1 Introduction

Helios, Sol, Ra, Amaterasu, Jua, Khorshid, Shemesh or Inti are among the names used by diverse cultures to refer to the ball of incandescent gas that is the source of life on Earth. The luminosity of the Sun varies over time, and such variations are the object of this thesis.

The energy released by the Sun reaches the Earth as particles and electromagnetic radiation. This radiation −photons− follows a long and intricate path after its generation in the Sun's core as a result of thermonuclear reactions. It passes first through the radiation zone, where it is scattered millions of times by ions and electrons, and then through the convection zone, the outer third of the solar radius, where it is transported outwards by the hot ascending gas. It is at the bottom of the convection zone, the tachocline or dynamo region, that the solar magnetic field is rooted. Helioseismological observations have shown that the core and the radiation zone rotate as a rigid body, while the convection zone shows differential rotation. Thus, plasma rotating at different velocities in the thin transition layer at the bottom of the convection region generates shear flows and amplifies the magnetic dynamo. The magnetic field generated in the tachocline plays a key role in solar variability. Finally, after a journey of millions of years, photons reach the solar surface, most of them as visible radiation, and escape to open space.

The last interaction of photons with solar plasma before continuing their path to Earth takes place in the solar atmosphere. This atmosphere is formed, in ascending order by the photosphere, the chromosphere and the corona. The photosphere is the atmospheric layer we see when we look at the solar disk, generally referred to as "the solar surface"; it is about 500 km thick. The chromosphere occupies the next 1500 to 2000 km. Roughly, the corona extends from 3000 km above the surface to about 6 solar radii ($R_\odot$), depending on solar activity. The temperature drops from around 5800 K in the photosphere to around 4000 K. Then it rises again, first gently but later rapidly in the transition region between the chromosphere and the corona, until it reaches values of the order of 10^6 K in the corona.

The study of the Sun provides a unique insight into many of the fundamental processes in astrophysics, for two reasons: the Sun is the only star that can be spatially resolved by direct observations, and second, solar plasmas and magnetic fields occur in conditions that are impossible to reproduce in terrestrial laboratories. However, only the photosphere and the chromosphere can be regularly observed from the ground. The transition region, the corona and the solar wind are mostly studied from space and, in particular, many properties of the photosphere had to await space-based observations for their determination or discovery. This is the case of solar variability.

1.1 Photospheric magnetic structures

The solar disk is a panoply where a whole spectrum of magnetic structures can be seen. These concentrations of magnetic origin form a hierarchy with a wide range of sizes, field strengths and degrees of compactness. Their properties depend on the total magnetic flux they contain, as summarized in table 1.1 (extracted from Schrijver & Zwaan 2000). The parts of the solar surface outside active regions (AR) are called quiet Sun regions, but even they contain small-scale magnetic fields.

Sunspots are the largest compact magnetic concentrations, and they are composed of umbrae and penumbrae; pores are small umbrae without penumbrae. The effective temperature of sunspots is around $T_{\rm eff} \sim 4000$ K, 1800 K cooler than the quiet photosphere and thus they are seen as dark features. In addition to sunspots and pores, there are localized concentrations of strong magnetic flux with intrinsic field strengths of around 1500 G; these concentrations −faculae and network elements− are brighter than the quiet photosphere. Within active regions faculae are tightly packed while the enhanced network appears more widely distributed. The facular effective temperature is about 100 K higher than the surrounding plasma. Outside active regions, the bright network patches form the so-called quiet network in close coincidence with supergranular boundaries. At very high resolution the faculae consist of conglomerates of many small bright points or facular points with diameters of about 100 km (Berger et al. 1995), which were called *crinkles* by Dunn

Table 1.1: Hierarchy of photospheric magnetic structures

	Sunspot with penumbra		Pore	Micropore (magnetic knot)	Faculae, network clusters	Filigree
Property	large	small				
Φ (10^{18} Mx)	3×10^4	500	250-25	≈ 10	≤ 20	≈ 0.5
R (Mm)	28	4	–	–	–	–
R_u (Mm)	11.5	2.0	1.8-0.7	≈ 0.5	–	≈ 0.1
B (G)	2900±400	2400±200	2200±200	$\approx 1500 - 2000$	≈ 1500	≈ 1500
Continuum contrast	dark	dark	dark	–	bright	bright
Location	⟵ exclusively in active regions ⟶				inside and outside active regions	
Cohesion	compact	compact	compact	–	clusters, clumps	?

Φ is the magnetic flux, R is the radius of a sunspot, R_u is the radius of a sunspot umbra or of a smaller magnetic concentration, and B is the magnetic field strength at its center. Adapted from Schrijver & Zwaan (2000).

& Zirker (1973).

In the hierarchy of magnetic features, magnetic knots occupy an intermediate position between dark and bright features. At high resolution, these knots presumably correspond to the micropores observed by Topka et al. (1997). Keller (1992) found that magnetic features larger than ~ 300 km in diameter appear with a dark core. According to Topka et al. (1997), the transition between bright points and dark micropores occurs at a diameter of about 300 km. Micropores therefore fill the gap between small bright points and larger dark pores.

Sunspot umbrae and pores are compact structures, with magnetic filling factors of 100% (the filling factor is the fraction of the solar surface within a given pixel covered by magnetic flux tubes). In contrast, faculae and network patches are composed of small clustered magnetic features, presenting magnetic filling factors of less than 25%, except locally where they can reach 50%. Figure 1.1 is a high-resolution image of a portion of the solar disk which shows a number of magnetic features. There is a sunspot together with some pores, and surrounding these dark features there are small bright points or facular points of about 150 km in diameter.

