Periodicity and Aperiodicity in Solar Magnetic Activity [and Discussion]

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Periodicity and aperiodicity in solar magnetic activity

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Solar activity varies irregularly with an 11-year period whereas the magnetic cycle has a period of 22 years. Similar cycles of activity are seen in other slowly rotating late-type stars. The only plausible theory for their origin ascribes them to a hydromagnetic dynamo operating at, or just below, the base of the convective zone. Linear (kinematic) dynamo models yield strictly periodic solutions with dynamo waves propagating towards or away from the equator. Nonlinear (magneto-hydrodynamic) dynamo models allow transitions from periodic to quasi-periodic to chaotic behaviour, as well as loss of spatial symmetry followed by the development of complex spatial structure. Results from simple models can be compared with the observed sunspot record over the past 380 years and with proxy records extending over 9000 years, which show aperiodic modulation of the 11-year cycle.

1. Introduction

There is evidence of solar variability on timescales ranging from 5 min to 10^{10} years. Variations on an evolutionary timescale are gradual and monotonic; at the other extreme, *p*-mode oscillations have small amplitudes and periods that are very precisely defined. On intermediate timescales behaviour is typically aperiodic. Magnetic flux erupts irregularly at the solar surface to form active regions within which sunspots may appear. Over the past 275 years the frequency and location of sunspots has varied cyclically with an average period of about 11 years. These aperiodic cycles are interrupted by episodes of reduced activity. Proxy records confirm that grand minima with a characteristic timespan of about 200 years have recurred aperiodically over the past 9000 years and there are suggestions of modulation on even longer timescales still.

This review is concerned with the implications for our understanding of the solar interior and for theories of solar magnetism of variations with timescales of 10–1000 years. I first summarize the relevant observational results. Next I describe the physical processes responsible for solar activity, together with models of the solar dynamo. Then I discuss periodic and chaotic oscillations in nonlinear deterministic systems and contrast chaotic with stochastic models of solar behaviour. Finally I indicate how such considerations affect our interpretation of time series derived from terrestrial data.

2. Observational constraints

The interaction of convection with rotation leads to magnetic activity in lower main-sequence stars like the Sun, with deep outer convective zones. By studying other similar stars we can therefore construct the magnetic history of our Sun (Soderblom & Baliunas 1988; Tayler 1989; Weiss 1989). Magnetic fields have been measured directly in some active stars while indirect evidence of magnetic activity comes from observations of coronal X-ray emission, chromospheric Ca^+ emission and photospheric starspots. These observations show that, for a star of given mass, magnetic activity depends on the rotation rate. Magnetic heating leads to the formation of a hot corona, which drives a stellar wind (Priest 1982) that carries angular momentum away from the star. Thus the star is spun down owing to magnetic braking at a rate that depends upon its angular velocity (Mestel & Spruit 1987). As its rotation rate decreases the star grows less active and decelerates more slowly. The Sun's activity is relatively feeble. Thus the timescale for solar spindown now is around 10^{10} years and its magnetic behaviour should show no significant evolutionary changes over the past 10^4 years (or even since the late Precambrian era).

Cyclic activity has been detected in about a dozen slowly rotating stars like the Sun. The principal features of the solar cycle are well known. Sunspots appear within active regions formed by the eruption of azimuthal flux tubes through the photosphere. Since 1714 the incidence of sunspots has varied cyclically; although the cycles are aperiodic they have a well-defined mean period of 11.1 years. The sense of the magnetic field reverses from one activity cycle to the next, so the underlying magnetic cycle has a 22-year period. Early telescopic observations indicate that the sunspot cycle proceeded much as now during the first few decades of the seventeenth century, but later (throughout the reign of Louis XIV) it was interrupted by the Maunder Minimum. The dearth of sunspots was recognized by many contemporary observers (Eddy 1976) and even referred to by the poet Andrew Marvell (Cohen 1961; Weiss & Weiss 1979).

