Non-Radiative Heating in “Flat Activity” Stars

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Abstract:

The Mount Wilson Ca II program has identified a group of stars with very low level, non-variable chromospheric emission over the ~25 year survey. Many of these stars are very likely in the stellar analog of the solar Maunder minimum — a period when the normal cyclic (αΩ) dynamo was in temporary quiescence. I study UV and X-ray emission for a sample of these “flat activity” stars. While their chromospheric Ca II and C II emission is consistent with “basal” (possibly acoustic) flux levels, and increase with $T_{\text{eff}}$, their transition region (TR) and coronal fluxes 1) are lower than in normal cyclic stars, 2) increase towards cooler $T_{\text{eff}}$, and 3) are independent of rotation. The TR and coronal fluxes thus appear to be formed by a largely non-acoustic process which is weak, non-variable, and depends on mass (convection zone depth) rather than rotation. These properties are consistent with magnetic heating due to a turbulent, distributed, convection zone dynamo. Turbulent dynamos thus likely operate at some level in all cool stars. I discuss implications of these results for dynamos and magnetic activity in late-type stars.

1. Introduction

Early on in the analysis of the Mount Wilson data (e.g., Baliunas & Vaughan 1985), it was clear that the time series of Ca II HK $S$ values for a given star could be characterized as being either irregularly variable, periodically variable, or non-variable. The irregularly variable stars typically showed the highest $\langle S \rangle$ and shortest rotation periods (at a given $T_{\text{eff}}$) and appeared to be the youngest. The cyclically variable (like the present Sun) exhibited a wide variety of cycle amplitudes, periods, and shapes, but typically showed more modest $\langle S \rangle$ and longer $P_{\text{rot}}$ than the irregular variables, implying they also were older. A few of the more active of these appeared to have multiple cycle periods.

The non-variable, or “flat activity” (FA) stars, comprising $\approx 15\%$ of the total Mount Wilson sample (Baliunas et al. 1995a, hereafter Bea95), are a bit more mysterious. Are their magnetic dynamos completely dead, or merely in temporary quiescence, as during the solar Maunder minimum? In this paper, I will examine this question, and explore what kind of magnetic activity (if any) remains in these stars. Some of this work is the result of collaboration with E. DeLuca, R. Donahue, and S. Baliunas at SAO (Saar et al. 1996; 1997).
2. "Flat Activity" Stars: What Are They?

Straightforward interpretation of the minimal $S$ values of FA stars in an activity-age relation (e.g., Donahue 1993) implies that they are among the oldest stars in the Mount Wilson sample. This in turn suggests an evolution over time from irregular variation $\rightarrow$ cycles $\rightarrow$ non-variability (e.g., Saar et al. 1994). Lack of activity and cycles in FA stars might then plausibly be due to dynamos which have completely ceased to function — perhaps (for example) because rotation has fallen below some critical value needed to sustain cyclic dynamo action.

There is another interpretation, however. Baliunas & Jastrow (1990) began with a sample of stars with strictly solar-like Ca II HK $S$ indices and colors ($0.13 \leq S \leq 0.20$, $0.60 \leq B - V \leq 0.76$, corresponding to ages $3 \text{ Gyr} \leq t \leq 10 \text{ Gyr}$ and spectral types $\sim$ G0 V–G8 V). They noted that the distribution of $S$ values (averaged in 0.1 year intervals) for this sample was distinctly bimodal, with a broad distribution at higher $S$ of predominantly time-varying stars, and a narrow peak at low $S$ of largely constant stars. They suggested that the FA stars dominating in the narrow, low $S$ group are actually in the stellar analog of a magnetic "grand minimum" on the Sun — a period (viz. the Maunder minimum) when the normal solar cycle vanishes or is drastically reduced (at least as reflected in sunspot number and proxies like terrestrial radiocarbon measurements; e.g., Damon 1977). They argued that FA stars are more likely in grand minima, rather than old stars with "dead" dynamos, because

1. FA stars exhibit a range of $v \sin i$, suggesting a range of ages, and

2. very old stars exist (e.g., HD 103095, age $t \geq 10$ Gyr; Smith, Lambert, & Ruck 1992) which have clear cycles, indicating dynamos may continue even for $t \gg t_\odot$.

