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Variability in the solar output

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Evidence for variability in the solar output is briefly discussed. If the solar neutrino flux and the solar oscillation frequencies vary over a solar cycle this could indicate that the solar cycle has its origin in the solar core rather than be due to dynamo action in the solar convective zone.

Direct observations of solar variability reveal little information about solar variability other than the 11- or 22-year solar cycle as determined from sunspot numbers, reliable data exists for less than 200 years. Thus most inferences about solar variability come either from proxy data, or from unreliable historic data on sunspots. There is more recent data from the Active Cavity Radiometer Irradiance Monitor (ACRIM) experiment on the *Solar Maximum Mission* (see P. Foukal, this Symposium), which shows a variation in solar output with sunspots and possibly a 0.1% variation in total irradiance over the last solar cycle, attempts to reconstruct recent cycle variations suggest that typically the solar luminosity varies by somewhat less than this, about 0.05%. There are also claims that the solar radius also varies over a solar cycle, and over longer timescales (see E. Ribes, this Symposium). As is well known the sunspot cycle itself appears to be modulated by a 200-year cycle giving rise to the Maunder and other minima and, it is conjectured, to 'little ice ages' on Earth. More startling is the claim that the solar neutrino flux measured on Earth also varies with the solar cycle, and that the properties of the *p*-modes of oscillation of the Sun may show a similar cyclical variation.

It is premature to take these claims seriously, but my task is to be the 'agent provocateur', so I must challenge both the accepted wisdoms and put forward provocative suggestions!

The standard explanation of the solar sunspot (and magnetic) cycle is that it results from a dynamo acting in, or immediately below, the solar convective zone (see N. O. Weiss, this Symposium). Why should we believe this explanation? It is true that detailed calculations of dynamo models have been carried out, but these are not based on the correct physics, in spite of their numerical intricacy they are really no better than back of the envelope calculations using incorrect physics. Cray time is no substitute for understanding. The models are based on the following foundations: convection in a rotating shell produces non-uniform rotation, non-uniform rotation of a magnetic field stretches out the field to produce enhanced toroidal field from an initial poloidal field, a convective cyclonic eddy rising under gravity can generate poloidal field from toroidal field. But the solar convective zone is not a simple laminar fluid, it is as far as we can see, and as far as we can predict from terrestrial physics, in a state of highly developed turbulence. Thus any model of the solar dynamo has to model the small-scale turbulence by some eddy transport coefficients, the resulting model is not based on the equations of magnetohydrodynamics, or plasma physics, but on a set of macro-model equations, which contain unknown quantities representing smaller-scale behaviour. These equations are solved and the unknown eddy coefficients and transport processes adjusted until one finds a result that bears some resemblance to the observed solar cycle. It is not obvious to me that this is a valid procedure, why should there be any cycle at all in a fully developed turbulent medium? We anyway know from observations that magnetic flux is concentrated into small-scale intense flux tubes, so the microscale behaviour is important and may be dominant. At best all one can infer from the detailed macro-models is that there are solutions of the macro-equations that can be adjusted to give something like the observed magnetic cycle.

The 200-year modulation is more difficult to explain. As has been shown by Weiss, one can construct sets of nonlinear equations that produce 'chaotic' solutions with something like a short period modulated by a longer period. Because the equations governing the behaviour of the convective zone are nonlinear then perhaps one could construct a set of macro-model equations for the solar dynamo that exhibited the same behaviour. But whether this is really what is going on in the Sun I cannot say.

An alternative hypothesis discussed by D. O. Gough (this Symposium), but with a long history, is that the 11- or 22-year period is determined by an internal clock. The obvious candidate for such a clock being the Alfvén travel time round an internal magnetic field of order 0.3 T. This could be a torsional oscillation of the solar interior. In this picture, the details of which remain unspecified, the solar convective zone responds to the oscillation, giving rise to the observed phenomena of the solar cycle. This hypothesis of an internal toroidal oscillation was raised by myself (Roxburgh, unpublished work) as a possible explanation of the non-uniform rotation of the solar interior deduced from solar oscillations; the idea was that because the Alfvén time varies throughout the interior different parts of the Sun will oscillate at different rates so that the differential rotation is time dependent, all we see, or rather deduce from oscillations, is a 'snap-shot', which may well have unusual properties.