Fortunately, modulation of the solar cycle can also be detected in terrestrial proxy records. A reduction in solar activity leads to enhanced production of unstable isotopes by galactic cosmic rays, and both the Maunder Minimum and the preceding Spörer minimum are apparent in the ^{14}C and ^{10}Be records (G. M. Raisbeck, this Symposium) and also in thermoluminescence profiles (Cini Castagnoli *et al.* 1988). Moreover, precise calibration of radiocarbon dates from tree rings reveals recurrent anomalies (the 'Suess wiggles') associated with grand minima. Stuiver & Braziunas (1988) have identified a total of 17 such minima over the past 9700 years. These episodes of reduced activity have a characteristic timescale of 150–220 years, but they recur aperiodically with no apparent pattern.

3. Origins of solar activity

It seems likely that solar magnetic fields are generated in a region of weak convective overshoot beneath the base of the convective zone (Weiss 1989). In this region toroidal fields are created from poloidal fields by differential rotation, so it is important to establish how the angular velocity ω varies in the interior of the Sun. The surface rotation rate is a maximum at the Equator and falls by about 30% towards the poles (Howard 1984). Recent measurements of the rotational splitting of solar p-mode oscillations imply that this latitudinal gradient persists throughout the convective zone and that there is a transition to a uniform angular velocity over a depth of order 50000 km at the top of the radiative zone (Brown & Morrow 1987; Dziembowski *et al.* 1989). Earlier in the Sun's history, when it rotated more rapidly, it is likely that the Proudman–Taylor constraint forced the angular velocity to be constant on cylindrical surfaces in the convective zone, as indicated by experiments (Hart *et al.* 1986). Indeed, it has been suggested that grand minima are associated with changes in the pattern of convection that would affect the distribution of angular momentum (Zel'dovich *et al.* 1983;

Jones & Galloway 1988). There are, however, no indications that the surface rotation changed substantially during the Maunder Minimum.

Two mechanisms for generating the Sun's alternating magnetic field have been proposed. Either the Sun is a magnetic oscillator with a fixed poloidal field and a toroidal velocity that oscillates with a 22-year period or else there is a dynamo, with a poloidal field generated owing to the persistent helicity of convective eddies in a rotating system. The observed poloidal field reverses around sunspot maximum while the only systematic variations in angular velocity are the so-called torsional waves with a period of 11 years at any latitude (Howard & LaBonte 1980; Ulrich *et al.* 1988). That is just what would be expected for torsional oscillations in a nonlinear dynamo, because the Lorentz force does not depend upon the sign of the magnetic field. Thus the observational evidence favours a hydromagnetic dynamo.

We are therefore led to consider a magnetic layer beneath the base of the convective zone (Spiegel & Weiss 1980; van Ballegooijen 1982; Gilman *et al.* 1989), where toroidal flux builds up until the layer is broken up by instabilities driven by magnetic buoyancy (Parker 1979; Hughes & Proctor 1988). There are several timescales associated with this process. Flux escapes through the convective zone to emerge in active regions in a convective turnover time of about a month (comparable with the rotation period). There are fluctuations in activity and luminosity on this timescale. Then there are variations corresponding to the 11-year activity cycle or the 22-year magnetic cycle. (Note that Spiegel & Weiss (1980) erroneously assumed that convective elements retained their excess energy, rather than excess entropy, as they rose through the convective zone; hence their estimate of the luminosity fluctuation should be reduced by the ratio of the temperature at the surface to that at the base of the convective zone, which is around 5×10^{-3}.) Finally, there are modulations associated with grand minima, on a timescale of 200 years.

