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Long-term variation of solar activity?

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ABSTRACT

The long–term evolution of solar activity is key to understanding variation, trends, and causality of the Sun's influence on the environment of our Earth. We examine the evidence for such changes using direct observation and several proxy-based reconstructions of past solar activity and find that there is no consensus, or to be more blunt: we simply do not know with any degree of confidence how the variable star, our Sun, has varied over the past 400 years, not to say over much longer time scales before that. It is thus difficult to assert future risk and to predict what to expect. The variation on the time scale of an 11-year solar cycle is well in hand, but is of less interest, because of its cyclic nature, than the question about the existence of the secular variation, if any, of the 'quiet' Sun. Is there a varying background which dominates all other variations and forms the first-order forcing and influence on our environment? We do not know.

Key words. Sun – Solar activity – Space climate – Proxies

1. Introduction

There are many varied indicators of solar activity, e.g. sunspot number (and area, magnetic Flux), solar radiation (TSI, UV, F10.7 flux), cosmic ray modulation, solar wind in-situ measurements, geomagnetic variations, aurorae, ionospheric parameters, perhaps even climate,... on time scales extending to millennia. Solar activity is the result of solar magnetic fields. If our Sun had no magnetic field it would be as dull as models of stellar constitution proscribe. The magnetic field makes the Sun *interesting*, which before the development of our technological civilization was of little consequence, but that the Sun is a variable magnetic star is today of immense practical importance; in fact, a potential danger to our modern way of life.

As the past is the key to the present and to the future, the variation of solar activity in the past, that is the *long-term* variation, becomes of vital interest for the assessment and prediction of the influence of solar activity on our environment. Because of their importance many attempts at constructions of time series of parameters of 'solar activity' have been made and are in use for correlative studies. Different parameters or indicators show somewhat different time variations as different physical processes are at work, so it is not even clear if an all-encompassing definition of the concept of 'solar activity' is meaningful. On the other hand "we know it when we see it" (Stewart, 1964).

2. The Sunspot Record

To assess the impact of solar activity and the chances of effective mitigation of its effect we need to monitor and understand not only current space weather, but also space climatology. Direct telescopic observation of solar activity, of course, begins with the discovery 403 years ago of sunspots. Our understanding of that historical record forms the basis for interpreting the indirect evidence both from natural archives (e.g. ^{10}Be from ice cores) and human naked-eye observations (aurorae; 日誌[ri-zhi] blemishes on the sun) stretching much farther back in time.

Reconstructions of other solar parameters often use the 400-year long sunspot number record as the underlying dataset together with some assumptions about how the physical parameter under consideration might depend on the sunspot number. Figure 1 shows typical examples of this.

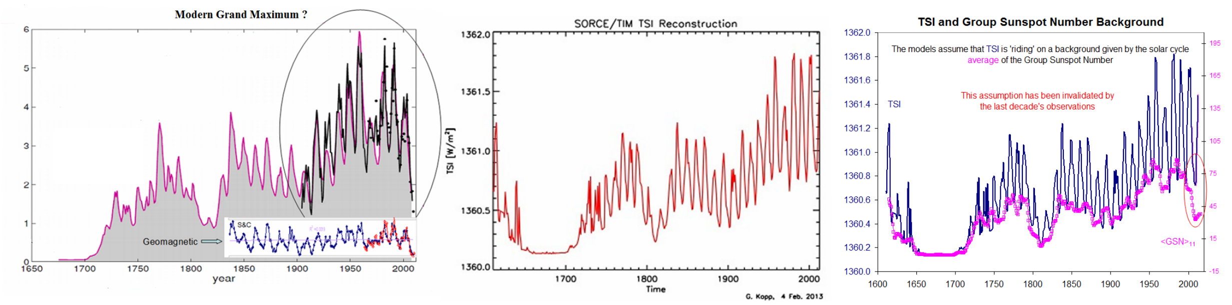

Fig. 1. Left panel: Purple curve above grey background: modeled estimate of the 'open magnetic flux' (Vieira & Solanki, 2010). Middle panel: Estimate of Total Solar Irradiance (TSI) `http://lasp.colorado.edu/home/sorce/data/tsi-data/` based on Wang et al. (2005). Right panel: Showing how the estimated TSI is just sunspot cycle variations 'riding' on top of a background which is simply the 11-yr running average of the Group Sunspot Number, assumed to be a proxy for the emerging 'ephemeral region' magnetic flux.

