Solar Variability

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With increasing sensitivity, wavelength coverage and photometric accuracy (including reliability in calibrations) it is becoming ever more clear that the Sun is a variable star at practically all wavelengths and timescales. A short and incomplete overview is given of the forms which this variability can take. Some of the underlying physics is also very briefly touched upon.

1.1 Introduction

The Sun is a variable star. It is variable at all observed timescales and at all wavelengths. In the visible and infrared (IR) its irradiance variations are not very large, on the order of 0.1 % or even less and require more accurate measurements than stellar astronomers generally carry out. This, and the relatively limited definition often applied to stellar variability, largely accounts for the fact that the Sun has in the past been judged to be a constant star. Thus the total radiative output of the Sun was (wrongly as it turned out) termed the ‘solar constant’. The Sun is variable not just in brightness (or irradiance, which corresponds most closely to flux in stellar terminology) but in a wide variety of ways. These include variability in its particle flux (solar wind), changes in its spectrum, evolution of the morphology of surface features (i.e., the appearance and distribution of sunspots, prominences, etc.), time dependence of the magnetic flux and its surface distribution, shifts of its p-mode oscillation frequencies, etc.

In addition to the type of variability we also need to distinguish between global and (spatially) local variability, variability at different timescales, variability with different underlying physical causes and, in the case of intensity or flux variations, the wavelength of the variable radiation.

In the present overview which, by force of the extremely broad nature of the topic covered and the limited space, only picks out a few aspects of solar variability, I shall discuss the timescales of solar variability and the wavelength dependence of solar brightness variations with the help of a few examples. The physical causes are, to the extent that they are understood, briefly discussed together with the observational evidence. For a far more detailed look at solar variability see the volume edited by Sonett et al. [1991].

The investigation of solar variability requires stable instruments, in particular with regard to their sensitivity. The long-term stability of the radiometric calibration of radiometers and UV-sensitive instruments has become the limiting factor for many investigations of solar variability. Thus, the work presented in this volume is an important contribution to
improving our knowledge of solar variability. Conversely, the present paper may be seen as providing scientific motivation for most of the other papers in this volume.

1.2 Timescales of Solar Variability

The Sun is known to be variable on timescales ranging from fractions of seconds to its lifetime on the main sequence, i.e., over a range of 17 orders of magnitude. In the following I list some of the timescales at which the Sun exhibits, or is thought to exhibit, significant variability without, however, attempting to be complete.

- Solar evolution timescale: $10^6$ to $10^{10}$ years [Sackmann et al., 1993]
- Timescale of the evolution of solar rotation (which is also the time scale of the long-term evolution of solar magnetic activity): $10^6$ to $10^{10}$ years
- Timescale for photons to reach the surface from the core: $10^6$ years
- Timescale of heat storage in the convection zone [Spruit, 1982]: $10^5$ years
- Timescale of ‘Maunder minima’, i.e., lengths of time when the Sun is almost free of spots and the ‘normal’ periods of cyclic magnetic activity between them: $10^2$ to $10^3$ years [Eddy, 1976, 1983; Strausser and Brazunias, 1989]
- Period of the Gleissberg cycle of sunspot activity: 80 to 90 years [Gleissberg, 1945], although the reality of this period is still under debate
- Solar magnetic cycle period: 22 years [Hale and Nicholson, 1925]
- Solar activity cycle period: 11 years [Schwabe, 1838]
- Oscillation in the rotation rate at the base of the convection zone: 1.3 years [Howe et al., 2000]
- Periodicity in the occurrence of gamma-ray flares: 154 to 158 days [Rieger et al., 1984]
- Lifetimes of active regions: weeks to months
- Lifetimes of sunspots: hours to months
- Solar synodic rotation period: roughly 27 days at the equator, which increases to over 30 days at the poles [Snodgrass, 1983; Wang et al., 1989]. In some cases the rotation period manifests itself in a roughly 14-day periodicity (for example when the signal is dominated by faculae).
- Lifetimes of granules, mesogranules and supergranules: minutes to days
- Timescales of flares, microflares and nanoflares, of blinkers and other forms of coronal and transition region brightenings: minutes to hours.
- Period of $p$-mode oscillations: approximately 5 minutes
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- Period of chromospheric oscillations and waves: approximately 3 minutes
- Shortest radio spikes: 0.01 s [Benz, 1986]

In the following I discuss a few of these examples, without going into detail.