When measuring the field strength of magnetic features it has to be taken into account that the line-of-sight magnetic signal in magnetographs drops to zero near

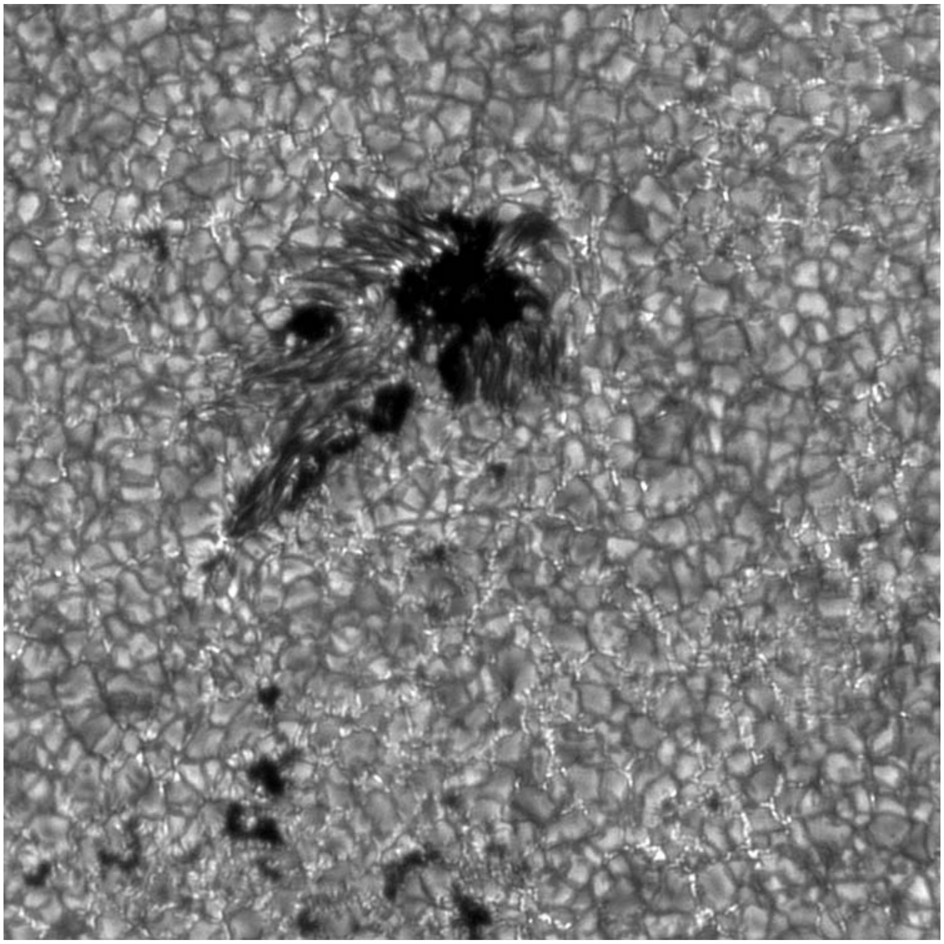

Figure 1.1: High resolution image of a part of the solar photosphere, 40 000×40 000 km wide. A sunspot is present together with some pores. Note the presence of small bright points whose diameter is about 150 km. Image taken with a G-band filter centered at 430.5 nm, by T. Berger and G. Scharmer at the Swedish Vacuum Solar Telescope (La Palma, Spain) on May 12, 1998.

the solar limb. This suggests that the photospheric magnetic field in faculae and the network is close to vertical. Sánchez Almeida & Martínez Pillet (1994), confirmed this by measuring bright points of the enhanced photospheric network, concluding that the inclination of their magnetic field with respect to the vertical is less than 10°. The situation of plage regions surrounding sunspots is rather different because they have large inclinations; it seems that isolated network structures are vertical while structures close to sunspots are not.

More than 90% of the measured magnetic flux that emerges into the photosphere is concentrated in strong fields, with intrinsic strengths of between 1000 and 2000 G

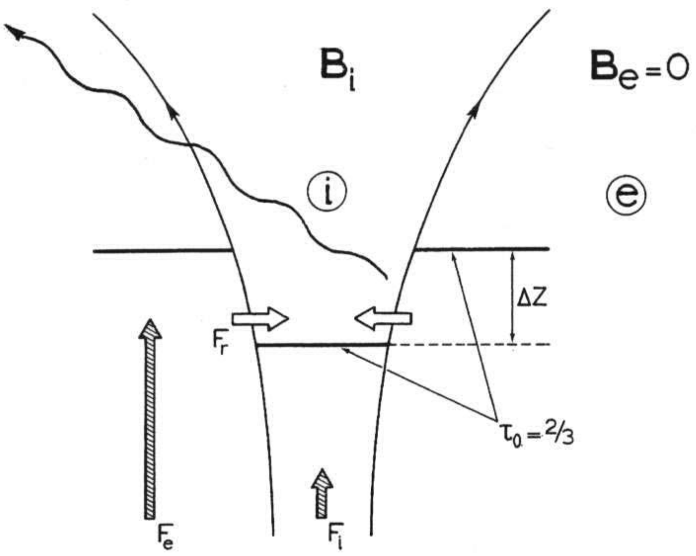

Figure 1.2: Simplified sketch illustrating the concept of the magnetohydrodinamic flux tube model. One level of constant optical depth in the continuum, $\tau_0 = 2/3$, is shown, with a Wilson depression Δz. The arrows labeled F_i and F_e stand for the flux densities in the (nonradiative) energy flows inside and outside the flux tubes, respectively. The horizontal arrows indicate the influx of radiation (F_r) into the transparent top part of the tube. The walls of the tube are bright due to the radiation leaking in from the surroundings, and radiation can thus escape from its walls. Taken from Schrijver & Zwaan (2000).