Baliunas & Jastrow (1990) found that the implied fraction of inactive solar-like stars in grand minima $(\sim 30\%)$ is similar to the fraction of time the Sun appears to be in such a state, based on radiocarbon records (Damon 1977), lending further support for the hypothesis that most or all FA stars are in grand minima. Recent observations of the solar-age cluster M 67 (Baliunas et al. 1995b) reveal a similar pattern of behavior $(\sim 25\%$ in a FA state).

These arguments can be further strengthened, as several of the FA stars now have measured $P_{\text{rot}}$ values (Baliunas, Sokoloff, & Soon 1996), and more stars have well determined cycle characteristics (Bea95). I first compare the distribution of rotation among FA and non-FA stars similar to the Sun. To be certain the stars are solar-like (following Baliunas & Jastrow 1990), I restrict the range of $B - V$ color, and the range of HK activity to less than the solar level at a typical cycle maximum. I use the normalized, photosphere corrected HK flux, $R'_{\text{HK}}$ (Noyes et al. 1984, hereafter Nea84) to define activity instead of $\langle S \rangle$, thereby removing the effect of the photospheric background on $\langle S \rangle$ to first order. This permits safer comparison of solar-like stars over a range of $T_{\text{eff}}$. The solar-like sample is composed of all stars from the Mount Wilson survey (Bea95) with $(R'_{\text{HK}} \leq R'_{\text{HK}(\odot, \text{max})} \sim 1.35(R'_{\text{HK}(\odot)} \approx 1.7 \times 10^{-5})$ and with $0.54 \leq (B - V) \leq 0.76$ ($\sim$ F8 V – G8 V). I broaden the definition of the FA group to include those stars in Table 1 of Bea95 with $\Delta S/(S) \leq 1.5\%$ (all appear essentially non-variable, though some are classified as long timescale
variables in Bea95). Since $R'_{HK}$ is correlated with the inverse Rossby number $\text{Ro}^{-1} = \tau_{\text{conv}}/P_{\text{rot}}$ (Nea84; $\tau_{\text{conv}}$ is the empirical convective turnover time), I use it as the measure of rotation (and avoid the sin $i$ uncertainty of $v \sin i$ data).

Comparison of Ro$^{-1}$ values for the FA and inactive non-FA stars in the solar-like sample indicates that FA stars do not have a significantly different Ro$^{-1}$ distribution (Figure 1, left). This in turn suggests that the FA and non-

![Graph showing distribution of Ro$^{-1}$](image)

Figure 1. Left: The distribution $N(\text{Ro}^{-1})$ of the inverse Rossby number $\text{Ro}^{-1} \equiv \tau_{\text{conv}}/P_{\text{rot}}$ ($\tau_{\text{conv}}$ given by Nea84) for stars with normalized Ca II HK flux $R'_{HK} \leq 1.7 \times 10^{-5} (\sim R'_{HK}(\odot, \text{max}))$ and $0.54 \leq (B-V) \leq 0.76$. Stars which have “flat activity” (FA) stars (solid histogram) are compared with non-FA stars (dashed) from the same sample; binning is 0.1 in Ro$^{-1}$. Right: The cumulative distributions for the FA (solid) and non-FA (dashed) stars yield a probability (using a K-S test) of $p \sim 95\%$ that the FA stars are drawn from the same distribution as the non-FA stars.

FA stars are not of significantly different age either, due to the well-known relationship between $t$ and rotation.

The stellar age can be roughly estimated by using the function connecting $t$ and $R'_{HK}$ derived by Donahue (1993),

$$\log t = 10.725 - 1.334R_5 + 0.4085R_5^2 - 0.0522R_5^3$$  \(1\)

(where $R_5 = 10^5 R'_{HK}$ and $t$ is in years). If FA stars are in grand minima, however, their $R'_{HK}$ values are temporarily reduced, and (1) will overestimate their ages. One way to derive a more accurate age calibration for FA stars is to convert (1) into an age – Ro$^{-1}$ relation. I have derived a new exponential fit (cf. Nea84) to the correlation between ($R'_{HK}$) and Ro$^{-1}$, using observed $P_{\text{rot}}$ values from (in order of preference) Donahue et al. (1996, 1997) and Baliunas et al. (1996). To avoid biasing the fit, I have neglected all FA stars and all stars with low $\Delta S/\langle S \rangle$ ($\leq 1.5\%$) from Table 1 of Bea95. I find

$$R'_{HK} \approx 5.80 \times 10^{-5} e^{-0.791\text{Ro}}$$  \(2\)

with an RMS of $5.5 \times 10^{-6}$ (for 71 stars). Substitution of (2) into (1) yields