The systematic properties of the solar cycle suggest that it can be modelled by averaging over small-scale, short-term variations. It is convenient to adopt a three-scale approach (Weiss 1981). By averaging over the smallest scales we obtain eddy diffusivities that can be fed into self-consistent dynamo models with motion extending across the whole convectively unstable region (Gilman 1983; Glatzmaier 1985). These numerical experiments confirm that the dynamo process works, even though details do not match the observations, which is scarcely surprising in view of the simplifications that have to be made to produce a tractable model. Next we can average azimuthally to produce a mean field dynamo (Parker 1979; Zel'dovich *et al.* 1983), where the α-effect describes the generation of poloidal flux through helicity and toroidal fields are produced by differential rotation. There are many examples of linear and nonlinear $\alpha\omega$-dynamos tuned to produce butterfly diagrams that accord with observations. Recently, there has been more interest in studying spatiotemporal structure in idealized nonlinear models (see, for example, Belvedere *et al.* 1990; Brandenburg *et al.* 1989). Even a simple cartesian model with parametrized nonlinearities can possess a complicated bifurcation structure: figure 1 illustrates the bifurcation pattern, involving steady and oscillatory modes with quadrupole and dipole symmetry, as well as mixed-mode solutions lacking any symmetry about the Equator, for a model investigated by Jennings & Weiss (1989). These bifurcations involve changes in spatial structure for solutions with straightforward time dependence. When such models are extended to allow more complicated dynamical interactions further bifurcations may lead to a rich variety of temporal behaviour, including chaos (Weiss *et al.* 1984).

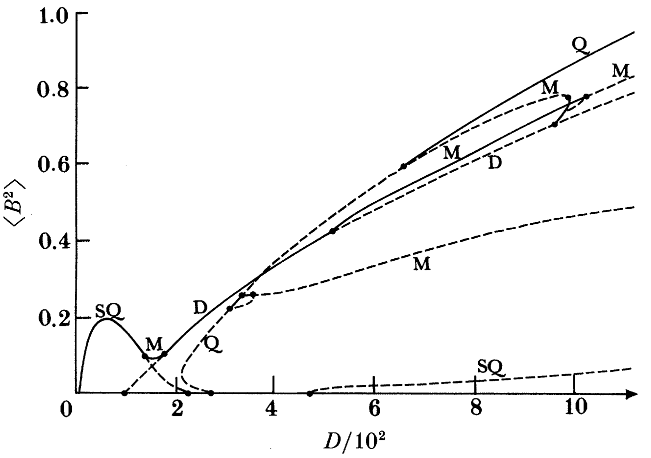

FIGURE 1. Bifurcation structure for a nonlinear dynamo showing transitions between quadrupole and dipole symmetries (after Jennings & Weiss 1989). The mean square toroidal field $\langle B^2 \rangle$ is plotted against the dynamo number D (proportional to ω^2) for a truncated 14-mode model. Stable solutions are indicated by full lines and unstable solutions by broken lines. There are branches of steady quadrupole (SQ) solutions and of oscillatory dipole (D) quadrupole (Q) and mixed-mode (M) solutions.

4. Deterministic chaos

To interpret time series derived from natural phenomena it is necessary to understand some theoretical aspects of the behaviour of nonlinear dissipative systems. We need to adopt a geometrical approach: instead of studying the periodic displacement of a nonlinear oscillator we follow trajectories in phase space, where they are attracted to a closed limit cycle. Now suppose that the system is subjected to small stochastic disturbances. (The classic example of a pendulum bombarded by small boys with peashooters was introduced by Yule (1927) in the context of the solar cycle.) Then trajectories will be contained within a tube enclosing the limit cycle and the attractor is only slightly distorted. Obviously, the situation changes as the intensity of the noise is increased (for example, if the peashooters are replaced by cannon).

This must be distinguished from chaotic behaviour associated with sensitivity to initial conditions (Schuster 1988). Figure 2 illustrates the development of a chaotic attractor in two-dimensional double-diffusive convection (Knobloch *et al.* 1986). The variation with time of the kinetic energy $E(t)$ can be followed either by projecting trajectories onto the $E\dot{E}$-phase plane or by forming a power spectrum $\hat{E}(\omega)$, where ω is the frequency. Figure 2*a* shows a periodic solution with a convoluted cycle and a line spectrum (limited by the finite data-set). In figure 2*b* the solution is aperiodic, with a chaotic attractor in the vicinity of the unstable periodic orbit; the spectrum is intrinsically noisy but the peaks are still clearly visible. (Such behaviour is called semiperiodic.) In figure 2*c* and *d* the trajectories are more obviously chaotic. Peaks corresponding to the basic cycle frequency and its first harmonic can still be discerned in figure 2*b*, but are submerged by noise in figure 2*d*. Such results indicate how sophisticated frequency analysis can pull convincing line spectra out of intrinsically aperiodic data. Moreover, the frequencies may indeed correspond to those of unstable periodic orbits that are approached by the chaotic trajectory.

