Solar Rotation, Irradiance Changes and Climate

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Magnetic activity cycles for solar-type stars are believed to originate from non-uniform internal rotation. To determine this depthwise angular velocity distribution, helioseismology is a valuable source of information. Surface rotation, as traced by sunspot motion, is a well-observed parameter with data going back to the beginning of the telescopic era. This long sunspot series can be used in understanding the behaviour of the Sun's surface rotation, the connection with its internal rotation, and thereby its magnetic activity. Apparent solar diameter is another important parameter. This is related to the structure of the convective envelope and how it reacts to the presence of magnetic fields. Both these parameters are related to the solar output, and can provide a surrogate for total solar irradiance, by way of a theoretical modeling of the response of the convective zone to the emergence of periodic magnetic fields. The impact of solar variability on the terrestrial climate is also addressed.

1. Introduction

Direct observation of solar rotation is available for the surface only. It is possible, however, to obtain information on the internal rotation of the Sun from surface oscillations, provided we have a theory explaining the 5 min oscillations. This is known as an inverse problem.

Magnetic tracers (sunspots, faculae, network, filaments) can be used to reconstruct solar rotation. This is also an inverse problem, for similar reasons, because a rotation curve deduced from tracers provides information only about those layers where the tracers originate. We believe that sunspots provide information on the distribution of azimuthal large-scale magnetic fields, and we adopt the idea that the azimuthal field is generated by the α-ω dynamo mechanism. These concepts are not as yet unanimously accepted. However, if the rotation curve deduced from seismic observations is compatible with that derived from magnetic tracers, this is a clear indication that observations and theories are compatible. So we shall adopt the framework of the α-ω dynamo theory and relate the properties of solar dynamics (meridional circulation and internal rotation) to the emergence of magnetic fields, and thereby to the strength of solar cycles. Then applying a simple model, we shall use the dynamics as a surrogate for solar output. An estimate of the solar output variation will become available and will be introduced in atmospheric circulation models to study the climatic response to solar forcing.

2. Parker migratory dynamo and the solar rotation curve

The distribution of solar activity through the solar cycle can be interpreted as a dynamo wave propagating from pole to equator (Parker 1955). From observations, this wave starts at about 70° latitude (Leroy & Noens 1982) and moves equatorwards in approximately 11 years.

According to Parker's migratory dynamo, the wave generation is controlled by two ingredients. The first is a radial shear in the angular velocity, $\frac{\partial\omega}{\partial r}$. The second ingredient is the helicity of the flow α. According to the usual explanation of helicity (due to the influence of Coriolis forces on cyclonic-type motions in a stratified medium), helicity is positive in the northern hemisphere and negative in the southern. So a dynamo wave moving equatorward, as shown in the butterfly diagram of sunspot activity, implies that $\frac{\partial\omega}{\partial r}$ should be negative.

It becomes clear that Parker's scenario should be adapted to this new picture of solar activity. There are two basic alternative ways to produce the observed distribution of solar activity of Figure 1, in the framework of the α-ω dynamo. One is to change the sign of helicity (as suggested by P. Gilman). Several sophisticated (compared with the standard explanation) ways exist to create this α effect, with an anisotropic tensor structure for α. The other alternative is to understand the complex solar activity distribution through the solar cycle as a result of the combination of two waves, as shown in Figure 1. In other words, the modification of the Parker migratory dynamo will depend on the description of the solar activity. Either we consider that the branches B_1 and A_1 are connected so as to make a continuous equatorwards wave (similarly, B_2 and A_2 are a continuous poleward wave) or we concentrate essentially on the A_2 and B_2 branches and leave the interpretation of the secondary A_1 and A_2 branches for further study. In the next section, we discuss these two possibilities for interpreting the new solar activity diagram, in the framework of the Parker dynamo.

Parker's dynamo is not completely successful, as it gives rise to a number of predictions inconsistent with observational data (Parker 1989). For example, the predicted period for the solar cycle should be controlled by the Sun's rotation period, i.e. 30 days, while the cycle lasts about 10 years. The role of helicity also has to be considered. However, if both helicity and radial shear are located in the same layers, it is difficult to extend the solar cycle to more than, say 10 rotation periods. Several ways have been suggested to overcome this difficulty, the most reasonable being to say that the helicity belongs to convective layers other than those subject to radial shear. The two regions of interest would be connected by turbulent diffusion, and the slow diffusion time-scale would lead to a long cycle of activity (Parker 1993). This view is supported by recent seismic observations, which seem to place the existence of a radial shear of the angular velocity at the bottom of the convective zone or even below it.