Prominent in Figure 1 is also the notion of a Modern Grand Maximum (marked by the oval in the left panel), that 20th century solar activity was unusually large, claimed by some researchers to be the highest in the last ~10,000 years, e.g. Usoskin (2013). The activity measures at solar maxima around 1900 are even smaller than at solar minima later in the century. In those models, the Group Sunspot Number (Hoyt & Schatten, 1998) was used. And herein lurks a problem, Figure 2.

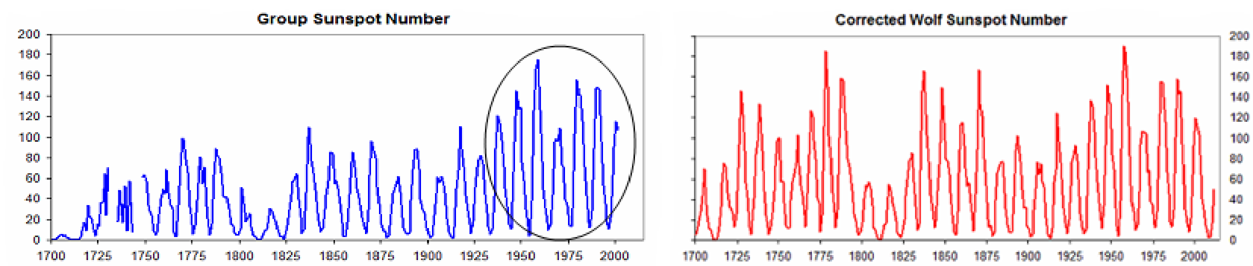

Fig. 2. Left: Yearly means of the Group Sunspot Number. Right: Yearly means of the International (Zürich, Wolf) sunspot number, after correction for sunspot size weighting from 1947 onwards, e.g Svalgaard (2013).

The Group Sunspot Number climbs up in the first half of the 20th century from a 'plateau' in the 18th and 19th centuries to the almost twice as high activity reported for the latter half of the 20th century, obviously creating the Modern Grand Maximum. On the other hand, the Wolf Sunspot Number indicates high, but not unusual 20th century activity. Cliver et al. (2013) report on the ongoing work of the Sunspot Number Workshops (`http://ssnworkshop.wikia.com/wiki/Home`) sponsored by the National Solar Observatory (NSO), the Royal Observatory of Belgium (ROB), and the Air Force Research Laboratory (AFRL), with the goal of providing the solar community with a vetted long-term (single) sunspot number and the tools to keep it on track. It is already clear that the Group Sunspot Number appears to be too low by up to 50% before ~1885, which when corrected resolves the difference between the two sunspot number series and removing the observational basis for a Modern Grand Maximum. Considering the interests vested in existing data sets and in correlations based on them, such a conclusion is naturally highly controversial at this time.

3. Total Solar Irradiance

For many researchers the roughly simultaneous occurrence of the Little Ice Age and the Maunder Minimum remains crucial in suggesting a dependence of Earth's climate on solar activity. This dependence is frequently attributed to a secular change in Total Solar Irradiance (TSI), estimated during that period using simple (or in some cases, complex) extrapolations of ad-hoc dependences based on correlations with sunspot numbers as mentioned in section 2. During the solar minimum 2008-2009 very few and feeble active regions were observed. However, thousands of small magnetic bipolar ('ephemeral') regions emerged every day. The ephemeral region emergence appears very nearly, if not truly, constant (Hagenaar et al., 2008). This is in contrast to the models behind Figure 1 where the ephemeral region emergence was assumed to depend on the cycle average of the Group Sunspot Number. The total magnetic flux is then assumed to be a proxy for TSI, Figure 3.