$$\log t = 10.725 - 7.740X + 13.751X^2 - 10.195X^3$$  \(3\)
where $X = \exp(-0.791 \text{ Ro})$. The average difference between FA star ages derived from $R'_{\text{HK}}$ (1) and $\text{Ro}^{-1}$ (3) is $\langle t_{\text{HK}} - t_{\text{Ro}} \rangle \approx 3.2 \pm 2.7$ Gyr (ignoring one discrepant point). This is exactly what would be expected for a star in a grand minimum, since $t_{\text{HK}}$ and $t_{\text{Ro}}$ can be reconciled if the $(R'_{\text{HK}})$ values for FA stars are systematically low. Assuming the hypothesis equating FA with grand minima is correct, use of (3) will help to avoid overestimating $t$ for FA stars.

A look at specific stars confirms that dynamos continue to function at large $t$, and that youthful FA stars exist. Several stars in Bea95 that show cycles (or suspiciously cyclic variations) have $\text{Ro}^{-1} < \text{Ro}^{-1}(\odot)$, and thus age $t > t_{\odot}$: HD 103095, HD 161239, and HD 224930 have estimated ages $\log t \approx 10$ (Smith et al. 1992), 9.92, and 9.96, respectively. These stars, which span $0.65 \leq B - V \leq 0.75$, suggest that dynamos may not die out, even in very old solar-like stars. Conversely, there are FA stars with $t < t_{\odot}$: HD 45067 ($\log t \approx 9.24$), HD 89744 ($\log t \approx 9.42$), and HD 178428 ($\log t \approx 9.41$), spanning $0.54 \leq B - V \leq 0.70$. These objects confirm that FA stars for a broad range of $T_{\text{eff}}$ can be significantly younger than the Sun.

To make the Ro$^{-1}$/age argument more quantitative, I apply a Kolmogorov-Smirnov test to the data. It shows that for our $R'_{\text{HK}}$ and color-restricted sample, the probability $p$ that the Ro$^{-1}$ distribution of FA stars (8 total) and non-FA stars (10 total) are drawn from the same parent population is $p \approx 95\%$ (Figure 1, right). While not conclusive due to the small sample sizes, this result is consistent with the hypothesis that FA and non-FA stars in the range F8 V – G8 V with $R'_{\text{HK}} \leq R'_{\text{HK}}(\odot, \text{max})$, may represent groups of physically similar stars glimpsed in transiently different dynamo states (cyclic and grand minimum).

To summarize, several lines of argument make it quite unlikely that FA stars have little activity due to old age accompanied by some sort of dynamo mortality. Instead, the evidence is reasonably strong that most (if not all) FA stars are essentially “snapshots” of cyclic stars taken at moments when their periodic dynamos have temporarily turned off (or nearly off; see Ribes & Nemse-Ribes 1993 and the discussion at the end of the talk). In other words, most FA stars are likely in magnetic grand minima.

3. Observations and Analysis

The calibration yielding $R'_{\text{HK}}$ values clearly suggests there is still some residual Ca II HK emission in FA stars, but exactly what causes this emission is unclear. Schrijver (1995) assembles a strong argument that it may be the result of acoustic heating, and recent models suggest the acoustic energy fluxes may be sufficient for the task (Ulmschneider et al. 1996). However, detailed analysis of high resolution UV lines in inactive evolved stars suggests that their shapes are not consistent with upwardly propagating acoustic waves (Judge 1994; WikstöI et al. 1997). Thus, the situation remains open as to the origin of chromospheric lines in inactive evolved stars, and thus likely FA stars as well.

Higher in the atmosphere, though, the source of the heating is clearer. Models imply that acoustic waves cannot transmit enough flux to heat the corona (Stepień & Ulmschneider 1989), and it is unlikely they contribute significantly to transition region (TR) heating either. Thus, a promising way to search for clearly magnetic heating in FA stars would be to look for TR and coronal emission.
To explore the question of activity and its origin in FA stars, we have undertaken a program to search for their TR emission (Saar et al. 1996; 1997). We selected four bright stars which were either defined FA in Bea95 (HD 10700, HD 142373) or in Donahue (1996; HD 9562) or have very low \( \Delta S/\langle S \rangle \approx 1.0\% \) and an essentially flat \( S \) record (HD 143761), plus one star which appeared (initially at least) to be entering a grand minimum (HD 3651; Donahue et al. 1995). Of these stars, only one (HD 10700) had reasonably well exposed IUE SWP spectra (e.g., Ayres et al. 1995); for the remainder, we obtained new observations with the GHRS on the Hubble Space Telescope.

