THE SUN AND SPACE WEATHER

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THE SUN AND SPACE WEATHER

Second Edition

by

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Special thanks to my wife Caroline and my children Roland, Christina and Alina; I was allowed to spend lots of nights at the PC.
Thanks for the patience of my collaborators.

Contents

Preface

The field of solar physics and solar--terrestrial relation, now called space weather, is evolving rapidly. As in the first edition, it is assumed that it is inevitable for the reader to get some basic knowledge in solar physics since the Sun is the main driver for space weather The term *space weather* itself has been gaining more and more attention during the past years as our society becomes more and more dependent on satellites, which are vulnerable to varying conditions in space. Space weather efforts and investigations are being made all over the world and more and more is known about the complex relations of processes on the Sun and the Earth and its space environment. The term *space climate* nowadays includes the long-term variations caused mainly by the Sun on the Earth and the interplanetary space.

As in the first edition of the book, this edition also covers these topics but new chapters have been introduced, e.g., a chapter on real-time space weather forecasts and some main space weather data sources. All the chapters have updated information, taking into account the results of new satellite missions and telescopes. The book also includes a great amount of new literature (more than 340 original citations) so that the reader is able to go into more details, if required in the respective chapters. Thus, the book should be helpful to scientists as well as to students interested in overview or finding a compendium with references to go deeper into special fields.

Furthermore, at the beginning of all the chapters, introductory books are cited, which could be recommended for the special topics addressed there. The number of keywords in the index has also been strongly enhanced so that the reader can find information easily. Besides all this, suggestions from readers of the first edition have been taken into account and are greatly acknowledged.

I want to thank all my colleagues who provided me with advice and figures and the students who attended my lectures at Graz and Innsbruck for their help. Last but not least I thank my family – Karoline, Roland, Christina and Alina – for the patience and understanding when I spent lots of nights at the computer.

Chapter 1

Introduction, What is Space Weather?

In this introduction we briefly describe the term space weather and give motivation why that interdisciplinary field gained high interest. Examples will demonstrate the high relevance of space weather not only from the scientific point of view but from the social and economic aspect of our modern civilization.

Since this is a very modern topic, there appeared several monographs about that subject, e.g. a collection of space weather related topics[1].

1.1 Definition of Space Weather

Modern society becomes strongly reliant to technologically advanced systems, often located in space such as telecommunication, navigation. Therefore, the conditions and variations in space where these satellites orbit the Earth are important to study and the question arises wether there are influences on such systems or not. We speak of geomagnetic disturbances in this connection. Systems that are susceptible to geomagnetic disturbances are satellites and power grids on Earth. That means that the geomagnetic environment is changed, but as we will see in the later chapters, these disturbances are triggered by our nearest star, the Sun.

It is generally accepted that the term *space weather* refers to the time-variable conditions in the space environment that may effect space-borne or ground based technological systems.

According to the US National Space Weather Programme the definition is: *conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.*

Thus we see that the definitions are slightly different but we want to keep the first one because it also includes other effects apart from the Sun.

[1] see e.g. P. Song, Howard J. Singer, George L. Siscoe, Paul Song, Space Weather, 2001, Am. Geophys. Union

Since we strongly depend on satellite systems and their availability, it is crucial that these systems are in full operation. Moreover, in the worst case, human health or life can also be endangered by space weather. Therefore, there are social and economic aspects of this type of research: one tries to avoid consequences of space weather events by system design or efficient warning and prediction. During the last few years space weather activities have expanded world-wide. Examples for such activities which of course are of national and international interest are:

- US Space Weather Program,
- US-NASA's Living With a Star program,
- ESA's space weather program,
- SWENET, Space Weather European Network,
- SIDC, Solar influences data center at the Royal observatory in Belgium,
- Lund space weather center,
- The Australian IPS Radio and Space Services , the Australian Space Weather Agency,
- The Canadian Space weather program,

and many others (such as the Group in Oulu, Finland). Today, space weather is monitored from a worldwide net of ground stations and from space. Both types of observations are complementary. From space the whole electromagnetic spectrum of the Sun can be observed including UV and X-rays.

An overview about space weather, environment and societies can be found in the monograph by Lilenstein and Bornarel, 2005 [196].

1.2 The Triggers of Space Weather

The main cause for space weather effects is our Sun. It emits light at all wavelengths that reaches the Earth within about 8 minutes as well as a continuous stream of particles which is called the solar wind. During one solar activity cycle which has a period of about 11 years both radiation and solar wind are modulated. The energy of the Sun drives temperature, precipitation, atmospheric circulation, ocean currents, evaporation and cloud cover. The short wavelength radiation (UV, X-rays) triggers many chemical reactions in the upper atmosphere of the Earth and also the ozone level is modulated by solar activity. It was R.C. Carrington who observed on September 1, 1859 a white light flare[2] that erupted from a group of sunspots and in the following night a great aurora was seen down to low geographic latitudes, even from Cuba. On the same night, a great magnetic disturbance was also recorded. For the first time it was recognized correctly, that a change on the Sun might have directly influenced the environment around the Earth.

