AN ACTIVE SUN THROUGHOUT THE MAUNDER MINIMUM

JÜRG BEER[1], STEVEN TOBIAS[2] and NIGEL WEISS[3]

[1]*EAWAG, CH–8600 Dübendorf, Switzerland*
[2]*JILA, University of Colorado, Boulder, CO 80309–0440, U.S.A.*
[3]*DAMTP, University of Cambridge, Cambridge CB3 9EW, U.K.*

Abstract. Measurements of ^{10}Be concentration in the Dye 3 ice core show that magnetic cycles persisted throughout the Maunder Minimum, although the Sun's overall activity was drastically reduced and sunspots virtually disappeared. Thus the dates of maxima and minima can now be reliably estimated. Similar behaviour is shown by a nonlinear dynamo model, which predicts that, after a grand minimum, the Sun's toroidal field may switch from being antisymmetric to being symmetric about the equator. The presence of cyclic activity during the Maunder Minimum limits estimates of the solar contribution to climatic change.

1. Introduction

The incidence of sunspots – which are the sites of strong magnetic fields – varies cyclically with a mean period of about 11 years, as first pointed out by Schwabe. Although this cycle was present at the start of the seventeenth century, sunspots were infrequent during the Maunder Minimum (1645–1715) (Eddy, 1976; Foukal, 1990; Wilson, 1994), whose reality has by now been established beyond all doubt (Ribes and Nesme-Ribes, 1993; Hoyt and Schatten, 1996). Moreover, those spots that did appear between 1680 and 1710 were almost all confined to the southern hemisphere of the Sun (Ribes and Nesme-Ribes, 1993). The drop in overall magnetic activity led to an increase of the cosmic-ray flux and hence to higher production rates of cosmogenic isotopes, such as ^{10}Be and ^{14}C. The ^{14}C record shows that similar grand minima have occurred repeatedly over the past 10 000 years (Stuiver and Braziunas, 1988, 1989).

Because sunspots were so scarce, it has been assumed that the solar dynamo and the solar wind were switched off during the Maunder Minimum. Here we demonstrate that this was not so. We first examine the ^{10}Be record from a Greenland ice core (Beer *et al.*, 1990, 1994a, b), and confirm that vigorous cycles persist in this time series throughout the Maunder Minimum. Our main purpose is to confront these observational results with theoretical predictions based on dynamo theory. To achieve this, we rely on an idealized nonlinear dynamo model (Tobias, 1997a; Weiss and Tobias, 1997) that describes chaotically modulated cycles and shows how equatorial symmetry is broken at grand minima. We argue that these results are generic, and show that numerical solutions of the model system can indeed

be related to variations in isotope abundances. In the theoretical model, as in the proxy record, the amplitude of cyclic variations remains large when overall activity is weak.

In the next section we describe the ^{10}Be record and discuss concentrations during the Maunder Minimum. Then, in Section 3, we switch to considerations of dynamo theory and the behaviour of a particular model, focusing on modulation and symmetry-breaking. Finally, in the concluding section, we complete our interdisciplinary survey by commenting on the implications of these results for estimates of the solar contribution to climatic change.

2. Cyclic Activity in the ^{10}Be Record

^{10}Be is produced by high-energy interactions of galactic cosmic-ray particles with oxygen and nitrogen within the atmosphere. The cosmic-ray flux is modulated by solar activity, since particles (preferentially those with low energies) are deflected by the frozen-in magnetic fields that are carried by the solar wind. During periods of high solar activity the emission of solar wind from the Sun is increased, leading to a decrease in the overall galactic cosmic-ray flux penetrating into the atmosphere and therefore to a reduction of the ^{10}Be production rate. Thus variations in the concentration of ^{10}Be (which is deposited and stored, e.g., in polar icecaps) are anti-correlated with direct measures of solar activity, such as the sunspot number (Beer *et al.*, 1990).

The concentration of ^{10}Be in a 300-m ice core from Dye 3, Greenland, has been measured with annual resolution by accelerator mass spectrometry. Beer *et al.* (1990) compared the smoothed ^{10}Be record from 1783 to 1985 with the corresponding sunspot numbers. Although there were some discrepancies, they found that the two datasets were in good agreement; the highest anticorrelation corresponded to a time lag of 1–2 yr, representing the sum of the time taken for the solar wind to spread out from the Sun and the mean atmospheric residence time of ^{10}Be. The proxy record has now been extended through the Maunder Minimum (Beer *et al.*, 1994a, b). Figure 1(a) shows the complete measured dataset, which runs from 1423 to 1985. The increases in the mean ^{10}Be concentration during the Spörer, Maunder and Dalton Minima are apparent, though the shape of the peak during the Maunder Minimum differs somewhat from that for ^{14}C.

