The Team proposal that you have submitted in response to the 2011 Call was evaluated by the Science Committee and the ISSI Directorate and considered to be of high scientific value and relevance . The proposal is thus approved for implementation.

International Teams in Space Science Proposal 2011

Title: Long-term reconstruction of Solar and Solar Wind Parameters

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Abstract: Following Lockwood's seminal paper on centennial-scale changes in the Sun's open flux, it became clear that there were long term changes in the interplanetary magnetic field (IMF) as a consequence of magneto-hydrodynamic processes on the Sun. After a decade of vigorous research, reasonable agreement has been achieved between IMF strength (and open flux) estimates based on geomagnetic data and the inversion of the paleo-cosmic radiation data for the last ~100 years. Fundamental questions have been raised on topics such as the existence of a floor in the IMF strength (*B*), the character of the solar wind during grand minima, the possible disappearance of the solar wind within historical times, and the evolution of future solar change. The purpose of the workshop is four-fold: (a) to extend/substantiate the geomagnetic-based reconstruction of solar wind parameters from ~1840-2010 and to resolve the remaining discrepancies among the geomagnetic-, cosmic-ray-, and sunspot-based reconstructions, (b) to explore the open questions regarding the technical issues that need to be addressed to make this possible; (c) to use the foregoing work and the long-term cosmogenic radionuclide record to improve existing estimates of heliospheric properties for the last 10^4 years, and (d) to address by numerical modelling the outstanding physical questions that have been raised thus far. Expected output of this effort: (1) A definitive/consensus time series, with uncertainties, of the IMF strength from ~1840-2010 that can be used as a key to calibrate/interpret the cosmogenic nuclide data for the last 10^4 years. Such a record will have implications on topics ranging from the solar dynamo to cosmic ray modulation to climate change. (2) Technical papers focused on such topics as the effect of Earth's changing dipole on the geomagnetic and cosmic ray record, inter-calibration of neutron monitor, ^{10}Be data, and sunspot data with spacecraft measurements of the solar wind magnetic field (*B*), and long-term calibration/homogeneity of the sunspot number. (3) Scientific papers focused on such topics as the disconnect between solar wind *B* and cosmic ray modulation in solar cycle 20, the amplitude of solar activity from ~1940-1990 relative to the last ~10^4 years, the possible existence of a floor in *B*, and the nature of the solar wind during the Maunder Minimum.

1. Scientific rationale, goals, timeliness

In his famous paper on the Maunder Minimum, Eddy (1976) conclusively demonstrated that the Sun is a variable star on long time scales. Lockwood et al. (1999) provided further insight to the nature of such long-term change by using geomagnetic activity indices to show that the Sun's open magnetic flux underwent significant – factor of two – changes during the course of the last century. The Lockwood et al. study reinvigorated the field of long-term solar variability and brought space data into play on the topic. Initially, the Lockwood et al. report was met with skepticism (e.g., Arge et al., 2002; Svalgaard et al., 2005). After a decade of vigorous research based on cosmic ray (e.g., Caballero-Lopez et al., 2004; Muscheler et al., 2005, 2007a,b, Bard et al., 2007; McCracken and Beer, 2007; McCracken, 2007; Steinhilber et al., 2010) and sunspot data (e.g., Solanki et al., 2002; Tapping et al., 2007; Wang et al., 2005; Vieira and Solanki, 2010; et al., 2011b)) as well as the geomagnetic activity record (e.g., Svalgaard and Cliver, 2005, 2007b, 2010; Lockwood et al., 2009; Rouillard et al., 2007; Lockwood and Owens, 2011; see Usoskin (2008) for a review), however, an emerging consensus reconstruction of solar wind magnetic field strength (*B*) has been forged for the last century (Svalgaard and Cliver, 2010; Lockwood and Owens, 2011). As noted by Lockwood and Owens (2011), "This is a significant development because, individually, each [method] has uncertainties introduced by instrument calibration drifts, limited numbers of observatories, and the strength of the correlations employed." The consensus reconstruction of Lockwood and Owens (2011) in Figure 1 shows reasonable agreement among the various reconstructions of solar wind *B* for the last ~100 years. Similarly good agreement can be seen between recon-structions of solar wind speed (*V*) by Rouillard et al. (2007) and Svalgaard and Cliver (2007b). Furthermore, new geomagnetic indices such as IDV have been developed for which the derivation is considerably easier and less subjective than, for example, the widely-used range indices and these open new possibilities for the exploitation of historic data.