More generally we may expect to find not only periodic but also quasi-periodic (i.e. multiply periodic) orbits, with trajectories that lie on tori in phase space. A two-torus can be identified

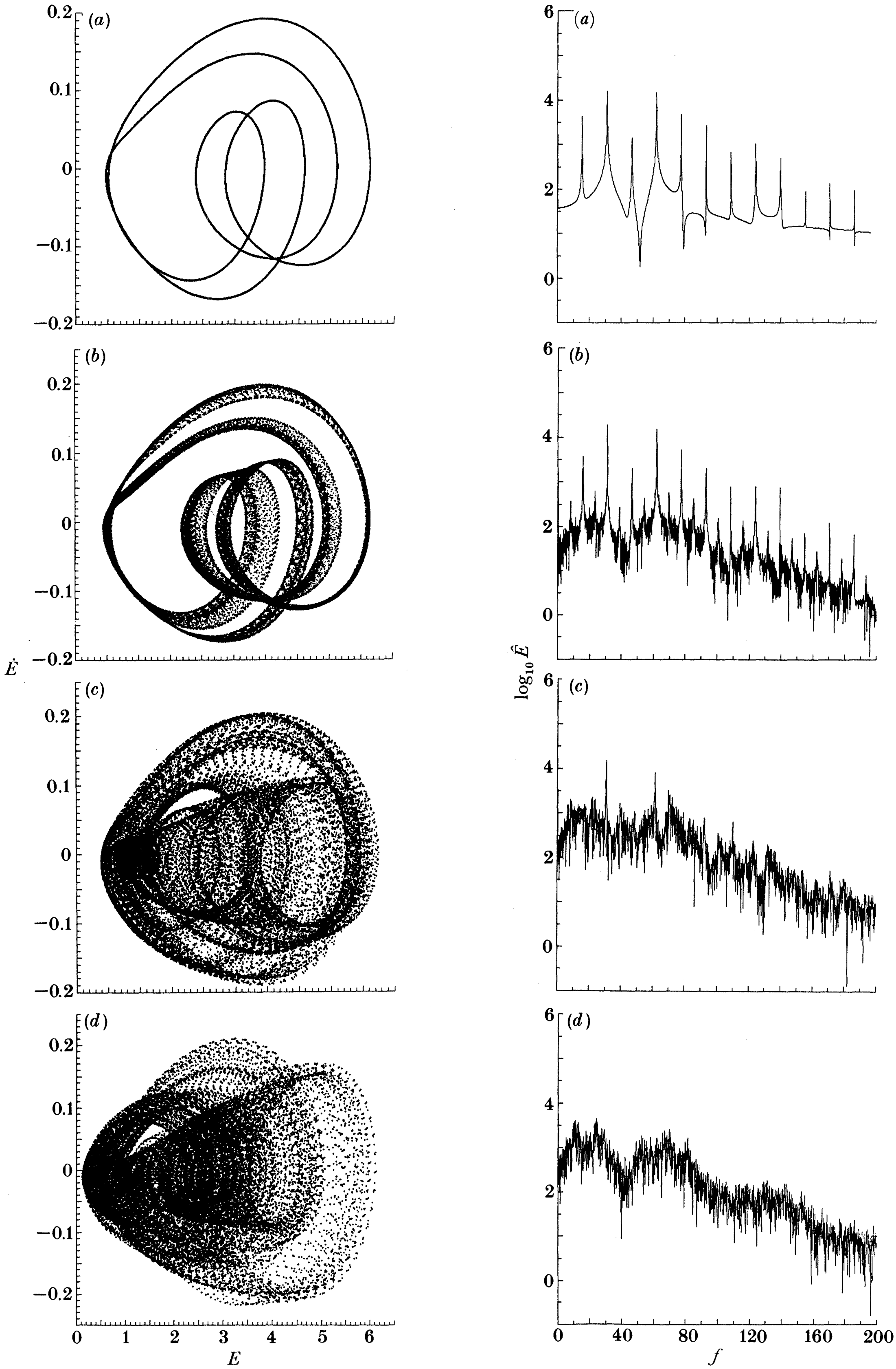

FIGURE 2. Chaos in thermosolutal convection (after Knobloch *et al.* 1986). Trajectories projected onto the $E\dot{E}$-plane and corresponding power spectra $\hat{E}(f)$ for different values of the Rayleigh number R. (*a*) $R = 10450$: periodic solution; (*b*) $R = 10475$: semiperiodic solution; (*c*) $R = 10625$: chaotic solution; (*d*) $R = 11000$: chaos.

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by taking a Poincaré section, which yields a closed curve. At every resonance this curve collapses to isolated points and frequency-locking may be followed by a transition to chaos (cf. Jones *et al.* 1985). Once again, the basic form of the attractor is not affected by adding weak stochastic disturbances, though violent disturbances can change its structure (Lorenz 1987).

The prevalence of chaos in complicated nonlinear systems could therefore be anticipated. On a laboratory scale transitions to chaos have been identified in experiments on convection, where temporal chaos is followed by weakly turbulent behaviour as more spatial structure is involved (Libchaber 1987). Meteorology and astrophysics provide examples of chaotic behaviour in natural systems (Lorenz 1984; Spiegel 1985). Short-term climatic changes are aperiodic (Ghil 1987) and the weather is notoriously unpredictable (Lorenz 1984, 1987). Turbulent convection in the Sun is a good example of spatiotemporal chaos and the solar cycle resembles a chaotic oscillator.