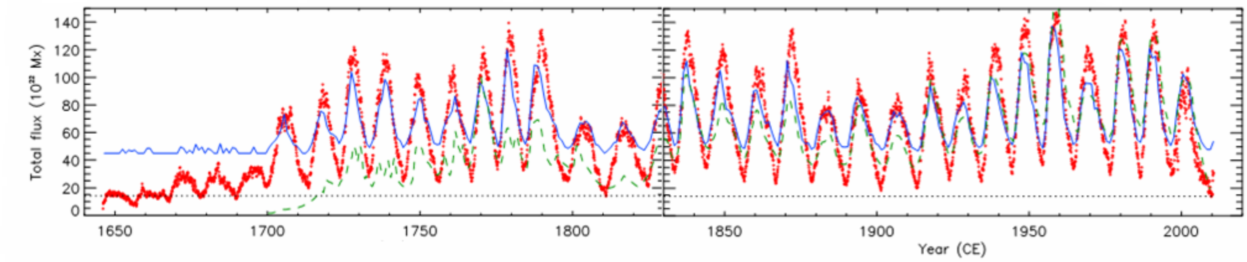

Fig. 3. Total absolute magnetic fluxes on the Sun, red diamonds for flux-dispersal model based on the yearly-average SIDC sunspot number, from Schrijver et al. (2011).

Schrijver et al. (2011) note that after a long absence of active regions the sun is left with a rapidly recycled network fed by a persistent ephemeral regions covering the solar surface between the polar caps and suggest that the Sun was as quiet as it could be by 2009 and that the extremely quiet solar conditions in 2009 may be taken as characteristic of the Maunder Minimum and that the network faculae associated with the ephemeral regions were the same in 2009 as at any truly quiet time in the past and thus also during the Maunder Minimum. Based on observations of the 'red flash' (possibly the chromosphere) during the total solar eclipses on 1706 and 1715, Foukal & Eddy (2007) also suggest the presence of magnetic network structures, and thus of substantial solar photospheric magnetism during at least the last decade of the Maunder Minimum.

The time variation of TSI appears to be mostly, if not entirely, set by the counteracting effects of dark pores and sunspots and bright small concentrations of magnetic field, the faculae. Faculae have been routinely observed for almost a century and provide a proxy for the network magnetic field and can thus also be in connection with the sunspot record be used to reconstruct TSI, Figure 4. This reconstruction also does not show the pronounced secular increase in the first half of the 20^{th} century. Instead, activity and irradiance at the present are back to what they were a century ago.

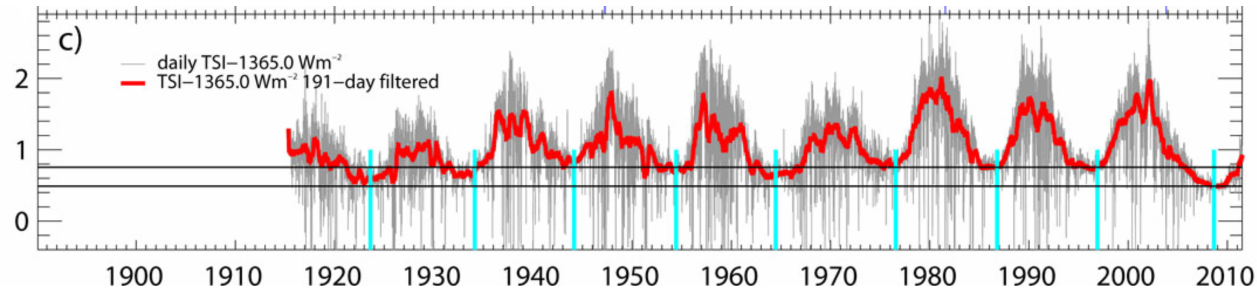

Fig. 4. TSI reconstructed from the Photometric Sunspot Index (PSI) supplemented by the extent of faculae, Fröhlich (2013).

