Comment on “The heliomagnetic field near Earth, 1428-2005” by K. G. McCracken

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McCracken (2007) inverted the galactic cosmic ray record for the interval 1428-2005 to estimate annual averages of the heliomagnetic field (HMF) near Earth during this interval. Quoting from his abstract, “There is good agreement with the results obtained by others using two independent methodologies based upon the sunspot [*Solanki, Schüssler, and Fligge*, 2002] and geomagnetic [*Lockwood, Stamper, and Wild*, 1999] records … There is disagreement with another method based on the geomagnetic record [*Svalgaard and Cliver*, 2005] that needs to be resolved.” In this comment, we address the reported disagreement of our long-term reconstruction of the HMF strength with that obtained in the other three studies. We show that a recent reconstruction of the HMF by *Rouillard, Lockwood, and Finch* [2007] agrees much more closely with that of Svalgaard and Cliver than that of Lockwood, Stamper and Wild. We also point out that the Solanki et al. model was developed to reproduce the Lockwood et al. HMF time variation; it does not provide independent support for the Lockwood et al. time series. We suggest that the discrepancy between McCracken’s cosmic-ray-based HMF reconstruction and those based on geomagnetic data originates in the Forbush and Neher ionization chamber data (1933-1957) used to bridge the time gap between the ^{10}Be time series (1428-1930) and the Climax neutron monitor record (1951-present).

1. *The Lockwood et al. [1999] reconstruction has been superceded, largely resolving the disagreement with Svalgaard and Cliver [2005]*

McCracken’s comparison of the four time series is shown in Figure 1. He noted that “the agreement between curves (1 [*Lockwood et al.*, 1999]), (3 [*Solanki et al.*, 2002]), and (4 [*McCracken*, 2007]) in (his) Figure 5 provides confidence in the overall validity of these three independent methods.” After McCracken’s paper was submitted, *Rouillard et al.* [2007] published an HMF time series that agrees substantially better with that of *Svalgaard and Cliver* [2005] than with that of *Lockwood et al.* [1999]. A comparison of the HMF reconstruction of *Rouillard et al.* [2007; red curve, based on the (corrected) *aa* index and their median (*m*) index], for their preferred derivation using Bayesian least squares regression, with that of *Svalgaard and Cliver* [2005; black curve, based on the interdiurnal variability (*IDV*) index][1] is given in Figure 2.

In the figure it can be seen that the agreement between the Rouillard et al. and Svalgaard and Cliver curves is quite good after ~1910 (RMS difference = 0.3 nT). The Rouillard et al. values before ~1910 are uncertain because of the paucity of available

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[1] Yearly values of all time series plotted or otherwise used in this comment are given in electronic Table 1.

stations used to derive the *m*-index for those times and, in addition, their HMF value for 1901 is likely in error (both points, A. Rouillard, personal communication, 2007).

Both the *Rouillard et al.* [2007] and the *Svalgaard and Cliver* [2005] reconstructions give evidence for a "floor" in the solar wind IMF of ~4.5 nT [*Svalgaard and Cliver*, 2007a] that is approached at each sunspot minimum. Figure 2 also contains an HMF series based on the polar cap potential index [*Le Sager and Svalgaard*, 2004; magenta curve], determined from magnetic observations within the polar cap from 1926-present and for a few isolated years from polar expeditions [*Svalgaard and Cliver*, 2007b] earlier in the 20th century. This index is highly correlated with the product of the HMF (*B*) and the solar wind speed (*V*). The *V* series reported in *Svalgaard and Cliver* [2007b] was used to deduce the plotted HMF strength; the *V* reconstruction of *Rouillard et al.* [2007] yields essentially the same result. In Figure 2, direct observations of the HMF strength, 1965-present are represented by a light blue curve.

We note that in Figure 1, from McCracken et al., the conversion from open flux on the left hand axis to field strength on the right hand axis is incorrect both with regard to scale and zero point. In Figure 3, we have recast correctly the *Lockwood et al.* [1999] open flux time series in terms of magnitude *B*. Also shown in Figure 3 are running 11-yr averages of the *Svalgaard et al.* [2005; green curve, based on *IDV*07], *Rouillard et al.* [2007; red curve], *Le Sager and Svalgaard* [2004; blue curve], and *McCracken* [2007] HMF strength time series, as well as 11-yr averages of direct observations of *B* (open black circles) for 1963-2007. The agreement between the three "upper" long-term curves is good except before ~1913 where the Rouillard et al. values begin to systematically dip below the IDV-based series (see above).