1.2.1 Solar Evolution

In the roughly 4.5 billion years it has spent on the main sequence the Sun has brightened (i.e., increased in luminosity) by roughly 30%. Over the full $10^{10}$ years of life on the main sequence the Sun’s luminosity has been calculated to change by a factor of two to three (see Figure 1.1). This is dwarfed by the more than three orders of magnitude by which its brightness is expected to rise as the Sun moves up the giant branch. The various excursions up this branch, helium flashes and the final collapse of its core into a white dwarf take place on more rapid timescales of $10^4$ to $10^7$ years. Note that all changes on timescales longer than $10^6$ years require a change in the energy production rate in the solar core, since the Sun cannot store energy for a significantly longer period of time. (This is roughly the time required by a photon to escape from the core, carrying its energy with it; neutrinos escape practically instantaneously.) The main factor determining the evolution of the energy production rate is the change in the Sun’s chemical composition with time as the helium abundance in the core increases through the continuous fusion of hydrogen.

1.2.2 The Solar Cycle and Related Timescales

The best known and most clearly visible variability is that due to the activity cycle, with a period of approximately 11 years. Note that the solar cycle is not strictly periodic, with both its amplitude and period being time-dependent. The solar cycle is thought to be basically a magnetic phenomenon, whose source, a dynamo, resides at the base of the convection zone. The cyclic behaviour is produced by the repeated conversion of poloidal field (dominating during solar activity minimum) into toroidal field (dominant during activity maxima) and back again.

The number of solar phenomena varying with the solar (or Schwabe) cycle is vast. Practically every global aspect of the Sun changes to at least some degree from solar activity minimum to maximum. This includes solar total irradiance [e.g., Fröhlich, 2000], but also the irradiance at practically all wavelengths (for example the EUV and the 10.7 cm radio flux, see e.g., Tapping [1987]). In addition, the equivalent widths of particularly sensitive spectral lines (e.g., He I 1083.0 nm [Harvey and Livingston, 1994]), bisectors of photospheric spectral lines [Livingston, 1982], shapes of chromospheric lines (Mg II core-to-wing ratio), the number of and area coverage due to sunspots, the total and the interplanetary magnetic flux [e.g., Harvey, 1994a, b; Lockwood et al., 1999], the speed of the polar solar wind [Woch et al., 1997; McComas et al., 2001], the spatial distribution of

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1. The figure is based on models that have the following deficiencies [A.I. Boothroyd, personal communication]:
1. The model ignores the effect of element diffusion. This might significantly affect the total main sequence lifetime.
2. Mass loss was included via a parameterized Reimers mass loss formula, which is known to be unsatisfactory. Thus, the amount of mass loss at the tip of the red giant branch is highly uncertain. The most probable effect of the mass loss uncertainty would be that the number of helium flashes on the asymptotic giant branch could be different from that in the figure.
prominences and coronal holes, the latitudes and shapes of coronal streamers, all change over a solar cycle, to name but a few. Not all these quantities vary by a similar amount, however. Whereas the total irradiance and $p$-mode frequencies change by far less than 1%, the magnetic flux varies by roughly a factor of two, and the number of sunspots actually fluctuates by one to two orders of magnitude. Most of these changes occur reasonably in phase with each other, although there are some phase shifts [e.g., Jiménez Reyes et al., 1998]. The evolution over the last three solar cycles of four such quantities is plotted in Figure 1.2. In general these changes can be understood in terms of the increase in magnetic flux at the solar surface and in the solar atmosphere from solar activity minimum to maximum, or in the changed distribution of this flux on the solar surface, for example into active regions harbouring sunspots and coronal loops.

One of the most intriguing results related to the solar cycle is that it also affects local properties, such as the emission from a patch of quiet Sun, or the properties of a typical sunspot. For example, the umbral brightness of sunspots is seen to change by 20% from beginning to end of a cycle [Albregtsen and Maltby, 1978] and the penumbra to umbra area ratio also depends on the phase of the cycle [Jensen et al., 1956]. Although proposals have been made to explain such effects [e.g., Schüssler, 1980] further work is definitely required.

