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6. AUTHOR(S)
Dr Edward A. Spiegel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Columbia Astrophysics Laboratory
Dept of Astronomy and Physics
Columbia University
538 West 120th Street
New York, NY 10027

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr Henry R. Radoski
AFOSR/NL
Building 410
Bolling AFB DC 20332-6448

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In modeling the solar cycle we proceed on the assumption that the processes driving the solar cycle are deterministic. In that case, a chaotic model is a good choice for a description of its complexity. In our modeling, we suppose that the solar activity variation is composed of two distinct, coupled proce-ses, one a conventionally chaotic system, and the other a nonlinear oscillator. This idea comes directly from our analysis of the observations. Since the sun's rotation period is one month, we do not use the daily sunspot number, but work with its monthly average. This quantity shows both the cyclic variation on the eleven year time scale and additiõnal strong fluctuations. If we smooth the data to remove periods less than a year to two, we see the solar cycle clearly exposed. When we subtract this smoothed sunspot number from the monthly average, we obtain the fluctuations in the sunpot number. In figure 1 we show a comparison between the monthly averaged number and the fluctuations for a few cycles. There is a clear correlation between the level of solar activity, as measured by the sunspot number, and the amplitude of the fluctuations in this number. The fluctuations and the cyclic behavior, we suggest correspond to two distinct but interacting processes.

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# ANNUAL STATUS REPORT FOR AFOSR F49620-92-J-0061

**Submitted to:** Dr. Henry R. Radoski
Program Manager
Air Force Office of Scientific Research
Building 410
Bolling AFB, DC 20332-6448

**Submitted by:** The Trustees of Columbia University
in the City of New York
Box 20, Low Memorial Library
New York, New York 10027

**Prepared by:** Columbia Astrophysics Laboratory
Departments of Astronomy and Physics
Columbia University
538 West 120$^{th}$ Street
New York, New York 10027

**Co-Principal Investigator:** Edward A. Spiegel
Rutherfurd Professor of Astronomy

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Progress Report

# CHAOTIC DYNAMICS OF THE SOLAR CYCLE

*November 1992*

In modeling the solar cycle we proceed on the assumption that the processes driving the solar cycle are deterministic. In that case, a chaotic model is a good choice for a description of its complexity. In our modeling, we suppose that the solar activity variation is composed of two distinct, coupled processes, one a conventionally chaotic system, and the other a nonlinear oscillator. This idea comes directly from our analysis of the observations.

Since the sun's rotation period is one month, we do not use the daily sunspot number, but work with its monthly average. This quantity shows both the cyclic variation on the eleven year time scale and additional strong fluctuations. If we smooth the data to remove periods less than a year or two, we see the solar cycle clearly exposed. When we subtract this smoothed sunspot number from the monthly average, we obtain the fluctuations in the sunpot number. In Figure 1 we show a comparison between the monthly averaged number and the fluctuations for a few cycles. There is a clear correlation between the level of solar activity, as measured by the sunspot number, and the amplitude of the fluctuations in this number. The fluctuations and the cyclic behavior, we suggest correspond to two distinct but interacting processes.

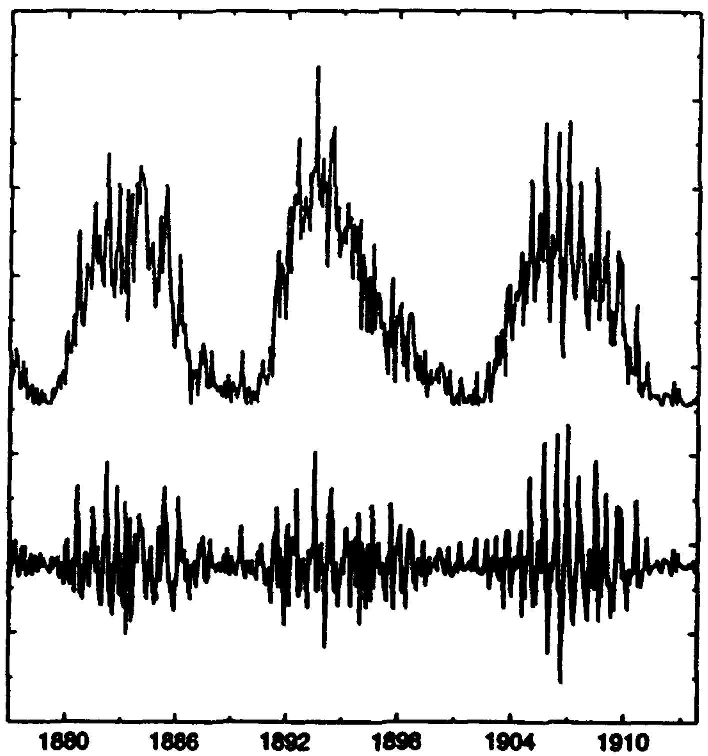


**Fig. 1**

An important feature of the observations is the Maunder minimum from about 1650 to 1715 when the solar cycle apparently switched off, even though sunspots were occasionally seen in this period. We suggest that the fluctuations shown in Figure 1 continued weakly during the Maunder minimum, even though the cycle stopped. This fits in with our view that there is a continuous, rather turbulent, dynamo process that is responsible for the rapidly fluctuating sunspot number. This is coupled to the much slower oscillatory process that produces the cyclic activity and this coupling causes the two to rise and fall together. From this image, we have been able to construct a reasonably convincing dynamical model of the solar activity cycle.