While the geomagnetic-based reconstruction of the solar open flux and HMF strength has sparked controversy (see the exchange between *Lockwood et al.* [2006] and *Svalgaard and Cliver* [2006]), Figure 3 reveals a strong convergence between the Lockwood/Rouillard and Svalgaard/Cliver/Le Sager reconstructions that is more impressive than the discrepancies that remain. For the intervals of overlap, the agreement between the *Le Sager and Svalgaard* [2004], *Svalgaard and Cliver* [2005], and *Rouillard et al.* [2007] series is significantly better than that of any of the three with the ^{10}Be-based HMF series of *McCracken* [2007] or with the superseded *Lockwood et al.* [1999] series.

2. *The Solanki et al. reconstruction is not independent of Lockwood et al.*

The *Solanki et al.* [2002] (see also *Solanki, Schüssler, and Fligge* [2000]) open flux model was developed in order to account for the doubling of the coronal magnetic field reported by *Lockwood et al.* [1999]. In this model, the open flux is a given fraction of the total magnetic flux over the Sun, which in turn is the sum of the flux from active regions (that falls to near zero at solar minimum), the flux from ephemeral regions, and the network flux. The decay time of the open magnetic flux in the model was adjusted in order to match the relative amplitudes of the cyclic flux to the doubling of the open flux reported by *Lockwood et al.* [1999] (also, observational evidence (from *Harvey* [1994]) regarding the sign of the contributions from active and ephemeral regions was discounted to maintain fidelity between the Lockwood et al. curve and the model output [see *Solanki et al.*, 2002, p. 710]). Presumably, the model could be similarly adjusted to reproduce the

HMF time series of *Rouillard et al.* [2007] or *Svalgaard and Cliver* [2005]. Thus the *Solanki et al.* [2002] reconstruction does not provide independent support for the HMF reconstruction of *McCracken* [2007], and is not included in Figure 3.

3. *The McCracken 1428-2005 HMF reconstruction needs to be re-examined*

Figure 3 casts doubt on *McCracken's* [2007] 1428-2005 HMF time series. We suggest that re-analysis begin with the underlying galactic cosmic ray time series, specifically the 1933-1957 ionization chamber measurements used to link the Climax neutron monitor data (1951-present) to the ^{10}Be-based measurements (1426-1930). The 1933-1957 interval encompasses the largest step-like change (~1.7 nT, "…from 3.5 nT to ~5.2 nT between the sunspot minima of 1944 and 1954") in McCracken's ~600-yr HMF time series. We note that, in Figure 7 from *McCracken and Beer* [2007], both the anti-correlation of sunspot number with cosmic ray intensity [*Forbush*, 1954; *Cliver and Ling*, 2001] and the alternating peaked and flat-topped cosmic ray cycles [*Jokipii, Levy, and Hubbard*, 1977; *Smith*, 1990] are less apparent for years before 1951 than for later years. The compelling reason for questioning the 1933-1951 portion of the cosmic ray record, however, is the absence of a significant increase in the HMF strength during this time in the independent concordant reconstructions of *Le Sager and Svalgaard* [2004], *Svalgaard and Cliver* [2005], and *Rouillard et al.* [2007]. For each of these series, the HMF at the 1944 and 1954 minima is essentially constant at ~5 nT (Figure 2).

In closing, the disagreement between the *McCracken* [2007] reconstruction and the three upper curves in Figure 3 [*Le Sager and Svalgaard*, 2004; *Svalgaard and Cliver*, 2005; *Rouillard et al.*, 2007] will need to be resolved by McCracken to permit use of the long ^{10}Be series to confidently extend the HMF series back in time.