(see, e.g., Stenflo 1973, 1985). At the solar surface, these magnetic fields are bundled into discrete elements. In order to describe the observed variety of magnetic features and predict their physical properties, the concept of a magnetohydrodynamic flux tube has been developed; figure 1.2 shows a simplified sketch of a flux tube, although a more detailed approach to different models of flux tubes will be given in Section 1.3.3.

Understanding the physics of the photospheric magnetic elements is fundamental for clarifying the mechanisms that produce the solar cycle. Furthermore, the study of the small magnetic elements is important to understand their contribution to solar irradiance variations, with the additional challenge that most of them remain below the limit of the attainable resolution.

As Robert Leighton once said: *"If it were not for its magnetic field, the Sun would be as dull a star as most astronomers think it is"*, US-Japan Solar Conference, Honolulu, February 1965.

1.2 A brief historical overview

1.2.1 The discovery of sunspots and the solar magnetic field

The Sun has been observed since the beginning of time. Large sunspots are visible without a telescope and naked-eye sunspot observations were described in many ancient chronicles and court chronologies. The two oldest records of a sunspot are found in the *Book of Changes*, compiled in China circa 800 B.C. Astronomers of the courts of the Chinese and Korean emperors made regular notes of sunspots. However, these observations were not carried out systematically but only when ordered by the emperor, basically for astrological prognostication. The surviving sunspots records, although incomplete, cover nearly 2000 years and represent the most extensive pre-telescopic sunspot record. In the West, the dominating views of Aristotle concerning the incorruptibility of the heavens made the existence of sunspots impossible, so sunspot sightings were ignored or ascribed to transits of Mercury or Venus across the solar disk.

The first surviving drawing of a sunspot appears in the *Chronicles of John of Worcester*, who drew it in 1128 A.C. But it was in the first years of the 17th century that four astronomers simultaneously turned the newly invented telescope towards the Sun. Among them, Galileo Galilei and Christoph Scheiner were the most active in using sunspots to attempt to infer physical properties of the Sun. Galileo discovered that they are indeed features of the solar surface and not planetary transits. Sunspot observations continued in the 17th century, although very few were observed from about 1645 to 1715, the period known as the Maunder minimum. Historical reconstructions of sunspot numbers indicate that this decrease was real rather than due to a lack of observers. It has been documented that exceptionally cold winters throughout Europe occurred during those years, which may be attributable to the reduced solar activity.

The physical nature of sunspots remained controversial for nearly three centuries. In the late 18th century, William Herschel suggested that sunspots were openings in the Sun's luminous atmosphere, allowing a view of the underlying, cooler surface of the Sun. In 1826, Samuel H. Schwabe was trying to discover intra-mercurial planets. To avoid confusing planets with small sunspots, he meticulously recorded the position of any sunspot visible on the solar disk whenever weather would permit it. In 1843, after 17 years of observations, Schwabe had not found any intra-mercurial planet, but discovered an important fact: the cyclic increase and decrease over time of the average number of sunspots visible on the Sun, with a period that he originally estimated to be of ten years, i.e. the sunspot cycle. Rudolf Wolf reconstructed the cyclic variations in the sunspot number back to the 1755-1766 cycle, which has been known ever since as Cycle 1.

In 1906-1907, George E. Hale provided the first unambiguous demonstration that sunspots are the seats of strong magnetic fields, by measuring the Zeeman splitting in the spectra of sunspots (Hale 1908). This was the first detection of a magnetic field outside the Earth. In the following decade, Hale and his collaborators demonstrated that sunspot pairs show the same polarity pattern in each solar hemisphere, but opposite polarity patterns in North and South hemispheres. Moreover, they showed that polarity patterns are reversed from one sunspot cycle to the next (Hale's polarity laws). These observations presented evidence for the existence of a well-organized large scale magnetic field in the solar interior.

However, it was necessary to wait more than 20 years to discover that the magnetic fields are also concentrated in small-scale structures outside sunspots. Even though Scheiner had described observations of faculae in his book in 1630 *Rosa Ursina* (*"ex admirando facularum et macularum et phaenomeno varius"*), it was not until 1930's that small scale magnetic structures were observed so that their physical properties, for example their contrast, could be inferred (Ten Bruggencate 1940).

1.2.2 Changes in the Sun's brightness and its link to the Earth's climate

Temperatures during the Maunder minimum were about one half of a degree Celsius lower than the mean value for the 1970's. John A. Eddy (Eddy 1976) suggested that the decrease in the decadal average solar irradiance during that period caused the Little Ice Age of 1600-1800, but this latter point is controversial.