To model aperiodic solar activity we once again assume a separation of scales in time. Convective timescales range from 5 min for the photospheric granulation to 25 days for giant cells that span the full depth of the convective zone, while the lifetime of active regions is comparable with the rotation period (also 25 days). Short-term fluctuations in solar activity can be regarded as a dynamic process associated with instabilities of the submerged magnetic layer (Spiegel & Wolf 1987). We shall, however, average over rapid variations with periods less than a year and regard the fluctuations as noise. Can medium and long-term variations, with timescales of 10–500 years be described by a relatively low-dimensional dynamical system? Here it is encouraging that a simple sixth-order model of the solar dynamo can yield aperiodic modulation with episodes of reduced activity resembling those found in the solar record (Weiss *et al.* 1984). These grand minima are associated with the persistence of a 'ghost' torus in the chaotic régime.

There are procedures that allow us to establish whether a given time series corresponds to a low-dimensional attractor (Schuster 1988). First the time series is converted into a trajectory embedded in an m-dimensional phase space by introducing time lags. Next we take N points $x_i (i = 1, \ldots, N)$ on this trajectory. Let $n(l)$ be the number of pairs (x_i, x_j) with separations $l_{ij} = |x_i - x_j|$ such that $l_{ij} < l$; then the quantity $C(l) = n(l)/N^2$ is an estimate of the correlation integral and $\nu = \mathrm{d}\ln C/\mathrm{d}\ln l$ is an estimate of the correlation dimension. To demonstrate the existence of an attractor with dimension ν we need $m > \nu$ and N sufficiently large. Smith (1988) has shown that the number of (independent) points required is of order $N = (40)^{\nu}$: so for $\nu \approx 3$ we require more than 10^4 data points and computational demands rapidly become prohibitive as ν increases.