To determine the amplitude of the basic Schwabe cycle, the ^{10}Be concentrations from Dye 3 were band filtered (with a bandwidth of 7–24 yr). Figure 1(b) shows the entire record, which indicates that cyclic behaviour persisted through all three minima. The interval spanning the Maunder Minimum is exhibited in greater detail in Figure 2(a), with the record shifted by 1.5 yr to compensate for the lag in deposition. Although the mean concentration increased during the Maunder Minimum period, the cycle amplitude remains in the same range of 20–30% (depending somewhat on the bandwidth) both for that period and for the following
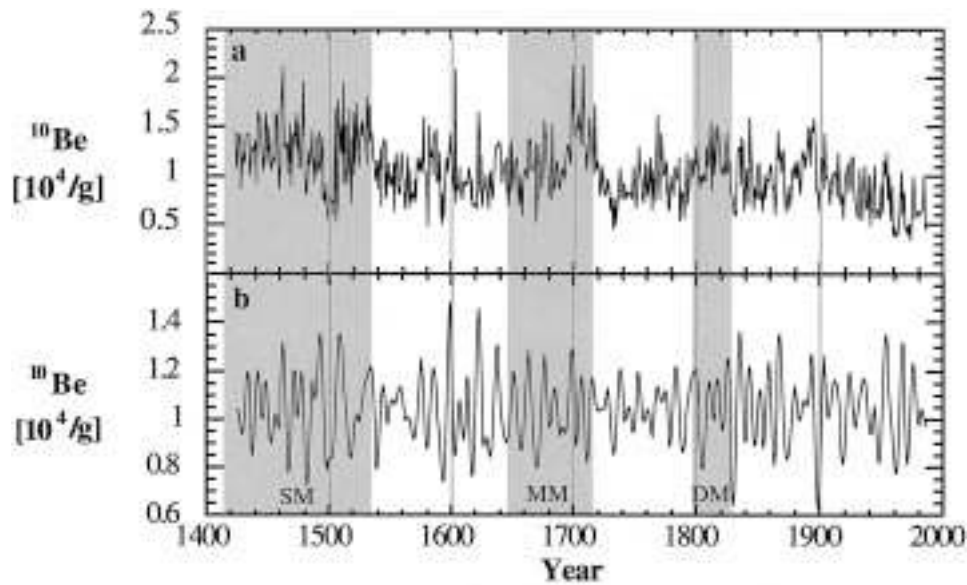
Figure 1. The ^{10}Be concentration data from the Dye 3 ice core from 1423 to 1985. (a) The measured raw data set. Intervals of reduced solar magnetic activity are shaded, and the corresponding increases in mean ^{10}Be concentration are clearly visible. (b) The same record, after applying a spectral band-pass filter (7–24 yr). The Spörer, Maunder and Dalton Minima are labelled. The measured sunspot numbers after 1715 are anti-correlated with ^{10}Be variations, and cycles persist through the grand minima.

centuries. The dates of minima and maxima in ^{10}Be concentration, which can be estimated with an accuracy of ± 0.5–1 yr, correspond to maxima and minima of solar activity, respectively. To explore the sensitivity of these results to details of the band filtering procedure, we show, in Figure 2(b), a similar record, obtained using a narrower bandwidth of 9–14 yr. The persistence of cyclic behaviour is not affected by this change; the exact positions of maxima and minima are slightly altered but it is clear that the associated dates are not sensitive to changes in the bandwidth, except in the vicinity of the 'double minima' around 1625 and 1690. Although we cannot expect exact agreement between two different measurements of solar activity, the dates in Table I are consistent with the observed sunspot maxima in 1720, 1730, and 1741 and are compatible with early observations by Galileo, Scheiner, and Hevelius (Hoyt, Schatten, and Nesme-Ribes, 1994). During the Maunder Minimum, however, they bear little relation to the traditional dates assigned by Wolf (Allen, 1973), who had to rely on the meagre sunspot record. Since the signal-to-noise ratio in the Dye 3 data is relatively small, additional records are needed in order to provide independent confirmation of our estimates; new results will emerge from the much longer GRIP ice core, which is currently being analysed.

TABLE I

Maxima and minima of solar activity during the Maunder Minimum, estimated from the ^{10}Be data in Figure 2. The weak minima at 1627 and 1690 have been ignored.

