$	0.78 $M_\odot$
Spectral Type	K2V
Age	12.4 Gyr

Note. All stellar parameters from B22.

The dramatic change in behavior is perfectly coincident with a gap in observations between Mount Wilson and the upgraded HIRES instrument, inspiring B22 to thoroughly explore and reject the possibility of a mismatch or error in the identification of the star across the two projects.

Further astrophysical interpretation of the data set is also somewhat complicated by a potential calibration mismatch among the three sets of measurements; most stars in B22 appear to be well calibrated but a few required adjustments. It is thus unclear if the present-day activity level of the star is truly similar to its ordinary cycle minimum observed by Mount Wilson or if it could be at a different level.

Here, we present two additional sets of data that help bridge the gap between the B22 data sets and trace out the entrance into a grand magnetic minimum. The first is some published Mount Wilson data not considered by B22 showing the completion of the star's final cycle before the grand minimum, and the second is new optical photometry during both the end of the final cycle and the present-day grand minimum.

These data both confirm the reality of the transition and suggest the calibration in B22 is very good for this star, meaning that the star's grand minimum activity level is similar to that of its last few cycle minima.

2. Data

2.1. S_{HK} Activity from Mount Wilson and Keck HIRES (B22)

We primarily use the time series given in B22 that initially identified HD 166620 as a Maunder minimum candidate. These data span a 50+ yr baseline. The majority of the data come from the Mount Wilson (MW) program, courtesy of the "HK_Project_v1995_NSO" data set (Radick & Pevtsov 2018), which obtained 107 observations of this star using the "HKP-1" photometer from 1966 to 1977, and continued to obtain 1547 observations with the upgraded "HKP-2" photometer from 1977 to 1995. The California Planet Search later picked up this target, obtaining 9 observations in June–September of 1997 with Keck HIRES ("HIRES-1"), and again after the 2004 detector upgrade ("HIRES-2"), obtaining 103 spectra between 2004 and 2020 March. $S_{\rm HK}$ values were measured following Isaacson & Fischer (2010). There is no guarantee that the $S_{\rm HK}$ values across all four instruments (MW HKP-1, MW HKP-2, HIRES-1, and HIRES-2) have absolute agreement. B22 investigated the need for offsets between the various instruments and found that the Mount Wilson data (HKP-1 and HKP-2) appeared to agree without needing any offset. For the Keck HIRES data, the $S_{\rm HK}$ values from HIRES-1 in 1997 *do* appear to be higher than the later HIRES-2 $S_{\rm HK}$ values. However, the HIRES-1 data fail to establish a long enough time baseline for any conclusive evidence of an offset. Further inspection by eye hints that the higher HIRES-1 $S_{\rm HK}$ values could be consistent with both the Mount Wilson and HIRES-2 values, occurring during a transition from higher cycling activity in Mount Wilson to lower flat activity in Keck HIRES. Thus, no offsets were applied to the reported $S_{\rm HK}$ values in any of the four instruments in B22. This time series can be seen in the top panel of Figure 1.

2.2. Additional Mount Wilson S_{HK} Activity (Oláh et al. 2016)

Upon investigating this star further, we were made aware of additional observations from the Mount Wilson program that took place between 1995 and 2002. A nightly binned version of the full Mount Wilson data (from 1966 to 2002) were published in a figure in Oláh et al. (2016) and we have acquired this data courtesy of K. Oláh and W. Soon. After binning the B22 data, we compared them to the the Oláh et al. (2016) data during the overlapping time (1966–1995) and in general found very good agreement in both the timestamp and $S_{\rm HK}$. We do note, however, that the timestamps do not agree to within 0.5 days. The cause for this discrepancy is not fully understood, as both data sets contain observations at times of day when the star would not have been visible from Mount Wilson. We notice that applying a 0.5 day offset to the B22 data prior to JD 2,444,000.5 and a −0.5 day offset to the Oláh et al. (2016) data after this date removes a first-order discrepancy. We attribute this discrepancy to previous MJD/JD conversion errors. Plotting the time of day versus the time of year for the observations in Oláh et al. (2016) after JD 2444000.5 reveals an additional perplexing structure that repeats on a 4 yr timescale and includes times when the star would not have been observable. We therefore choose to retain the B22 data for observations prior to 1995 June 4 (the final MW observation in that data set). We use the MW data in Oláh et al. (2016) for observations after that date. Since our results are insensitive to these small timestamp differences, we do not apply any adjustments to the timestamps in either data set and report the values as we inherited them to avoid creating yet another time series that may add future confusion. The new MW data therefore span from 1995 June to 2002 June and contain 158 observations. The additional MW data from Oláh et al. (2016) can be seen in the second panel of Figure 1. All activity data are presented in Table 2.