[2] The observations were reported to the Royal Astronomical Society

The NASA's Sun-Earth Connections program aims to improve our understanding of solar variability and how this transforms into interplanetary space, how e.g. eruptive events on the Sun (like CMEs, Coronal mass ejections) impact geospace, weather and climate. In the long term NASA plans manned missions to the Moon and even Mars and the need of spaceweather forecasts becomes evident.

A software package called CACTUS, Computer Aided CME tracking detects automatically CME events that could be dangerous by scanning through images produced by the SOHO/LASCO satellite [3].

Related to the solar activity are important effects on spacecraft such as spacecraft charging (surface charging and deep discharges) and single event upsets. The effects on humans in space are also to be considered (radiation, particles). Space weather effects also play a rôle on high altitude/high latitude air-flight; cosmic rays penetrate to the lower atmosphere and pose problems to humans and electronic components of modern aeroplanes. Other influences of space weather include radio wave propagation, satellite-ground communications, global satellite-based navigation systems, power transmission systems etc. Changes of the solar irradiance may be one of the causes for climatic changes on the Earth.

Materials located on the exterior of spacecraft in low Earth orbit are subjected to a number of environmental threats, including atomic oxygen, ultraviolet radiation, thermal cycling, and micrometeorid and debris impact. The number of space debris now clearly exceeds the number of meteroids[4].

A compendium of space weather related scientific papers can be found in the book of Scherer, Fichtner and Heber[5]. A book on Solar And Space Weather Radiophysics appeared recently[6].

1.2.1 Examples

Let us give some examples of space weather influences on satellites[7]

- Space Shuttle: numerous micrometeroid/debris impacts have been reported.
- Ulysses: failed during peak of Perseid meteoroid shower.
- Pioneer Venus: Several command memory anomalies related during high-energy cosmic rays.
- GPS: photochemically deposited contamination on solar arrays.

On the Earth we know very well radio fadeouts. The HF communication depends on the reflection of signals in the upper Earth's atmosphere. This layers are strongly influenced by the Sun's shortwave radiation.

[3] see http://sidc.oma.be/products/cactus/index.php

[4] The term meteorite denotes the piece that was fallen to the surface of the Earth

[5] see: Scherer, Fichtner and Heber (Eds.), Space Weather - The Physics behind a Slogan, Lect. Notes in Phys., Springer, 2004

[6] see: Solar And Space Weather Radiophysics: Current Status And Future Developments, D. E. Gray and Ch. U. Keller, ASSL, 2005, Kluwer

[7] see also: The Space Environment, A. C. Tribble, Princeton Univ. Press, 2003

How can we study the propagation of solar disturbances through the interplanetary medium from Earth? A common technique is to measure scintillations in the radio wavelength. Let us consider very distant radio sources like quasars. If the interplanetary medium is not disturbed, the signal from this object is constant in amplitude. But similar to the twinkling of starlight in the visible, the radio signal becomes absorbed and refracted when passing through a plasma cloud emitted from the Sun. By measuring many point sources distributed all over the sky, one gets a map of areas of high scintillation which shows where the plasma wave is propagating.

There are similarities with atmospheric weather, however the most important differences between atmospheric and space weather systems are:

- Meteorological processes are localized; it is possible to make good local weather forecasts. Spaceweather is always global in the planetary scale.
- Space weather events occur over a wide range of time scales: the Earth's magnetosphere responds to solar-originated disturbances within only a few minutes, global reconfiguration occurs within some 10 minutes. Enhanced fluxes of energetic particles in radiation belts decay in time scales of days, months or even longer.
- Spaceweather predictions must rely on the input of just a few isolated measurements of the solar wind and the observations (both ground based and from space) have only a global character sometimes without details.

Therefore, successful space weather activities aiming to make prediction of dangerous events need to be performed on a global scale. Space-borne and ground based observations are complementary.

1.3 Who are the Users of Space Weather?

Presently, the most important users of space weather research are spacecraft engineering, spacecraft operations, RF communications. Spacecraft launchers can make use of exact knowledge of space weather conditions and the re-entry of spacecrafts depends on the atmospheric drag conditions. When the International Space Station, ISS, is in operation, forecasts will become even more important. Other users are telecommunication operators, users of global positioning systems, electric power industry etc. Commercial airlines must be careful with the radiation doses to their crews and passengers.

In 1989 (March 13th) solar activity induced a huge geomagnetic storm causing a saturation in the transformers and the power grid servicing Canada's Quebec province was completely shut down. The blackout resulted in a loss of 19 400 MW in Quebec and 1325 MW of exports. Service restoration took over 9 hours (after R. Thompson, IPS, Radio and Space Service).

Long term variations of space weather are also called space climate . We know that there were periods of reduced solar activity during the past 1000 years (called Spörer Minimum, Maunder Minimum and Dalton Minimum). Though also other influences such as the eruption of big volcanoes played a role, it is assumed that during these phases the global climate on Earth was cooler than on the average.