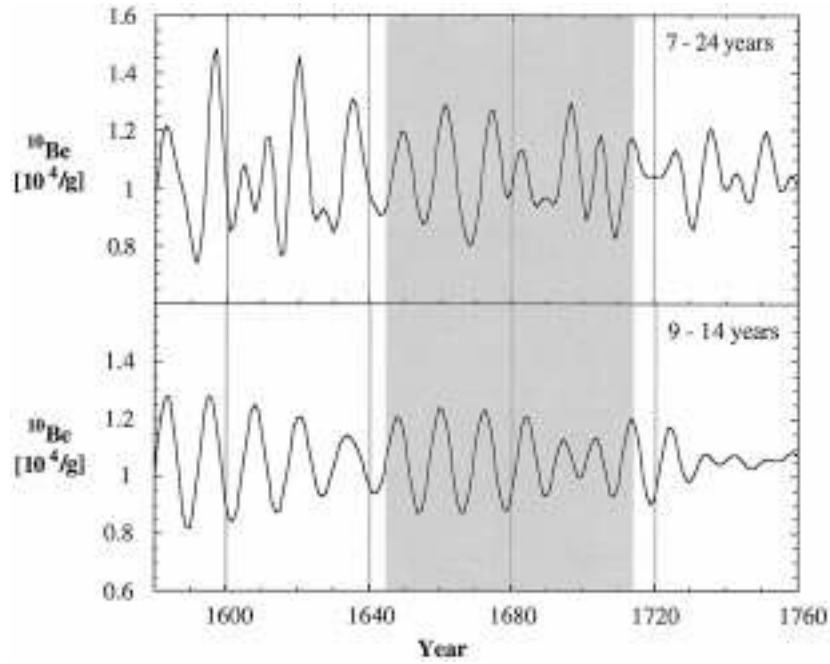| Maxima of solar activity (^{10}Be minima)	Minima of solar activity (^{10}Be maxima)
1591	
	1596
1601	
	1605
1608	
	1611
1615	
	1620
1630	
	1635
1644	
	1649
1655	
	1661
1668	
	1674
1679	
	1683
1689	
	1696
1701	
	1705
1709	
	1714
1720	
	1726
1731	
	1736
1740	
	1743

Figure 2. (a) Detail from Figure 1(b), showing the Dye 3 [10]Be concentration from 1580 to 1760, shifted by 1.5 yr to compensate for the atmospheric residence time of [10]Be. The amplitude of the cycles varies but remains significant throughout the Maunder Minimum. The weak cycles centred on 1628 and 1690 are uncertain, though Scheiner did observe a decrease in solar activity between 1625 and 1627. (b) The same, but with the bandwidth reduced from 7–24 yr to 9–14 yr. Positions of maxima and minima (apart from the double minima around 1625 and 1690) are only slightly shifted.

To understand how cyclic variations can persist with a similar amplitude through a grand minimum we must consider the effect of changing solar activity on the primary cosmic-ray flux, which can be expressed by the modulation parameter Φ (Castagnoli and Lal, 1980). In Figure 3, $\Phi = 0$ corresponds to the estimated interstellar cosmic-ray flux with no solar modulation effect, while $\Phi = 850$ reflects a very active Sun with a significant shielding effect on cosmic rays. We assume that the basic Schwabe cycle is superimposed on a mean level of solar activity as indicated by the shaded areas in Figure 3. At present the mean solar activity corresponds to $\Phi \approx 550$ and Φ varies in the range 450–850. Unfortunately we do not know the precise level or amplitude of solar activity during a period of low activity such as the Maunder Minimum. As a first-order guess we assume $\Phi = 150(-150, +200)$. The production rate $P(\Phi)$ of [10]Be can then be calculated by integrating over the product of the proton and neutron fluxes in the atmosphere with the corresponding cross sections. The amplitudes calculated for the two scenarios shown in Figure 3 are: $P(400)/P(850) = 1.23$, $P(0)/P(350) = 1.25$ (Masarik, personal communication). These are consistent with the observed changes in amplitude of the measured [10]Be.
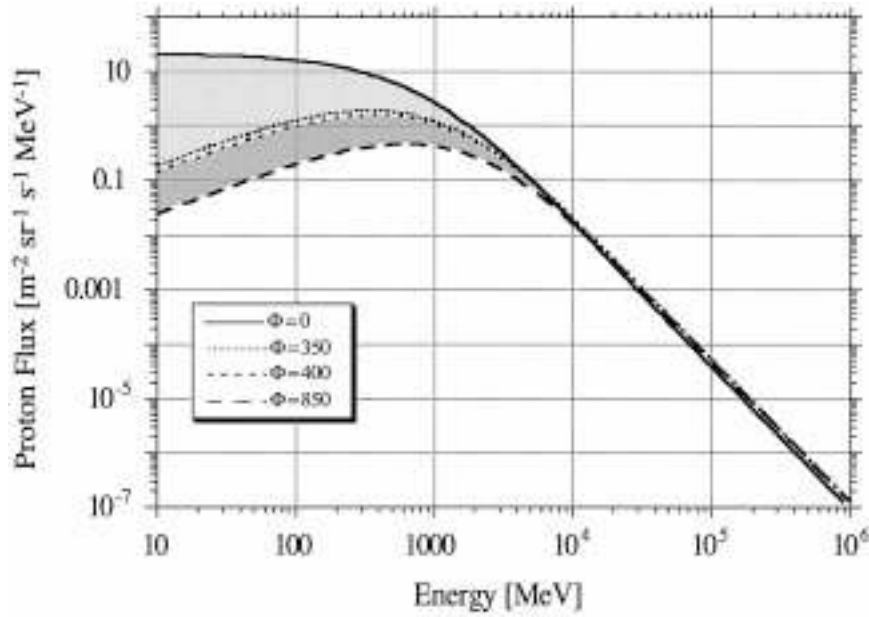
Figure 3. Differential cosmic-ray proton fluxes as a function of the solar modulation parameter Φ (Castagnoli and Lal, 1980). $\Phi = 0$ corresponds to the unmodulated interstellar flux, $\Phi = 850$ to the flux during a period of high solar activity. The heavily shaded region represents the range from maximum to minimum of a normal solar cycle, while the lightly shaded region is the conjectured range during the Maunder Minimum.