The Maunder minimum is not an isolated event in history. A shorter and less severe minimum, the Dalton minimum, was found in historical records to have happened from 1795 to 1825. Since then, the Sun has gradually brightened. The present epoch is called the Modern maximum. However, this increase in solar irradiance accounts for only about one half of the temperature increase since 1860, and less than one third since 1970; the rest is due to the greenhouse effect (Lean et al. 1995). Pang & Yau (2002) have compared ancient Chinese, Korean and Japanese catalogs of aurora and sunspot records concluding that, including the Modern maximum and the Dalton minimum, there have been nine cycles of solar brightness in the last 1800 years, all of them genuine periods of low or high solar activity that affected the Earth's climate. Thus, it is important to study changes in the solar energy output because of their influence on the terrestrial climate, as well as to fully understand the solar-terrestrial relationships. For a deeper insight into ancient records of changes in solar brightness see Pang & Yau (2002) and references therein. Reconstructions of solar irradiance variations back in time have been carried out, among others, by Foukal & Lean (1990), Lean et al. (1992), Lean et al. (1995), and Solanki & Fligge (1998, 1999).

1.3 Solar irradiance variations

The *solar constant*, or total solar irradiance, is a measure of the Sun's luminosity. By convention, it is defined as the amount of normally incident energy per second and square meter ($\mathrm{W\,m^{-2}}$) at the top of the terrestrial atmosphere, at a distance of 1 AU from the Sun. Its value is 1366 ± 3 $\mathrm{W\,m^{-2}}$.

The first attempts to measure the Sun's energy output were made independently by Claude Pouillet and John Herschel in 1838. They designed pyrheliometers, in which a mass of water was heated by sunlight for a fixed period of time. They inferred values which were about half the modern value, because they failed to account for absorption by the Earth's atmosphere. To overcome this limitation, expeditions to high altitudes were organized. Samuel Langley carried out an expedition to Mount Whitney in 1881 to determine the solar constant. He used a bolometer and other instruments to measure the solar irradiance at different wavelengths and altitudes, demonstrating the strong variation of the atmospheric absorption with wavelength (Langley 1903).

But is the solar constant really a constant? Now we know that the answer is no. Variability of the solar total irradiance has been suspected and investigated for more than a century, with no definitive success. There were many early and inconclusive observations from ground-based observatories, and later, during the late 60's, from airplanes, balloons, rockets, and even the Mariner VI and VII missions. These early observations could not detect the variability of the solar constant owing to the inadequacy of the available technology, but also perhaps to a perceived interest in measuring a single number – "the solar constant".

It was not until the launch of Nimbus-7 in 1978 that measurements achieved sufficient precision to detect irradiance fluctuations. The new era of space-born radiometers launched since then has provided unprecedented opportunities for research on solar variability. Space-based radiometers such as the ERB/Nimbus-7 (Hickey et al. 1988), the ACRIM/SMM (Willson 1981), the ACRIM II/UARS (Willson 1994) and SOLSTICE/UARS (Woods et al. 1993), the SARR/ATLAS 2 (Crommelynck et al. 1995), the SOVA/EURECA platform (Crommelynck et al. 1991) and the VIRGO/SOHO (Fröhlich et al. 1995) have been – and some of them still are – monitoring solar irradiance variations for the last two and a half decades. Their precision and accuracy has allowed measurement of irradiance variations on time scales ranging from minutes to the length of the solar cycle (11 years) (Willson & Hudson 1988; Fröhlich 2000). Irradiance dips of up to 0.3% are related to the passage of large sunspot groups across the solar disk; these variations are produced on time scales ranging from days to weeks. Total irradiance is about 0.1% brighter when solar activity peaks during the eleven-year solar cycle, relative to that at solar minimum (Willson & Hudson 1988; Foukal & Lean 1988). Surprisingly, solar irradiance is higher when sunspots cover the solar surface. The time scales of interest for our study are those of solar rotation and the solar cycle.

As mentioned above, several radiometers have monitored the evolution of the solar irradiance variations during different periods. This allows the construction of a composite time series yielding an estimate of the variability of solar irradiance over the last two decades. In order to compose a uniform time series, these series have to be homogenized and adjusted to a common scale. A detailed description of the procedures followed to construct the composite is given by Fröhlich & Lean (1998a,b). Figure 1.3 shows the result of their composite solar irradiance, which spans for more than twenty years; both short and long time-scale variations are clearly seen.

The fact that the solar constant is not actually constant raises the possibility that solar radiation may have a direct effect on terrestrial climate, as commented in