L. A. Smith has compared the sunspot record with two very different models. The first is a well-known third-order system that exhibits chaotic oscillations associated with a heteroclinic bifurcation (Spiegel 1985). For suitably chosen parameters there is a chaotic attractor with dimension $\nu \approx 2.1$. The estimate converges to this value over an acceptable range in l for $N > 2^{12}$ and $m = 3$, but more points are needed as m is increased. The second model is purely stochastic, constructed to mimic solar activity by filtering gaussian noise with a frequency corresponding to that of the magnetic cycle (Barnes *et al.* 1980). This stochastic (ARMA) oscillator yields a remarkably convincing simulation of the solar cycle and the computed dimension ν approaches the embedding dimension m if the time series is adequately long. The actual record of annual sunspot numbers provides a time series with $N \approx 2^8$. Figure 3*a* shows the estimated dimension ν as a function of l for an embedding dimension $m = 3$, compared with

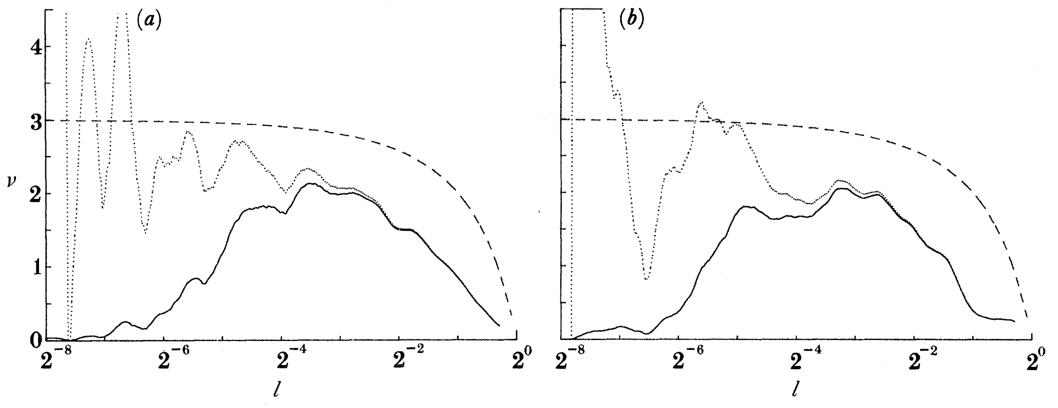

FIGURE 3. Estimating the dimension of an attractor. The correlation dimension ν is plotted as a function of l for an embedding dimension $m = 3$ and a total of $N = 2^8$ points. (*a*) Annual sunspot numbers and (*b*) the stochastic oscillator of Barnes *et al.* (1980). ——, Excluding points with $i = j$; ·····, including points with $i = j$; – – –, white noise. The actual record and the artificial series cannot be distinguished.

that for white noise, where $\nu \rightarrow m$ as $l \rightarrow 0$. Results for the stochastic oscillator, again with $N = 2^8$, are shown in figure 3*b* and the two figures are virtually indistinguishable. This demonstrates that the sunspot record since 1714 is not long enough to distinguish between stochastic and chaotic models.

We might also attempt to discover whether modulation of the solar cycle is chaotic, by averaging over the 11-year cycles. The bidecadal averages of fluctuations in the ^{14}C production rate provide just such a record, extending over the past 9000 years (Stuiver & Braziunas 1988). This yields a time series with $N \approx 2^9$. Once again, this series is too short for us to establish whether there is a low-dimensional attractor.

5. Conclusion

Periodicity is characteristic of linear systems, where periodic solutions can be superposed to produce a complicated signal. Nonlinear systems are likely to be intrinsically aperiodic, though frequency analysis may still yield peaks in the power spectrum of a chaotic record. Historically, attempts to interpret the record of solar activity seem to have favoured aperiodic and periodic descriptions at different epochs. After the Maunder Minimum astronomers apparently regarded variations in the Sun's activity as deviations from its normal spotted state. Thus Herschel (1801), referring to the prolonged minimum of 1795–1800, commented: 'It appears to me, if I may be permitted the metaphor, that our Sun has for some time past been labouring under an indisposition, from which it is now in a fair way of recovering'. Such interruptions were thought to be irregular both in duration and in frequency. It took Schwabe (1844), who ignored previous observations and referred only to his own, to recognize the 11-year activity cycle. Since then it has been fashionable to look for periodic modulations of solar activity. Both the sunspot record since the first telescopic observations and the ^{14}C proxy records are, however, consistent with aperiodic modulation and irregularly spaced grand minima. Unfortunately, the data are insufficient to establish whether this aperiodic modulation is a consequence of stochastic disturbances or deterministic chaos. Thus the latter cause can only be preferred on the grounds that it provides a more economical explanation of the observations.