3. Modulated Cycles in a Nonlinear Dynamo Model

It is generally accepted that sunspots are surface manifestations of an underlying toroidal (azimuthal) magnetic field, which is generated by a hydromagnetic dynamo at the base of the solar convection zone (Thomas and Weiss, 1992; Weiss, 1994). Mean field dynamo theory captures the essential physics of this process, and mean field ($\alpha\omega$) dynamo models allow us to explore generic properties of magnetic fields in stars like the Sun (Parker, 1979; Stix, 1989). Parker (1993) devised an idealized model in cartesian geometry, in which dynamo action was concentrated near the interface between an upper region (the convection zone), where poloidal fields were generated by cyclonic eddies (the α-effect), and a lower region (the radiative zone), where toroidal flux was created by differential rotation (the ω-effect), in agreement with the rotation profiles derived from helioseismology. Linear (kinematic) properties of this model have been studied in both cartesian (Parker, 1993) and spherical (Charbonneau and MacGregor, 1997) geometries, while Tobias (1997a,b; Weiss and Tobias, 1997) has systematically investigated behaviour in the nonlinear domain.

   The proxy record of solar activity is unfortunately too short to determine whether modulation by grand minima is a deterministic or stochastic process. Schmitt,
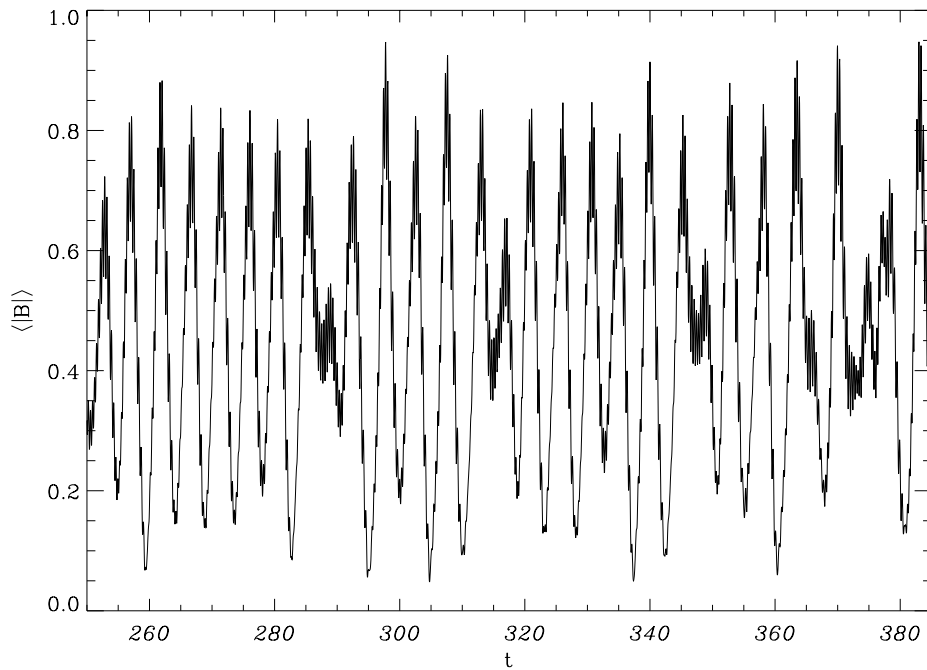
Figure 4. Time-series of rms magnetic energy $\langle |B| \rangle$ of the toroidal field in the nonlinear dynamo model. The basic (Schwabe) magnetic cycle provides the high-frequency oscillation, and intervals of reduced energy, corresponding to grand minima, are clearly visible. The time units are arbitrary.

