Preface

"Dazzling source of the light, of heat, of movement, of life and beauty, the divine Sun has, through the ages, welcomed the grateful and zealous tributes…". These few words from the French popularizer Camille Flammarion, taken from his famous book "Astronomie populaire" (1881), places this new book "Solar Astronomy" in a context that is still alive today, as evidenced by the tremendous popular enthusiasm for the "American" total eclipse of August 21, 2017. It is said 350 millions of people witnessed the phenomenon while merrily and often emotionally celebrating the return of the light of our marvelous day star – at least for the tens of millions amateurs who enjoyed the totality phase. They admired the silvery aureole of the solar corona with its spikes and polar plumes, as the Sun was near the minimum of its cycle. Tens of thousands amateurs, armed with telescopes and cameras pointing to the sky, offered a surrealist spectacle of a tribute to the big luminary. A modern vision of a cult devoted to the Sun, since Zarathustra, Akhenaton (see figure 1), Inti of the Incan and many others, for it drives everyday life, and ongoing study, for it still harbors mysteries and even secrets that would be exciting to disclose, since they could be vital to humanity.

The study of the Sun, which is the purpose of this book, is a true opportunity for the amateur astronomer. This is the star from which we receive, by day, a billion times more photons than received, by night, from all the other stars of the Universe. Even the light of the planets and of our celestial companion the Moon are from solar origin. One could think that the study of all this light would quickly allow us to solve the fundamental questions, but this would be without considering the specific types of studies of the unique star we are able to observe at a close distance: high resolution imaging allows to scrutinize in detail its surface; dispersing the spectrum of the light coming from different areas of its surface reveals the different layers of its atmosphere. Better still, the curves, swings and twists of gas flows imprint their signatures in the spectral lines of elements, such as hydrogen and helium, revealing important information about the solar atmosphere, or in the lines of less abundant metallic vapors, carrying even more information about the state of the plasma.

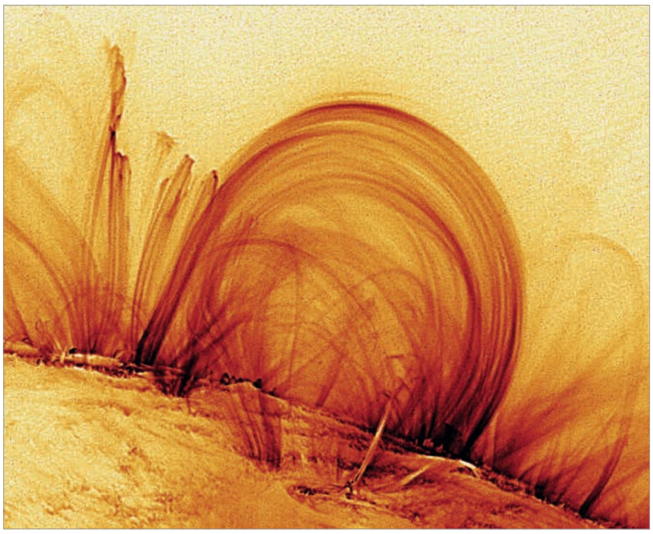
Finally, the activity of the Sun changes over longer periods of time, while its surface is variable over short periods of time. With the level of resolution that is reached today thanks to high frame-rate imaging, complex phenomena of differential rotation, convection, eruption, explosion and ejection can be observed by the amazed observer. As time goes by, he becomes eager to learn more, something that is possible nowadays given the panoply of the commercial instruments and cameras available. However, even if the Earth atmosphere protects us from the harmful radiations of the Sun, it sets a frustrating limitation on the quality of observations. Even at high altitude sites where less absorbent layers of air are found, the turbulence of the air remains significant, and extends up to very high altitudes in the stratosphere. The advanced observer will be able to partially or even substantially reduce its effects. This is a complete state-of-the-art skill that is developed inside this book, immersing us in the arcane of image processing, with an ever increasing computing capacity.

1 Bas-relief exhibited at the Cairo Museum, portraying the Akhenaton Pharaoh and its wife Nefertiti around 1350 BC. He was the one who enjoined his people to honor the solar disk as the sole divinity or as the universal god. At that time, the Sun was awarded with extended beneficial powers, symbolized there by the rays darting from the solar disk. Image: Cairo Museum.

Studying the Sun from space

The professional solar astrophysicists have found a workaround to this issue, thanks to the huge funds allocated to space conquest and its applications, not to mention the military defense whose systems are somewhat vulnerable to the whims and jolts of the Sun. After a few attempts with balloons and then with rockets, considerably more sophisticated solar experiments have been put in terrestrial orbit and even further away.

Towards the end of the seventies, a wonderful solar laboratory was operated for several years onboard Skylab (NASA) thanks to crews of well trained astronauts. Those observations opened new spectral windows towards the ultraviolet (UV), the X-rays, and as well towards the deep imagery of the solar corona, well beyond what was possible in terms of radial distance from the ground with the Lyot coronagraph. Breaking discoveries were immediately made, noticeably in the highest layers of the chromosphere. It was still the era of film photography, visual inspections (or almost), and single pixel electronic detectors or scanners.