2.3. Photometry from the T4 Automated Photoelectric Telescope

We acquired 1278 photometric observations of HD 166620 covering 17 observing seasons from 1993 to 2020 (we did not observe the star during the 2005 through 2015 observing seasons). The observations were all obtained with the T4 0.75 m automatic photoelectric telescope (APT) at Fairborn Observatory in southern Arizona. The T4 APT is equipped with a single channel photometer that uses an EMI 9124QB bi-alkali photomultiplier tube to measure stellar brightness successively in the Strömgren *b* and *y* passbands.

The observations of HD 166620 (star d) were made differentially with respect to three nearby comparison stars (a, b, and c). Intercomparison of the six combinations of differential magnitudes (d–a, d–b, d–c, c–a, c–b, and b–a) reveals that only comparison star b (HD 166640) appears to be constant to the limit of our precision. Therefore, we present our results as

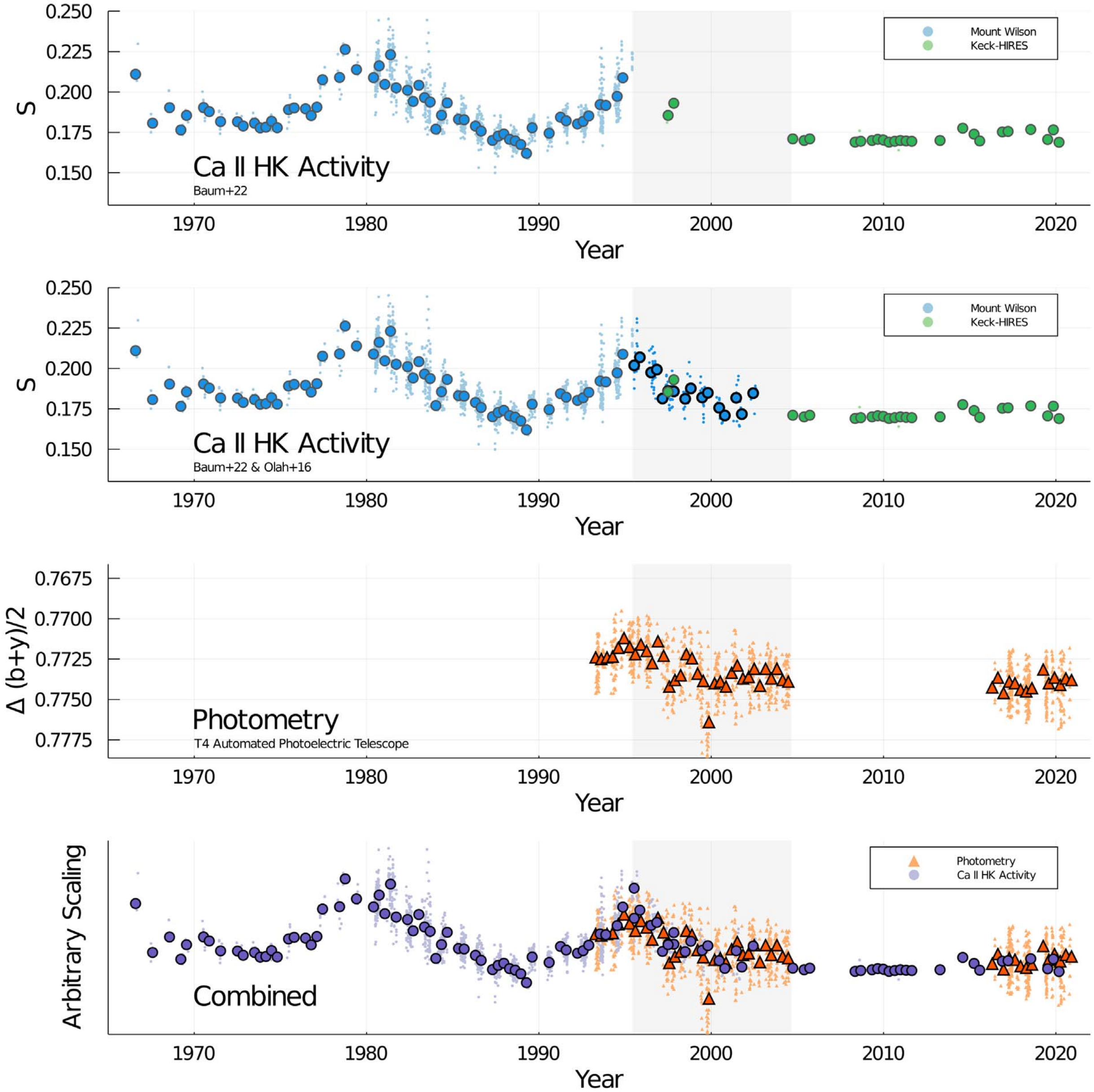

Figure 1. Photometry and S_{HK} time series for HD 166620 showing transition into Maunder minimum. The top panel shows the S_{HK} time series from B22 used to identify HD 166620 as a Maunder minimum candidate. Blue points are data from the Mount Wilson program; green points are from Keck HIRES. Large circles show the same data in 120 day bins. The gray shaded region indicates the gap between the Mount Wilson data and the post-2004 HIRES data (after the upgrade). The second panel shows the same data, but now includes the additional Mount Wilson data from Oláh et al. (2016), which fills in the previous gap and shows the clear transition from activity maximum to flat activity seen in Keck HIRES. The third panel shows the T4 APT photometry, which similarly shows a transition from brighter to fainter during the transition period. Recent data (2016 onwards) are at roughly the same magnitude as at the end of the transition. The bottom panel places the activity and photometry on the same scale by subtracting off the median of pre-2004 data, and multiplying the photometry by a scale factor of 10. The activity and photometry time series show remarkable agreement and unambiguously show a star transitioning from cycling to flat behavior.

Table 2
All S_{HK} Activity Data

BJD	Year	S_{HK}	Inst
2439342.80	1966.5926	0.211	MW