Summarizing, the following branches strongly depend on space weather:

- Spacecraft & Aircraft,
- Communication Systems,
- Power Distribution Networks and Pipelines,
- Oil and mineral Prospecting,
- Risks to human health,
- Space weather influence on climate change,
- Insuring against space weather effects.

The effects of space weather on technology infrastructure were discussed in the monograph of Daglis[8].

1.4 Organization of the Book

The book is organized as follows. First we want to give a brief review about the main source of space weather effects, our Sun. The basic physics of the Sun will be discussed since it is essential to understand the mechanisms that cause solar variability. This is necessary in order to make prediction models for space weather forecasts. Then we will speak about the influence of solar variability on the Earth's atmosphere. The last chapters deal about other than solar influences on the conditions in space such as meteoroids, space debris.

The field of space weather and solar physics itself as well as dynamics of space is rapidly evolving. In this second edition new material was included. Additionally, to each chapter recommended textbook references are given. Suggestions from readers of the first edition have been taken into account and are greatly acknowledged.

[8]see: I.A. Daglis, Effects of Space Weather on Technology Infrastructure, 2004, Kluwer

Chapter 2

The Sun a Typical Star

Our Sun is the only star which is close enough to observe details on its surface such as sunspots, faculae, prominences, coronal holes, flares etc., which are all summarized as solar activity phenomena. Therefore, the study of the Sun is important for astrophysics in general. Theories about stellar structure and evolution can be studied in detail on the Sun[1].

On the other hand, the Sun is the driving factor for the climate on the Earth and the structure and shape of the Earth's magnetosphere thus determining and influencing the near Earth space environment. Therefore, the study of solar terrestrial relations is of great importance for our modern telecommunication systems both based on Earth and in space.

2.1 The Sun and Stars

2.1.1 Location of the Sun

More than 99% of the mass of the solar system, to which the Sun, 8 great planets, dwarf planets (such as Pluto) satellites of planets, asteroids, etc. belong, is concentrated in the Sun. The Sun is the nearest star to us and our solar system is located in the Milky Way Galaxy. Our galaxy contains more than 2×10^{11} solar masses (i.e. at least as many stars). The mass of the galaxy can be inferred from the rotation of the system. All stars rotate about the center of the galaxy which is at a distance of about 27 000 light years (Ly) to us [2].

At the location of the Sun in the galaxy, one period of revolution about the galactic center is about 200 Million years. Galaxies in general contain some 10^{11} stars. About 50% of the stars have one or more stellar companions. Up to now more than 150 planetary companions were detected around nearby stars, so called

[1] For textbooks see e.g. Zirin, H., 1988, Astrophysics of the Sun, Cambridge University Press; The Cambridge Encyclopedia of the Sun, K.R. Lang, 2001, Cambridge Univ. Press; A Guide to the Sun, K.H. Phillips, 1995, Cambridge Univ. Press; The Sun, M. Stix, 2002, Springer Verlag

[2] 1 Ly $=10^{13}$ km, the distance light travels within one year propagating through space at a speed of 300 000 km/s

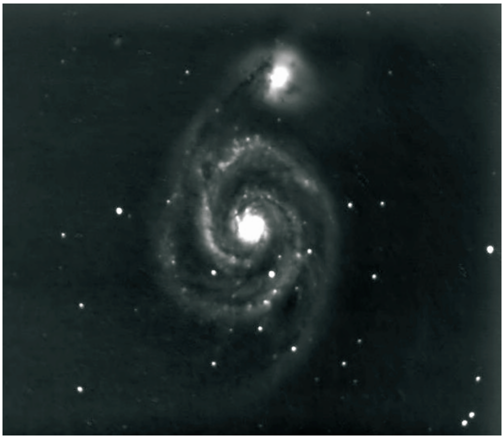

Figure 2.1: A typical spiral galaxy. From a distant galaxy, the Sun would be located in one of the spiral arms. Image: A.H., private observatory.

extrasolar planets. The diameter of our galaxy is about 100 000 Ly. Galaxies are grouped into clusters- our galaxy belongs to the so called local group of galaxies. The small and large Magellanic cloud are two small dwarf galaxies which are satellites of our system. The nearest large galaxy is the Andromeda galaxy which is at a distance of more than 2 Million Ly.

Many galaxies appear as spiral galaxies. Young bright stars are found in the spiral arms, older stars in the center and in the halo of the galaxy. An example is given in Fig.2.1.

2.1.2 Properties of Stars

The only information we can directly obtain from a star is its radiation and position. In order to understand the physics of stellar structure, stellar birth and evolution we have to derive quantities such as stellar radii, stellar masses, composition, rotation, magnetic fields etc. We will just very briefly discuss how these parameters can be derived for stars.