The result found by Schühle et al. [2000] that the quiet Sun brightness increases towards solar activity maximum also belongs to this category. It questions the very concept of the quiet Sun as a ‘standardized’, time-invariant quantity. Recently, Pauluhn and Solanki [2002] have shown that the magnetic flux in the quiet Sun increases along with the total solar magnetic flux. In particular, the amount of magnetic flux in the regions observed in the EUV by SUMER (Solar Ultraviolet Measurements of Emitted Radiation, cf., Wilhelm
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Figure 1.2: Monthly smoothed records of the following observables over sunspot cycles 21 to 23 (from top to bottom): Zürich Sunspot Relative Number, $R_z$, Core-to-wing ratio of the Mg II h and k lines (Mg II index), total solar irradiance (TSI) and 10.7 cm radio flux.

et al. [1995]), and CDS (Coronal Diagnostic Spectrometer), see Harrison et al. [1995], changes in step with the EUV brightness. It is mainly the flux in the stronger features, i.e., in the enhanced network, which is variable. This magnetic flux is directly associated with enhanced chromospheric and EUV emission [e.g., Frazier, 1971; Schrijver, 1990].

Timescales longer than 11 years are also of considerable relevance for the solar dynamo. The most obvious example is the 22-year period, which corresponds to the true periodicity of the solar magnetic field if magnetic polarity is taken into account (the so-called Hale cycle [Hale and Nicholson, 1925]). Systematic differences between odd and even 11-year solar cycles in sunspot numbers have also been found, and have been interpreted by Mursula et al. [2001] as a sign of a non-varying background field. Furthermore, both the amplitude and length of the solar activity cycle fluctuate from one cycle to the next (e.g., as manifested in the number of sunspots or other sufficiently long records of solar activity). In Figure 1.3 the yearly mean sunspot number is plotted, along with the
cycle amplitude and cycle length records deduced therefrom for the interval for which it is possible to reliably deduce these parameters from the original record.

Such fluctuations in the properties of the solar cycle can be followed on the basis of telescopic observations of sunspots for almost four centuries. The most remarkable feature in this record is that sunspots are virtually absent for a large fraction of the 17th century, during the so-called Maunder minimum [Eddy, 1976]. Using $^{14}$C/$^{12}$C and $^{10}$Be/$^{9}$Be abundance ratios (in essence measures of the open solar magnetic flux) as a proxy it is possible to follow solar activity back even further. These records reveal the presence of further Maunder minimum-like periods, in which solar activity was extremely low (and hence the cosmic-ray flux responsible for the production of the cosmogenic isotopes $^{14}$C and $^{10}$Be correspondingly high).

These fluctuations, including extreme cases such as Maunder minima, are finally also driven by the dynamo. What causes the dynamo to fluctuate is still being debated, and basically two proposals have been made, one being that non-linear dynamos may lead to a chaotic evolution of the field [Rüdiger, 2000; Weiss and Tobias, 2000], the other invoking stochastic influences produced by the interaction with magnetic fields in the convection zone [Schmitt et al., 1996].

The concentrations of the cosmogenic isotopes indicate that the Sun’s open magnetic flux also exhibits a significant secular increase since the Maunder minimum. From independent data Lockwood et al. [1999] deduced that the Sun’s open magnetic flux has doubled in strength over the last century, in good agreement with the $^{10}$Be data [Beer, 2000; Solanki et al., 2000]. Thus, not just the active phenomena exhibit a secular trend, but also the ‘quiet Sun’ appears to vary on timescales longer than the solar cycle. This is also supported by observations of Sun-like stars. The intensity in the cores of the Ca II H and K lines, which is a chromospheric index of activity and of magnetic flux, is considerably lower in stars that are in a non-cyclic state (presumably similar to the Maunder minimum [Baliunas and Jastrow, 1990]) than in stars exhibiting a cyclic behaviour similar to the current trend. These observations have also been employed to deduce a secular variation of solar irradiance. According to quantitative estimates it has increased by at least 2 W m$^{-2}$ (or 0.17 %) since the Maunder minimum [White et al., 1992; Lean et al., 1992; Zhang et al., 1994]. The underlying secular change of the magnetic flux is thought to be caused by overlaps between consecutive magnetic cycles in the sense that flux belonging to the new cycle starts to emerge before the old cycle has ended [Solanki et al., 2002]. Such overlaps are expected within the concept of the extended solar cycle [Wilson et al., 1988]. In particular Harvey [1992] and Harvey [1993] have shown that considerable magnetic flux in the form of small-scale bipolar regions, the so-called ephemeral active regions, erupts already years before the sunspots of that cycle, while the previous cycle is still in full flow.