Schüssler, and Ferriz-Mas (1996) and Schüssler, Schmitt, and Ferriz-Mas (1997) have developed an on-off dynamo model in which modulation is stochastically driven. In what follows we shall, however, assume that aperiodic modulation results from the chaotic dynamics to be expected in a complex nonlinear system such as a stellar dynamo. This process has been demonstrated for an idealized mean field dynamo in cartesian geometry. In Tobias's (1997a) nonlinear extension of Parker's (1993) cartesian dynamo model, the generation of the basic cyclic magnetic field self-consistently drives large-scale velocity fields which then modulate the basic cycle. This stellar dynamo model reveals various generic patterns of behaviour. First, it shows that grand minima naturally occur (Tobias, 1996). Secondly, the pattern of magnetic activity during grand minima can be contrasted both with sunspot observations and with the [10]Be record.

Here the dynamo model is, for the first time, studied in a parameter regime where the modulational time scale is of the same order as that observed for the Sun. Figure 4 shows the rms value of the toroidal field (a quantity that would be correlated with the sunspot number) as a function of the dimensionless time. The basic Schwabe cycle is clearly modulated and undergoes many intervals of reduced activity (grand minima). Close-ups of the magnetic energy for two sepa-
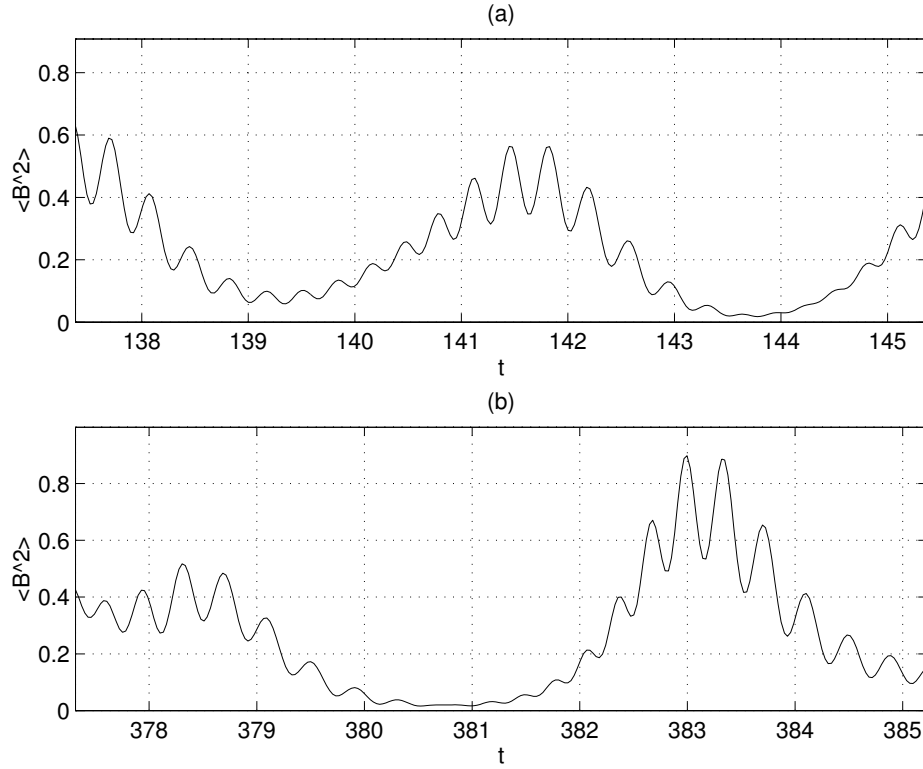
Figure 5. (a) Close-up of the time-series in Figure 4, showing in detail the behaviour of the average magnetic energy $\langle B^2 \rangle$ for two grand minima. Here the time-series displays 'normal' behaviour with a dipolar magnetic field for large energies and mixed symmetry during grand minima, as shown by the corresponding butterfly diagram in Figure 6(a). (b) As for (a), except that here the model enters the grand minimum with dipole symmetry, but emerges with the opposite symmetry; the corresponding butterfly diagram is in Figure 6(b).

rate intervals are shown in Figure 5, with the corresponding butterfly diagrams in Figure 6.