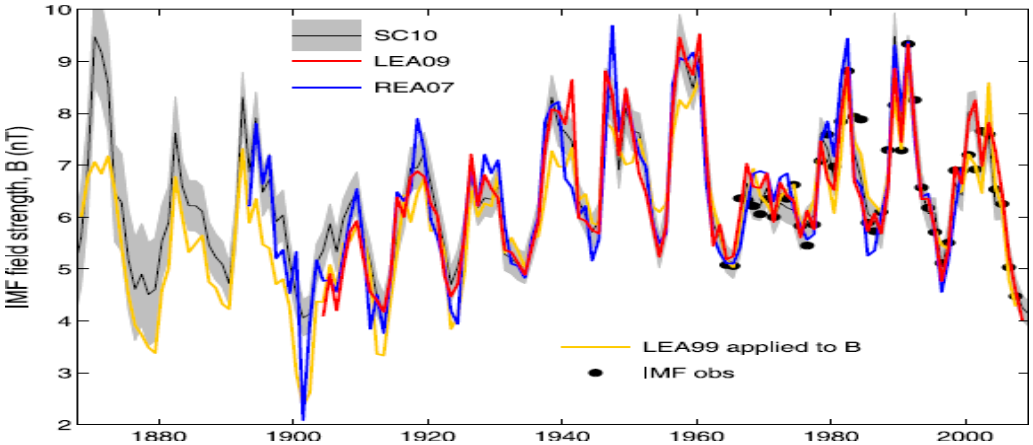

Fig. 1 Comparison of geomagnetic-based-reconstructions of solar wind *B* from 1870-2009 (Lockwood and Owens, 2011). SC10 = Svalgaard and Cliver (2010), LEA09 = Lockwood et al. (2009), REA = Rouillard et al. (2007), LEA99 = Lockwood et al. (1999) applied to *B*.

We propose to build on and probe this consensus by: (1) substantiating/extending the geomagnetic-based time series of solar wind *B* and *V* as far back as possible into the 19th century using thus far unexploited magnetometer data; (2) comparing the geomagnetic-based time series with reconstructions based on cosmic ray data and the sunspot record to identify discrepancies; and (3) resolving these discrepancies or identifying open questions and/or shortcomings concerning the various techniques. The end goal of this effort is to use a vetted record of IMF *B* (or the Sun's open flux (Φ)) for the past ~170 years to extend this time series back through the Holocene (~11,000 years before present) using the long-term ^{10}Be and ^{14}C data sets. On the road to our end goal, we will need to address a number of technical issues related to the inter-calibration of the various proxies and their relationship to *in situ* solar wind measurements of *B* and *V*. In addition, we will investigate in an interdisciplinary fashion the basic physical questions that have been raised by long-term solar wind studies thus far.

The geomagnetic-based reconstructions are the key to our overall goal. They are more quantitative/robust than the sunspot number (SSN) and are more directly converted and simply related to solar wind parameters than the cosmic ray data. While the SSN time series is often treated as sacrosanct, this is not the case. There are currently two widely-used sunspot numbers – the international series maintained by the Royal Observatory of Belgium and the group SSN (Hoyt and Schatten, 1998) – which differ significantly (by as much as ~30%) during the 19th century. In regard to the utility of the cosmic ray data for inferring solar wind parameters by themselves, we note that recent ^{10}Be-based reconstructions of *B* (Figure 2) have shown more volatility than those based on the geomagnetic record (Figure 1). Clearly, it is desirable/necessary to use all three approaches as a check on each other.