As Shapiro et al. (2011) point out "a proxy for the long–term activity of the quiet Sun does not yet exist", so we are hostages to assumptions about what might be reasonable estimates (read 'guesses') of said activity. Shapiro et al. (2011) assume that proxies of solar activity averaged over two solar cycles can also describe the activity of the quiet Sun on the basic proposition that averaging of proxies allows sufficient time for the magnetic components to decay to the quiet network. In other words that small-scale activity is proportional to medium-scale activity which in turn is proportional to large-scale activity, resembling a fractal structure.

Considering the quiet Sun to be a combination of different brightness components: 1) faint supergranule cell interiors, 2) average supergranule cell interiors, 3) average network or quiet network, and 4) bright network, Shapiro et al. (2011) calculated synthetic spectra of these components employing a non-local thermodynamic equilibrium code for solar irradiance (Haberreiter at al. (2008); an example of a complex extrapolation). For proxies Shapiro et al. (2011) used two composites (red and cyan curves in Figure 5) of ice core ^{10}Be datasets for a 22-yr slowly varying background and the (Group) Sunspot Number for the 11-yr cycle variations.

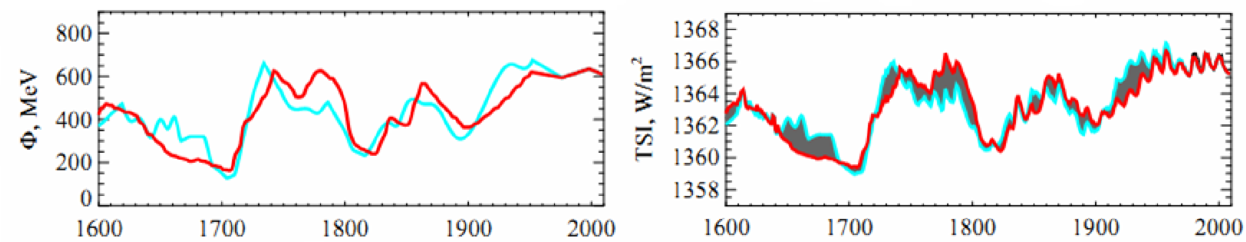

Fig. 5. Modulation potential (left panel) and TSI reconstructions (right panel) for the last 400 years. The grey-shaded area indicates the postulated intrinsic uncertainty, from Shapiro et al. (2011).

It is instructive – and somewhat depressing – to place the various reconstructions of TSI and solar magnetic flux (and hence their purported solar forcing of climate) on the same scale, Figure 6. The 'secular' change from 1900 to the 1950s and then on to the present day varies from a factor of ~5 in terms of the regular solar cycle variation to nothing depending on the model assumptions or on the ‘data’.

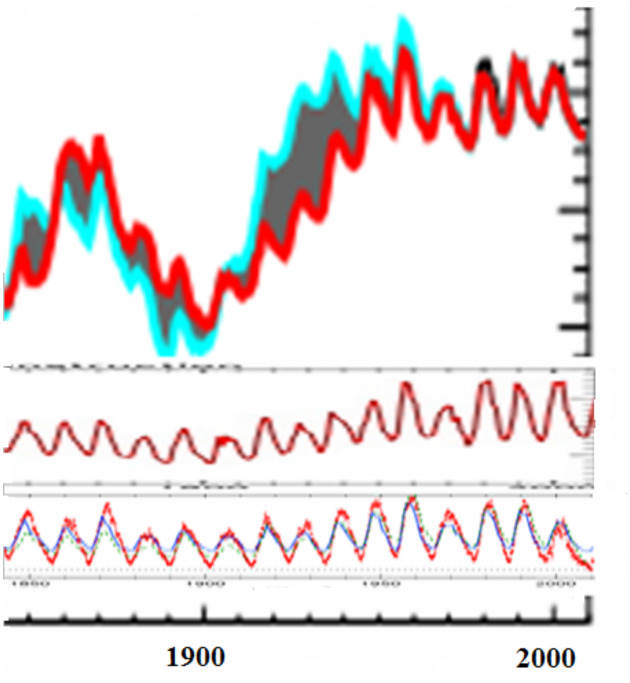

Fig. 6. Three reconstructions discussed in this paper for the time since 1845 scaled to equal variation during solar cycles 21 and 22.