Figure 5 shows that the amplitude of cyclic variations in the toroidal field (which affect the parameter Φ) scarcely changes as a grand minimum is entered, but that it drops during the rise out of the minimum. The ^{10}Be record provides some observational indication of this distinction not only for the Maunder Minimum but also for both the Spörer and the Dalton Minima. Another comparison between theory and observations is through the period of the basic cycle. When the field is large, this period deviates only slightly from a well-defined mean. The dynamo calculations show, however, that during grand minima the cycle period, although well-defined for *each* such minimum, varies significantly from minimum to minimum. The deepest minima (i.e., those with the weakest field) seem to have cycle periods that are slightly longer than the norm – as was indeed the case for the Maunder Minimum (Beer *et al.*, 1994b) – but in some minima the period is shorter than when
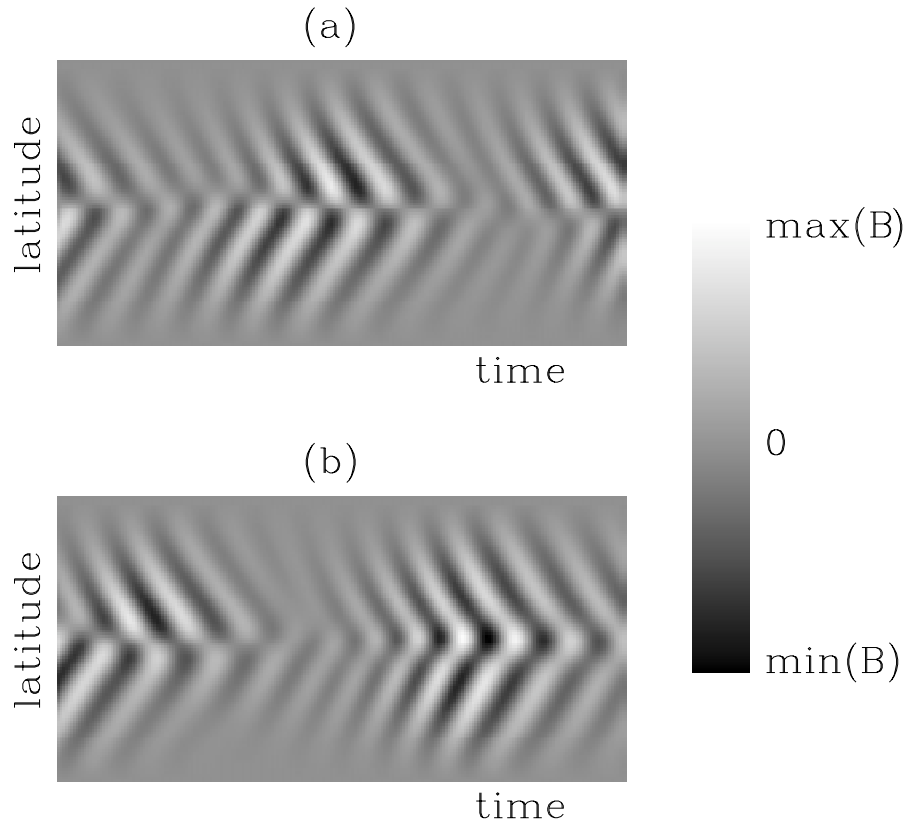
Figure 6. Butterfly diagrams: the grey-scale maps show the toroidal field at a given radius as a function of latitude and time; the extremes (black and white) represent fields of opposite signs. (a) Diagram corresponding to the time-series in Figure 5(a): the toroidal field is almost antisymmetric about the equator when the field is strong but is asymmetric during and just after the grand minima. (b) Diagram corresponding to the time-series in Figure 5(b): here the solution emerges from the grand minimum with quadrupolar symmetry (i.e., the toroidal field is symmetric about the equator) despite entering that minimum in a dipole (antisymmetric) state. The Sun's magnetic field is likely to have undergone similar temporary changes in symmetry as it emerged from some grand minima in the past.

the dynamo is working normally. These correspondences between observations and theory lend support to the hypothesis that modulation of the activity cycle is indeed an intrinsic, deterministic process, rather than a consequence of stochastic on-off switching.

The butterfly diagrams in Figure 6 also show that the dynamo may exhibit two quite different types of behaviour. Normally (about 90% of the time) the model possesses a dipole field (i.e., the toroidal field is antisymmetric about the equator) when the field is large, but occasionally the field is predominantly quadrupolar (symmetric). Detailed analysis of the results shows that the symmetry of solutions does not change while the field is large. Instead, it is apparently decided as the field

emerges from a grand minimum. When the field is small (i.e., as the star enters or exits from a grand minimum) both dipole and quadrupole components are present and any spots are asymmetrically distributed, as shown in Figure 6(a). That is just what happened on the Sun as it emerged from the Maunder Minimum (Ribes and Nesme-Ribes, 1993). Since then, for approximately 300 years, the Sun's magnetic field has remained essentially dipolar.

Figure 6(b) indicates, however, that it is possible for a star to emerge from a grand minimum with a largely quadrupole field (*even if it entered the minimum with dipole symmetry*). This happens occasionally, after particularly deep grand minima. Such a switching of symmetry is a new effect. It is possible to analyse the mathematical structure underlying this behaviour and to demonstrate that it is generic (Knobloch, Tobias and Weiss, 1997). Hence it follows that symmetry-flipping is likely to have happened in the Sun. After some previous grand minima, sunspot fields would have had the same sense in both hemispheres and Hale's polarity laws would no longer have applied. The corresponding poloidal fields would be quadrupolar, producing an equatorial coronal hole and high-speed streams near the plane of the ecliptic. We expect that the enhanced solar wind would lead to a marginally greater reduction in the abundances of cosmogenic isotopes.