The first step toward construction of long-term reconstruction of solar wind *B* is identification, reduction, and calibration of as yet unused geomagnetic observations from the 19th century. Svalgaard and

Cliver (2007) identified 36 magnetic observatories with long time series of data, several of which (Helsinki, Greenwich, and Colaba) extend back to the 1840s. Svalgaard and Cliver (2010) used Bartels' extension of the *u*-index (itself based on data from several observatories) to extend their IDV-based record of *B* (1872-2009) back to 1835. Their *B* record for these years agrees reasonably well with the Steinhilber (2010) preferred Φ_{PCA} ^{10}Be-based reconstruction of *B* (Figure 2) but needs to be substantiated using additional geomagnetic data for the 19th century. Recently, Lockwood and colleagues have located the valuable Greenwich data set and will soon begin work on its reduction, quality control, and digitization. Similarly, Svalgaard is continuing to locate and digitize data sets that were not available for the Svalgaard and Cliver (2010) reconstruction of *B*. It is anticipated that, by the first team meeting in April 2012, these new data will have been applied to the reconstructions.

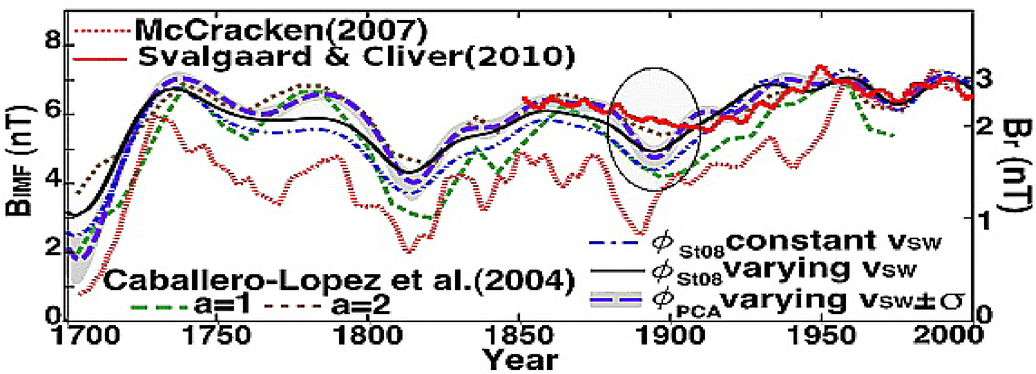

Fig. 2 Comparison of the Svalgaard and Cliver (2010) reconstruction of IMF *B* (red curve, 25 year running means) with other reconstructions as reported by Steinhilber et al. (2010)),e.g., their 25-year running mean of their PCA-based reconstruction (purple dashed curve) of *B*. The oval outlines an area of disagreement for which sufficient geomagnetic data exists that may be used to resolve the discrepancy.

In the second step of this process we ask the following questions: Where do the reconstructions based on geomagnetic data differ amongst themselves and from those based on cosmic ray and sunspot data? What can we learn from these discrepancies about both the technical issues involved in converting the raw data to solar wind *B* and the underlying physics?

Thus far we have identified four key discrepancies:

(1) The discrepancy between geomagnetic-based reconstructions for 1901 (Figure 1). This discrepancy should be easily resolved as more data from this period become available.

(2) The disconnect between geomagnetic- and cosmic-ray-based reconstructions of solar wind *B* centered on ~1895 (oval in Figure 2). The 25-year running averages of *B* in the ^{10}Be-based reconstructions in Figure 2 (purple curve from Steinhilber et al., 2010) show a minimum at this time while the SSN had its 11-yr peak in 1894 and the geomagnetic record (Figure 15 in Svalgaard and Cliver, 2010) had a corresponding local maximum. The inter-calibrations between the ^{10}Be data, the neutron monitor records, and the satellite measurements of *B* are based on an inversion of the cosmic ray propagation equation and may need revision as a result of spacecraft and other observations made during the long sunspot minimum of 2006-2009.

(3) The disconnect between geomagnetic-based reconstructions of *B* or Φ and reconstructions based on the sunspot number (e.g., Solanki et al., 2002; Wang et al., 2005; Vieira and Solanki, 2010; Jiang et al., 20011). Figure 3, from Jiang et al. (2011), shows that the Steinhilber (2010; SAMB) and Svalgaard and Lockwood (2010, SC10) curves generally lie above the sunspot-based curves (WLS05, VS10, R_Z, R_G) before ~1950. These are the types of detailed discrepancies we hope to address when all of the principals are in the room. The converging agreement on geomagnetic-based reconstructions for the 20th century (Figure 1), gives us confidence that the various *B* and Φ time series can be brought into further agreement.