- Stellar distances: a fundamental but not an intrinsic parameter. Stellar distances can be measured by determining their parallax, that is the angle the Earth's orbit would have seen from a star. This defines the astrophysical distance unit *parsec*. A star is at a distance of 1 parsec if the parallax is $1''$. 1 pc = 3.26 Ly.

- Stellar radii: once the apparent diameter of a star is known than its real diameter follows from its distance d. The problem is to measure apparent stellar diameters since they are extremely small. One method is to use interferometers, one other method is to use occultation of stars by the moon or mutual occultations of stars in eclipsing binary systems. All these methods are described in ordinary textbooks about astronomy.

- Stellar masses: can be determined by using Kepler's third law in the case we observe a binary system. Stellar masses are very critical for stellar evolution, however we know accurate masses only for some 100 stars.

- Once mass and radius are known, the density and the gravitational acceleration follow. These parameters are important for the stellar structure.

- Stellar rotation: For simplicity we can assume that a star consists of two halves, one half approaches to the observer and the spectral lines from that region are blueshifted, the other half moves away and the spectral lines from that area are redshifted. The line profile we observe in a spectrum is a superposition of all these blue- and redshifted profiles and rotation causes a broadening of spectral lines;

- Stellar magnetic fields: as it will be discussed in more detail when considering the Sun, magnetically sensitive spectral lines are split into several components under the presence of strong magnetic fields.

2.1.3 Stellar Spectra, the Hertzsprung-Russell-Diagram

The analysis of stellar radiation is fundamental for the derivation of physical quantities describing a star. Putting a prism or a grating inside or in front of a telescope, we obtain a spectrum of a star. Such a spectrum contains many lines, most of them are dark absorption lines. Each chemical element has a characteristic spectrum.

In the Hertzsprung Russell Diagram (HRD) the temperature of stars is plotted versus brightness. The temperature of a star is related to its color: blue stars are hotter than red stars. In the HRD the hottest stars are on the left side. The temperature increases from right to left. Stellar brightness is given in *magnitudes*. The magnitude scale of stars was chosen such that a difference of 5 magnitudes corresponds to a factor of a 100 in brightness. The smaller the number (which can be even negative) the brighter the star. The brightest planet Venus e.g. has magnitude $-4.^{\mathrm{m}}5$ and the Sun has $-26.^{\mathrm{m}}5$. The faintest stars that are visible to the naked eye have magnitude $+6.^{\mathrm{m}}0$. Since the apparent magnitudes depend on the intrinsic luminosity and the distance of a star absolute magnitudes were invented: the absolute magnitude of a star (designated by $^{\mathrm{M}}$) is the magnitude a star would have at a distance of 10 pc. In the HRD we can plot absolute magnitudes as ordinates instead of luminosities. The relation between m and M is given by:

$$m - M = 5 \log r - 5 \tag{2.1}$$

r is the distance of the object in pc. The Sun has $M = +4.^{\mathrm{M}}5$; seen from a distance of 10 pc it would be among the fainter stars visible with the naked eye.

How can we determine stellar temperatures? Stars can be considered to a very good approximation as *black body* radiators. A black body is a theoretical

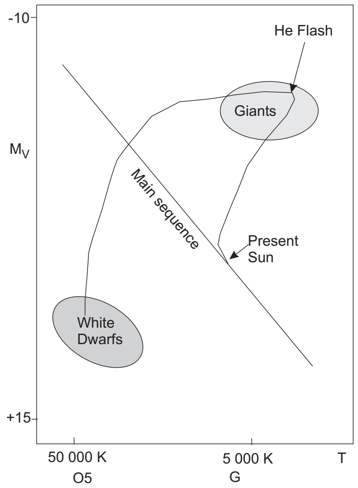

Figure 2.2: Sketch of the Hertzsprung-Russell-diagram with evolutionary path of the Sun.

idealization: an object that absorbs completely all radiation at all wavelengths. The radiation of a black body at a given temperature is given by the *Planck law*:

$$I_\nu = B_\nu = (2h\nu^3/c^2)/\exp(h\nu/kT_\mathrm{S}) - 1 \tag{2.2}$$

thus it depends only on the temperature T_S of the object. Here, I_ν is the intensity of radiation at frequency ν; h, k, c are Planck's constant, Boltzmann's constant and the speed of light. $h = 6.62 \times 10^{-34}$ Js^{-1}, $k = 1.38 \times 10^{-23}$ JK^{-1}. If that equation is integrated over all frequencies (wavelengths), we obtain a formula for the total power emitted by a black body, Boltzmann law:

$$\int_0^\infty B_\lambda d\lambda = \sigma T^4, \tag{2.3}$$

and for the luminosity of a star:

$$L = 4\pi r^2 \sigma T_\mathrm{eff}^4 \tag{2.4}$$

For the Sun $T_\mathrm{eff} = 5\,785\,\mathrm{K}$. This formula defines the effective temperature of a star. $\sigma = 5.67 \times 10^{-8}\,\mathrm{W/m^2K^4}$ is the Stefan Boltzmann constant.