Finally, it should be noted that the dynamo model we present here is a highly simplified representation of the processes that occur in the Sun. Although its characteristic properties are generic and therefore robust, it lacks detailed predictive power. Thus we cannot expect to reproduce the exact behaviour of the solar cycle. Furthermore, even if the model system were able to mimic exactly the behaviour of a dynamo at the base of the convection zone, it is not clear how to relate the field generated there to observable magnetic features at the solar surface. Many physical processes not modelled here (e.g., magnetic buoyancy) may play a rôle in determining characteristics of the solar cycle. In particular, the sunspot record may differ substantially from that of the mean field, since spots can only appear when the overall magnetic energy is very high.

4. Solar Variability and Climatic Change

Although ice cores from the Arctic and Antarctic all show an overall increase in ^{10}Be abundance associated with a reduction in solar magnetic activity during the Maunder Minimum, the Dye 3 record demonstrates that the activity cycle persisted, at a reduced level and with scarcely any sunspots, throughout this interval. We have shown that this is consistent with the theoretical results displayed in Figures 5 and 6. Despite the lack of sunspots, magnetic flux was still being generated and must have emerged through the surface of the Sun to form small active regions, resembling the ephemeral active regions that are widely distributed over the solar surface today (Wilson, 1994). These emerging fields continued to heat the corona and so

to produce a solar wind, which carried fluctuating fields that produced aurorae and deflected cosmic rays.

The ephemeral active regions would, moreover, have ensured that a weak magnetic network was present during the Maunder Minimum. That sets a limit to any reduction in total solar irradiance, for the magnetic network gives rise to faculae which produce Ca II K emission, and there is an empirical relationship between Ca emission and total irradiance (Lean, 1994; Lean, Skumanich, and White, 1992). Recent observations show that enhanced facular emission more than compensates for the coolness of sunspots (Foukal and Lean, 1990). Consequently, the solar irradiance falls by about 0.15% between sunspot maximum and sunspot minimum (Willson and Hudson, 1991). Although some other Sun-like stars show greater photometric variability (Lockwood *et al.*, 1994), they have a much higher level of activity than the Sun (Foukal 1994). The sunspot cycle produces a directly forced effect of $0.15-0.3\ °C$ on temperature on Earth (Lean, 1994; White *et al.*, 1997).

During grand minima, the presence of ephemeral active regions and a weak network field guarantee a base level of Ca II emission. From the behaviour of the star HD 3651, which has recently entered a quiescent phase (Baliunas *et al.*, 1995; Baliunas and Soon, 1995), we infer that this base level is lower than that at a normal sunspot minimum, and that it corresponds to a reduction in irradiance of $0.1-0.2\%$ below the mean value in a normal cycling state, which is less than the difference of 0.24% that corresponds to an almost total lack of activity (Lean, 1994; Lean, Beer, and Bradley, 1995). We estimate that the direct climatic effect of changes in total irradiance during the Maunder Minimum would be a drop of $0.2-0.3\ °C$ in temperature relative to today.

Global warming is currently dominated by the influence of greenhouse gases (Houghton *et al.*, 1996). Nevertheless, there is increasing evidence from the past that the climate is also sensitive to variations in solar activity, on time scales ranging from 11 years to centuries and possibly millennia (Friis-Christensen and Lassen, 1991; Beer *et al.*, 1994b; Stuiver, Grootes, and Braziunas, 1995; O'Brien *et al.*, 1995; Baliunas and Soon, 1995; Butler and Johnston, 1996; White *et al.*, 1997). If so, the direct climatic effect of fluctuations in irradiance (whether associated with cyclic or secular changes in solar activity) must be enhanced by more subtle processes – such as chemical effects of ultraviolet radiation (Haigh, 1994), the influence of cosmic rays on cloud formation (Svensmark and Friis-Christensen, 1997), or strong nonlinear amplification associated with resonant effects. Given the persistence of the Schwabe cycle through grand minima, such resonances deserve to be investigated.

References

Allen, C. W.: 1973, *Astrophysical Quantities*, 3rd ed., Athlone Press, London.

Baliunas, S. L. and Soon, W.: 1995, *Astrophys. J.* **450**, 896.

Baliunas, S. L. and 26 others: 1995, *Astrophys. J.* **438**, 269.

Beer, J., Blinov, A., Bonani, G., Finkel, R. C., Hofmann, H. J., Lehmann, B., Oeschger, H., Sigg, A., Schwander, J., Staffelbach, T., Stauffer, B., Suter, M., and Wölffli, W.: 1990, *Nature* **347**, 164.

Beer, J., Baumgartner, St., Dittrich-Hannen, B., Hauenstein, J., Kubik, P., Lukasczyk, Ch., Mende, W., Stellmacher, R., and Suter, M.: 1994a, in J. M. Pap, C. Fröhlich, H. S. Hudson, and S. K. Solanki (eds.), *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge University Press, Cambridge, p. 291.