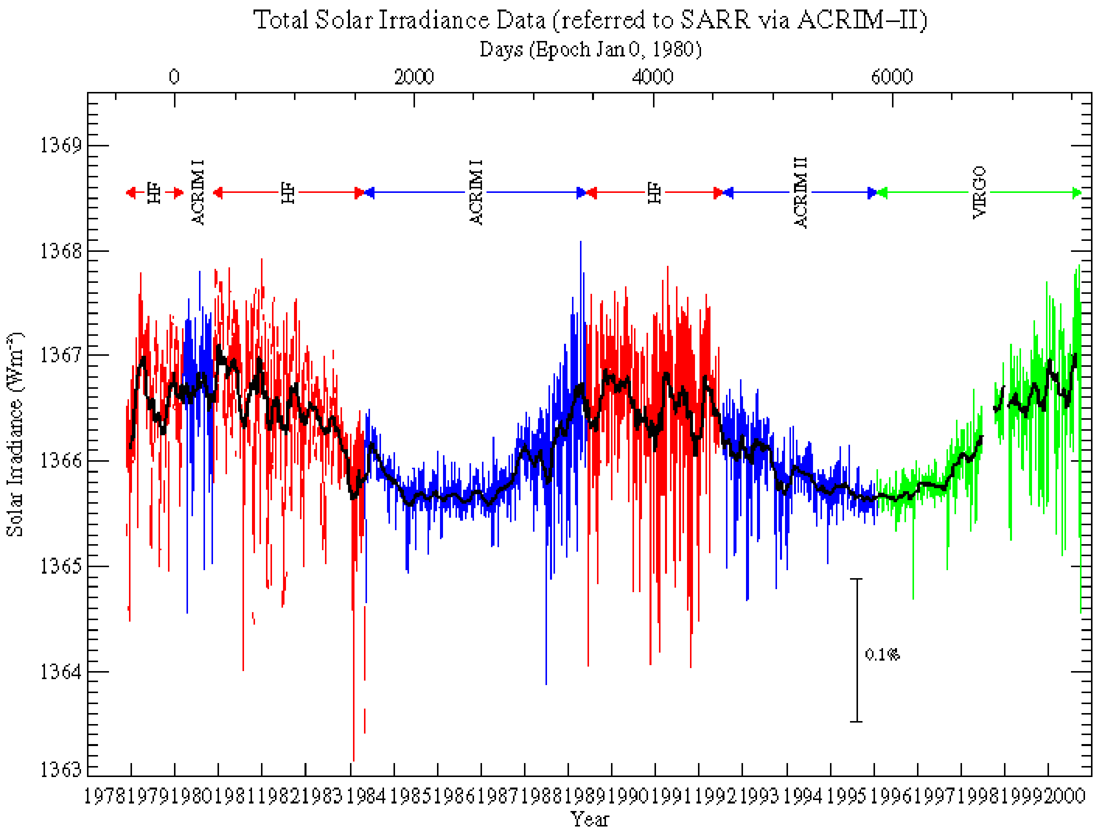

Figure 1.3: Composite total solar irradiance spanning more than 20 years, with indication of which time series are used at different times. Time series come from HF/Nimbus-7, ACRIM I/SMM, ACRIM II/UARS and VIRGO/SOHO respectively; (from Fröhlich 2000).

Section 1.2.2. Changes in the visible and near-infrared radiation, which dominate solar output, can affect the Earth's surface temperature and the biosphere. Ultraviolet (UV) radiation near 200 nm, emitted from the middle photosphere, exhibits much larger variations than visible radiation (about 8% through the solar cycle); moreover, variations of more than a factor of two can occur in extreme ultraviolet (EUV) radiation at wavelengths shorter than 120 nm. UV radiation creates and maintains the atmospheric ozone layer while the greater EUV variations significantly affect the thermodynamics of the upper atmosphere and ionosphere.

Another more indirect way in which the Sun may influence the terrestrial climate has been proposed by Svensmark & Friis-Christensen (1997). According to them, the global cloud coverage correlates well with the cosmic ray flux, which in turn is

Table 1.2: Identified mechanisms for solar total irradiance variability

Mechanism	Time scale	Amplitude of the variation	Reference
Oscillations	5 min	few ppm	Woodard & Hudson (1983)
Granulation	tens of min	tens of ppm	Hudson & Woodard (1983)
Sunspots	few days	$<$ 0.2% peak-to-peak	Willson et al. (1981)
Faculae	tens of days	$<$ 0.1% peak-to-peak	Willson et al. (1981)
Rotation	27 days	variable	Fröhlich (1984)
Active network	11 years	$\sim$ 0.1% peak-to-peak	Foukal & Lean (1988)

(ppm: parts per million; from Hudson 1988).

anticorrelated with the solar magnetic activity.

1.3.1 Sources of solar irradiance variations

It is difficult to compile a complete list of the sources of variability in solar irradiance. Hudson (1988) lists and discusses six well-established mechanisms contributing to solar variability, which are reproduced in table 1.2; his main conclusion is that there are likely to be other mechanisms that remain to be established.

Most of the variations arise from the changing presence and evolution of the magnetic features described in Section 1.1. Variability on the solar rotation time scale is associated with the passage of sunspots and active region faculae across the solar disk (e.g., Foukal & Lean 1986; Chapman 1987; Lawrence & Chapman 1990; Fligge et al. 2000b; Solanki & Fligge 2002). It is worth noting that less than twenty years ago, the contribution of active region faculae to irradiance variations was still questioned. Today, it is still under debate whether or not magnetic features alone are the *only* sources needed to account for the long-term variations on the solar cycle time scale (i.e. the $\sim$ 0.1% increase of the solar brightness from minimum to maximum), or whether additional mechanisms of non-magnetic origin are needed.