2 Negative image of coronal loops observed in the extreme ultraviolet (EUV emission in Fe IX at 171 Å) with the four quadrant telescope of the TRACE mission. No doubt the best image of the collection. These structures were in the past observed at lower resolution with the Lyot coronagraph in the Fe X and Fe XIV lines. They were called coronal condensations. The fine structures of the loops, implying a fairly constant magnetic flux tube sections, do not cease to amaze. Indeed, we would expect to see the sections growing with altitude, because of the conservation of the magnetic flux and the decrease of the field amplitude. These loops are forming after a flare and are also called "post-flares loops". They can be visible during several hours, in particular thanks to the hydrogen and helium emission lines. Processed image taken from the TRACE mission archive, NASA.

More efficient detectors were later installed aboard the robotic laboratory SolarMax, first launched by the Space Shuttle, then by the reusable probes SPARTAN. SolarMax specialized in the study of the solar flares determined to be dangerous for the survival of astronauts. It did an excellent job but later faced a mixed success partly due to repairs which required human interventions on the satellite.

The era of digital imaging then opened with the YOHKOH mission, mainly operated by the Japan Space Agency JAXA, with the transmission of millions of X-ray images, with a most outstanding performance, opening the era of movies from space.

But it was the SOHO mission that opened in 1996 the true solar epic that is still ongoing today. First European, the mission became Euro-American (ESA-NASA), growing up to the size of a minibus laden with a battery of sophisticated instruments. This was the beginning of the modern digital study of the Sun, with numerous spectroscopic analysis in ultraviolet and extreme ultraviolet (EUV), including spectro-polarimetric measures in the visible. Millions of full-disk magnetograms and EUV spectra have been obtained by SOHO since its launch, gigabytes of extremely precise photometric measures, a legendary EUV imagery of the full disk and an abundant and sophisticated coronagraphy extended to several solar radii, fortuitously discovering thousands of grazing comets. Giant eruptions pushing threatening clouds of magnetized plasma inside the interplanetary medium could be continuously monitored all day long, and this was completely new. This amount of information appears fundamental when, after 20 years of uninterrupted observations, the origin of the irradiance and flares variations need to be analyzed.

In 1998, a less ambitious mission was launched by the NASA, the TRACE mission, with the help of Lockheed in the United States. Its 30-cm aperture solar telescope was inspired from the four quadrant SOHO's EIT camera. It allowed recording innumerable and very interesting partial frame EUV images, which can be displayed as high frame-rate time lapse videos (see figure 2). However, the field-of-view did not cover the full solar disk. The mission lasted a dozen years, with limited diagnostics capability because there was no equipment for spectroscopic analysis. TRACE made it possible to image the high chromosphere in detail to unveil the mysteries of the coronal heating, which originates in this region of the solar atmosphere, called the transition region, where the temperature suddenly increases on several orders of magnitude. Physics is still unable to explain what is observed and only a diagram (see figure 3) can depict what is going on inside this off-balance region so hard to understand. Continuously crossed by waves and ionized streams of gas, subject to the twists and tangles of the magnetic lines emerging from the photosphere, the chromosphere produces a rich spectrum containing many emission lines.

It was no surprise that the TRACE mission served as a prototype to other very important NASA missions.

In 2006, the Japanese agency JAXA, associated in a trans-pacific effort with the NASA, launched the orbital solar observatory first known as Solar B, renamed HINODE (Sunrise) after its successful launch. Its set of scientific instruments consists of:

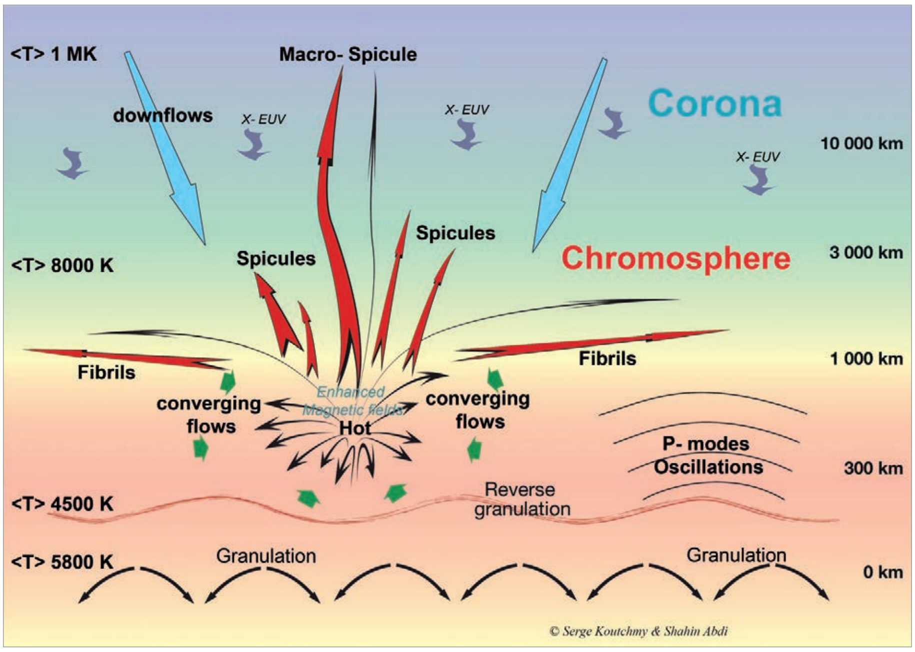
- a new X-ray imager (XRT experience), partly built by the Harvard-Smithsonian group, to reach a resolution higher than the YOHKOH X-ray imager,
- an EUV scanning spectrometer (EIS experience), partly developed in the UK,
- and above all the 50-cm aperture SOT telescope (Solar Optical Telescope), operating in visible light, with several sophisticated focal plane polarimetric and photometric spectroscopic facilities, whose nearly perfect primary mirror was made in France.

