SOLAR AND STELLAR ACTIVITY CYCLES

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Introduction

> 'Where shall I begin, please your Majesty?' the White Rabbit asked.
> 'Begin at the beginning,' the King said, very gravely...
>
> *Lewis Carrol*

1.1 The significance of stellar activity cycles

During the twentieth century, our perception of the fundamental nature of stars and stellar systems has undergone a revolution almost as profound as that initiated by Copernicus in relation to the solar system. In the nineteenth century, a star was regarded as a luminous, spherically symmetric system, for which the only available energy source appeared to be the energy released by gravitational contraction. Unfortunately, simple calculations showed that, on this basis, the Sun's luminous lifetime (the Kelvin–Helmholtz time) was far too short to accommodate the age of geological structures, the development of life, and the evolution of species.

The discovery that nuclear energy could provide the source necessary to prolong the luminous lifetimes of stars by several orders of magnitude was the first significant development in our understanding and provided the background structure for the picture of a star that emerged in the first half of this century: i.e. that of an *equilibrium system*, in which the internal generation of nuclear energy remained in long-term balance with the radiation emitted at the surface. In this system, it was assumed that hydrostatic pressure balance applied and that the outward temperature gradient was monotonically negative, in conformity with the well-understood principles of thermodynamics.

This comfortable picture did not, however, survive into the second half of the twentieth century. Gradually, astrophysicists were forced to accept that a star is a *non-equilibrium system*, from which energy is lost in the form of both matter and radiation. The expected monotonically negative outward temperature gradient was replaced by a steep temperature rise through a chromosphere and corona. These characteristics of the outer solar atmosphere were at first thought to be peculiar to the Sun but are now recognized as properties of many, if not most, late-type stars.

Again, while *solar activity*, in the form of sunspots, flares, and related phenomena has long been known, the discovery that such activity occurs on most stars, and that it frequently appears in more violent forms on stars other than the Sun, prompted a further reassessment of the nature of stars. When solar studies revealed that activity is a manifestation of the interaction between plasma motions and magnetic fields, the widespread occurrence of the phenomena of activity provided evidence for the almost universal presence, and importance, of *stellar magnetic fields*.

This discovery represents the next major development in our understanding, for, although the energy associated with the magnetic fields is generally far less than that stored in the convective or rotational motions of the stellar plasma, a variety of mechanisms are now known whereby these fields can exert a disproportionate influence on the motions and on the radiation emitted from the surface. Thus, whereas formerly it was believed that the structure of an equilibrium star could be determined, in principle, once its mass, chemical composition and age were given, it is now accepted that real stars of similar masses and compositions may exhibit remarkably different atmospheric (and probably internal) structures and activity phenomena because of the varied effects of the magnetic fields which they possess.

The realization that magnetic fields and their interaction with moving plasmas might hold the key to phenomena as diverse as small ephemeral regions and spicules on the Sun and the structure of galaxies has, of course, concentrated considerable attention on this interaction, the many facets of which continue to challenge our understanding. A dramatic example, and one of considerable importance to this study, is the sunspot. Although sunspots can be clearly resolved on the solar surface and have long been the subject of intense investigation, their true nature continues to elude us. We have progressed from regarding them as blemishes on an otherwise perfect sphere, to holes in the solar atmosphere through which the (then believed to be) cooler solar interior could be viewed, to solar surface tornados, and, finally, to the modern view in which they are recognized to be regions where powerful concentrations of magnetic field emerge through the surface. Nevertheless, as E. N. Parker (1975) succinctly expressed it, 'sunspots are too unstable to form and, if once formed, should immediately break apart.

But observations show the contrary, indicating that there is much we do not understand'.

An intriguing aspect of sunspots is the 11-year variation of their annually averaged number count, which is known as the *sunspot cycle.* Although sunspot number counts had been carefully monitored at certain observatories since the early 1700s, it was not until 1843 that the German apothecary and amateur astronomer, Heinrich Schwabe, discovered that their comings and goings exhibited a well-defined period of $\sim$ 10 years. More recently, it has been recognized that the period is closer to 11 years and that the frequency of occurrence of the related activity phenomena also fluctuates with a similar period. Today, the term *solar activity cycle* is now used to embrace the cyclic variation of all such phenomena.