Another difficulty has come from seismic observations, with the sign of the observed angular velocity shear, $\frac{\partial\omega}{\partial r}$, and the direction of propagation of the dynamo wave in Parker migratory dynamo. However, some recent observations of solar activity provide new insight into the subject. It has been noticed (Harvey 1992) that a few active regions do not follow the Hale polarity rule: namely the leading sunspot has a magnetic polarity that is opposite to what is expected in a given cycle, for a given hemisphere. These active regions appear close to the equator shortly after sunspot maxima, and move poleward (up to 20°). This is suggestive of another activity wave of opposite direction and of weak amplitude (Mouradian & Soru-Escaut 1991). Furthermore, the large-scale magnetic field as traced by H_α filaments do show a poleward migration from sunspot minimum to maximum (Makarov 1984). On the other hand, the small ephemeral regions that appear in each hemisphere near the latitudes of 70° (Martin & Harvey 1979) move equatorwards. So there seems to exist two waves, one poleward and the other equatorward. The two corresponding branches of solar activity are represented schematically in Figure 1. The solid lines in Figure 1 correspond to the well-established migration of sunspots, the so-called sunspot butterfly diagram (equatorward branch, B_1). The dotted lines describe the migration of the small bipolar active regions A_1 (Martin & Harvey 1979). The dashed lines represent the migration of sunspots violating the Hale polarity rule A_2. The dotted-dashed lines trace the migration of large-scale magnetic fields (poleward branch B_2).

3. Possible scenario for normal activity cycles

3.1. *Two intersecting dynamo waves*

From seismic observations, the radial shear has a negative sign in the latitude range between 90° and 40°. So the dynamo number will be negative there, with the conventional sign for helicity (positive in the northern hemisphere). As a result, a wave propagating equatorward can be generated there as long as the (negative) dynamo number exceeds some critical value. Because helicity is antisymmetric with respect to the equator, it is natural to expect the dynamo number to be maximum somewhere around ± 40°, which corresponds precisely to the latitudes where sunspots appear (branch A_1).

To account for the additional dynamo wave generated near the equator and moving polewards, the sign of the radial shear should be positive; this is the case for the latitudes ranging between the Equator and 30°. So a poleward wave will be generated at around 5° to 10° (branch A_2).

What occurs when these two waves collide, which is somewhere near $\theta \sim 30°$? The answer probably lies in our understanding of the nonlinear influence of the dynamo wave on the α-coefficient. In a nonlinear regime, α is the sum of both hydrodynamic and magnetic helicity. If we accept such an idea, the magnetic helicity can exceed the hydrodynamic, so the value of $\alpha\frac{\partial\omega}{\partial r}$ varies within the dynamo wave. This means that, after collision, the poleward and equatorward waves may continue on their way in a nonlinear regime through regions which would not be permitted in the kinematic approach. As a result of such propagation, one obtains the branches B_2 and B_1 respectively. Though these waves probably become unstable, it is natural to believe that their lifetime is of the order of the solar cycle. Two intersecting waves can be produced in the framework of α-ω dynamo theory.

3.2. *Two distinct dynamo waves*

There is another way to produce the schematic butterfly diagram of Figure 1. We assume that helicity does not have the conventional sign, i.e. it is negative in the northern hemisphere. In this case, the poleward wave (branch B_2) would occupy the latitude domain $\theta > 40°$, and the equatorwards wave (branch B_1), the region $\theta < 30°$. There would be a region without sunspots around $\theta \sim 35°$. One reasonable test for this type of model would be the existence of an empty region on the butterfly diagram. This seems to be the case, as a gap around $\theta \sim 30°$ is visible on both the Meudon and Greenwich sunspot data, approximately one year before sunspot maximum. However, this gap is not observed during the whole cycle. If we accept this explanation for the butterfly diagram, it would be necessary to explain how and why this gap disappears in the more intensive phase of solar activity and what is the origin of the phenomena, referred previously to as branches A_1 and A_2.

4. Characteristics of the Maunder Minimum

There are times when solar activity cycles are very low. Such episodes have possibly occurred several times over the past millenia (Stuiver & Braziunas 1993). We have at our disposal only one such long-lived minimum that is well-documented: the "Maunder Minimum". This minimum can be described as follows (Ribes & Nesme-Ribes 1993).