Although we know that the solar luminosity does vary slightly with the sunspot cycle there is as yet no clear evidence of a direct correlation between solar activity and the weather or between the Maunder Minimum and the Little Ice Age (Stuiver 1980). It may be more profitable to think of the solar dynamo and the Earth's climate as two weakly coupled nonlinear systems, each behaving chaotically with a variety of characteristic timescales. Occasionally oscillations with nearby frequencies will be locked in phase but this locking should be temporary and unlikely to persist.

References

van Ballegooijen, A. A. 1982 *Astron. Astrophys.* **113**, 99–112.
Barnes, J. A., Sargent, H. H. & Tryon, P. V. 1980 In *The ancient sun* (ed. R. O. Pepin, J. A. Eddy & R. B. Merrill), pp. 159–164. New York: Pergamon.
Belvedere, G., Pidatella, R. M. & Proctor, M. R. E. 1990 *Geophys. Astrophys. Fluid Dyn.* (In the press.)
Brandenburg, A., Krause, F., Meinel, R., Moss, D. & Tuominen, I. 1989 *Astron. Astrophys.* **213**, 411–422.
Brown, T. M. & Morrow, C. A. 1987 *Astrophys. J.* **314**, L21–L26.
Cini Castagnoli, G., Bonino, G. & Provenzale, A. 1988 *Solar Phys.* **117**, 187–197.
Cohen, I. B. 1961 *The birth of a new physics*. London: Heinemann.
Dziembowski, W. A., Goode, P. R. & Libbrecht, K. G. 1989 *Astrophys. J.* **337**, L53–L57.
Eddy, J. A. 1976 *Science, Wash.* **192**, 1189–1202.
Ghil, M. 1987 In *Irreversible phenomena and dynamical systems analysis in geosciences* (ed. C. Nicolis & G. Nicolis), pp. 313–320. Dordrecht: Reidel.
Gilman, P. A. 1983 *Astrophys. J. Suppl.* **53**, 243–268.
Gilman, P. A., Morrow, C. A. & DeLuca, E. E. 1989 *Astrophys. J.* **338**, 528–537.
Glatzmaier, G. A. 1985 *Geophys. Astrophys. Fluid Dyn.* **31**, 137–150.
Hart, J. E., Toomre, J., Deane, A. E., Hurlburt, N. E., Glatzmaier, G. A., Fichtl, G. H., Leslie, F., Fowlis, W. W. & Gilman, P. A. 1986 *Science, Wash.* **234**, 61–64.
Herschel, W. 1801 *Phil. Trans. R. Soc. Lond.* **91**, 265–318.
Howard, R. 1984 *A. Rev. Astr. Astrophys.* **22**, 131–155.
Howard, R. & LaBonte, B. J. 1980 *Astrophys. J.* **239**, L33–L36.
Hughes, D. W. & Proctor, M. R. E. 1988 *A. Rev. Fluid Mech.* **20**, 187–223.
Jennings, R. L. & Weiss, N. O. 1989 In *Solar photosphere: structure, convection, magnetic fields* (ed. E. A. Gurtovenko & J. O. Stenflo). Dordrecht: Kluwer.
Jones, C. A. & Galloway, D. J. 1988 In *Secular solar and geomagnetic variation over the last 10,000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 97–108. Dordrecht: Kluwer.
Jones, C. A., Weiss, N. O. & Cattaneo, F. 1985 *Physica* D**14**, 161–176.
Knobloch, E., Moore, D. R., Toomre, J. & Weiss, N. O. 1986 *J. Fluid Mech.* **166**, 409–448.
Libchaber, A. 1987 *Proc. R. Soc. Lond.* A **413**, 63–69.
Lorenz, E. N. 1984 *Tellus* A **36**, 98–110.
Lorenz, E. N. 1987 In *Irreversible phenomena and dynamical systems analysis in geosciences* (ed. C. Nicolis & G. Nicolis), pp. 159–179. Dordrecht: Reidel.
Mestel, L. & Spruit, H. C. 1987 *Mon. Not. R. astr. Soc.* **226**, 57–66.
Parker, E. N. 1979 *Cosmical magnetic fields*. Oxford: Clarendon Press.
Priest, E. R. 1982 *Solar magnetohydrodynamics*. Dordrecht: Reidel.
Schuster, H. G. 1988 *Deterministic chaos*, 2nd edn. Weinheim: VCH.
Schwabe, S. H. 1844 *Astr. Nachr.* **21**, 233–236.
Smith, L. A. 1988 *Phys. Lett.* A **133**, 283–288.
Soderblom, D. R. & Baliunas, S. L. 1988 In *Secular solar and geomagnetic variations over the last 10,000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 25–48. Dordrecht: Kluwer.
Spiegel, E. A. 1985 In *Chaos in astrophysics* (ed. J. R. Buchler, J. M. Perdang & E. A. Spiegel), pp. 91–135. Dordrecht: Reidel.
Spiegel, E. A. & Weiss, N. O. 1980 *Nature, Lond.* **287**, 616–617.
Spiegel, E. A. & Wolf, A. 1987 *Ann. N. Y. Acad. Sci.* **497**, 55–60.
Stuiver, M. 1980 *Nature, Lond.* **286**, 868–871.
Stuiver, M. & Braziunas, T. F. 1988 In *Secular solar and geomagnetic variations over the last 10,000 years* (ed. F. R. Stephenson & A. W. Wolfendale), pp. 245–266. Dordrecht: Kluwer.
Tayler, R. J. 1989 *Q. Jl R. astr. Soc.* **30**, 125–161.
Ulrich, R. K., Boyden, J. E., Webster, L., Snodgrass, H. B., Padilla, S. P., Gilman, P. & Shieber, T. 1988 *Solar Phys.* **117**, 291–328.