In brief, we see TR emission in Si \( \text{iv} \) (1394Å, 1402Å) and C \( \text{iv} \) (1550Å) in all of the stars. When compared with chromospheric HK or C \( \text{ii} \) (1335Å) emission however, the TR behavior is distinctive. The HK and C \( \text{ii} \) fluxes both generally agree with previously determined minimum levels of emission in these lines (so-called “basal” levels; Schrijver 1995; Figure 2, dotted). They also more

![Figure 2. Surface fluxes for FA stars in chromospheric lines C \( \text{ii} \) (○) and Ca \( \text{ii} \) HK (\( F_{\text{HK}}/150; \square \)), the transition region sum of Si \( \text{iv} \) + C \( \text{iv} \) (\( =F_{\text{TR}}; \times \)) and the corona (\( F_{X}/1.8; \times \)) versus \( B-V \) color. The C \( \text{ii} \) flux lies near the “basal” level of Schrijver (1995; dotted) and agrees with a scaled acoustic flux model (thin solid line; Ulmschneider et al. 1996). The TR fluxes in FA stars are much less than the corresponding “basal” TR level (dashed; Schrijver 1995), and unlike the chromospheric fluxes, both \( F_{\text{TR}} \) and \( F_{X} \) increase with \( B-V \) (cooler \( T_{\text{eff}} \)). Possible scaling laws for \( F_{\text{TR}} \) and \( F_{X} \) are shown: Flux \( \propto d_{\text{CZ}}^{3} \) (where \( d_{\text{CZ}} \) is the normalized CZ depth; dash-dotted), and Flux \( \propto D_{\alpha}^{2} \), where \( D_{\alpha} \) is the \( \alpha \) effect term from simple mean-field dynamo theory (heavy solid; see text for details).

or less follow acoustic scaling laws as they decrease with \( T_{\text{eff}} \) (Ulmschneider et al. 1996; Figure 2, thin solid), though, as discussed above, whether this means they actually are acoustically heated is an open question. In contrast, \( F_{\text{TR}} \)
values are all well below previous observed minimum values (Figure 2, dashed; I combined the separate “basal” fluxes for Si IV and C IV from Schrijver 1995). And unlike the chromospheric lines, the TR fluxes appear to increase somewhat with decreasing $T_{\text{eff}}$. The few available ROSAT observations of our targets (Hempelmann et al. 1996) suggest that they follow a similar trend. Thus, whether or not the chromospheric lines in FA stars are acoustically heated, the hotter TR lines and X-rays follow a different trend with $T_{\text{eff}}$. This trend can be seen even more clearly in the ratio $F_{\text{TR}}/F_{\text{CII}}$ (Figure 3); values of the ratio increase sharply with decreasing $T_{\text{eff}}$ for FA stars, while non-FA stars (drawn from Ayres et al. 1995) show no clear pattern. Interestingly, HD 3651 follows the pattern of the non-FA stars, consistent with recent HK data indicating that it still shows cyclic behavior, though at a reduced level (e.g., Donahue 1996).

Since the $F_{\text{TR}}$ of FA stars do not appear to be acoustic in origin, magnetic heating seems the only logical alternative. Standard dynamo theory predicts increasing magnetic flux production (and thus activity) with increased rotation and shear (differential rotation) — see e.g., Parker (1979). We have gathered $P_{\text{rot}}$ values for our targets from Baliunas et al. (1996). Unfortunately, two of the five (HD 29645 and HD 142373) only have estimated values for $P_{\text{rot}}$, and these are likely to be overestimates, since they are based on $R'_{\text{HK}}$. For the limited data available, though (Figure 4), there is no obvious relationship between $F_{\text{TR}}$ or $F_{\text{X}}$ and rotation, whether parameterized as $1/P_{\text{rot}}$ or inverse Rossby number, $\tau_C/P_{\text{rot}}$ (taking $\tau_C$ from Nea84).
Figure 4. $F_{\text{TR}}$ (●) and scaled $F_X$ (divided by 1.8, ×) versus inverse rotational period $1/P_{\text{rot}}$ and inverse Rossby number, $\tau_C/P_{\text{rot}}$, (with $\tau_C$ from Nea84); larger symbols denote measured $P_{\text{rot}}$, smaller are estimated. No clear correlations are seen.