What is the power emitted per unit area of the Sun's surface? Answer: Put T = 6 000 K we find that the Sun radiates 70 MW per m^2 of its surface[3]

[3]The worldwide nuclear energy generation is about 350 GW. Thus an area of 5000 m^2 on the Sun generates this amount.

Table 2.1: Central wavelength and bandwidth of the UBVRI filter set

Name	Meaning	Central λ	Bandwidth [nm]
U	Ultraviolet	360	66
B	Blue	440	98
V	Visual (green)	550	87
R	Red	700	207
I	Infrared	900	231

By taking the derivative with respect to λ of Planck's Law and setting it equal to zero, one can find the peak wavelength, where the intensity is at maximum:

$$T\lambda_{\max} = 2.9 \times 10^{-3}\,\mathrm{m\,K} \tag{2.5}$$

This is also called *Wien's law.*

At about which wavelength can planets be expected to radiate most of their energy? Answer: Let us assume the temperature of the Earth = 300 K. Then

$$\lambda_{\max} = 2.9 \times 10^{-3}/300 \sim 10\,\mu \tag{2.6}$$

The Sun has a surface temperature of about 6 000 K. At what wavelength does the Sun's spectrum peak? Answer:

$$\lambda_{\max} = 2.9 \times 10^{-3}/6000 \sim 0.5\,\mu = 500\,\mathrm{nm} \tag{2.7}$$

From the spectrum stellar temperatures can be obtained. The temperature derived from the peak wavelength is called Wien Temperature, the temperature derived from the difference of intensity between two wavelengths (=color) Color temperature etc. In order to define color, a filter system must be defined. The most commonly used system is the UBV system which has three bands that are located in the UV (U), blue (B) and visual (V) to measure the intensity I_ν. The luminosity of stars is given in magnitudes which are defined as follows:

$$\text{Magnitude} = \text{const} - 2.5\log(\text{Intensity}) \tag{2.8}$$

The color of a star is measured by comparing its magnitude through one filter (e.g. red) with its magnitude through another (e.g. blue).

E.g. m_V means the magnitude measured with the V filter. Therefore, instead of determining temperatures from the comparison of the spectrum of a star with the Planck law, one can use e.g. color indices. If we calculate B-V, than this value will be (see e.g. table 2.2):

- positive for the cooler star, since it is brighter in V than in B (blue). If the cool star is brighter in V it means that its magnitude has a lower value and therefore B-V is positive.

Table 2.2: B-V colors and effective temperatures of some stars

Star	B-V	Effective T
Sun	+0.6	5 800 K
Vega	0.0	10 000 K
Spica	-0.2	23 000 K
Antares	+1.8	3 400K

- negative for the hotter star. The hotter star is brighter in B than in V, therefore for the magnitudes in these two bands: $m_B < m_V$ and B-V<0.

2.1.4 Stellar Evolution

Stars are not randomly distributed in the HRD:

- Main sequence stars: most stars are found along a diagonal from the upper left (hot) to the lower right (cool).
- Giants, supergiants: they have the same temperature as the corresponding main sequence stars but are much brighter and must have larger diameters (see equation 2.4).
- White dwarfs are faint but very hot objects thus from their location at the lower left in the HRD it follows that they must be very compact (about 1/100 the size of the Sun).

This leads to the question why most of the stars we observe lie on the Main sequence. The answer is quite easy: because this denotes the longest phase in stellar evolution. Let us discuss this briefly for the Sun:

The main steps in the evolution of the Sun are (compare with Fig. 2.2):

- Pre main sequence evolution: from a protostellar gas and dust cloud the Sun was formed and before it reaches the main sequence where it spends most of its life, the contracting Sun has passed a violent youth, the T Tauri phase.
- At the main sequence the Sun changes extremely slowly remaining there about 10^{10} years. In the core H is transformed to He by nuclear fusion.
- The Sun evolves to a red giant, it will expand and the Earth will become part of the solar atmosphere. The expansion starts when all H is transformed to He in the core. Then a H burning shell supplies the energy. The He flash sets in as soon as in the center He burning sets in. The Sun will evolve to a red giant for some 10^8 ys. It will extend beyond the Earth's orbit.
- Finally, the Sun becomes a white dwarf which slowly cools.

Table 2.3: Spectral classification of stars

O	ionized He, ionized metals
B	neutral He, H stronger
A	Balmer lines of H dominate
F	H becomes weaker, neutral and singly ionized metals
G	singly ionized Ca, H weaker, neutral metals
K	neutral metals molecular bands appear
M	TiO, neutral metals
R,N	CN, CH, neutral metals
S	Zirconium oxide, neutral metals

Table 2.4: Effective Temperature as a function of spectral type

Spectral Type	O	B0	A0	F0	G0	K0	M0	M5
T_{eff} [K]	50 000	25 000	11 000	7 600	6 000	5 100	3 600	3 000

During its evolution, the Sun dramatically changes its radius (the subscript $\odot$ denotes the present day value):

1 $R_\odot$ (present Sun) $\rightarrow \sim 10^4\,R_\odot$ (red giant), $\rightarrow 0.01R_\odot$ (white dwarf).