It should be clear that there is no consensus and that the question mark in the title of the present paper is fully justified: we do not know what the variation of solar activity has been even over the most recent ~170 years, let alone in centuries and millennia past. It is somewhat of a travesty that we cannot provide the climate research community with that fundamental piece of input to their debate. It is also clear that the issue boils down to assumptions about the ‘background’ quiet sun magnetic flux.

4. The Heliospheric Magnetic Field

The solar wind carries the sun’s magnetic field frozen into the plasma out into the heliosphere where it impinges on the Earth and its magnetic field. Interactions (which are relatively well-understood) between to two fields generated electric currents in space around the Earth. The magnetic effects of those currents have been measured at ground-level for almost two centuries and as Bartels (1932) noted long ago ”Terrestrial-magnetic activity reveals therefore solar influences which cannot be traced in the direct astrophysical observations”. In the past decade great strides have been made in inferring solar wind properties from geomagnetic variations (e.g Svalgaard & Cliver (2010) and Lockwood & Owens (2011)). In particular, the strength of the Heliospheric Magnetic Field, HMF B, is well constrained at least back to the 1870s. The rationale for the method used in inferring HMF B is illustrated in Figure 7.

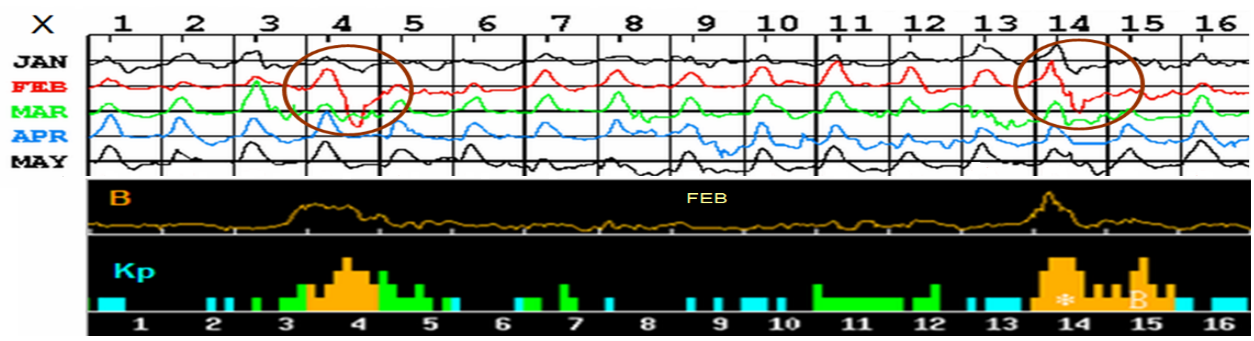

Fig. 7. Diurnal Variation of X at geomagnetic observatory Alibag for the first 16 days of Jan.-May 2009 and corresponding HMF B and K_p for February 2009. On days where HMF B is high (orange curve) the normally regular diurnal variation of the geomagnetic field is greatly disturbed (ovals). Any measure of that extra variance, such as the IDV-index (Svalgaard & Cliver 2005), can serve as a proxy for B.

Using the IDV-index and other variance-based proxies calculated from geomagnetic observatories back into the 1840s, HMF B can be reconstructed with confidence (undisputed from 1872 to the present). Figure 8 shows one such reconstruction.