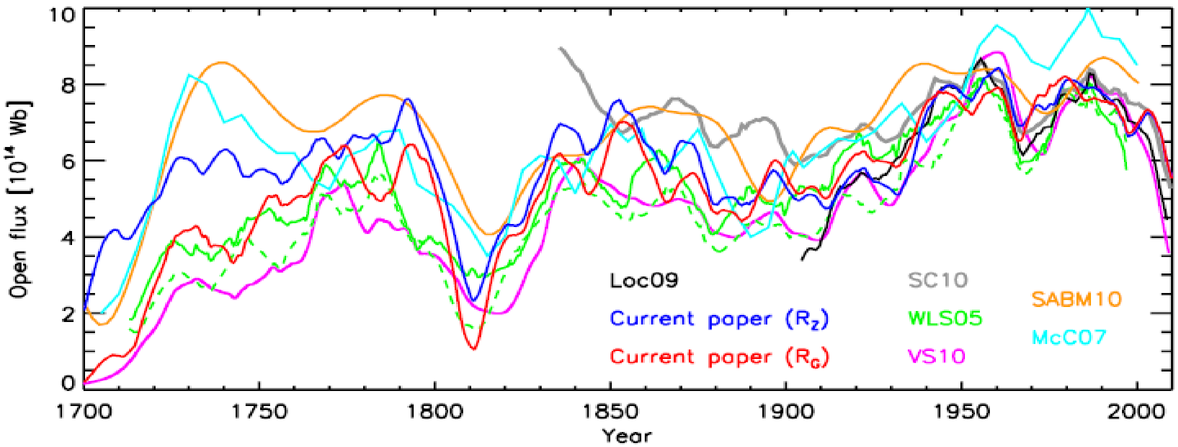

Fig. 3 Comparison of the reconstructed open flux with other reconstructions. Loc09: Lockwood et al. (2009). WLS05: Wang et al. (2005); solid and dashed green are their models S1 and S2, respectively. SC10: Svalgaard & Cliver (2010). A factor 0.4 used to convert their data into open flux. VS10: Vieira & Solanki (2010). SABM10: Steinhilber et al. (2010, PCA composite). McC07: McCracken (2007). All data are 11-yr running averages, except SABM10 which is a 25-yr running average.

(4) Finally, we note that there was a "localized" discrepancy between the SSN and the solar wind *B* and cosmic ray intensity during the 20th solar cycle (1964-1976). For this cycle (and to a lesser extent cycle 14 (1901-1913), *B* was relatively flat across the peak of the solar cycle (minimum of cosmic ray intensity). This anomaly has been well-documented (e.g., Mathews et al., 1971; Cliver et al., 2011). As can be seen in Figure 9 of Svalgaard and Cliver (2005), this discrepancy does not appear to be due to inaccurate measurements of *B* at the beginning of the space age as suggested, e.g., by Belov (2000). What is the cause of the missing flux at 1 AU?

In the third step of our process to obtain a consensus record of solar wind *B* over the last ~170 years, each of these disconnects will be examined in detail to gain insights into the under- lying physics, identify the inherent shortcomings of each proxy, and help set error bars and confidence levels for the eventual Holocene-epoch reconstruction based on cosmic ray data. This aspect of the proposed work will also address such questions as the effect of the decreasing strength of Earth's dipole field on the measurement of geomagnetic activity, the relative merits of the various geomagnetic indices for inferring solar wind parameters, determination of Φ from solar wind *B* measurements at 1 AU, and calibration of the SSN.

The end result of the above process – a continuous record of the open flux on the Sun and solar wind *B* at the Earth during the past ~10,000 is of fundamental importance for a better understanding of solar activity and its terrestrial and heliospheric effects.

The reconstruction of long-term solar and solar wind parameters has given rise to a number of new concepts and attendant controversies:

Modern Grand Maximum. Usoskin et al. (2003) and Solanki et al. (2004, 2005) have reported that solar activity level from ~1940-1990 was the highest in ~10,000 years. Evidence presented by Muscheler et al. (2005, 2007a,b) and Svalgaard (2010) indicates otherwise. The ~170-yr record we obtain will be critical to the resolution of this debate. It will also help to substantiate the existence of the various cycles [Gleissberg (~90 yr), de Vries (208 yr), Eddy (960 yr), and Hallstatt (2300 yr)] that have thus far been identified in the longest-term reconstructions of *B*.

