THE SUN AS A VARIABLE STAR

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ABSTRACT. The variability of the Sun observed as a star is reviewed and it is shown that variability studies are a powerful tool to investigate the dynamo mechanisms at the origin of solar activity. Variability on all time scales, from seconds to centuries, is discussed, both at specific wavelengths and in the solar bolometric flux. The possibility that long-term variations of the Solar Constant, and of the spectral distribution of the solar output, may affect Earth’s climate is briefly considered. The solar variability is then compared with variability of other solar-type stars and it is shown that stars present a much wider range of variability and dynamos than presently observed on the Sun.

1. Introduction

Although we may not realise it when we look at the total solar luminosity from the ground, the Sun is a highly variable star. This variability occurs on all time scales, from seconds, to hours, days, months and even years and centuries. It is most evident when we observe the Sun at specific wavelengths, for instance in X-rays or in the radio. It is also evident when we make spatially resolved observations of the solar disk. Sunspots were first observed by Galileo in the seventeenth century, and their cyclic behaviour with a period of approximately 11 years was discovered by Schwabe at the middle of last century. Yet, in spite of this variability, the total radiative output of the Sun is remarkable constant. Only space observations over the past twenty years have clearly demonstrated that the Solar Constant is not “constant” at all, but varies in response to variations of the solar magnetic activity.

There are several reasons why it is important to study solar variability. First, it is a powerful tool to study the magnetic activity of the Sun and understand the complex dynamo mechanisms that we believe are at the origin of solar activity. Second, it is a way to investigate the possible effects of solar variability on the Earth’s climate, and therefore on life on Earth. Although the Sun can be observed at high spatial resolution, observations of its disk-integrated emission (i.e. by observing the Sun as a star) are important both to determine the variations of the total solar irradiance (integrated over the whole spectrum) and to compare the Sun with other stars and with their variations at different wavelengths.

In this paper, I will give a short overview of solar variability with emphasis on disk integrated observations. I will first summarises variations observed at specific wavelengths, and then I will discuss variations of the total solar irradiance and their possible effects on Earth’s climate. I will also discuss stellar variability as observed in solar-type stars, i.e. in otherwise “normal” dwarf stars with outer convective zones. These stars,
of spectral type from middle F to late K, show evidence of magnetic activity similar to, but often much more pronounced than solar activity and thus offer the best opportunity to investigate dynamo mechanisms under conditions of convection and rotation different from those operating at present on the Sun. From the comparison of solar and stellar data, there is the hope that we can get a better understanding of the physical processes at the basis of solar and stellar activity, and hence a better understanding of both the Sun and stars.

2. Solar variability at different wavelengths

Observations of the Sun at different wavelengths with high spatial and temporal resolution show variations on all temporal and spatial scales. There are short term variations (on time scales from seconds to hours) associated to flares and microflares, as well as variations on longer time scales of weeks to months, due to the rotation of the Sun on its axis and to the evolution of active regions. There are also variations on time scales of years to decades, associated to the well known sunspot cycle; and finally there are variations on time scales of centuries to millenia, related to long-term changes in the amplitude of the solar cycle, including the existence of quiescent periods (like the Maunder Minimum) where all signs of activity were virtually absent (see Pap et al. 1994 and references therein; PAP94 hereafter).

These variations are not the same at all wavelengths, but a high degree of correlation exists between variability at different wavelengths. In X-rays, time-sequence images of the Sun obtained recently by the Japanese satellite YOHKOH show a complex pattern of variability phenomena, on different temporal and spatial scales (Shibata 1994). When the emission from individual elements of the solar disk is summed-up, the integrated emission shows variations on time scales of months (due to the solar rotation) as well as variations on time scale of years (related to the sunspot cycle), in addition to short-term variability due to flares. This high variability of the Sun in X-rays has been known from the sixties, and has been monitored for decades by full-disk solar instruments on board of the SOLRAD and GOES satellites (see, e.g., Cheng & Pallavicini 1992 and references therein; Aschwanden 1994). The observed long-term variations of the total output in X-rays (taking out the short-term effects of flares and rotational modulation) are quite large, and increase at shorter wavelengths. For instance, the total output of the Sun in soft X-rays was observed to decrease by at least a factor of 30 in the YOHKOH SXT passband, from 1992 to 1996, i.e. during the declining phase of cycle 22. Previous observations with GOES have shown variations of more than a factor 85 from sunspot minimum in 1975 to maximum in 1981 and back to minimum in 1986. Although these variations during the solar cycle are quite remarkable, one should keep in mind that they represent only \( \approx 10^{-6} \) of the bolometric luminosity of the Sun, i.e. they are energetically unimportant.