One of the questions often addressed regarding this longer timescale is whether the modulation of the activity cycle is (roughly) periodic. The approximately 90-year Gleissberg cycle is the strongest periodicity seen in historic data (in particular in the sunspot record [Gleissberg, 1945]), although its reliability is much lower than that of the 11-year cycle, due to the limited length of the sunspot record and the lower reliability of earlier data.
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Figure 1.3: Yearly mean sunspot numbers over the last four centuries along with the cycle amplitude and cycle length records deduced from this data set. Note that these parameters can only be determined for cycles after approximately 1700.

1.2.3 Solar Rotation and Related Timescales

Periodicities at close to the Carrington rotation period of roughly 27 days and sometimes at half this period are seen in a number of records of solar observables. These periodicities are of course not due to any changes on or in the Sun, but rather to the fact that regions on the solar surface such as sunspots or active regions move in and out of view of the observer as the Sun’s surface rotates past. As sunspots pass over the solar disk they
cause solar total irradiance to decrease markedly while they are visible from Earth.\textsuperscript{2} If the sunspots live longer than a rotation period, multiple dips in the brightness are produced with a period corresponding to the sunspot rotation period at the corresponding latitude (modulated by any proper motion that the sunspots might display). The solar wind speed often also exhibits such an (approximate) periodicity due to the repeated passage of coronal holes (mainly extensions to low latitudes of the polar holes), which can live for multiple rotations. Figure 1.4 exhibits solar wind speed and the O\textsuperscript{7+}/O\textsuperscript{6+} abundance ratio in the solar wind measured by Ulysses between 1992 and 1993 as well as a part of 1996. [cf., \textit{von Steiger et al.}, 2000]. At these times Ulysses was at intermediate latitudes.

Solar rotation introduces a two-week period into signals that are susceptible to the passage across the solar disk of photospheric faculae, i.e., the bright parts of active regions, composed of small flux tubes. Strong faculae, i.e., those associated with spatially-averaged magnetic field strengths of a few hundred Gauss, are almost invisible at disk centre, or even slightly darker than the quiet Sun there [e.g., \textit{Topka et al.}, 1997; \textit{Ortiz et al.}, 2002]. They are, however, bright close to the limb. Hence the passage of a long-lived facular

\textsuperscript{2}Here the solar total irradiance refers to the total brightness of the Sun as measured from outside the terrestrial atmosphere and at the mean distance between Sun and Earth.
structure produces two brightness peaks during a solar rotation period, namely when the structure is close to each limb. It was probably this effect which led Claverie et al. [1982] to misinterpret their helioseismic data in terms of a solar core rotating at twice the surface rate, as pointed out by Durrant and Schröter [1983], Anderson and Maltby [1983] and Edmunds and Gough [1982].