In Schwabe's time, the sunspot cycle was regarded as a curiosity. It was not until the present century that it was recognized as one facet of a more general type of stellar phenomenon. While certain classes of variable stars (e.g. the Cepheids, and the RR-Lyrae stars) were recognized in the nineteenth century, it was generally believed, and not only among scientists, that the majority of stars were unchanging in their properties, at least on human timescales. ('Bright star! would I were steadfast as thou art', wrote the poet, John Keats). The recognition that variability is a universal property of stars, that it may appear in many forms, and that the sunspot cycle is simply a particular example was yet another development in our understanding during the present century.

While the Cepheids and the RR-Lyrae stars vary in their total luminosity, sometimes by an order of magnitude, the sunspot cycle is principally an activity variation. It is now known, however, that luminosity variations, albeit of considerably smaller amplitudes, also accompany stellar activity variations, and that they are sometimes in phase and sometimes out of phase with the activity variations.

Thus, today, we recognize that the sunspot cycle is simply an example of *cyclically varying stellar activity*, the subject of this volume.

1.2 The solar–stellar connection

An essential ingredient of this study is an understanding of the relationship between solar and stellar activity cycles, which is an important component of a more general methodology known as the *solar–stellar connection.*

Most of our information comes, of course, from the Sun, for which the full disk can be resolved, and our growing knowledge of solar activity provides direction for our study of activity in other stars. Stellar investigations, however, are essential to an understanding of cyclic activity phenomena, for only in this way can we investigate the dependence of stellar activity on parameters such as age, size, surface temperature, rotation rate, and convection zone structure, which, for our studies of the Sun, are necessarily fixed. Since *cyclic activity* is a property of some, but by no means all, active stars, a knowledge of the properties of those active stars which behave in this way, and of those which do not, should be of importance to an understanding of the cyclic phenomenon.

1.3 The solar cycle and the terrestrial environment

Quite apart from contributing to our understanding of the mechanics of stellar activity, the cyclic behaviour of the Sun is of special importance for our terrestrial environment. The effect on radio communications of particle streams incident on the ionosphere is well known, as is the apparent relationship of these streams to solar flares, whose number and intensity vary with the cycle. On 10 March 1989, an X-flare gave rise to a geomagnetic storm two days later which blacked out the Hydro-Quebec power system. Transformers failed, hundreds of relay and protective systems malfunctioned, and voltage and power fluctuations were widespread across North America.

Dosimeters registered alerts on high-flying Concordes during the October 1989 proton event. On long intercontinental flights in the auroral zones a 'chest X-ray' dosage of radiation can occur. So seriously does NASA regard these interactions with the geosphere in the planning of the space program, that it is an active sponsor of research aimed at more accurate predictions of the parameters (amplitude, period, etc.) of the cycle. Nevertheless, the only flare-research spacecraft programs actively underway are the Japanese *Solar-A* and the Russian *Coronas*.

Of considerably greater long-term importance to our environment, however, is the variation of the total radiative output of the Sun during the cycle. One might intuitively expect that, when the Sun is covered with a larger number of cooler spots, its radiative output should decrease. Satellite radiometer measurements since 1980 have, however, shown that the output actually declined until 1986, coinciding with sunspot minimum, and that, since then, it has undergone a steady increase (at least until 1990). Although the amplitude of the increase is less than one per cent, corresponding to a temperature change of $\sim 0.2\,K$, it is likely that, because of the non-linear nature of the interactions, the climatic effects could be considerably greater, particularly if changes in the solar output give rise to non-uniform temperature variations over the geosphere.