Beer, J., Joos, F., Lukasczyk, C., Mende, W., Rodriguez, J., Siegenthaler, U., and Stellmacher, R.: 1994b, in E. Nesme-Ribes (ed.), *The Solar Engine and its Influence on Terrestrial Atmosphere and Climate*, Springer-Verlag, Berlin, p. 221.

Butler, C. J. and Johnston, D. J.: 1996, *J. Atmospheric Terrest. Phys.* **58**, 1657.

Castagnoli, G. and Lal, D.: 1980, *Radiocarbon* **22**, 133.

Charbonneau, P. and MacGregor, K. B.: 1997, *Astrophys. J.* **486**, 502.

Eddy, J. A.: 1976, *Science* **192**, 1189.

Foukal, P. V.: 1990, *Solar Astrophysics*, Wiley Interscience, New York.

Foukal, P. V.: 1994, *Science* **264**, 238.

Foukal, P. V. and Lean, J.: 1990, *Science* **247**, 505.

Friis-Christensen, E. and Lassen, K.: 1991, *Science* **254**, 698.

Haigh, J. D.: 1994, *Nature* **370**, 544.

Houghton, J. T. *et al.* (eds): 1996, *Climate Change 1995: The Science of Climate Change*, IPCC/Cambridge University Press, Cambridge.

Hoyt, D. V. and Schatten, K. H.: 1996, *Solar Phys.* **165**, 181.

Hoyt, D. V., Schatten, K. H., and Nesme-Ribes, E.: 1994, in E. Nesme-Ribes (ed.), *The Solar Engine and its Influence on Terrestrial Atmosphere and Climate*, Springer-Verlag, Berlin, p. 57.

Knobloch, E., Tobias, S. M., and Weiss, N. O.: 1997, *Monthly Notices Royal Astron. Soc.*, in press.

Lean, J.: 1994, in E. Nesme-Ribes (ed.), *The Solar Engine and its Influence on Terrestrial Atmosphere and Climate*, Springer-Verlag, Berlin, p. 163.

Lean, J., Beer, J., and Bradley, R.: 1995, *Geophys. Res. Lett.* **22**, 3195.

Lean, J., Skumanich, A., and White, O. R.: 1992, *Geophys. Res. Lett.* **19**, 1591.

Lockwood, G. W., Skiff, B. A., Baliunas, S. L., and Radick, R. R.: 1992, *Nature* **360**, 653.

O'Brien, S. R., Mayewsky, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S., and Whitlow, S. I.: 1995, *Science* **270**, 1962.

Parker, E. N.: 1979, *Cosmical Magnetic Fields: their Origin and their Activity*, Clarendon Press, Oxford.

Parker, E. N.: 1993, *Astrophys. J.* **408**, 707.

Ribes, J. C. and Nesme-Ribes, E.: 1993, *Astron. Astrophys.* **276**, 549.

Stix, M.: 1989, *The Sun: an Introduction*, Springer-Verlag, Berlin.

Stuiver, M. and Braziunas, T. F.: 1989, in F. R. Stephenson and A. W. Wolfendale (eds.), *Secular Solar and Geomagnetic Variations in the Last 10 000 Years*, Kluwer Academic Publishers, Dordrecht, Holland, p. 245.

Stuiver, M. and Braziunas, T. F.: 1989, *Nature* **338**, 405.

Stuiver, M., Grootes, P. M., and Braziunas, T. F.: 1995, *Quaternary Res.* **44**, 341.

Svensmark, H. and Friis-Christensen, E.: 1997, *J. Atmospheric Terrest. Phys.* **59**, 1225.

Thomas, J. H. and Weiss, N. O.: 1992, in J. H. Thomas and N. O. Weiss (eds.), *Sunspots: Theory and Observations*, Kluwer Academic Publishers, Dordrecht, Holland, p. 3.

Tobias, S. M.: 1996, *Astron. Astrophys.* **307**, L21.

Tobias, S. M.: 1997a, *Astron. Astrophys.* **322**, 1007.

Tobias, S. M.: 1997b, *Geophys. Astrophys. Fluid Dyn.* **86**, 287.

Weiss, N. O.: 1994, in M. R. E. Proctor and A. D. Gilbert (eds.), *Lectures on Solar and Planetary Dynamos*, Cambridge University Press, Cambridge, p. 59.

Weiss, N. O. and Tobias, S. M.: 1997, in G. M. Simnett, C. E. Alissandrakis, and L. Vlahos (eds.), *Solar and Heliospheric Plasma Physics*, Springer-Verlag, Berlin, p. 25.

White, W. B., Lean, J., Cayan, D., and Dettinger, M. D.: 1997, *J. Geophys. Res.* **102**, 3255.

Willson, R. C. and Hudson, H. S.: 1991, *Nature* **351**, 42.

Wilson, P. R.: 1994, *Solar and Stellar Activity Cycles*, Cambridge University Press, Cambridge.