The source of this controversy is that one component of brightness appears to be missing. Reproductions of the irradiance changes on the solar cycle time scale that only take into account sunspots and facular emission, underestimate the observed solar cycle irradiance modulation by roughly a factor of two (Lean 1991). Foukal & Lean (1988) and Lean et al. (1998), for example, have pointed to the magnetic network − bright, small-scale magnetic features below the limit of the attainable resolution produced by active region decay and spread through the solar disk − as the missing bright component. However, quantifying the network contribution to irradiance modulation has proved to be extremely difficult. Furthermore, Foukal et al. (1991) add to the controversy by showing that the amplitude of the network contribution is probably sufficient to explain the missing component of the eleven-year total irradiance variation. These authors distinguish between quiet and active magnetic network. Walton et al. (2001) maintain the opposite point of view, claiming that the network is equally prevalent during all phases of the solar cycle, and thus could not account for changes in solar irradiance. More recently, Fligge & Solanki (2000) and later Solanki & Fligge (2002), claim that models of irradiance variations based exclusively on the solar surface magnetic field can account for over 90% of the short-term variations (i.e., those on a solar rotation time scale), and at least 70% (and even up to 90%) of the variations on a solar cycle time scale. Finally, in the same line, Krivova et al. (2003) claim excellent agreement between irradiance reproductions and observations, based on the assumption that solar surface magnetism is entirely responsible for irradiance changes.

On the other hand, certain studies relying on solar limb photometry suggest, instead, that the source of the brightness increase from solar activity minimum to maximum is of non-facular origin, possibly a global mechanism such as temporal changes in the latitude-dependent surface temperature of the Sun (e.g., Kuhn et al. 1988). Other authors have tried to explain these variations by modelling structural changes in the convection zone during the solar cycle (Balmforth et al. 1996).

We now contribute to this debate by analyzing the contribution of faculae and small magnetic elements to irradiance fluctuations on both the short and long time scales.

1.3.2 Contrast of faculae and small magnetic elements

Sunspots are dark while small flux tubes are generally bright. Sunspots have been the subject of many studies and it is generally believed that they are well understood, and that their influence on the solar irradiance has been modelled quite accurately (Foukal 1981; Hudson et al. 1982). However, our knowledge of the brightness of small scale magnetic features composing the faculae and the network is still very incomplete (e.g., Solanki 1994). It is difficult to observe these features, due to their complex morphology and their low contrast relative to the quiet Sun. Their brightness signature is a function of their heliocentric angle (θ, the angle between the local vertical and the line of sight), size, averaged magnetic field, wavelength and spatial resolution of the observation; see, for example, Solanki (1993, 1994) for a review.

As the Sun rotates, a feature on its surface is viewed at different angles. At disk center we have a straight overhead view of a magnetic feature, whereas at the limb we see it from the side. The contrast of sunspots is nearly independent of the viewing angle. However, the contrast of AR faculae and smaller magnetic elements varies strongly with heliocentric angle, presenting a minimum at disk center and a maximum near the limb (see Section 1.3.3). The nature of this center-to-limb variation (CLV) is attributable to the structure of the flux tubes making up the facular elements.

As mentioned above, the contribution of small scale features –faculae and network– to solar irradiance variations is, probably, the largest unknown in present irradiance reconstructions, especially on time scales of the solar cycle. Regarding these contributions, Lawrence et al. (1993) suggest that different contrast functions may apply to AR faculae and quiet Sun network, and thus their contribution to irradiance fluctuations will be different.

Simple models of irradiance fluctuations based on proxy data (e.g. published calcium plage or sunspots areas and positions) were developed in the 1980's. The Photometric Sunspot Index, PSI, was applied to estimate the irradiance deficit of sunspots (Willson et al. 1981; Hudson et al. 1982). The PSI is defined, in parts per million (ppm) of the irradiance of the quiet Sun, as

$$PSI = C_s \sum_i A_{S,i} \mu_i \frac{\Delta I}{I} LD(\mu_i) \tag{1.1}$$

where C_s is an empirically determined coefficient, A_S is the published sunspot group area in millionths of the solar hemisphere, $\mu = \cos\theta$ is the foreshortening (θ is the heliocentric angle), $\Delta I/I$ is the local contrast of the sunspot (assumed constant), and LD(μ)=$I(\mu)/I(0)$ is the quiet Sun limb darkening; the sum is taken over the population of spot groups simultaneously present on the solar disk. Usually, the gray approximation is assumed for the quiet Sun limb darkening, where LD(μ)=(3μ+2)/5 (Mihalas 1970).

The facular contribution to irradiance variations can be estimated with a proxy function, the Photometric Facular Index, PFI (Chapman & Meyer 1986), in an analogous way to the PSI. Two problems arise with the PFI, namely the greater uncertainty in facular area and the uncertainty in the CLV of the facular contrast. The PFI is given (in ppm) by

$$PFI = C_p \sum_i A_{p,i} \mu_i \frac{\Delta I}{I} LD(\mu_i) \tag{1.2}$$

where C_p is again an empirically determined coefficient (the conversion factor from chromospheric plage areas to photospheric facular areas), A_p is the tabulated Ca plage area −as a proxy for direct white-light photometry of individual faculae−, LD(μ) is the limb darkening, and $\Delta I/I$ describes the CLV of the facular contrast. The summation is taken over the number of plages present on the solar disk. Steinegger et al. (1996) modified these proxy functions by introducing, in analogy to the PSI and PFI models, a dependence of the constant empirical coefficients on plage brightness.

The functional form of the CLV of the facular contrast remains poorly defined, and it is the major source of uncertainty in the evaluation of the PFI index or any other estimation of the facular contribution to irradiance variations (e.g., Lean et al. 1998). Chapman et al. (1992) compiled several parameterizations that have been proposed to reproduce the observed CLV of the facular contrast. The difficulties in finding a description of the facular CLV arise from the fact that facular contrast is hard to measure, because it comes from unresolved bright points with low contrast. This has led to widespread use of proxies of the magnetic features, such as Ca II K, Mg II k or He I 1083 nm radiation, which are formed in chromospheric layers. In general, chromospheric plages have much higher contrast than white-light faculae (Chapman 1987), but these layers are dominated by different physical processes than the photospheric layers. For example, the CLV of the contrast of white-light faculae is different from that of a calcium plage, because the latter is equally visible across the solar disk.