2439369.81	1966.6666	0.207	MW
2439392.80	1966.7296	0.2298	MW
2439669.80	1967.4885	0.1751	MW
2439670.79	1967.4912	0.1863	MW
⋮	⋮	⋮	⋮

Note.
(This table is available in machine-readable form.)

differential magnitudes in the sense of star d minus star b, which we designate as d–b.

To improve the photometric precision of the individual nightly observations, we combine the differential b and y magnitudes into a single $(b+y)/2$ "passband." The precision of a single observation with T4, as measured from pairs of constant comparison stars, typically ranges between 0.0015 mag and 0.0020 mag on good photometric nights. The T4 APT is described in Henry (1999), where further details of the telescope, precision photometer, and observing and data reduction procedures can be found.

Table 3
T4 APT Photometry

BJD	Year	$d - b$	Inst
2449094.91	1993.29153	0.7746	APT
2449102.92	1993.31348	0.7724	APT
2449103.89	1993.31613	0.7739	APT
2449105.88	1993.3216	0.7728	APT
2449108.88	1993.32981	0.7746	APT
⋮	⋮	⋮	⋮

Note.
(This table is available in machine-readable form.)

We compute the standard deviations of the nightly observations for each observing season, which range from 0.0009 to 0.002 mag, indicating little or no short-term variability within each observing season. We also compute the seasonal means and perform a frequency analysis of each individual observing season using the method of Vaníček (1971), which confirms the lack of any periodic variability. Henry et al. (2022) show extensive examples of this method of period analysis.

The APT photometry can be seen in the third panel of Figure 1 and are given in Table 3.

3. Analysis

3.1. Activity Time Series

Considering only the S_{HK} time series from the combined B22 and Oláh et al. (2016) data, we see excellent agreement between all data sets and instruments. These data paint a picture of a star fully transitioning from cycling behavior to flat behavior, indicative of the beginning of a Maunder minimum–like phase.

As a result, we can conclude that the HIRES-1 data (the pre-upgrade Keck HIRES data in 1997) are consistently calibrated with both the HIRES-2 observations and all Mount Wilson observations, thus dispelling any doubts about potential offset errors between the Mount Wilson and Keck-HIRES data, while also confirming that these are observations of the same star.