Synoptic observations of the Sun at different wavelengths (from the optical, to X-rays, to radio wavelegths) show a clearly modulated pattern, with a period corresponding to the solar rotation period of about 27 days. The X-ray and radio emissions of the Sun as a star clearly follow the passage across the solar disk of sunspots and are modulated by the variable numbers of spots (or, more generally, active regions) present at any given
time over the visible disk. Similarly, the Ca II K flux, which is a good tracer of solar plages, varies in phase with the spot number and with all other indices of solar activity (e.g. Zombeck et al. 1978). Observations of the integrated emission of the Sun at UV wavelengths by the UARS/SOLSTICE Irradiace Monitor show that this is true also for UV emission, from Lyman-α at 1216 Å to ≈ 4000 Å. The changing appearance of the Sun as it rotates is clearly due to the inhomogeneous distribution of active regions over its surface and to the ever changing emergence of magnetic flux at the surface.

The same high degree of correlation shown by rotational modulation at different wavelengths is also present when comparing the appearance of the solar cycle in different passbands. The 10cm radio flux shows the same modulation as the average sunspot number, and a similar behaviour is shown by the soft X-ray flux and the number of X-ray flares. Perhaps even more interesting for a comparison with stellar data (see section 4 below) is the appearance of the solar cycle in full-disk observations of the Ca II H and K and Mg II h and k chromospheric lines. Long-term variability in the Ca II lines

Fig. 1. Variability of the Sun at different wavelengths over several rotations (from Zombeck et al. 1978).

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over more than one solar cycle has been monitored from the ground (at NSO) in the Ca II K line at $\approx 3935$ Å. Similarly, the NIMBUS 7 satellite has recorded the cyclic variations of the Mg II lines at 2800 Å from space. These variations (particularly the Ca II variations) can be directly compared with similar observations of stellar cycles made at Mt. Wilson.

More difficult is to study solar variability on time scales of centuries to millenia, since our records of the sunspot number date back at most to 1610, when Galileo first observed sunspots with the aid of an instrument. The records however are sufficiently complete from the middle of the seventeenth century and thus span now three and half centuries. From 1700, the Sun has shown a regular sunspot cycle with an average period of about 11 years and variable amplitude. It is remarkable however that between 1650 and 1700, all available records point at an almost complete absence of signs of solar activity. This period is known as the Maunder Minimum and its existence raises the
Fig. 3. Variability of the Sun during cycle 21 in the Ca II K line at 3935 Å and in the Mg II lines at 2800 Å (from Donnelly et al. 1994).

interesting question whether other similar periods of dormant solar activity existed in the past. Inferring the past activity of the Sun is not easy, and we must rely on indirect evidences. These include reports of naked eye sunspot sightings as well as observations of the C\textsuperscript{14} isotope in tree rings and of Be\textsuperscript{10} in ice cores (e.g. Eddy 1976, 1977). On the basis of these indirect evidences, attempts have been made to reconstruct the solar activity over the past millenium. If these reconstructions are reliable, they show the presence of other minima in addition to the Maunder Minimum (for instance a Spörer Minimum between 1450 and 1550) as well as of periods of greater than average activity (like the Medieval Maximum between 1100 and 1250). The fact that the Maunder and Spörer Minima corresponded to periods of unusual cold whether in Europe raises the
Fig. 4. Variability of the Sun over the past millennium as reconstructed on the basis of $^{14}$C data in tree rings (from Eddy 1976).

interesting question whether these long term variations in the solar activity cycles have a direct or indirect effect of the Earth climate.

3. Variations of the total solar irradiance

Detecting variability in the total bolometric flux of the Sun is much more difficult and early attempts at detecting variations of the Solar Constant from the ground gave inconsistent results. Things have changed since the late seventies with the advent of accurate irradiance monitors on board space missions like SMM, NIMBUS 7 and more recently SOHO. The first reports of variations of the solar irradiance (at the level of $\leq 0.3\%$) at the time of the passage of large spot groups over the solar disk were obtained in 1980 by the ACRIM experiment on SMM. In addition to that, variations of $\approx 0.1\%$ were monitored along the solar cycle, and a signature of 5 min p-mode oscillations was also found (Willson & Hudson 1988). The ACRIM experiment showed a clear decrease of the solar constant from the maximum in 1980 to the minimum in 1986, followed by an increase to the next maximum in 1990. Data collected by the ERB experiment on NIMBUS 7, the ACRIM experiment on SMM, and by ACRIM II on UARS, all indicated the presence of this long-term modulation, in phase with the sunspot cycle (cf. Fröhlich et al. 1991, Willson 1994, Fröhlich 1994, and references therein). The amplitude from max to min is at the level of 0.1%, which is comparable to or smaller than the absolute calibration of the measuring instruments, but much larger than the relative accuracy of each instrument. There is no doubt therefore on the reality of such a variation. It is interesting to note that the minimum of the Solar Constant is at the time of minimum spot coverage, which indicates that the total output of the Sun is not modulated on the long-time scale by dark spots, but rather by bright faculae (Lean et al. 1994). In other words, the effect of bright faculae overcomes that of spots in the optical radiation of the Sun (which is by far the largest contributor to the total bolometric flux).