1.2.4 Lifetimes of Convection Cells and $p$-mode Periods

The hierarchy of solar convection cell sizes translates into a hierarchy of lifetimes, with larger cells living longer. Thus supergranules (average size 20 Mm to 30 Mm, lifetime 20 h) live longer than the smaller mesogranules (5 Mm, 1 to 2 h), which in turn live longer than granules (1 to 2 Mm, 5 to 10 minutes).$^3$ The physical processes acting during the birth and death of granules have been reviewed by Spruit et al. [1990], cf., Ploner et al. [1999]. For a first study of the physics of mesogranule evolution see Ploner et al. [2000]. Since most convection cells are associated with a brightness contrast, at least at some wavelengths, their evolution and in particular their birth and death produce fluctuations in the Sun’s brightness. In Figure 1.5 the power spectrum of the solar irradiance time series obtained by the VIRGO (Variability of IRadiance and Gravity Oscillations) instrument on SOHO [Fröhlich et al., 1995] is plotted. (For the latest update on the total solar irradiance, see Fröhlich [2002].) The rapid decrease of solar noise towards higher frequencies is clearly visible. This allows the group of peaks due to the solar $p$-modes to stick out above the noise at the high-frequency end. In addition to these sources, faculae and sunspots also contribute to the power. Since faculae have a high contrast and evolve slowly, they significantly raise the power at the low frequency end. The contribution of sunspots is small for the period near solar activity minimum to which these data refer.

Two parameters determine how strongly a certain type of convection cell influences the solar brightness (or the wavelength shifts of the spectral lines in the disk-integrated spectrum). One is the brightness contrast, the other is the cell size or the number of cells on the solar disk. According to the first parameter granules should have the largest influence, since they exhibit by far the largest contrast in the visible. Supergranules, on the other hand, dominate in the cores of strong lines and at shorter wavelengths, since the (magnetic) network is located at their boundaries.

Since supergranules have a 10 to 30 times larger linear dimension than granules, there are typically 100 to 1000 times more of the latter on the solar surface at any given time. Statistically the influence of a given type of convection cell on global properties decreases as $1/\sqrt{n}$, where $n$ is the number of cells at a given time ($n \approx 10^6$ for granules).

Given this statistical factor, supergranules may have a larger effect on irradiance; however, the question is still open. The considerable uncertainty regarding the contribution of supergranules is related to the question of how strongly the magnetic network reacts to the evolution of the supergranules: do the magnetic elements flicker as supergranules evolve, or are they simply rearranged without changing brightness? This question is unanswered and may be moot, since the network magnetic flux itself evolves on the timescale of supergranule lifetimes by possibly quite independent means (for example emergence and evolution of ephemeral active regions [Harvey and Zwaan, 1993; Hugenaar, 2001]).

$^3$The reality of mesogranules is still a subject of debate. Recent arguments for and against their existence have been given by Shine et al. [2000] and Hathaway et al. [2000], respectively.
Figure 1.5: Power spectra of the total and spectral irradiance time series measured by the VIRGO instrument on SOHO. The spectral irradiance is measured in three 5 nm wide bands. The group of peaks near the right edge of the figure is produced by the \( p \)-mode oscillations (Figure adapted from Fröhlich et al. [1997]).

In a comparison of stars of different sizes Schwarzschild [1975] has shown that the size of granules is expected to increase faster than the stellar radius, so that the number of granules on the surface of giant and supergiant stars decreases accordingly. Hence granules could become an effective source of stellar variability for these stars. (See, however, Gray [2001, 2002], who does not find conclusive evidence for a granular cause of supergiant variability.)

The \( p \)-modes produce a distinct row of peaks in spatially unresolved (Sun-as-a-star) data (just visible in Figure 1.5) and a pattern of ridges in the \( k - \omega \) diagram obtained from spatially resolved data (\( k \) is the spatial wavenumber, \( \omega \) the temporal frequency). At any given point of the solar surface the overlap of all the oscillation modes present on the Sun gives rise to a seemingly chaotic signal. The regular pulse of an individual mode can be picked up by filtering out a single spatial and temporal frequency. The lowest degree (\( l = 0 \) to 3) modes also give a measurable signal in disk-integrated brightness and ve-
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Locality. Even for a given mode, the oscillation is strongly modulated on longer timescales by stochastic excitations followed by an exponential decay, with the decay time decreasing with increasing mode frequency. This combination produces complex profiles of the $p$-mode peaks in the power spectrum, which on the one hand have Lorentzian damping wings (from the finite lifetimes of the modes) and a strong $\chi^2$-noise (from the stochastic excitations and the limited number of realizations) [Toutain and Appourchaux, 1994]. The former affects short-lived high-frequency modes most, while the latter is a problem mainly for the long-lived low-frequency modes.