The simplest version of our model consists of two coupled sytems corresponding to the two processes we see in the data. This produces a new mechanism of intermittency that is described in

"On/Off Intermittency: A Mechanism for Bursting," by N. Platt, E.A. Spiegel and C. Tresser, *Phys. Rev. Lett.*, (in press).

In the on/off process, a nonlinear oscillator is rendered effectively unstable through coupling to a chaotic system. The periods of instability last for a fraction of the time that depend on the parameters of the coupling terms and, in those times, we see a mildly chaotic or semi-regular oscillation. Our solar model based on this process is a composite of two coupled subsystems. One has a large range of time scales and is continuously chaotic. The other is a potentially unstable oscillator that is in a stable condition in the absence of coupling between the two subsystems. The combined system has a moderately large phase space whose dimension is between five and eight in most of our modeling.

When the solar oscillator is in an effectively stable state, the combined system is nearly in a low-dimensional subspace where it may linger for decades, as we suggest it did in the Maunder minimum. But in fact, the system is just temporarily confined to this subspace, much as a suitably adjusted pendulum may pass slowly by its vertical equilibrium point before falling back down to perform some lively oscillations. Mathematically speaking, the low dimensional subspace is an invariant hyperplane that contains a strange attractor maintaining contiuous chaos, even when the cycle is dormant. But when the cycle is active, that chaos is reinforced and intensified. The mathematical details are being written up for publication and will be forwarded shortly. Figure 2 shows a comparison between the output from the model (upper panel) and two of the measured, monthly averaged cycles from Figure 1.

The physical picture that motivates our mathematical model is that the intense turbulence in the outer convection zone of the sun is responsible for dynamo action and the production of magnetic flux ropes that may occasionally grow to a size and strength that can produce a sunspot. The convection zone is represented by the chaotic subsystem of our model. The magnetic fields produced in the convection zone are also fed into a convectively stable layer beneath the zone which, though turbulent, is placid enough to allow a large scale oscillatory behavior that produces the solar cycle.

This thin layer below the convection zone has a significant shear that stretches out the magnetic fields that rain down on it from the convection zone. These stretched fields make the sublayer unstable when the rain from above is abundant; that is how coupling works to trigger the solar activity. Our picture of what happens within the sun is supported by the

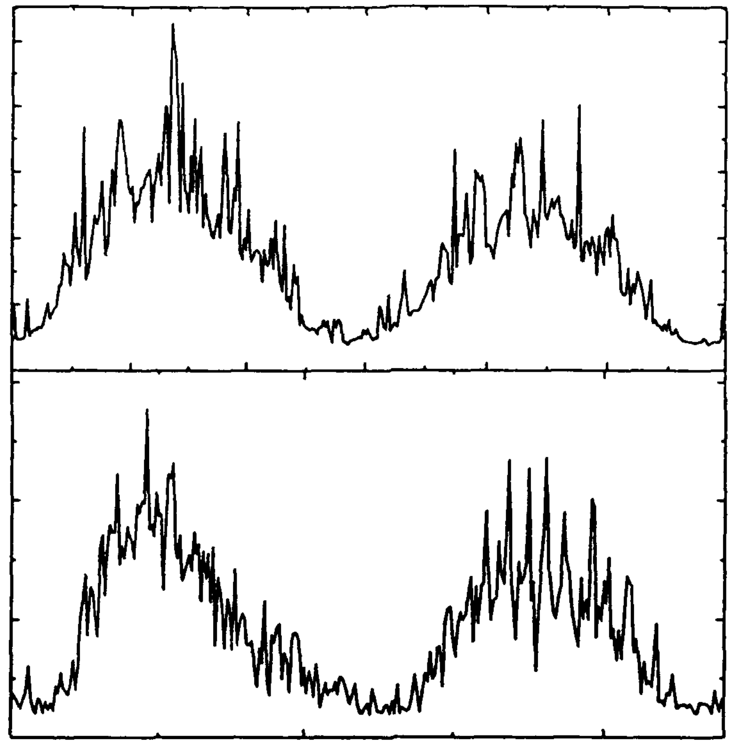

**Fig. 2**

helioseismological discovery that such a subconvective layer does exist. (Previously, this had been merely adumbrated on uncertain theoretical grounds.) We have been attempting to understand the fluid dynamics of this layer, which we call the ***solar tachocline***. So far, we have ***assumed*** that there is strong horizontal turbulence in the tachocline because of the shear there. Thus we have been able to derive a picture of its structure. We illustrate this in Figure 3 showing the stream lines of the flow in the tachocline as seen in the rotating frame of the sun. The calculations behind this figure are given in

"The Solar Tachocline," by E.A. Spiegel and J.-P. Zahn, ***Astron. & Asrophys.***, (in press).