For space weather long term evolutionary effects are negligible. But it is interesting to investigate them especially for the early Sun (see the chapter on the faint young Sun problem).

For the main sequence stars there exists a relation between their mass and luminosity:

$$L \sim M^{3.5} \tag{2.9}$$

From 2.9 we see that more massive stars are very luminous and therefore they use up their nuclear fuel much more rapidly than low massive stars like our Sun. Massive main sequence stars that are observed today must have been formed in very recent astronomical history[4].

2.1.5 Spectral Classes

According to their spectra, stars can be classified in the following sequence: O-B-A-F-G-K-M. This is a sequence of temperature (see Table 2.4): O stars are hottest, M stars coolest; the number of absorption lines increase from O to M. Some characteristics are given in Table 2.3.

The luminosity of a star depends on a) temperature $\sim T^4$, b) surface which is $\sim R^2$. Since e. g. a K star may be a dwarf main sequence star or a giant, luminosity classes have been introduced. Class I contains the most luminous supergiants, class II the less luminous supergiants. Class III are the normal giants, class IV the sub giants and class V the main sequence.

[4]In some large interstellar nebulae one observes stars that have an age of some 10^5 years

Now we understand the spectral classification of our Sun: it is a G2V star.

2.2 The Sun

2.2.1 Basic Properties

As it has been mentioned, the Sun is a G2V star in the disk of our Galaxy. The mass of the Sun is:

$$M_\odot = 1.99 \times 10^{30}\,\mathrm{kg} \tag{2.10}$$

An application of Kepler's third law gives us the mass of the Sun if its distance is known which again can be derived from Kepler's third law:

$$\frac{a^3}{P^2} = \frac{G}{4\pi^2}(M_1 + M_2) \tag{2.11}$$

In our case a denotes the distance Earth-Sun (150×10^6 km), P the revolution period of the Earth around the Sun (1 year), M_1 the mass of the Earth and M_2 the mass of the Sun. One can make the assumption that $M_1 << M_2$ and therefore $M_1 + M_2 \sim M_2$.

If we know the distance of the Sun and its angular diameter the solar radius is obtained:

$$r_\odot = 6.96 \times 10^8\,\mathrm{m} \tag{2.12}$$

The measurement of the Sun's angular diameter is not trivial; one possibility is to define the angular distance between the inflection points of the intensity profiles at two opposite limbs. Such profiles can be obtained photoelectrically and the apparent semi diameter at mean solar distance is about 960 seconds of arc ($''$). The orbit of the Earth is elliptical and at present, perihelion (smallest distance of the Sun) is in January.

Knowing the mass and radius of the Sun, the mean density can be calculated:

$$\bar{\rho} = 1.4\,\mathrm{g/cm^3} \tag{2.13}$$

The gravitational acceleration is given by:

$$g = GM/R^2 = 274\,\mathrm{m/s^2} \tag{2.14}$$

The *solar constant* is the energy crossing unit area of the Earth's surface perpendicular to the direction from the Earth to the Sun in every second. In SI the units are $\mathrm{W\,m^{-2}}$. UV and IR radiation from the Sun is strongly absorbed by the Earth's atmosphere. Therefore, accurate measurements of the solar constant have to be done with satellites. ACRIM on SMM and ERB on Nimbus 7 showed clearly that the presence of several large sunspots which are cooler than their surroundings depress the solar luminosity by $\sim 0.1\%$. The Variability IRradiance Gravity Oscillation (VIRGO) experiment on the SOHO satellite is observing total solar and spectral irradiances at 402 nm (blue channel), 500 nm (green channel), and

862 nm (red channel) since January 1996 (for a review see e.g. Pap *et al.* (1999) [243]). The solar luminosity is:

$$L_\odot = 3.83 \times 10^{26}\,\mathrm{W} \tag{2.15}$$

And the effective temperature:

$$T_{\mathrm{eff}\odot} = 5780\,\mathrm{K} \tag{2.16}$$

2.2.2 Basic Equations

How a ball of gas and plasma, like a star remains stable against gravitational collapse or free expansion? Let us assume a sphere of mass M and radius R. In most cases there are only two forces:

- gravity: acts inward
- pressure: acts outward

Let us consider a shell inside a star, the lower boundary is at r from the center and the upper at $r + \Delta r$. ΔA is a surface element and P_{outer}, P_{inner} denote the pressure at r and $r + \Delta r$. The net force on such a shell is:

$$F_{\mathrm{net}} = F_{\mathrm{grav}} - F_p \tag{2.17}$$

and $F_p = (P_{\mathrm{outer}} - P_{\mathrm{inner}})\Delta A$. From the above equation:

$$F_p = [P(r) + (dP/dr)\Delta r - P(r)]\Delta A = (dP/dr)\Delta r \Delta A \tag{2.18}$$