For example, it has been shown (J. Lean, private communication) that the temperature differential between land and ocean on the eastern seaboard of the United States tracks the sunspot cycle very closely. Although the actual differential is small, it may give rise to alternating wind patterns which may cause significant changes in the local climate. Indeed, correlations between terrestrial weather patterns and the sunspot cycle have been claimed. Xanthakis (see Giovanelli 1984) finds that the mean precipitation in the northern hemisphere latitude range N70° – 80° has varied in phase with the sunspot cycle from 1880 to 1960, while that in the range N60° – 70° has varied out of phase. In the southern hemisphere Bowen (see Giovanelli 1984) finds that, over the same period, the rainfall at Hobart (Tasmania, latitude S43°) is greatest at sunspot maximum, while that at Cairns (Queensland, latitude S17°) is least.

Since the time-span of these records covers only a few cycles, these results should be regarded with some caution. It is interesting, however, that, between 1640 and 1705, remarkably few sunspots were observed, and the Earth's climate suffered a significant cooling during the same period, now referred to as the 'Little Ice Age'. If there is a physical connection between these two excursions from the norm (and it is now generally accepted that there is), the need to be able to make reliable predictions about likely future climatic variations resulting from solar variability reinforces the need to understand the nature of stellar activity cycles.

There are many other terrestrial phenomena for which links with the sunspot cycle have been claimed, sometimes on rather dubious scientific grounds. In 1937, Harlan T. Stetson, then a research associate at MIT, published a volume entitled *Sunspots and their Effects*, in which links between the sunspot cycle and variations in (i) human behaviour, (ii) agriculture, (iii) radio communication, (iv) business and the stock market, (v) the weather, (vi) geomagnetic phenomena, and (vii) the performance of carrier pigeons were claimed. For some of these, such as radio communication and geomagnetic phenomena, the evidence is well documented and the mechanisms at least partly understood. Since there is some evidence that weather patterns vary with the cycle, it is possible to understand how agricultural output may also be related not only to normal sunspot fluctuations but also to gross excursions, such as occurred during the Little Ice Age.

The possible links with human behaviour, business, and the stockmarket are far more speculative. Stetson shows several figures, some of which are reproduced in Figure 1.1, in which sunspot number fluctuations during the 1920s and 1930s are compared with business activity, automobile production, and building contracts of that period. At first glance, these rather picturesque