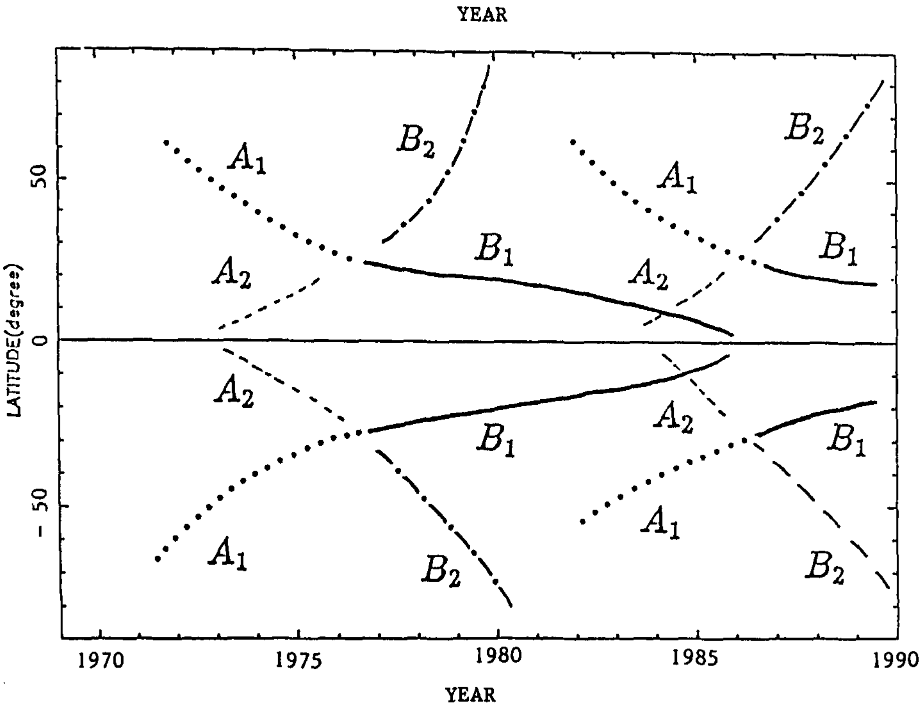

FIGURE 1. Schematic butterfly diagram of solar activity: two dynamo waves (equatorward and polarward) are presented during each 11-year cycle. The dotted lines describe the migration of the small ephemeral regions, the solid lines correspond to the well-known sunspot butterfly diagram. The dashed lines represent the migration of sunspots violating the Hale magnetic polarity rule, the dotted-dashed lines correspond to the migration of large-scale magnetic field as traced by H_α filaments.

The sunspot number was extremely low for at least 50 years (from 1660 to 1710), and was restricted to the southern hemisphere only. Activity resumed in the northern hemisphere starting in 1715, though the cycle was nonetheless still weak. The sunspots then remained close to the Equator, as happens during the decreasing phase of the solar cycle (after sunspot maximum). The sunspot rotation rate was low and the variation of rotation (with respect to latitude) was more differential. This is in conformity with what is observed during the minimum of a modern 11-year cycle, when the rotation is more rigid at the sunspot maximum and more differential near the minimum (Nesme-Ribes *et al.* 1993b). The difference, however, is that the differential rotation was more pronounced during the Maunder Minimum than at present. Lastly, the solar diameter appeared larger than at present, and showed a strong 10-year modulation, thereby suggesting that the cycle was still at work (Ribes *et al.* 1989). It should be noted that, in spite of difficulties in correctly interpreting the observed variations of the solar diameter, the modulation (larger at the time of sunspot minimum and smaller at the time of high activity) was in conformity with the present variation of the solar diameter (Ribes *et al.* 1992). Furthermore, the abundance of cosmogenic isotopes during the Maunder Minimum (Stuiver & Braziunas 1993) coincides with a 10-year modulation in phase with the sunspot number and the apparent solar diameter (Ribes *et al.* 1989).

There are also some more empirical indications that a 10-year cycle was at work.

The state of the corona was observed at various times, during solar eclipses (Ribes & Nesme-Ribes 1993), showing periods of alternating quiet and activity.