4. Discussion

Based on the analysis above, FA stars

- are likely to be in the stellar analogs of solar grand minima, displaying very weak activity and negligible variability (§2);
- show evidence for weak magnetic heating in their TR and coronae, but ...
- this heating is largely independent of rotation (Figure 4), and
- increases with decreasing $T_{\text{eff}}$ (Figs. 2 & 3).

A plausible magnetic mechanism consistent with these properties is a turbulent dynamo seated within the convection zone (CZ; Durney et al. 1993; Weiss 1993). This is in contrast to the boundary layer $\alpha\Omega$ type dynamo thought to drive magnetic cycles on the Sun and late-type stars (e.g., Spruit & van Ballegooijen 1982; Schmitt & Rosner 1983), and the “usual suspect” blamed for their magnetic activity. A turbulent CZ dynamo would be non-variable (or at least not cyclically variable), generate less magnetic flux in most cases (since it cannot store and amplify fields in a stable overshoot layer), and should scale with some function of the CZ depth. Turbulent dynamos should also be less dependent on rotation than the $\alpha\Omega$ cyclic type, since for turbulent dynamos, the crucial parameter is small-scale helicity, and not large-scale rotation or rotational shear (e.g., Durney et al. 1993; Brandenburg & Donner 1997). This is true, largely independent of whether the helicity is due to cyclonic convection (e.g., Parker 1955) or magnetic (e.g., Schüssler 1980; Brandenburg 1998) in origin. It is also expected that magnetic regions generated in a turbulent dynamo should probably more diffuse (perhaps showing fewer/smaller spots) and more uniformly distributed in latitude (Durney et al. 1993).
Turbulent CZ dynamos have long been thought important for full convective stars (cooler M dwarfs and giants, many pre-main sequence/T Tauri stars); our work implies they have a role in all cool stars with surface CZ. There are several interesting implications of this result. In most cool stars, fields generated by turbulent dynamos may dominate heating during periods of cyclic dynamo quiescence (i.e., magnetic grand minima) and perhaps play a significant role at cycle minima. On the Sun the CZ dynamo may also be responsible for high latitude X-ray bright points and their relatively uniform distribution (Golub et al. 1975), the constancy of the total small-scale magnetic flux over the cycle (Harvey 1992), and its spatial uniformity (the ubiquitous “magnetic carpet” Title speaks of in these proceedings). This “carpet” can clearly be seen, for example, in the small-scale emission features visible almost everywhere in the lovely SOHO EIT images (Figure 5). Fluxtube emergence models with a

![Figure 5. SOHO EIT image of the Sun in the Fe XII emission line (195 A), formed at T \( \approx 1.5 \times 10^6 \) °K showing small-scale features are present almost everywhere. The relatively uniform latitude distribution of these features supports the idea that much of the associated magnetic flux was likely formed by a turbulent CZ dynamo, rather than in the boundary layer \( \alpha \Omega \) dynamo believed responsible for the magnetic cycle and larger-scale, typically low latitude active regions.](image)