We can then examine the activity level during its grand magnetic minimum as compared to the activity minima during cycling behavior. We identify two cycle minima prior to the transition period: the minimum occurring from 1971 to 1975 and the minimum occurring from 1986 to 1990. The mean activity level during the first minimum (1971.0–1975.0) is $S_{HK} = 0.181 \pm 0.004$. The second minimum (1987.0–1991.0) has a mean activity level of $S_{HK} = 0.172 \pm 0.006$. The period of flat activity (2004 onwards) has a mean activity level of $S_{HK} = 0.171 \pm 0.002$. Thus, the period of flat activity associated with the grand magnetic minimum is not significantly lower than what the star exhibits during regular cycling behavior. However, these values also suggest that the cycle minima decayed in the final cycles before the transition into grand magnetic minimum (and this is also suggested by the decaying cycle maxima in 1980 and 1995). Thus, it may be the case that we have caught this star at the end of a much larger interval of decaying cycles.[8] Without a longer time baseline prior to 1966, it is impossible to tell whether that is part of a larger trend. Either way, these results imply that the grand magnetic minimum is not the result of a qualitatively different surface magnetic field than is present during regular activity cycles. We do note, however, that the variability in the grand minimum *is* significantly lower than during either preceding cycle minimum. In the Sun, S_{HK} in cycle minima are dominated by the roughly spatially uniform network, with occasional small active regions providing limited variability (e.g., Milbourne et al. 2019). If we assume that cycle minima in HD 166620 are similarly dominated by the network, the lower S_{HK} variability observed during the grand minimum is consistent with the hypothesis that there were even fewer active regions during this time.

We need to be careful though, as the S_{HK} data from the Mount Wilson and Keck programs have different average noise levels. Baliunas et al. (1995) give $\sigma_S \approx 1.2\%$ from observations of their least variable stars. Wright et al. (2004) give a similar value for their differential S_{HK}; when looking on the timescale of a single season, however, it seems this is an overestimate. The calculated σ_S is less than this in six of the nine seasons with more than one S_{HK}(Keck) measurement. The lowest seasonal σ_S values approach 0.3%; we adopt this as an upper limit to the seasonal noise for Keck. If we subtract these estimates of the random noise on S_{HK} in quadrature from the observed values, we have $\sigma_S(\text{min. }1) = 0.0027$, $\sigma_S(\text{min. }2) = 0.0054$, and $\sigma_S(\text{grand}) = 0.0019$. Even when corrected for intrinsic noise differences, the variability in the grand minimum is still significantly lower than preceding minima; for example, an F-test gives 8.78×10^{-6} chance that σ_S(grand) is drawn from the same distribution as σ_S(min. 1).

3.2. Combined Photometry and S_{HK}

We combined the APT photometry and S_{HK} onto a common scale in the bottom panel of Figure 1. To do so, we subtracted off the median of each data set prior to 2004, choosing to center the data on the cycling portion of the time series. We then multiplied the APT photometry by a scale factor of 10 to cover a similar range to S_{HK}, chosen arbitrarily by eye (scale factors of 8–12 all looked similarly consistent). The resulting combined time series show excellent agreement between activity and brightness, showing that when the star transitioned from cycling to flat behavior, the star also became slightly fainter. Its mean brightness varied for the first several years over a range of 2–3 mmag. After 2004, the scatter in the mean magnitudes is only 0.35 mmag. Combined with the scarcity of strong rotationally modulated signals in either the activity or photometry, we see this as evidence that the star is not dominated during active periods by spots, but rather by faculae and a network of bright magnetic regions (as seen on the Sun, e.g., Milbourne et al. 2019) that lead to the star dimming as it decreases in activity. Similar correlations and interpretations have been made for other stars, e.g., Lockwood et al. (2007).

3.3. Period Analysis of the HK Data

We computed a floating-mean Lomb–Scargle periodogram for each season of data containing more than 10 observations. We searched for significant (false alarm probability (FAP) $\leqslant 5 \times 10^{-5}$) periodogram peaks near (within $\pm \approx 20\%$) the previously reported mean period ($P_{rot} = 42.4$ days; Donahue et al. 1996). Since double active longitudes are common, especially in less active stars (Basri & Nguyen 2018),

[8] This interpretation lends additional evidence that HD 4915 (Shah et al. 2018a) may soon be entering its own grand magnetic minimum.

we also searched for significant periods within ±20% of $P_{rot}/2 = 21.2$ days. We compared the results with computed harmonics and the data window function to discard aliases. We found a total of nine seasons with significant periods, yielding an unweighted average (including doubled $P_{rot}/2$ detections) of $\langle P_{rot}\rangle = 45.06 \pm 4.07$ days. The full range of detections spanned from 37.96 days to 50.99 days. The scatter of P_{rot} values likely reflects a complex combination of surface differential rotation, plus activity growth and decay. This updated P_{rot} and range should improve on the value given in Donahue et al. (1996), as it includes more seasons (nine versus seven), while discarding some less certain previous P_{rot} values by using a more stringent FAP threshold.

4. Discussion and Conclusions

The dramatic nature and suspicious timing of the change in behavior of HD 166620 led B22 to explore the possibility of a misidentification of stars between the two sets, and the presence of offsets among the HIRES and Mount Wilson data for a few stars raised questions about the strength of conclusions one can draw about the relative activity levels before and after this change.