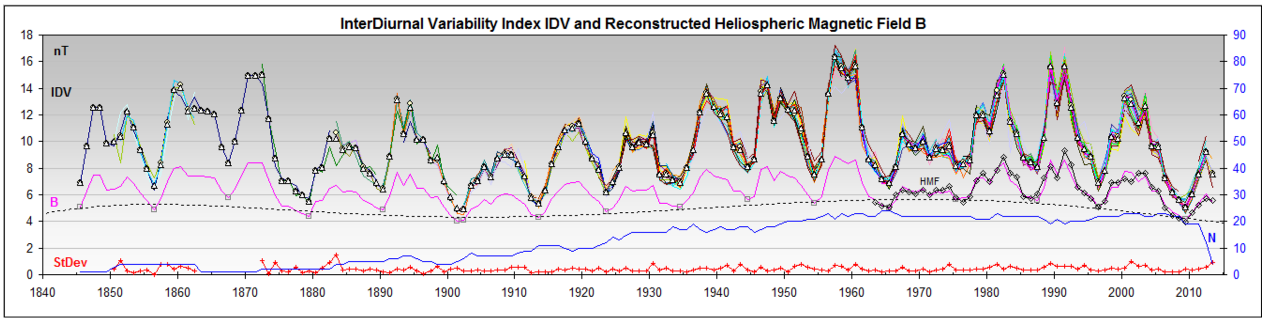

Fig. 8. Reconstruction of annual means of 169 years of near-Earth Heliospheric Magnetic Field strength B (pink line in middle of graph) 1845-2013 compared with in-situ spacecraft measurements 1963-2013 (black line marked HMF) plotted using different colors for each station, from Svalgaard & Cliver (2014). Open triangles (or circles) show the median (or mean) of all stations in each year. The red line at the bottom of the graph shows the standard deviation of the values of IDV in each year. The blue line marked 'N' shows the number of stations for each year.

The several cycles leading up to cycle 14 (1901-1913) did not have significantly different activity (B) from the several cycles leading up to cycle 24 (2009-2021?), so there should have been "sufficient time for the magnetic components to decay to the quiet network", making it hard to understand why TSI should be larger now by several W/m^2 compared to what it is purported to have been at the turn of the 20th century.

5. The Cosmic Ray Record

The solar cycle modulation of galactic cosmic rays depends on the strength of the heliospheric magnetic field and is typically parameterized (McCracken, 2006) by B^n where n is approximately 1.8. The HMF B derived from the modulation parameter (with a suitable choice of n) generally agrees with B derived from the geomagnetic record, Figure 9.

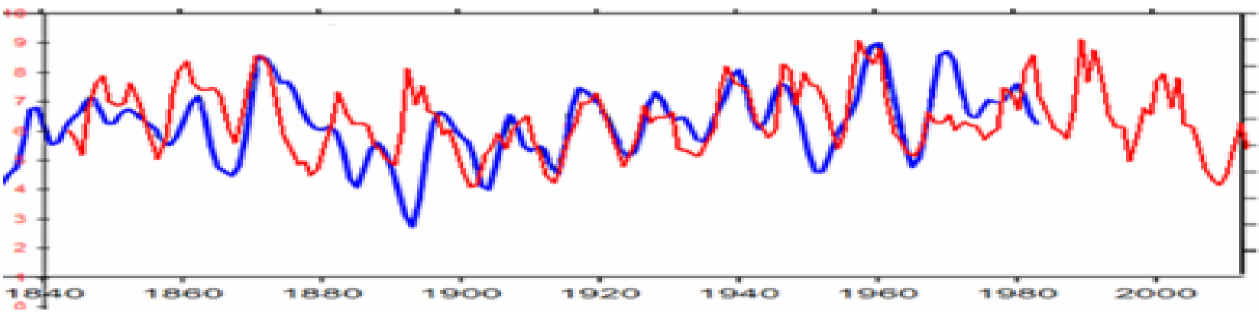

Fig. 9. HMF B as derived from cosmogenic ^{10}Be flux from several ice cores (blue curve, preliminary composite, (Ken McCracken, pers. comm.) and B derived from the geomagnetic record (red curve).