Weiss, J. E. & Weiss, N. O. 1979 *Q. Jl R. astr. Soc.* **20**, 115–118.
Weiss, N. O. 1981 In *Solar activity* (ed. C. Jordan), pp. 35–50. Oxford: EPS.
Weiss, N. O. 1989 In *Accretion discs and magnetic fields in astrophysics* (ed. G. Belvedere), pp. 11–29. Dordrecht: Kluwer.
Weiss, N. O., Cattaneo, F. & Jones, C. A. 1984 *Geophys. Astrophys. Fluid Dyn.* **30**, 305–341.
Yule, G. U. 1927 *Phil. Trans. R. Soc. Lond.* A**226**, 267–298.
Zel'dovich, Y. B., Ruzmaikin, A. A., & Sokoloff, D. D. 1983 *Magnetic fields in astrophysics*. London: Gordon & Breach.

Discussion

P. Foukal (*CRI, Cambridge, Massachusetts, U.S.A.*). To return to the subject of solar irradiance variations, Richard Radick, Wes Lockwood and Sallie Baliunas have reported recently on the behaviour of flux variations in stars similar to the Sun, but much younger (about 3.5×10^9 years younger). They find that in such stars high levels of magnetic activity tend to anticorrelate with stellar brightness. That is, unlike the present Sun, these young stars get darker at high activity periods of their sunspot cycles. Presumably the propensity to form dark spots in these younger stars dominates over the formation of faculae, the opposite of what we now see in the Sun.

N. O. Weiss. That is a significant observation. It confirms my view that one has to be cautious before extrapolating from the Sun to young, rapidly rotating and more active stars. The pattern of convection, the angular velocity distribution and the behaviour of the dynamo are likely to be very different. In particular, stars with spots that produce variations of up to 30% in luminosity must have far more flux in their poloidal fields than the Sun.

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