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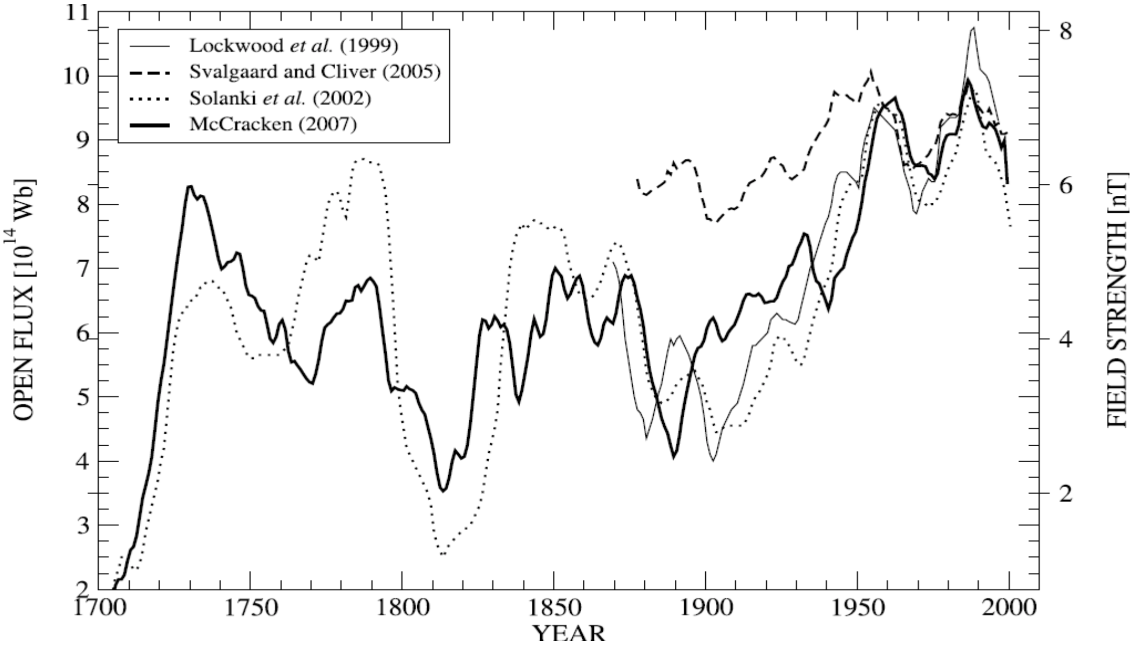

Figure 1. 11-yr running averages from 1700-2000 of the heliomagnetic field strength [HMF] near Earth based on three different methodologies. Curves 1 and 2 are obtained using the short-term fluctuations of the geomagnetic field. Curve 3 is one of several estimates based on the historical sunspot record. Curve 4 is derived from the cosmic ray record. This figure is from *McCracken* [2007; Figure 5 in that paper].

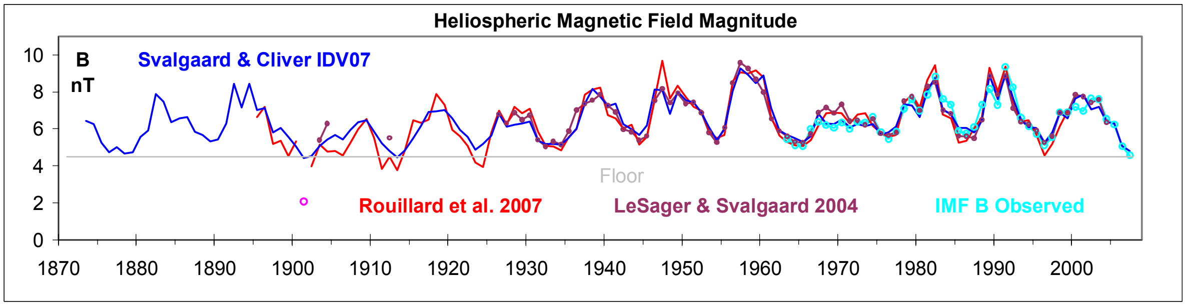

Figure 2. Three reconstructions of the HMF strength near Earth from 1873-2007 based on geomagnetic data: *Rouillard et al.* [2007; red curve], *Svalgaard and Cliver* [2005; blue curve, using IDV07], and *Le Sager and Svalgaard* [2004; magenta curve]. Direct solar wind observations of the HMF are also shown for 1965-present [*Omni data*, light blue curve].