In this paper it is shown that, if the turbulence in the tachocline is strongly anisotropic, the tachocline will be shallow, in accord both with observations and the needs of our model. The main grounds for assuming this anisotropy are, in effect, that the tacholine appears to be thin. Though this is self-consistent, we need to do better and have been preoccupied with the problem of shear flow instability in thin layers in the past few months. There is a large literature on this problem in oceanography and the theory of astrophysical disks that is relevant to this problem and we have been adapting it to our needs. Also, Zahn has pursued the role of subconvective fluid dynamics in stellar mixing and its influence on stellar evolution:

"Effect of Horizontal Turbulent Diffusion on the Transport by Meridional Circulation," by B. Chaboyer and J.-P. Zahn, ***Astron. & Astrophys.*** **253**, 173.

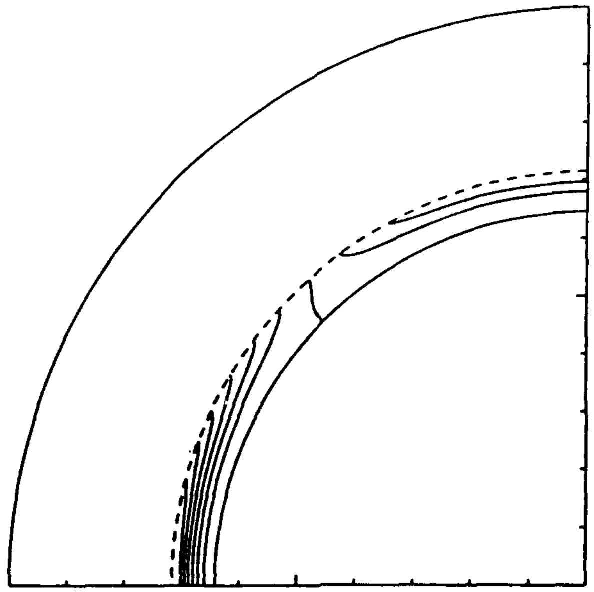

**Fig. 3**

"Circulation and turbulence in the rotating star," by J.-P. Zahn, *Astron. & Astrophys.* (in press).

A closer look at the data shows that the solar variation takes place in space and time. The longitudinally averaged space-time portrait of activity looks like a row of ragged butterflies flying along the time axis with their wings spread in latitude. This butterfly diagram provides an empirical description of the temporal evolution of a Poincaré map of the solar magnetic field, with the sun's outer boundary as the surface of section. We have earlier modeled this behavior with M.R.E. Proctor in a simple way, as described in previous reports. We are now trying to build the on/off intermittency process into this model which, being spatio-temporal, requires nonlinear partial differential equations rather then the ordinary differential equations of the phenomenological model. There is some promise that our nonlinear field equations will exhibit the formation of spots as well as a measure of the spatio-temporal distribution of activity. However, this phase of the work is still in a preliminary state and it will be a year or so before we can be confindent of the details.

A number of ancillary projects have also been undertaken. With Blamforth and Ierley, Spiegel has worked on methods for developing timing maps that are useful in understanding puslatile chaotic systems like the solar cycle. They have also been working With Predrag Cvitanović on dynamo activity in chaotic flows. A paper on slow thermonuclear convection in the solar core is in preparation (a sequel to ealier work done on the project) by Ghosal and Spiegel. Zahn has continued to work on convective penetration processes:

"Evidence for convective penetration in the Sun," by G. Berthomieu, P. Morel, J. Provost and J.P. Zahn, *7th Cambridge Conf. on Cool Stars, Stellar Systems and the Sun* (M.S.

Giampapa & J.A. Bookbinder, eds.) *Astron. Soc. Pacific Conf. Series*, Astron. Soc. Pacific Conf. Series) **26**, 158 (1992).

"Seismological constraints on convective penetration in the Sun," by G. Berthomieu, P. Morel, J. Provost and J.P. Zahn, *Inside the Stars* (A. Baglin & W. Weiss, eds.) *Astron. Soc. Pacific Conf. Series*, (in press).

We have also been joined by two graduate students who have begun with research projects before beginning their theses in the next few months. O. Umurhan has been working on acoustic propagation in a medium of variable ionization, which will bear on several aspects of solar fluid dynamics. He has been especially interested in the radiative processes involved. A. Casti has been looking into the advection of passive scalars by chaotic flows. Though this choice of topic is partly dictated by the fact that his financial support is not in the project, the compromise has been made to provide an introduction to the kind of chaotic process of interest to our own efforts. Several visitors have participated in the work, including G.R. Ierley and J. Massaguer. With the latter, a paper on the interaction of convection and large scale production was produced:

"Convection-induced shears with general planforms," by J. Massaguer, E.A. Spiegel and J.-P. Zahn, *Phys. Fluids A* 4, 1333, (1992)