Floor in Solar Wind *B*. Fisk and Schwadron (2001) provided theoretical support for a floor since their model for the 11-yr cycle assumed conservation of Φ and Svalgaard and Cliver (2007a), Owens and Crooker (2008), Crooker and Owens (2011), and Cliver and Ling (2011) provided observational evidence for such a floor. The low level of solar wind *B* recorded during the recent minimum (Smith and Balogh, 2008), however, undercut the idea of a floor. In a recent paper, Schrijver et al. (2011) reported that solar surface magnetic activity due to ephemeral bipoles reached a minimal state everywhere outside the polar coronal holes during 2008-2009 and hypothesized that this minimal level of activity was essentially that which existed during the Maunder Minimum. We ask: Will the solar wind persist in the absence of the polar fields /sunspot cycle? Does the solar wind have a floor in B? Can the “minimal magnetic state” of the Sun reported by Schrijver et al. give rise to a floor?

Nature of the solar wind during Grand Minima. Both Parker and Eddy suggested that the solar wind might have been of “gale force” in all directions during the Maunder Minimum. During 2009, our best glimpse to date of what the Maunder Minimum might have looked like, the solar wind was primarily of the slow type (Cliver & Ling, 2011). We ask: Is the solar wind at the floor during Grand Minima? Were the weak polar fields during the recent minimum (Wang et al., 2009) responsible for the low *V* and low *B* at this time? How does the Sun transmit its message of changing magnetic field to the heliosphere (Cliver et al., 2011; Owens et al., 2011)?

Disappearance of the solar wind during the Holocene. Steinhilber et al. (2010) reported several instances during the last ~10^4 years when the solar wind magnetic field apparently went to zero. We ask: Can the solar dynamo (Charbonneau, 2010) turn on/off on time scales as low as ~100 years? Can an unmagnetized solar wind exist?

The proposed team possesses the requisite theoretical expertise to model the solar dynamo and solar wind for extreme conditions ranging from intermittent dynamos to Grand Maxima and Minima. The current well-observed (e.g., SOHO, Hinode, STEREO, SDO) low epoch of solar activity is propitious/stimulating for the investigation of Grand Minima conditions.

2. Expected Output

Published outputs will include: (1) a consensus record, with uncertainties, of solar wind *B* (and Φ) from ~1840-2011 (and *V* from ~1870-2011) based on geomagnetic and cosmogenic radionuclide data; and (2) an extension of this record via cosmogenic radionuclide data to the last ~10^4 years. The 10^4-yr record represents a 200-fold increase in the space age records of *B* and Φ. Such a record, sanctioned by those who have been passionately debating the issue over the past decade, will be invaluable for modelers of the solar dynamo, cosmic ray modulation, and climate change. In addition, we will confront with modelling efforts a number of intriguing ideas that have already arisen from the effort to extend our knowledge of the Sun and the solar wind back in time, e.g., a recent grand maximum, a floor in the solar wind, the nature of grand minima. The collaboration of a group of experts on solar magnetic fields, cosmic rays, and geomagnetism will result in a joint review article summarizing the state of the art of the field and in numerous specific papers on the related technical aspects and scientific questions.

3. Schedule

1st Meeting in April 2012 (5 days), Second Meeting in April 2013 (5 days). The relatively late timing of the 1st meeting and the year delay between the two meetings permits recovery and inclusion of additional historical geomagnetic data and allows time for modelers to frame and pursue their efforts. In addition, it allows for planned smaller scale workshops on related topics which will involve certain of the current team members in the fall of 2011 (calibration of the SSN) and 2012 (long-term geomagnetic indices) at Sacramento Peak Observatory in Sunspot, NM.

4. Facilities Required

From ISSI we will require the usual conference (room, projector, internet, coffee) and travel (lodging/per diem) support for 13.5 participants (Cliver and Wang will not require ISSI reimbursement and Crooker/Siscoe will share a room). The most valuable support that ISSI provides is its institutional imprimatur/sanction/prestige and its neutral/appealing site which aid immeasurably in assembling such a diverse (and often divergent) group of experts.

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