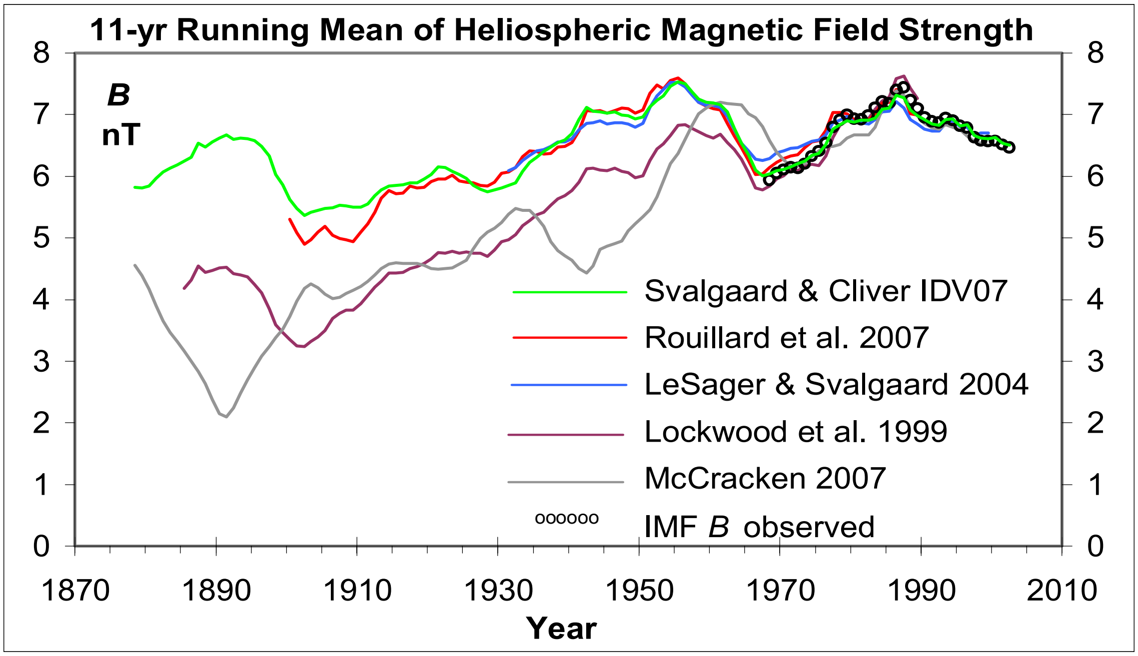

Figure 3. 11-yr running averages of the HMF reconstructions of *Svalgaard and Cliver* [2005; green curve, using IDV07], *Rouillard et al.* [2007; red curve], *Le Sager and Svalgaard* [2004; blue curve], *Lockwood et al.* [1999; magenta curve] (supplanted by *Rouillard et al.* [2007]), and *McCracken* [2007; gray curve]. Also shown are 11-yr averages of observed HMF strength values (open black circles) for 1963-2007.

Continues on next page with McCracken's response:

Response to L. Svalgaard and E.W. Cliver
by K.G. McCracken (University of Maryland).

I welcome the communication by *Svalgaard and Cliver* [2008] that the long-running differences between the several estimates of the heliomagnetic field (HMF) based on the properties of the geomagnetic field have been resolved. I am surprised, however, that they then "suggest that the discrepancy between the cosmic-ray based HMF reconstruction and those based on geomagnetic data originates in the Forbush and Neher ionization chamber data". Thus it appears that (1) they have overlooked my suggestion that there are several valid physical reasons why the percentage changes in the HMF estimates based on the cosmic ray data could show time varying differences from those obtained from geomagnetic data or by satellites near Earth, and (2) they may have misunderstood the role of the ionization chamber data in the inter-calibrated cosmic ray record of *McCracken and Beer* [2007].

As emphasized in *McCracken* [2007], the estimates based on the geomagnetic data refer to the physical properties of the solar wind and HMF in the ecliptic only; while the cosmic radiation at Earth is due to the integrated effects of the HNF and the solar wind over a large volume of the 3-dimensional (3-D) heliosphere. The nature of the secular changes in the 3-D morphology of the heliosphere throughout the Gleissberg cycle are not known at present (e.g., the persistence of the heliospheric current sheet); and the time dependent differences between the percentage changes in the geomagnetic and cosmic ray derived estimates of the HMF could be due to these. Furthermore, the majority of sunspots and CME occur in mid-heliographic latitudes, and the HMF at those latitudes may have considerably higher scattering properties than on the ecliptic. Yet again, *McCracken* [2007] pointed out that a validated difference between the percentage changes in the geomagnetic and cosmic ray based estimates could be due to the extent to which the HMF correlation length (due to turbulence in the solar wind) decreases between the minimum and maximum of the Gleissberg cycle.

Having resolved the discrepancies in the estimates based on the geomagnetic data, it therefore appears to me that *Svalgaard and Cliver* [2008] have missed the opportunity to emphasize (or even mention) the exciting possibility that the differences between the percentage changes in the geomagnetic and cosmic ray based estimates provide insights, and limits on the variable nature of the heliosphere throughout the Gleissberg cycle.