5. Possible Maunder Minimum scenario

It seems likely that the (rigid) rotation of the radiative zone has remained unchanged over the last three centuries. Assuming sunspots are an effective tracer of the convective zone rotation, it becomes clear that this rotation changed during the Maunder Minimum, for the latitude between ± 30°, as shown in Figure 1 of (Nesme-Ribes *et al.* 1993a). Adopting a conventional (positive) sign for helicity in the northern hemisphere, the low-latitude poleward branch of activity was suppressed, as both helicity near the Equator and positive shear were weak. Above 30°, no tracers were available during the 17th century to determine the rotation rate at high latitudes. It is possible, however, that the negative shear was still large, allowing an equatorward dynamo wave. It is also natural to believe that the latitudinal distribution of $\alpha\frac{\partial\omega}{\partial r}$ was much sharper near the Equator during Maunder Minimum than during a normal cycle. It can be shown that the solar dynamo is then nearer the bifurcation point between non-oscillatory and oscillatory regimes. Under such conditions, mixed parity solutions are expected (Brandenburg *et al.* 1989). A corresponding mixed parity solution has been obtained by Jennings (1991) in numerical simulations: the dynamo wave was suppressed in one hemisphere and confined to the equatorial region in the other (see more about computer simulations of mixed parity in solar dynamo Brandenburg *et al.* 1990). Azimuthal magnetic fields (that of active regions) in this mixed parity solution are produced from the combination of a dipole and a quadrupole field of comparable strengths (Sokoloff & Nesme-Ribes 1993).

This scenario of Maunder Minimum solar activity assumes a standard sign for helicity. As a result, one obtains a single wave A_1 in the southern hemisphere and no wave in the northern.

6. Meaning in terms of solar output variation and climatic impact

We must first address the problem of relating the strength of the solar cycles to the solar output. To do so, a self-consistent theoretical model has to be developed to solve the dynamics and the thermodynamics. This is far from being done. However, an approximation has been made by relating the change in the kinetic energy throughout the solar cycle empirically to the change of total solar irradiance (Nesme-Ribes & Mangeney 1992). The total solar irradiance has been reconstructed from the properties of solar dynamics as observed during the 17th century. Furthermore, a certain amount of structural change in the solar envelope (apparent diameter and luminosity) (Spruit 1992) also results from the magnetic field emergence. So the diameter constitutes another surrogate for deriving the solar output. Systematic observations of the apparent diameter were made during the Maunder Minimum, which gives us two independent ways of reconstructing the solar output (Nesme-Ribes *et al.* 1993a).

One interesting feature was a 10-year modulation of the solar output, over the period 1666 to 1719. The decrease ranged from .1% to 1% with respect to a reference value, which was the total solar irradiance measured by radiometers at the sunspot maximum in the year 1989 (Wilson & Hudson 1991). To address the question of climatic response to such solar forcing, equilibrium climate models were used. We adopt a constant decrease of the total solar irradiance, i.e. 0.4% over approximately 50 years. Assuming a planetary albedo of 30%, a 0.4% decrease of the solar output would correspond, on the average over the spherical surface of the Earth, to a variation of approximately -1W m^{-2} of the absorbed solar energy. For such a perturbation equilibrium climate simulations are expected to produce an average cooling of 0.3 to 1.2 °K, depending on the atmospheric general circulation model used (Cess *et al.* 1990). These values are compatible with those found in the literature of the Little Ice Age reconstructions, although most data there concern Europe only (e.g. Pfister 1992, among others). On the other hand, the equilibrium climate assumption is not very realistic, as it neglects the effect of slow oceanic circulation transients; other external perturbations like volcanic dust might have played a significant role in the Little Ice Age event.