By dividing the net force F_{net} by $-\Delta m = -\rho(r)\Delta r \Delta A$, we find the equation of motion of the shell:

$$-\mathrm{d}^2 r/\mathrm{d}t^2 = g(r) + [1/\rho(r)](\mathrm{d}P/\mathrm{d}r) \tag{2.19}$$

If the acceleration is set to zero (when there is a balance), then the *hydrostatic equilibrium* becomes:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM(r)\rho(r)}{r^2} \tag{2.20}$$

Therefore, the pressure at depth h must be high enough to support the weight of the fluid per unit area above that depth. Let us derive an estimate for the central pressure of a star. The pressure is given by:

$$P = g\rho h \tag{2.21}$$

At the center $h = R$; from $g = GM/R^2$ we find the central pressure P_c:

$$P_c = \frac{GM\rho}{R} \qquad \rho = \frac{M}{4\pi R^3/3} \tag{2.22}$$

which leads to:

$$P_c = \frac{3}{4\pi}\frac{GM^2}{R^4} \tag{2.23}$$

For the Sun: $M_\odot = 2\times10^{30}$ kg, and $R_\odot = 7\times10^8$ m. This gives $P_c = 3\times10^{14}\,\mathrm{Nm}^{-2}$ compared to the atmospheric pressure at sea level on Earth of $10^5\,\mathrm{Nm}^{-2}$. This is a very crude approximation, since in reality the density increases with depth and the true central pressure of the Sun is 100 times larger than the estimate.

What happens if a star contracts (which will be the case when the hydrostatic equilibrium condition is not established)? According to the *Virial Theorem* half of the gravitational energy which is set free is radiated away and the other half heats the star.

In most phases of stellar evolution, the structure of a star can be determined by the solution of four first order differential equations:

- hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2} \tag{2.24}$$

- mass continuity

$$\frac{dM}{dr} = 4\pi r^2\rho \tag{2.25}$$

- gradient of luminosity

$$\frac{dL}{dr} = 4\pi r^2\rho\epsilon \tag{2.26}$$

- temperature gradient

$$\frac{dT}{dr} = -\frac{3\kappa L\rho}{16\pi acr^2T^3} \tag{2.27}$$

In these equations r is the distance from the stellar center, P, ρ, T are the pressure, density and temperature at radius r, M is the mass contained within r, L the energy carried by radiation across r, ϵ the nuclear energy release. The quantities P, ϵ, κ depend on density, temperature and composition. κ is the *opacity* and measures the resistance of the material to energy transport.

2.2.3 Energy Generation in the Sun

In principle, a variety of different energy generating processes can take place in stars. During the formation and contraction of a protostar in an interstellar cloud no nuclear reactions take place and half of the released gravitational energy is radiated away, the other half increases the temperature of the core (Virial Theorem). As soon as the central temperature exceeds about 10^6 K nuclear reactions start. Energy is generated by the fusion of two lighter particles to form a heavier particle whose mass is smaller than the mass of its constituents, the mass defect being transformed into energy according to $E = \Delta M c^2$.

Let us consider the fusion of H into He. The mass of 4 H is[5]:

[5] 1 AMU= 1/12 of the mass of the Carbon isotope ^{12}C $= 1.66\times10^{-27}$ kg $=$ 931MeV/c^2

Table 2.5: The principal reaction of the pp chain

Reaction Number	Reaction	Neutrino Energy (MeV)
1	$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$	0.0 to 0.4
2	$p + e^- + p \rightarrow {}^2\text{H} + \nu_e$	1.4
3	${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$	
4a	${}^3\text{He} +^3 \text{He} \rightarrow {}^4\text{He} + 2p$	
4b	${}^3\text{He} +^4 \text{He} \rightarrow {}^7\text{Be} + \gamma$	
5	$e^- + {}^7\text{Be} \rightarrow {}^7\text{Li} + \nu_e$	0.86, 0.38
6a	${}^7\text{Li} + p \rightarrow {}^4\text{He} +^4 \text{He}$	
6b	$p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma$	
7	${}^8\text{B} \rightarrow^8 \text{Be} + e^+ + \nu_e$	0...15

$$4 \times 1.008145\,\text{AMU} \tag{2.28}$$

The mass of the resulting He atom is

$$4.00387\,\text{AMU} \tag{2.29}$$

Thus the mass difference ΔM is

$$0.02871\,\text{AMU} \sim 4.768 \times 10^{-29}\,\text{g} \sim 4.288 \times 10^{-12}\,\text{J} \sim 26.72\,\text{MeV} \tag{2.30}$$

and 0,7% of the mass is converted to energy by Einstein's relation[6]

$$E = mc^2 \tag{2.31}$$

If one assumes that the Sun consists of pure hydrogen which is converted into He, then the total energy ($E = 0.007mc^2$) would be 1.27×10^{45} J. The luminosity of the Sun is $L_\odot = 3.8 \times 10^{26}$ J/s thus there would be energy supply for 10^{11} years.