Having overlooked the possibility that the differences are real, *Svalgaard and Cliver* [2008] seem to make the tacit assumption that the cosmic ray time series contains errors. Thus they "suggest that (McCracken's) reanalysis (of the data should) begin with the underlying galactic cosmic ray time series, specifically the 1933-1957 ionization chamber measurements". As discussed in *McCracken and Beer* [2007] the long term trends in the cosmic ray time series throughout that period were determined from the very extensive series of high altitude measurements made by *H. V. Nehrer* [1971 and references therein] between 1933 and 1965]. Great care was taken by Neher in his long-term calibrations; on a number of occasions multiple flights were made on the same day to investigate the detailed reproducibility of the data; and there were month or longer campaigns that provide important baseline data (see extended discussion in section 3 and the Appendix of *McCracken and Beer* [2007]). The regression plot between the Neher data and the Climax neutron monitor for the interval 1954-1965 in Figure 3 of *McCracken and Beer* [2007] demonstrates a very close agreement. All the evidence indicates that the Neher data was extremely reliable, and they provide 15 years overlap with the neutron monitor era as well. Furthermore, the ^{10}Be data from both the Arctic and the Antarctic exhibit large long-term decreases from 1900 to 1960 which are consistent with the ionization chamber data. While some of the short-term time variations in Figure 7 of *McCracken and Beer* [2007] prior to 1951 may reflect the ten year absence of observations by Neher due to World War 2 and its aftermath, the quality and calibrations procedures of the Neher data provides confidence in the validity of the long-term changes between the 1930s and 1950s.

The most striking difference in Figure 3 of *Svalgaard and Cliver* [2008] is that the cosmic ray derived field is consistently ~1.2nT below the geomagnetic consensus between 1900 and 1930. It is important to note that the estimates of the HMF between 1900 and 1930 are derived from ^{10}Be data (via the inter-calibrated cosmic-ray record, Figures 7 and 8, *McCracken and Beer* [2007], without reference to the results obtained from the ionization chambers, 1933-1957. That is, both the cosmogenic and the ionization were inter-calibrated to the neutron data independently using completely different sets of computer models based on the GEANT and FLUKA codes. That ism there is no end-matching of the results derived from the three different sources of data. Stated differently, the ~1.2nT difference throughout 1900-1930 would be well determined even if the ionization chamber data were not available for the interval 1933-1951.

As discussed by *McCracken* [2007], the modulation of the galactic cosmic radiation varies approximately as the ratio between the solar wind speed, *Vp*, and the diffusion coefficient, *k(t)* (see *Caballero-Lopez and Moraal* [2004]). The diffusion coefficient, in turn, depends upon the magnetic field strength, and the correlation length of the HMF. Using equation 2 in *McCracken* [2007], the *Rouillard et al.* [2007] result that the solar wind speed increased by 14.4% between 1903 and 1965 indicates that the cosmic ray estimate for 1903 would be 8% higher than given by *McCracken* [2007]. That is, the McCracken estimate would increase from 3.23nT to 3.48nT for 1903, which is still considerably less than the "consensus" value of 5.1nT. Throughout the period in question, the inferred change in solar wind velocity does not account for the differences between the cosmic ray and geomagnetic estimates of the HMF.

As mentioned above the cosmic ray diffusion coefficient is a function of the HMF field strength and the correlation length of the HMF. Thus as discussed in *McCracken* [2007], the cosmic ray estimates of the HMF could be forced to agree with the consensus magnetic fields by assuming a very low level of turbulence (*i.e.* very large correlation lengths)prior to 1951, and particularly, during the Gleissberg minimum of 1900. This appears unlikely in view of the fact that large geomagnetic storms occurred very frequently at the time (e.g., the two years 1892 and 1894 contained 17 of the 112 great storms between 1874 and 1952 [*Royal Greenwich Observatory*, 1955]. If anything, I could speculate that the temporal changes in the correlation length may have been less pronounced than used in the inversion process, leading to lower values of the cosmic ray derived HMF prior to 1951 than in *McCracken* [2007].

In conclusion, I suggest that the welcome agreement between the HMF estimates will now allow us to proceed to investigate the secular changes in the 3-D heliosphere during the Gleissberg cycle. The Rouillard estimates of the secular change in the solar wind velocity leaves a substantial between the percentage changes in the cosmic ray and geomagnetic estimates that may be indicative of (a) changes in the 3-D morphology of the heliosphere, or (b) very large changes in the turbulence of the solar wind during the Gleissberg cycle.

Finally, I note that *Svalgaard and Cliver* [2005] have previously suggested that the presently commencing sunspot cycle may be comparable to those in the interval 1890-1910. This would be a most welcome contribution by our Sun to this discussion; in particular it would allow (1) the geomagnetic consensus to be tested against satellite measurements, and (2) the assumptions inherent in all the estimation methods to be tested over a wider dynamic range. In particular, it would allow the cosmic ray inversion methodology to be further refined, to improve the accuracy with the ^{10}Be and ^{14}C data can be used to study the HMF over the past 10,000 years.

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