The global structure of equilibrium climate change associated with a -0.4% perturbation of solar luminosity has been described in Nesme-Ribes *et al.* (1993a) for a relatively sensitive version of the Laboratoire de Météorologie Dynamique atmospheric general circulation model (referred to as LMD agc model, Sadourny & Laval 1984). The response is found to be very similar to the case of a greenhouse gas perturbation of equivalent radiative magnitude, which points to the major role of internal feedback processes in climatic change; this would also mean that, if the Little Ice Age was indeed due to the weakening of solar output during the Maunder Minimum, the difference between the present climate and that of the XVIIth century would be a good analogue to the present anthropogenic greenhouse warming (at least to the second order, as we must take into account the strong nonlinearity of the response, which, starting from the present state, produce an asymmetry between warming and cooling). Some of the main characteristics of the response (likely to be equally valid for a solar or long-wave radiative perturbation) have been discussed by Nesme-Ribes *et al.* (1993a). One prominent feature of the climatic modeling is the decreased weight of latent energy compared to enthalpy in the global energetics of the atmosphere (including the mean Hadley-Walker circulation and middle-latitude transients) associated with a decrease of the solar constant, which follows from the strong concavity of the Clausius-Clapeyron law relating saturation water vapor mixing ratio to temperature. The response of the Hadley circulation has been analyzed in detail by Sadourny (1993). It is shown that the Hadley circulation is likely to increase in strength as the solar constant decreases, due to the combined effects of cooling and the increased vertical static stability following tropical drying in the lower layers. In addition, the meridional extent of the Hadley circulation would have decreased at the Maunder Minimum, due to the decrease in the meridional temperature gradient in the upper troposphere. This is a direct consequence of angular momentum dynamics theory (Held & Hou 1980).

The analysis of the simulated decrease of Monsoon rainfall is at first sight, more elusive. In the LMD agc model, the decrease of the water cycle strength overcomes the increase of the divergent Hadley-Walker circulation mass flux. This again might be a reliable result: a decrease of the solar constant should induce a lesser continental energy excess in the summer season, and thus weaker energy transport, reflected primarily in the rainfall, again because of the sensitivity of the Clausius-Clapeyron relation.

7. Conclusion

In the framework of the α-ω dynamo, we have described qualitatively how to relate the changes in the internal rotation with the strength of the solar cycles and the solar output. As there is compelling evidence that the dynamics (thereby the strength of the 11-year cycles) changed significantly during the Maunder Minimum, we have been able to estimate crudely the solar output decrease from the available surrogates, the apparent solar diameter and the sunspot rotation rate. A mean 0.4 % decrease in the solar constant is likely to have lasted at least 50 years.

Such a variation in the solar output (which is equivalent to a solar perturbation of 1 W/m^2 at the top of the Earth's atmosphere) is sufficient to induce climatic fluctuations which are similar to those expected during a little ice age. The main climatic characteristics will be a reduction of the mean surface temperature and a decrease of water precipitations and soil moisture. However, the energetics of the Hadley circulation is complex; and as a result, we should expect less Monsoon rainfall in spite of a more vigorous Hadley circulation.

In conclusion, we mention two problems of importance for climatic predictions. The first is that solar activity should be monitored if we are to predict episodes of the Maunder Minimum type, insofar they coincide with periods of lower total solar irradiance. Along this line of thought, it would be helpful to study the onset of the Maunder Minimum and the corresponding characteristics of solar rotation. The second problem is the pronounced solar activity asymmetries which seem to be typical of solar activity minima. This could be the case for the Dalton Minimum detected in the abundance of cosmogenic isotopes (cycles V and VI of the early ninenteenth century). Such minima seem to influence solar irradiance significantly.

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REFERENCES

BRANDENBURG A., MEINEL R., MOSS D. & TUOMINEN I. 1990 Variation of even and odd parity in the solar dynamo. In *Solar Photosphere: Structure, Convection and Magnetic Fields* (ed. J.O. Stenflo). pp. 379–382. Kluwer. Dordrecht.

BRANDENBURG A., TUOMINEN I. & MOSS, D. 1989 On the nonlinear stability of dynamo modes. *Geophys. Astrophys. Fluid Dynam.* **49**, 129–141.

CESS R.D., POTTER G.L., BLANCHET J.P., BOER G.J., DEL GENIO A.D., DÉQUÉ M., DYMNIKOV V., GALIN V., GATES W.L., GHAN S.J., KIEHL J.T., LACIS A.A., LE TREUT H., LIANG Z.-H., MCAVANEY B.J., MELESHKO V.P., MITCHELL J.F.B., MORERETTE J.-J., RANDALL D.A., RIKUS L., ROECKNER E., ROYER J.F., SCHLESSE U., SHEININ D.A., SHINGO A., SOKOLOV A.P., TAYLOR K.E., WASHINGTON W.M., WETHERALD R.T., YAGAI I. & ZHANG M.-H. 1990 Intercomparison and interpretation of climate feedback processes in nineteen atmospheric general circulation models. *J. Geophys. Res.* **95**, 166501–16615.