1.3.3 Photometric observations and theoretical flux tube models

The aforementioned difficulties in observing faculae and smaller elements lead to many discrepancies in the literature regarding such measurements. The fact that different reported observations are made at different wavelengths, spatial resolutions or field strengths makes the comparison between them difficult (Solanki 1994), and contributes to the scatter between contrast measurements.

There is a consensus that the facular contrast is low at disk center, and that it increases rapidly towards the limb (see, e.g., Frazier 1971; Muller 1975; Ingersoll & Chapman 1975; Chapman & Klabunde 1982; Libbrecht & Kuhn 1984, 1985; Lawrence & Chapman 1988; Lawrence et al. 1988; Auffret & Muller 1991). Nevertheless, there is no agreement about the values of the continuum facular contrast near the disk center. Topka et al. (1992) report a negative continuum contrast (-3%) for faculae near 500 nm at disk center, and Lawrence et al. (1993) show that quiet Sun network features are bright, while AR faculae are dark at disk center, but these results are in contradiction with most of the observations of the contrast at disk center.

Moreover, there is an important debate as to whether the contrast continues to increase towards the limb, beyond $\mu \leq 0.20$ (as suggested for example by Chapman & Klabunde 1982; Lawrence 1988), or whether it peaks somewhere around $\mu \sim 0.20$ and then decreases again for smaller μ's (Libbrecht & Kuhn 1984, 1985; Auffret & Muller 1991). Figure 3 of Unruh et al. (1999) shows examples of such disagreements on contrast measurements. The influence of wavelength on the observations is evident in Wang & Zirin (1987); these authors found that the contrast for shorter wavelengths ($\leq 500\,\mathrm{nm}$) increases monotonically limbwards, while for longer wavelengths the facular contrast peaks around $\mu = 0.10$ to 0.15 and then decreases. Spatial resolution is also a significant factor on which the contrast of small magnetic elements depends, because higher spatial resolution usually leads to higher contrast values (see Solanki 1994, and references therein).

Various models of small flux tubes have been constructed in order to predict the physical properties of small magnetic elements. The major generic types of facular models, at least as far as geometric configuration is concerned, are the *hot wall* (e.g., Spruit 1976; Deinzer et al. 1984a,b; Knölker et al. 1988; Grossmann-Doerth et al.

1989; Steiner et al. 1996) and the *hot cloud* (see Schatten et al. 1986) models. In the hot wall model, the facular emission comes from the hot walls of a partially evacuated (due to magnetic pressure) cylindrical magnetic flux tube with diameter D and effective depth, or Wilson depression, Z. For a more complete discussion of this model see Spruit (1976); the geometry of the hot wall model is shown in figure 1.4. When viewed from directly overhead −at disk center−, only a small fraction of the hot walls are exposed to the observer, therefore the facular element appears faint or even dark, depending on its diameter. As the facular element moves away from disk center, the wall becomes increasingly exposed and the facula grows in apparent brightness until it reaches a maximum. At this point, the bottom of the evacuated tube is obscured by the wall closer to disk center, and the maximum wall becomes exposed. As the facula moves towards the limb, more of the hot walls become less visible and the facular element appears fainter. Finally, the hot wall is completely obscured and the facular element vanishes at the limb itself. Thus, this model predicts an increase in the CLV of the facular contrast, a peak at around $\mu \leq 0.20$ (Spruit 1976), and then a decrease.

The hot cloud model is characterized by facular-emitting material which protrudes above the surrounding photosphere. This could mean that faculae are composed of raised photospheric material, as in the hillock-and-cloud model of Schatten et al. (1986), or it could indicate hot, optically thin material suspended above the opening of a facular flux tube. Such faculae would not vanish at the limb, but would still display excess emission there. Therefore, maximum measured contrasts in the hot cloud case will occur closer to the limb than in the case of hot wall faculae. Nowadays, observations of the CLV of the facular contrast favour the hot wall model over the hot cloud model (Topka et al. 1997; Sánchez Cuberes et al. 2002).

1.4 Motivation of the thesis

In this introduction we have presented the general scenario and the most relevant open questions concerning solar irradiance variations induced by magnetic activity −specifically those produced by magnetic features that make a positive contribution to irradiance variations. Summing up, we know that solar irradiance variations contain clues to the enigmatic solar magnetic cycle and to its potential impact on the Earth's climate. These variations are not fully understood, especially on the solar