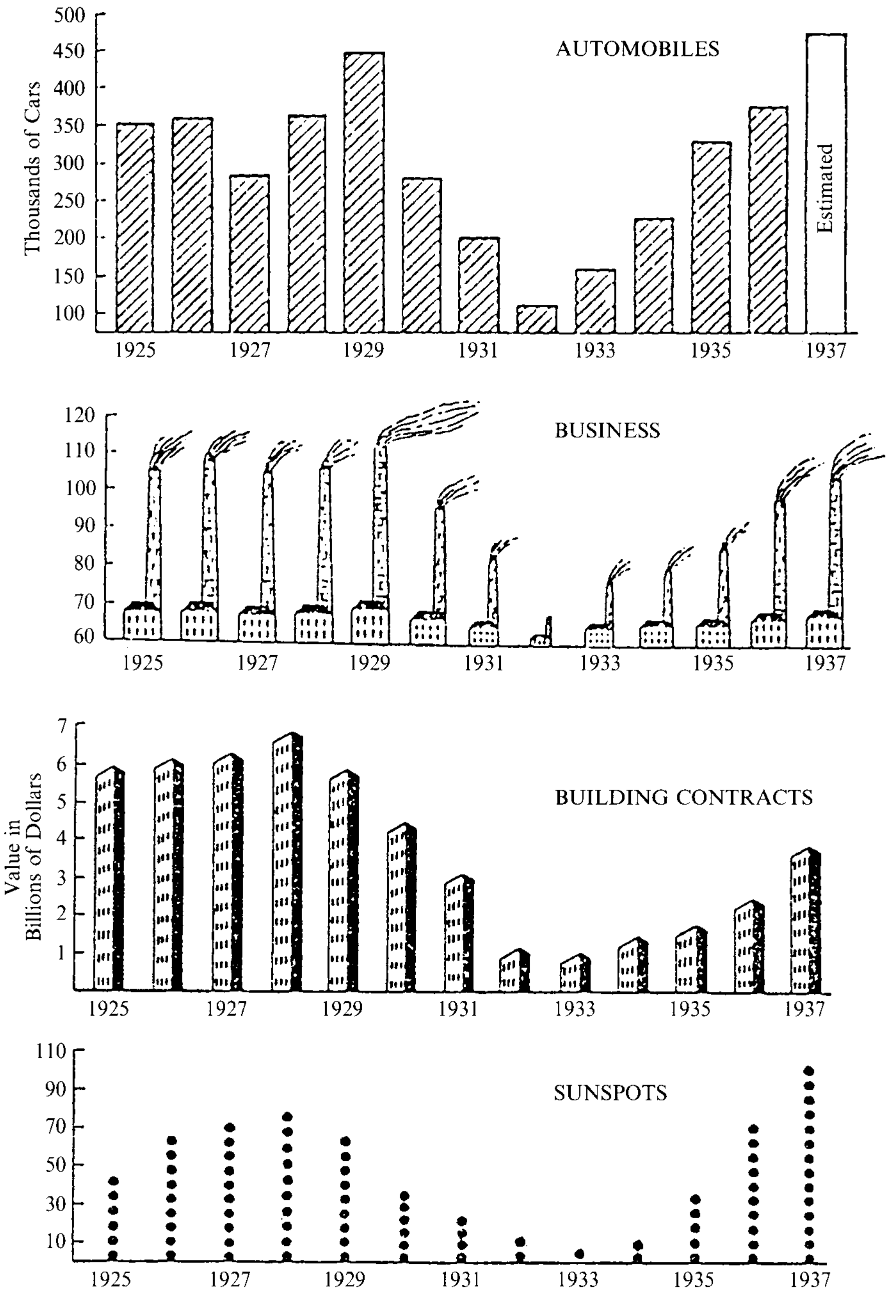

Fig. 1.1 Four histograms, taken from Stetson (1937), compare automobile production in the US, business activity (in unspecified units), and the value of building contracts written in the period 1925–37 with the sunspot number during that period.

histograms appear to show a remarkable correlation, but the coincidence of the sunspot minimum of 1933 with the trough of the Great Depression may well be just that: a coincidence. Indeed, the fact that the current world recession (1989–91) following the stock market crash of 1987 coincided with the *maximum* of Cycle 22 does *not* support the likelihood of such a connection.

An even more bizarre claim of a correlation between sunspot number and human mortality was made a few years earlier by a German physician, Bernard Dull, and his wife, Traute (1934). From a study of all the deaths in the city of Copenhagen between 1928 and 1934, they claimed to have detected a 27-day periodicity by averaging over 68 successive 27-day periods. They also noted a parallel with a 27-day fluctuation in sunspot numbers arising from solar rotation and a concentration of sunspots in what they call 'the M-zone', and claimed that a relation was established. The statistics of the study were less than impressive, however, the amplitude of the mortality fluctuations being only a few per cent, and the standard analytical techniques, such as power spectral analysis (see Chapter 5), unreported. As we shall see, the phase of the 27-day periodicities in solar phenomena is subject to change due to the changing distribution of active regions in the solar surface. No reference was made to cyclic changes in the Dulls' study, although the period in question included the minimum of Cycle 17. Modern medical statisticians find no correlation between human mortality and the sunspot number, and, as a result of these and similar claims, sunspot correlation studies became somewhat discredited.

It would nevertheless be unwise to ridicule the possibility of connections between the sunspot cycle and various fields of human activity without investigation. The Sun is such an integral part of our environment that its effects are frequently taken for granted, and we should not reject *a priori* the possibility of some forms of interaction. The preferred approach is to assess the reliability of the data-gathering process and the statistical significance of the correlations before attempting to underpin any such correlations with a physical theory (see further Chapter 14).

1.4 Conclusion

The aim of this volume is to explore the phenomena of solar and stellar activity and activity cycles and to attempt to understand the physical processes that govern them. By doing so, it is hoped to achieve a greater understanding of the relationship between solar activity and its cyclic variation and our terrestrial environment.

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