But this model is difficult to sustain. If the oscillation of neighbouring parts of the solar interior are out of phase, large gradients will be established on a short timescale (22 years), this will lead to enhanced dissipation which will tend to destroy the differential rotation. For a given angular momentum the lowest energy state is uniform rotation so that one should expect either uniform rotation or disordered differential rotation, in neither case would one have a nice clock.

Although it is still premature to reach conclusions there is some hint that the p-modes detected as solar oscillations show some variation with the solar cycle. The high-order modes are reflected in the surface convective zone and might therefore be expected to show some dependence on the solar cycle; but if, as seems to be suggested, the low-order modes show differential effects, then this may be some hint that the interior of the Sun also varies with the solar cycle. This would be more difficult to understand, although a change in the properties of the base of the convective zone could possibly effect the interior structure.

An even more puzzling phenomenon, if real, is the possible variation of the measured solar neutrino flux with the solar cycle. This suggests that the central temperature undergoes an 11-year variation of the order of a few percent. This is large and were it true would presumably give rise to variations of the internal structure that would in turn effect the properties of low-order p-modes of oscillation. But what could cause such a variation? One suggestion that has not been explored is that the nuclear reaction network plus internal structure is unstable to long-period (11-year) oscillations, driven by overstability in the reaction network (Roxburgh 1985). Another is that the outer convective zone generates gravity waves that propagate into

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the interior and are focused into the centre (Press 1981); because the outer convective zone varies on a solar cycle so too would the generation of gravity waves and hence their contribution in the very central regions where the neutrinos are generated (Roxburgh & Schatzman 1989). In this scenario the basic 22-year period, or quasi-period, is due to dynamo action in the convective zone.

And what about changes over a longer timescale? Models of the solar interior are really still in their infancy. A great deal of effort and computer time is spent on calculating spherically symmetric hydrostatic models with the latest equation of state, nuclear reaction cross sections, opacity; comparatively little is spent on studying time-dependent three-dimensional models. A good example is the ^{3}He instability discovered by Dilke & Gough (1972), nothing is really known about the development of this instability; these authors suggested it could drive episodic mixing in the solar core leading to variations in solar output over a timescale of 10^8 years. Perhaps there are other instabilities waiting to be uncovered by the questioning scientist. Then our models of the solar convective zone are crude, based on a steady-state mixing-length analysis. It is not even obvious to this author that this bears any relation to reality. Perhaps the convective zone does not settle down to some quasi-steady-state but spends some time in one state then switches to another, as suggested some years ago by Tavakol (1978). There are plenty of examples of nonlinear systems that can behave in this way. Since the thermal relaxation lifetime of the whole solar convective zone is of order 10^5 years it is possible to imagine that somehow this timescale enters into the nonlinear dynamo leading to variations in solar output on this timescale (Roxburgh 1980). Then if the internal magnetic field is only of the order of 1 mT the Alfvén travel time is reduced to 10^6 years and this timescale could enter into the variations in solar flux. Perhaps there are other instabilities on long timescales in the solar interior waiting to be uncovered.

Finally, what about the energetics of the variations of luminosity over a solar cycle? The *SMM* observations imply a variation of up to 0.1 % over the last cycle, and perhaps somewhat less during previous cycles, this is some 10^{-9} of the internal energy of the Sun over a cycle. If this were stored in the equatorial regions of the convective zone its contribution to the distortion of the Sun would be small, but if a larger amount is stored over longer periods during 'Maunder Minima' then it is of the order of magnitude where the distortion would produce an external gravitational field comparable with the solar gravitational quadrupole moment and therefore sufficient to have some effect on the orbits of the interior planets.

I do not claim that any of the above thoughts are correct. My brief is not to provide answers but to stimulate discussion!

References

Davis, R. 1989 In *The solar interior and atmosphere* (ed. A. N. Cox, W. C. Livingstone & M. S. Mathews). Tucson: Arizona Press.

Dilke, F. & Gough, D. O. 1972 *Nature, Lond.* **240**, 262.

Press, W. H. 1981 *Astrophys J.* **245**, 286.

Roxburgh, I. W. 1980 In *Soleil et climat*, p. 261. CNES, Toulouse.

Roxburgh, I. W. 1985 *Sol. Phys.* **100**, 21.

Roxburgh, I. W. & Schatzman, E. 1989 In *The solar interior and atmosphere* (ed. A. N. Cox, W. C. Livingstone & M. S. Mathews). Tucson: Arizona Press.

Tavakol, R. K. 1978 *Nature, Lond.* **276**, 805.