There is one anomaly: the two solar cycles in 1880-1900, where the cosmic ray record indicates very low values of HMF *B*, i.e. peaks in cosmic ray flux. We know from the modern neutron monitor record that the two equally low cycles 23 and 24 had the 'normal' response in cosmic ray flux. So the 1880-1900 period remain puzzling and unexplained.

Extending the cosmic ray record back 600 years (Figure 10) reveals several cosmic ray minima (solar activity maxima) on par with what we had mid- and late 20th century, showing that although that activity was high, it was not exceptional.

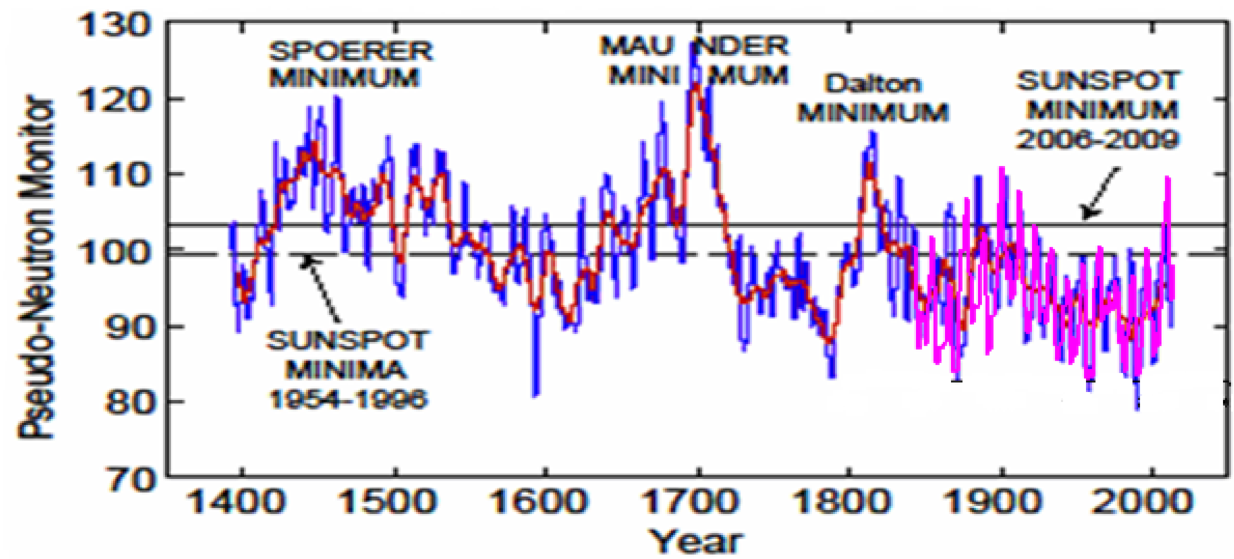

Fig. 10. HMF *B* as derived from cosmogenic ^{10}Be flux from several ice cores (blue curve, preliminary composite, (Ken McCracken, pers. comm.) and *B* derived from the geomagnetic record (overlain pink curve).

The solar cycle modulation appears to be equally strong at all times, except (and this is the crucial point) for the cycles near 1700, 1810, 1885 where large cosmic ray fluxes were record. One might be allowed to speculate that it is perhaps not mere coincidence that large volcanic eruptions took place during those decades (1693 Hekla, 1809 unnamed Indonesian eruption, 1814 Mayon, 1815 Tambora, 1883 Krakatoa). Webber et al. (2010) suggest that "more than 50% of the 10Be flux increase around, e.g., 1700 A.D., 1810 A.D. and 1895 A.D. is due to nonproduction related increases". Alternatively, the calculation of the cosmic ray solar modulation parameter may not be quite correct for low solar activity – for which the assumption of a spherically symmetric heliosphere is not valid. The issue remains unresolved, although the recent low solar activity combined with an actual measurement of the intensity in the Local Interstellar Medium may eventually provide the empirical evidence needed to settle the matter.

6. Conclusion

There is no consensus or agreement about the level and variation of several measures of solar activity over the past 400 years, severely hampering the interpretation of the previous ten millennia of cosmic ray proxy record.

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