Note that $p$-modes are solar eigenmodes resonantly excited by turbulent convection, mainly the granulation, so that any solar variability introduced by them is ultimately also due to granulation.

The granulation also excites propagating waves (i.e., those with periods shorter than the acoustic cutoff of three minutes). In the chromosphere these waves steepen into shocks, which are associated with particularly large temperature enhancements. Hence, such waves exhibit significant variations in the radiation emanating from chromospheric layers (for example the Ca II K line core Cram and Démé [1983]). Carlsson and Stein [1992, 1995, 1997] have pointed out that the variability in intensity is much smaller than the temperature variations since the hottest part of the chromosphere radiates most strongly. Thus, the bulk of the radiation in the K line core arises from the shock front as it propagates through the chromosphere in their simulations.

1.2.5 Flares, Microflares, Blinkers

One of the major discoveries of recent space missions (Yohkoh, SOHO, TRACE) has been the immense variability of the solar transition region and corona. In addition to the variability due to the sources mentioned so far there are relatively sudden brightenings in radiation sampling the chromosphere, transition region and corona of the Sun. The most energetic and spectacular of these are flares. Flares are generally detected in X-rays, coronal EUV lines, or in Hα. Flares cover a broad range of total emitted energies, peak brightnesses (for example in X-rays) and durations. See Tandberg-Hanssen and Emslie [1988] for an introduction to flares and an overview of their properties. The number of flares increases rapidly with decreasing amount of energy released per event [Crosby et al., 1993; Benz and Krucker, 2002]. The very weak events are often termed microflares (or nanoflares in the case of the weakest). There are proposals by, e.g., Parker [1993] that these micro- and nanoflares are the main cause of coronal heating. Energy released through magnetic reconnection is thought to drive the brightening associated with a flare.

In transition-region lines similar brightenings as the microflares are seen. They have been termed blinkers [e.g., Harrison, 1997; Harrison et al. 1999; Brković et al., 2001]. Examples of typical blinkers are the biggest brightenings seen in the upper right frame of Figure 1.6 (from Brković et al. [2002]). In CDS data plotted in the upper two frames, blinkers are significant brightenings, typically $>1.5$ times the background brightness for O V 63.0 nm, which generally last between 5 and 50 minutes. A comparison with data recorded by the SUMER instrument, which are simultaneous and cospatial to the extent possible (the two lower frames in Figure 1.6), shows that SUMER exhibits over a factor of three larger variability than CDS wide-slit data. A part of the reason is that in the wide-slit mode spectral information is lost, so that the less variable nearby continuum is analyzed along with the line. Nevertheless, this still leaves over a factor of two unaccounted for, which
1.3 Wavelength Dependence of Solar Variability

The magnitude of solar variability is strongly wavelength dependent. On the timescale of the solar-activity cycle, brightness variations have a minimum in the IR at around 1.6 µm and increase toward both shorter wavelengths, up to X-rays, and longer wavelengths to radio waves. For example, whereas the total solar irradiance (which is dominated by variations in the visible [e.g., Solanki and Unruh, 1998]) varies only by 0.1 % over the solar activity cycle, the EUV and X-ray flux can change by over an order of magnitude [Acton, 1999].

A number of causes combine to produce this wavelength dependence. In the following a few of these causes are listed.

- The temperature dependence of the Planck function increases from radio to near UV wavelengths. This means that a given change in temperature produces a larger variation in the thermal radiation at UV wavelengths than in the IR. This effect helps determine the wavelength dependence of the variability due to granulation and sunspots, but plays a minor role for, e.g., faculae or flares. For the former the
height-dependence of the temperature is more important, for the latter the radiation has a strong non-thermal component.

- Radiation formed at greater heights, i.e., lower densities (e.g., X-rays, radio), exhibits larger variations than radiation arising in deeper and denser atmospheric layers (e.g., optical radiation). In particular, the minimum in solar cycle variability at 1.6 \( \mu \)m is partly due to the opacity minimum located at this wavelength, so that the radiation is emitted at the greatest depth. The reason for this behaviour becomes clear when one bears in mind that the amount of energy potentially available to inject into the gas decreases more slowly with height than the gas density. Gas at a lower density is more strongly affected by the input of a given amount of energy (e.g., from the dissipation of waves or magnetic reconnection).