overshoot layer origin for the fields have difficulty producing low latitude active regions on rapid rotators (Schüssler & Solanki 1992; DeLuca et al. 1997). A turbulent CZ dynamo offers a plausible mechanism for generating the near equatorial features seen on many rapid rotators (e.g., Strassmeier 1996 and references therein). Convective pumping of weak fields generated by the CZ dynamo into the overshoot layer may provide the “seed” field to eventually “restart” the \( \alpha \Omega \) dynamo, bringing its amplitude back to normal levels at the end of a grand minimum (Schmitt et al. 1996).
We can try to explore our hypothesis by seeing if turbulent dynamo theory can estimate the $T_{\text{eff}}$ dependence of the TR and X-ray fluxes. Unfortunately, the theory of such turbulent dynamos is not fully developed. Naively, one might expect that the efficiency of a turbulent dynamo should increase as some function of the CZ depth. A trend $\propto d_{CZ}^3$, where $d_{CZ}$ (from Ruciński & VandenBerg 1986) is the fractional CZ depth, does indeed fit the TR and X-ray data reasonably well (Figure 2; dash-dotted). To connect with theory more directly, simple mean-field dynamo models predict that the magnitude of cyclonic convection ($\alpha$ effect) component, which should dominate turbulent dynamos, can be parameterized as $D_{\alpha} \sim \alpha L/\eta$. Here, $L$ is the characteristic length scale of the dynamo, $\eta$ is the turbulent magnetic diffusivity and $\alpha$ is related to the mean helicity. If $\ell$ is the typical correlation length of the turbulence, and $t_{\text{corr}}$ as the typical turbulent timescale, the usual approximations are $\eta \sim \ell^2/t_{\text{corr}}$ (e.g., Parker 1979) and (by simple dimensional arguments) $\alpha \sim \ell \Omega$ (e.g., Krause & Rädler 1980). If we then identify $\ell$ with $d_{CZ} r_*$ (taking the stellar radius $r_*$ from Gray 1992), $\ell$ with $H_p$ (the pressure scale height), and $t_{\text{corr}}$ with $\tau_{\text{conv}}$, we have $D_{\alpha} \sim (d_{CZ} r_*/H_p) \times \text{Ro}^{-1}$, and the corresponding dynamo number $N_\alpha \propto D_{\alpha}^2$. This simplistic scaling probably overestimates the dependence on rotation (Durney et al. 1993). Fortunately, our FA stars span a relatively small range in Ro$^{-1}$ (Figure 4), and so uncertainties in the rotational dependence of $D_{\alpha}$ are reduced. Since Ro$^{-1} \sim$ constant for our FA stars anyway, if we instead just take $D_{\alpha} \sim (d_{CZ} r_*/H_p)$, we again find a reasonable fit for $F_{\text{TR}}$ and $F_X \propto D_{\alpha}^2 \sim N_\alpha$ (Figure 2, heavy solid). Thus we conclude that the trends in $F_{\text{TR}}$ and $F_X$ are at least not inconsistent with (very) simple turbulent dynamo scaling relations.

Our association of FA star TR and coronae with magnetic heating generated in turbulent dynamos must be considered somewhat tentative at this point, due to the scarcity of relevant FA star observations and the highly simplified theory. Future work might include

- more measurements of rotation, X-ray and TR fluxes for FA stars,
- detection and study of a larger sample of FA stars to better understand their dependence on age/rotation and spectral type. Work on work on clusters of known age (e.g., Baliunas et al. 1995b) and field stars (the extended HK survey; Baliunas et al. 1998), and
- more theoretical work on turbulent dynamos, exploring the dependence of flux generation on CZ depth, rotation, etc. and the differences between turbulent dynamos in FA and very active dMe/T Tauri stars (Schmitt et al. 1998).

We are actively pursuing several of these avenues to better understand FA stars, grand minima, and the role of turbulent dynamos in cool stars.

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Discussion

Axel Brandenburg: There is something important to be learned from the \(^{10}\)Be records taken from ice cores. They show a clear anti-correlation with sunspot number and, more importantly, the cyclic modulation in the \(^{10}\)Be continues through the Maunder minimum. In other words, the \(\alpha \Omega\) dynamo does not turn off; it is just unable to produce sunspots.

Steve Saar: Thanks for pointing that out — I was unaware of the \(^{10}\)Be data. It is also important to note that even spots didn’t completely vanish in the Maunder minimum (see e.g., Ribes & Nesme-Ribes 1993). Thus, it would be more accurate to say that the Maunder minimum was a period when the primary cyclic (\(\alpha \Omega\)) dynamo was greatly reduced, though perhaps not entirely eliminated. This doesn’t change the fundamental idea of the talk; grand minima are still epochs when, due to the relative quiescence of the cycling dynamo, the background turbulent dynamo becomes more prominent (and perhaps dominates).

Steven Tobias: The \(^{10}\)Be data shows not only a clear cycle during the Maunder minimum, but also indicates a change in period. Hence, the \(\alpha \Omega\) dynamo is still going (if weakly). The evidence that you presented that there is little dependence of flux on rotation rate can be explained if non-linear dynamo effects are weaker in “Maunder minimum” stars, and so the magnetically controlled properties of their dynamos are not as important. In this phase the underlying turbulent dynamo will have a more important effect, but the linear \(\alpha \Omega\) model may still determine \(P_{cyc}\).

Steve Saar: Interesting; and it seems consistent with the general scenario.

Alan Title: Note that the magnetic flux on the Sun emerges uniformly over the surface during cycle minimum.

Steve Saar: This is probably due, in part, to the background turbulent dynamo, which generates a low, constant level of magnetic flux independent of latitude (to first order). The flux thus generated would be more prominent during solar cycle minimum in the relative absence of large active regions from the cyclic dynamo.

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