The new Mount Wilson data here are contemporaneous with the pre-2004 HIRES data in B22 and are consistent with it, demonstrating that the mutual calibration there is robust, and that the HIRES data do show the end of the star's last activity cycle.

Our new photometry spans the pre- and post-2004 HIRES data, and shows qualitatively and quantitatively the same behavior, that is, a consistent and positive correlation between the star's optical brightness and Ca II H and K activity level. A possible exception is in seasonal variability in S_{HK}, which is notably lower in the grand minimum. Together, these photometric data span the three data sets of B22, removing any concern that the sets might not be of the same star or that large calibration offsets exist among them.

The cosmogenic isotope Be^{10}, produced by cosmic rays that are modulated by the changing large-scale solar magnetic field, seem to show clear evidence for cycle-timescale modulation that is well correlated with the sunspot number in modern records, but which continues to show clear and strong cycling behavior during the Maunder grand minimum (1645–1715; Beer et al. 2018, their Figures 2 and 3), despite the small number of sunspots and lack of periodicity in their numbers then. Beer et al. (2018) suggest this is because Be^{10} production is more closely related to magnetic field global geometry than global field strength, and that the global geometry continued to cycle even when the surface field was too weak to produce sunspots.

We see no clear evidence of variability in either S or in photometry in HD 166620 after ≈2005. It is possible that cyclic activity of some type continues on HD 166620 below our current ability to clearly detect it; indeed, the tiny, poorly resolved increase in S in 2014 may be a hint of such residual activity. At any rate, since they both trace surface magnetic activity, one would expect our H and K measurements to trace starspot number better than global field geometry.

We conclude that HD 166620 is the first unambiguous Maunder minimum analog, identified by its activity time series as it switched from a cycling to a flat-activity state. Its activity history shows that, at least in this case, the average activity level in grand activity minima like the Maunder minimum is not significantly lower than a star experiences when cycling, complicating efforts to identify such stars via their mean or instantaneous activity levels. Lower variability in S_{HK}, though, may prove useful in diagnosing grand minima; more observed minima are needed to test this, however.

This also implies that the grand minimum is not the result of a dramatically weaker surface magnetic field than is present during ordinary magnetic minima, for instance due to a complete collapse of the dynamo, but is essentially an ordinary minimum extended in time, perhaps with fewer residual active regions to explain the further reduced variability. This interpretation is consistent with the fact that the Sun had a small number of sunspots during the Maunder minimum (e.g., Ribes & Nesme-Ribes 1993) and that cosmogenic Be^{10} continued to vary (modulated by changing solar field topology, e.g., Beer et al. 1998) showing that the surface magnetic fields were still present then.

We also note that the mean activity level of HD 166620 is $\log R'_{HK} = -5.03$ (Brewer et al. 2016),[9] which is at about the level identified by Brandenburg et al. (2017) and Metcalfe & van Saders (2017) as the threshold for experiencing Maunder minimum behavior. Furthermore, taking $P_{rot} = 42.4$ days (Donahue et al. 1996) or our revised $P_{rot} = 45.06$ days, the star's Rossby number is slightly larger than the Sun's (2.08 or 2.21 versus 1.99 using a turnover time τ_C from Noyes et al. 1984). This is consistent with it being slightly older[10] and less active than the Sun, and also consistent with their model.

The star was observed with ROSAT HRI in late 1996, just past the last cycle maximum; it displayed an X-ray luminosity of $\log L_X = 26.96$ (Schmitt & Liefke 2004). Adopting $R = 0.80\ R_\odot$ (Brewer et al. 2016), this L_X implies a surface flux of $F_X = 4.7 \times 10^4$ erg cm^{-2} s^{-1}, a value above the minimum level seen in dwarfs ($F_X = 10^4$ erg cm^{-2}s^{-1}; Schmitt & Liefke 2004), but less than the average solar level of $F_X \approx 1.3 \times 10^5$ erg cm^{-2} s^{-1} (converted from the average L_X from Judge et al. 2003). This again, together with our updated rotation period of $P_{rot} = 45.06$ days, is consistent with a star older and less active than the Sun, perhaps with a similarly faltering dynamo (Metcalfe & van Saders 2017).

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[9] $\log R'_{HK} = -5.07$ after correcting for metallicity following Saar & Testa (2012).

[10] Note that simple Barnes (2007)-style gyrochronology should still be valid for HD 166620, since with $T_{eff} \approx 4970$K (Brewer et al. 2016), the star is warmer than the zone of spin-down "stalling" (see Curtis et al. 2020).

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