Can these variations of the Solar Constant (both on short and long time scales) affect the Earth's climate? This is a controversial topic on which there is a lively debate.
Fig. 5. Solar irradiance variations on time-scale of months as measured by the ACRIM experiment on SMM. The largest dips are due to the passage of large spot groups (from Willson 1994).

Fig. 6. Solar irradiance variations on time scales of years as measured by various space experiments. The sunspot number is plotted in the upper panel (from Withbroe & Kalkofen 1994).
at present, but no definite conclusions. It is unlikely that short-term variations of the Solar Constant due to the passage across the disk of spots and faculae, or to the occurrence of flares, may have significant effects: these variations are very small (≤ 0.3%) and, more importantly, are of too short duration. Long-term variations associated to the solar cycle, albeit small as well, are more likely to have an effect on Earth’s temperature and climate, and indeed correlations have been reported between the solar cycle and various parameters of climatological relevance, such as sea temperature, ground temperature, rainfall, etc. (cf. Withbroe & Kalkofen 1994 and references therein). Some of these correlations are striking, and may represent true physical effects. However, one should keep in mind that the solar cycle has been correlated over the years to almost everything, and most of these apparent correlations are either accidental or statistically not significant. For instance, in an amusing book published in 1937, the sunspot cycle was found to correlate with the numbers of automobiles built per year, with the number of buildings contracts, and with other parameters measuring the annual level of industrial and commercial business (Stetson 1937, as quoted in Wilson 1994). Needless to say, the minimum in these distributions (which covered one and half solar cycles) occurred around 1933, shortly after the great economic depression of 1929!

What we can safely state is that the amplitude of the long-term variations of the solar irradiance measured at present (≈ 0.1%) are probably too small to have a significant effects on the Earth’s climate. A larger variation (of the order of 0.3%) could have occurred during the Maunder Minimum (see next section), and this could have led to a variation of the Earth’s temperature of ≈ 0.5° and possibly more. If the Maunder Minimum is not unique, and other grand minima and maxima occur (as inferred from indirect evidences of long-term variations over the past millenium), these could have a significant effect on climate, and could have been responsible for exceptionally cold or warm periods in the past epochs. So the question is: can variations of the Solar Constant occur on a much larger scale than presently observed? To answer this question, one must turn to other stars to see if they show the same activity cycle as the Sun at the present epoch or if they show instead a much larger variety of behaviours.

4. Stellar variability

In the late sixties, the American astronomer Olin C. Wilson started a long-term observational program at Mt. Wilson Observatory to detect activity cycles in other solar-type stars. The idea was to measure variations in Ca II H and K chromospheric emission, which on the Sun have a much larger amplitude than variations in the integrated optical emission (which are in fact undetectable from the ground). To this purpose, he measured the light in a narrow (1 Å) passband centered on the chromospheric emission cores at the center of the Ca II H and K lines, and compared this emission to that in two broad (20 Å) passbands on either sides of the Ca II lines. This ratio, the so-called Mt. Wilson S index, is a measure of the contrast between chromospheric emission and the photospheric continuum emission. If chromospheric emission is mostly due, as on the Sun, to the contribution of plages and network elements, the variations of the S index would provide information on the number of plages present at any one time on the stellar disk.
After ten years of systematic monitoring of the S index over a sample of 64 stars (mostly G and K dwarfs), Olin Wilson published in 1978, at the time of his retirement, a fundamental paper in The Astrophysical Journal announcing the discovery of activity cycles in other stars (Wilson 1978). Since then, the monitoring program of Olin Wilson has been continued and extended by his fellow colleagues at Mt. Wilson and we now have a continuous record of Ca II emission variations in late-type stars spanning nearly three decades. One of the most interesting aspects of these observations is that not all late-type stars have activity cycles like the Sun, but only a fraction of them show the regular cyclic behaviour that we are observing at present on the Sun (Baliunas & Vaughan 1985, Baliunas 1991).