The so called pp chain (Table 2.5) dominates in stars with relatively low central temperatures (between 5 and $15{\times}10^7$ K, like the Sun) and the CN cycle[7] is dominant in stars with higher central temperatures.

The energy production rate, ϵ, for the pp cycle depends highly on the temperature:

$$\epsilon \sim \rho T^5 \tag{2.32}$$

[6] 1 eV=1.6×10^{-19} J

[7] In the CN cycle C acts as a catalyst to convert H into He

2.2.4 Convection Zone

In the solar core nuclear fusion generates the energy which is transported outwards by radiation. At a depth of a third of the solar radius below the solar surface the convection zone starts, where energy is transported outwards by convective motions. This zone occupies only 2% of the solar mass. Hydrogen and He are practically neutral at the solar surface but they are ionized just below the surface. In these ionization zones the ratio of the specific heat at constant pressure (c_p) to the specific heat at constant volume (c_v) is much lower than the value 5/3. This value is appropriate either to a neutral gas or fully ionized gas. Because $c_p/c_v << 5/3$ convection occurs. For the temperature gradient we already have seen that:

$$\frac{dT}{dr} = -\frac{3\kappa L_{\mathrm{rad}}\rho}{16\pi acr^2T^3} \tag{2.33}$$

The total luminosity L is:

$$L = L_{\mathrm{rad}} + L_{\mathrm{conv}} \tag{2.34}$$

Basically, convection can be treated as an instability; if an element of material is displaced upwards, then it continues to rise if it is lighter than its surroundings. By assuming that the rising element moves sufficiently slowly that it is in pressure balance with its surroundings but that at the same time its motion is adiabatic (no heat exchange between the element and the surroundings), then convection occurs if:

$$\frac{P}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}P} < \left(\frac{P}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}P}\right)_{\mathrm{ad}} \tag{2.35}$$

If the stellar material is an ideal classical gas with constant ratio of specific heats γ, then:

$$\frac{P}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}P} < \frac{1}{\gamma} \tag{2.36}$$

The theory which is usually used contains a free parameter, the so called *mixing length* l:

$$l = \alpha H_{\mathrm{p}} = \alpha \left| P\frac{\mathrm{d}P}{\mathrm{d}r} \right| \tag{2.37}$$

where H_{P} is the pressure scale height. It is supposed that α is of order unity. As we will discuss later, information about the depth of the convection zone comes from a detailed study of solar oscillations. Apart from energy transport one has also to consider that in convection zones there is a uniform chemical composition. This prevents any attempt of heavy chemical elements to settle in the Sun's gravitational field.

2.2.5 Model: Internal Structure of the Sun

In this paragraph we give a table showing the variation of temperature, luminosity and fusion rate as a function of increasing distance from the solar center. Such a model can be calculated from the basic set of equations discussed above.

Table 2.6: Solar model: variation of temperature, luminosity and fusion rate throughout the Sun

Radius fraction in $R_\odot$	Radius $[10^9]$ m	Temperature $[10^6]$ K	% Luminosity	Fusion rate [J/kg s]
0	0.00	15.7	0	0.0175
0.09	0.06	13.8	33	0.010
0.12	0.08	12.8	55	.0068
0.14	0.10	11.3	79	.0033
0.19	0.13	10.1	91	.0016
0.22	0.15	9.0	97	0.0007
0.24	0.17	8.1	99	0.0003
0.29	0.20	7.1	100	0.00006
0.46	0.32	3.9	100	0
0.69	0.48	1.73	100	0
0.89	0.62	0.66	100	0

As it will be discussed later, the interior of the Sun can be investigated by the propagation of waves. Solar models computed with mass loss, microscopic diffusion of helium and heavy elements, and with updated physics have been evolved from the pre-main sequence to present day (Morel *et al.*, 1997 [225]); they are compared to the observational constraints including lithium depletion and to the seismic reference model derived by inversion. Microscopic diffusion significantly improves the agreement with the observed solar frequencies and agree with the seismic reference model within $\pm 0.2\%$ for the sound velocity and $\pm 1\%$ for the density, but slightly worsens the neutrino problem. A review on the current state of solar modeling was given by Christensen-Dalsgaard *et al.* (1996) [67] .

2.3 Observing the Sun

2.3.1 General Remarks

In this short chapter we want to give a few examples of modern solar telescopes. Some remarks are also made concerning optical design and features as well as disturbances caused by the Earth's atmosphere.

Earth-based telescopes must contend with image distortion and scintillation caused by atmospheric disturbances as light reaches us from outer space, stars twinkle, images blur and dance when viewed with telescopes or binoculars. This effect worsens as the zenith angle increases. Temperature changes and winds create variations in atmospheric refractive indices resulting in image distortions. This condition is called "seeing", and is a prime consideration in selecting the location of an observatory. Good sites for observatories are the Canary islands or Hawaii located at heights above the inversion. Thus clouds form deeper than the site of the telescope.