- Saturation effects restrict the variability of optically thick radiation, so that optically thin radiation (usually emitted from the less dense parts of the atmosphere) exhibits the largest variation.

- The structure and dynamics in the transition region and corona and the thermal energy input into them are determined by the magnetic field. Since, in the corona, gas pressure is almost negligibly small compared to magnetic pressure (but see Gary [2001]), large density gradients can exist stably across field lines. Similarly, since heat transport along field lines is far more efficient than across them, large cross-field thermal gradients can be built up. The hotter parts of the solar atmosphere are thus far more inhomogeneous than the cooler parts (as indicated by the very high contrast fine structures seen in data obtained by the TRACE satellite at a given wavelength). Also, magnetic heating processes (reconnection, MHD wave dissipation) tend to be very time dependent.

The wavelength dependence of the relative change in the solar irradiance between solar activity maximum and minimum of cycle 22 is plotted in Figure 1.7. Shortward of 400 nm the dashed curve corresponds to observational data from Lean [1997] while the solid curve results from the model calculations of Unruh et al. [1999]. The minimum in variability around 1.6 \( \mu \)m is clearly visible as is the steep increase towards the FUV and the more gentle increase towards the FIR.

Although brightenings over a large wavelength range often happen simultaneously, in extreme cases the Sun can exhibit the opposite behaviour in two different wavelengths. Perhaps the most striking example is the contrasting evolution of the solar luminosity in the visible (or integrated over all wavelengths) and in X-rays over its lifetime. Whereas the Sun has become brighter in visible light with time (see Section 1.2.1, Figure 1.1) its X-ray luminosity is expected to have decreased by between one and three orders of magnitude. This follows from the X-ray versus rotation period relationship exhibited by late-type stars. This relationship is tightest when instead of rotation period \( P \), we use the Rossby number \( R_o = P/\tau \) [e.g., Simon, 2001], where \( \tau \) is the convective turnover time, which has remained relatively constant during the Sun’s main-sequence lifetime. The rotation rate of the newborn Sun was considerably higher than the current value (like that of almost all young main sequence stars); however the Sun’s exact initial rotation rate cannot be deduced from its current state [Pinsonneault et al., 1989]. The X-ray luminosity of the most rapidly rotating stars is roughly three orders of magnitude larger than that
of the Sun; this indicates the maximum value that the solar X-ray luminosity could have reached in the past. The intermediary connecting the stellar rotation rate to the X-ray flux is the magnetic field. The magnetic dynamo works more efficiently in a rapidly rotating star, producing more magnetic flux [Valenti and Johns-Krull, 2001], which in turn leads to stronger chromospheric and coronal heating.

The magnetic field also influences the rotation of the Sun by extending the Sun’s moment arm and leading to an enhanced loss of angular momentum through the solar wind [e.g., Schatzman, 1962; Mestel and Spruit, 1987; Keppens et al., 1995; Solanki et al., 1997; MacGregor, 2001]. It is basically this back reaction which is responsible for the spin-down of the Sun to its current rotation rate.

1.4 Conclusion

A brief overview has been given of the variability of the Sun. The Sun varies at all timescales, although by different amounts and partly also at different wavelengths. Some of the most interesting timescales have been discussed in greater detail. The wavelength dependence of the variability has also been considered. The relative variability of the Sun increases heavily towards more extreme wavelengths. However, the absolute variation in solar irradiance or flux is largest in the visible, simply because most of the radiation is emitted in this wavelength band, so that even a small (0.1 %) relative variability leads to a large fraction of the total variability, namely 40 % [Solanki and Unruh, 1998].

Perhaps most intriguing is the wide range of physical processes responsible for making the Sun variable. These range from slow changes in the solar core to rapid magnetic reconnection in the solar corona. Unfortunately, the physics behind the variability has been touched upon only very rudimentarily in this overview. Another very important as-
pect which has not been considered here, but which is the subject of the other papers in this volume is the need for well-calibrated and stable instruments to reliably record solar variability. The calibration and intercalibration efforts culminating in this volume should therefore lead to a significantly improved and enhanced knowledge of solar variability.

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