HARVEY, K. 1992 The cyclic behaviour of solar activity. In *The Solar Cycle* (ed. K. Harvey). pp. 335–337. Astron. Soc. Pacif. San Francisco.

HELD I.M. & HOU A.Y., 1980 Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *J. Atmosp. Sci.* **37**, 515–533.

JENNINGS R.L. 1991 Symmetry breaking in stellar dynamos. *Month. Not. R. astr. Soc.* **252**, 249–260.

LEROY, J.L. & NOENS, J.C. 1983 Does the solar activity extend over more than an 11-year period? *Astron. Astrophys.* **120**, 1–2.

LE TREUT H. & LI Z.X. 1991 Sensitivity of an atmospheric general circulation model to prescribed SST changes: feedback effects associated with the simulation of cloud optical properties. *Climate Dynamics* **5**, 175–187.

MAKAROV, V.I. 1984 Do prominences move equatorwards? *Solar Phys.* **93**, 59–79.

MARTIN, S.F. & HARVEY, K.L. 1979 Ephemeral active regions during solar minimum. *Solar Phys.* **64**, 93–108.

MOURADIAN Z., SORU-ESCAUT I. 1991 On the dynamics of the large-scale magnetic fields of the Sun and sunspot cycle. *Astron. Astropys.* **251**, 649–654.

Nesme-Ribes E., Mangeney A. 1992 On a plausible mechanism connecting the Maunder Minimum to the Little Ice Age. *Radiocarbon* **32**, 63–270.

Nesme-Ribes E., Ferreira E. N., Sadourny R., Le Treut H. & Li L. 1993 a Solar Dynamics and its impact on solar irradiance and the terrestrial climate. *J. Geophys. Res.* **98**, 18923–18935.

Nesme-Ribes E., Ferreira E. N. & Mein P. 1993 b Solar dynamics over solar cycle 21 using sunspots as tracers. I. Sunspot rotation. *Astron. Astrophys.* **274**, 563–570.

Parker E.N. 1955 Hydromagnetic dynamo models. *Astrophys. J.* **122**, 293–314.

Parker E.N. 1989 Solar and stellar magnetic fields and atmospheric structures:theory. *Solar Phys.* **121**, 271–288.

Parker E.N. 1993 A solar dynamo surface wave at the interface between convection and nonuniform rotation. *Astrophys. J.* **408**, 707–719.

Pfister C. 1992 *Monthly Temperatures and precipitation in central Europe 1525-1979: quantifying documentary evidence on weather and its effects.* Climate since A.D. 1500. London.

Ribes E., Ribes J.-C., Merlin Ph. & Barthalot R. 1989 Absolute periodicities in the solar diameter derived from historical and modern data. *Annales Geophysicae* **7**, 321–329.

Ribes J.C. & Nesme-Ribes E. 1993 The solar sunspot cycle in the Maunder Minimum AD1645 to AD1715. *Astron. Astrophys.* **276**, 549–563.

Ribes E., Beardsley B., Brown T. M., Delache Ph., Laclare F., Kuhn J. & Leister N. V. 1992 The variability of the solar diameter. In *The Sun in Time* (ed. C.P. Sonett, M.S. Giampapa & M.S. Matthews) pp. 59–97. Arizona Univ. Tucson.

Sadourny R. 1993 Climate sensitivity, Maunder Minimum and the Little Ice Age. ESF, Bologna.

Sadourny R. & Laval, K. 1984 January and July performances of the LMD general circulation model. *New Perspectives in Climate Modelling.* Elsevier.

Schweingruber F.H., Fritts O., Bräker U., Drew L.G. & Schaar E. 1978 The X-ray technique as applied to dendrochronology. *Tree Ring Bulletin* **38**, 61–91.

Sokoloff D. & Nesme-Ribes E. 1993 The Maunder Minimum, a mixed-parity dynamo mode? *Astron. Astrophys.*, in press.

Spruit H. 1992 Theory of luminosity and radius variations. In *The Sun in Time* (ed. C.P. Sonett, M.S. Giampapa & M.S. Matthews), pp. 118–159. Arizona Univ. Tucson.

Stuiver M. & Braziunas T.F. 1993 Sun, Ocean, Climate and Atmospheric $^{14}CO_2$ variation: an evaluation of causal and spectral relationships. *The Holocene* **3**, in press.

Willson R. C. & Hudson H. 1991 The Sun's luminosity over a complete solar cycle. *Nature* **351**, 42–44.