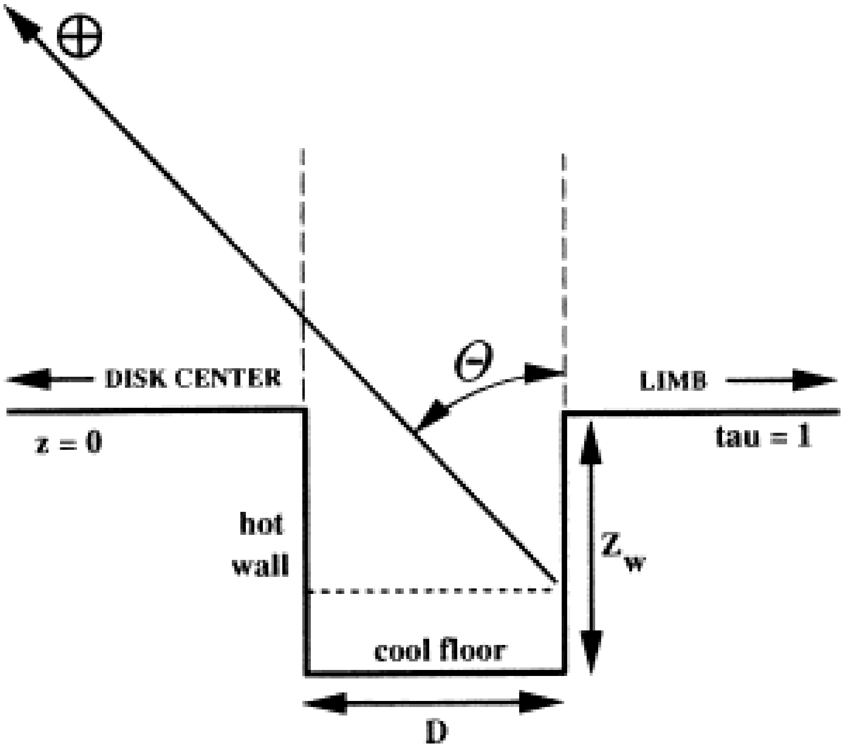

Figure 1.4: Geometry of a thin flux tube in the hot wall model. D is the tube diameter, Z_W is the Wilson depression, and θ is the heliocentric angle, the angle between the local vertical and the line of sight. From Topka et al. (1997).

cycle time scale. One of the most controversial aspects is the long-term contribution of the small magnetic elements conforming AR faculae and the enhanced and quiet network. Their identification and contrast measurement is difficult and, furthermore, in order to determine their contribution, it is necessary to understand their contrast center-to-limb variation. But this CLV remains poorly defined, and is thus an important source of uncertainties in any estimation of the facular contribution to irradiance variations.

The aim of this study is to analyze in detail the contrast of small photospheric magnetic elements and their contribution to solar variability both on short (solar rotation) and long (solar cycle) time scales. Specifically, we have focused on the contrast dependence of faculae and network on heliocentric angle and magnetic field. The study of the contrast of these features is useful because it is necessary to:

- improve the reconstructions of solar irradiance variations, taking into account that AR faculae and network may contribute rather differently,
- estimate the facular contribution to AR energy budget,
- test the existing flux tube models and put some constraints on them, since the nature of the CLV of the contrast is driven by the tube properties,
- remove its uncertainties, a challenge *per se*.

Previous measurements of this kind were essentially photometric studies, and none of them distinguished these features by magnetic flux (see for example, Libbrecht & Kuhn 1984; Lawrence 1988; Lawrence & Chapman 1988; Steinegger et al. 1996). As far as we know, there are a few works that include the magnetogram signal (e.g., Frazier 1971; Foukal & Fowler 1984; Topka et al. 1992, 1997; Lawrence et al. 1993), and they always refer to isolated or single events.

SOHO, launched in 1995 and still operational, provides a unique occasion for studying the Sun continuously and under stable conditions. Defined as the "watchdog" of the Sun, SOHO is a powerful tool to study the variations of the solar constant on many timescales. In fact, thanks to its state-of-the-art instruments we have been able to produce high-quality measurements of the contrast. The main advantages of our data sets are the lack of seeing effects due to the Earth's atmosphere, and their continuity and homogeneity which lasts for at least seven years. The work presented in this thesis is exclusively based on data provided by the SOHO spacecraft, specifically by the MDI and VIRGO instruments. The lower resolution of MDI ($4''$) in full disk mode does not allow high resolution observations as some ground-based instruments do, but the quality, continuity, stability and extension of the data gathered compensate for that, and these characteristics are of great importance for the type of analysis we are going to perform in this work (for example, we have sampled a large number of AR's spread throughout the whole solar disk, during the rising phase of cycle 23).

In this thesis, we attempt to answer some of the questions listed in the former paragraphs. We study the photospheric magnetic features in both the short and long time scales, and associate the evolution of the excess radiance of an isolated AR to changes in its spatial extent and aging. We analyze the contrast of AR faculae and the network in order to clarify whether or not their CLV's are different, and whether their contribution to irradiance variations is significant (especially on the solar cycle time scale). Taking advantage of SOHO, we combine simultaneous photometric and magnetograph data for the whole solar disk, during a period of six years (1996-2001), coinciding with the rising phase of solar cycle 23. We will try to obtain a 2-dimensional analytical contrast function that describes the contrast dependence both on position and spatially averaged magnetic field strength; to our knowledge, no similar determination has been done before.

Chapter 2 of this thesis describes the instruments on board the SOHO spacecraft of direct interest for our work, as well as the data sets used and analysis procedures used to correct data from instrument-related effects. In Chapter 3 we analyze the contribution to irradiance variations on the short time scale of an isolated active region, as a particular case. Chapter 4 analyzes in detail the intensity contrast of AR faculae and network as a function of position and magnetic field strength. In Chapter 5 we extend the analysis performed in Chapter 4 to the rising phase of solar cycle 23 in order to inspect long-term variations. Finally, Chapter 6 states the conclusions of this thesis and previews future work that would complete the task presented here.