Basically, three types of different behaviours have been identified in the Mt. Wilson sample. About one third of the observed stars, mostly old quiet stars like the Sun, show a cyclic behaviour, with periods ranging from about 3 to 15 years. Another group of stars, usually young active stars, show a chaotic behaviour with no obvious periodicities. Finally, the remaining stars appear to be constant, with no indication of activity cycles. These stars could be in a dormant state of magnetic activity, similar to the Maunder Minimum, or could be stars where all form of magnetic activity is permanently suppressed. Whichever the case, it is clear that the stellar data suggest a much more complex picture of the dynamo process than the one indicated by the present Sun. The difference probably arises from the much wider range of physical parameters (e.g. rotation, convection zone depth, age, etc.) that occur in the stellar case with respect to the single set of parameters that we have for the Sun.

If other solar-type stars behave differently than the Sun with regard to their magnetic activity, have some of them variations so large to be detectable from the ground in broad-band optical emission? It has been known for decades that some classes of very active late-type stars (like the BY Dra variables, the RS CVn binaries and the T-Tauri stars) show photometric variations that are attributed to the presence of spots over their surface. These spots have much larger areas than spots on the Sun, and cover a much larger fraction of the stellar disk. The new result that has been revealed by recent more sensitive photometric observations is that “normal” late-type stars (i.e. not belonging to the above mentioned classes of active stars) may present subtle photometric variations that are large enough to be detectable from the ground at the present sensitivity levels (Lockhood 1994, Radick 1994). Stars which show photometric optical variations are typically those that are more active in terms of chromospheric Ca II H & K flux. Not only these stars are more active than the Sun, but also the amplitude of their Ca II variations is larger than in the Sun. Thus, whereas the Sun, observed from the ground, does not show any significant variation in broad-band optical photometry, these active stars show measurable variations, which are mostly due to rotational modulation, i.e. to the inhomogeneous distribution of active regions over their surface. In particular, it has been found that stars similar to the Sun with regard to spectral type, but younger and more active than the Sun, show photometric variations of up to a few percent, i.e. almost one order of magnitude larger than the photometric variations that could be produced on the Sun by the passage of a large spot group.

The monitoring of solar-type stars in broad-band optical light is still going on, but we have already for some stars a database covering more than a decade. The observed
variability over any observing season is mostly due to rotational modulation, but there are also indications of long-term variations that could possibly be associated to stellar cycles. The available data clearly indicate that some solar-type stars may be much more variable than the Sun, both in chromospheric emission and in photospheric (continuum) emission. Other stars, on the contrary, are much quieter than the Sun, at least with regard to their Ca II chromospheric emission, and could be temporarily in a state of dormant dynamo activity, as we believe occurred to the Sun during the Maunder Minimum. If stars are representative of the range of possible activity conditions through which the Sun can go, we can use the stellar data to infer the value of the Solar Constant during the Maunder Minimum. The Ca II emission of the contemporary Sun can in fact be used to estimate the present facular emission, whereas the Ca II emission of the quiescent (non-cyclic) stars with respect to the present Ca II emission of the Sun can be used to infer the solar facular emission during the Maunder Minimum. This
Fig. 8. Photometric variability of two active stars, compared to their Ca II variability and to analogous data for the Sun (from Radick 1994).

In turn gives the variation of the Solar Constant from the Maunder Minimum to the present. If these extrapolations are correct, the Solar Constant may have varied during this time interval by a factor 3 more than the variations measured at present over one solar cycle (Lean et al. 1994). A variation of $\approx 0.3\%$ in the value of the Solar Constant could produce a variation of $\approx 0.5^\circ$ in the global Earth’s temperature, and could have therefore a significant effect on climate. Although this is consistent with the occurrence of the so-called Little Ice Age during the Maunder Minimum, it should be stressed that climatological models have large uncertainties, and that solar irradiance is just one of the parameters that enter into these models.

5. Conclusions

As it appears from the discussion above, variability is a powerful tool to investigate dynamo-generated magnetic activity in the Sun and stars. Comparison of disk-integrated solar observations with observations of other stars shows that solar variability may have been larger and/or of a different character at other times. The Sun was probably much more active, and had a chaotic dynamo, when it was much younger and more rapidly rotating than at present. On the other hand, the Sun might have gone through extended periods of dormant activity, of which the Maunder Minimum is only the most recent episode. Variations of the total (bolometric) solar irradiance, and of the spectral distribution of the solar output, might have significant effects on the Earth’s climate, particularly on long time scales, but this remains to be established conclusively. To this
end, continued monitoring of solar activity and variability over long-time scales (decades) is extremely important. Similarly, there is a need for continued observations of other stars (both from the ground and from space) in order to understand dynamo activity under conditions of rotation/age different from those relevant to the present Sun. This in turn should lead to a better understanding of the Sun and of other late-type stars as well.

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References