The telescope and the focal plane instrumentation were designed by Lockheed (California), the Mitaka teams (Tokyo) and the JAXA. The SOT is the largest solar telescope still in orbit around Earth and has produced the best solar images ever obtained, especially in the near UV. With its focal plane instrumentation, like the high-resolution vector magnetograph (the three components of the magnetic field are measured in the high photosphere at around 200 km, see figure 3), and CCD cameras equipped with narrowband filters, a surprising harvest of images, magnetograms and dopplergrams has been gathered. What's more, accelerated time lapses have casted a new light on spicules and prominences, thanks to a wealth of details, and have been deeply investigated and have enriched still ongoing theoretical works. Vortices and Alfvén waves are now observed. Images of the solar disk (see for example figure 4) and the surprising vector magnetograms obtained by the SOT have somewhat made obsolete the best that could then be achieved from ground in term of spatial resolution. The success of that mission that is still running in 2019 should have convinced the space agencies to fund a new orbital SOT of one-meter aperture. For now, this project, which has indeed been proposed for a long time in USA and in China, is estimated to be too expensive and is frozen. In Europe, a balloon program called SUNRISE was developed with a similar 1-m solar telescope. It was launched successfully in 2009 and 2013, the 3rd flight being prepared for 2021. Laboratories in Germany, Japan, Spain and in USA are involved.

Among the unexpected discoveries made by SOHO, the CMEs (Coronal Mass Ejections) played an important role, giving birth to a new solar discipline, the spaceweather, and its scientific counterpart, **heliophysics**.

One of the highly variable and very energetic components of the solar radiation is to be studied in the hard X-ray and gamma rays. Accordingly, a dedicated mission, RHESSI, was launched in 2002 by the NASA to observe in these wavelengths. Numerous spectra and low resolution images have been analyzed since then, complementing the ground radio observations of the same energetic events.

Geophysicists and climatologists are now definitely interested in solar physics. It's not pointless to recall here that the SOHO mission had been defined by its instigators as a "quiet Sun" mission, which implies a certain constancy and stability of the star, mainly to study its internal structure and its atmosphere by the methods of the solar seismology, and during a minimum of activity. In an unexpected turn of event, it also became a superb mission of maximum solar activity, with the success we recognize today.



Caption:

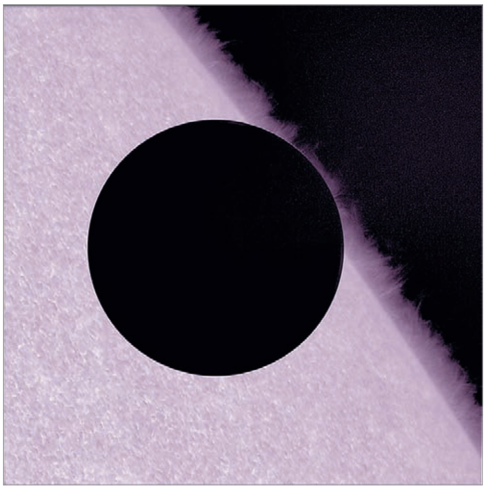
- *<$\overline{T}$>: mean temperature of the chromospheric region. The zones where the local temperature is higher than T correspond to the bright points of the chromosphere.*
- *The green arrows above the 4500 K temperature minimum level indicate the streams of gas compressing the structure. This is the region where spicules and fibrils initiate and where the temperature starts to rise.*
- *The black lines represent the magnetic lines of force guiding the spicular flows, including towards the corona.*
- *The downward blue arrows in the corona indicate the stream of cooling gas pouring down along the lines of force, due to gravity, down to the top of the chromosphere.*

3 *Schematic section of the solar atmosphere, from the photosphere (height 0) up to the base of the corona. Note the logarithmic height scale graduated in thousands of km to the right (for comparison 1" = 720 km at disk center). The successive altitudes correspond to:*

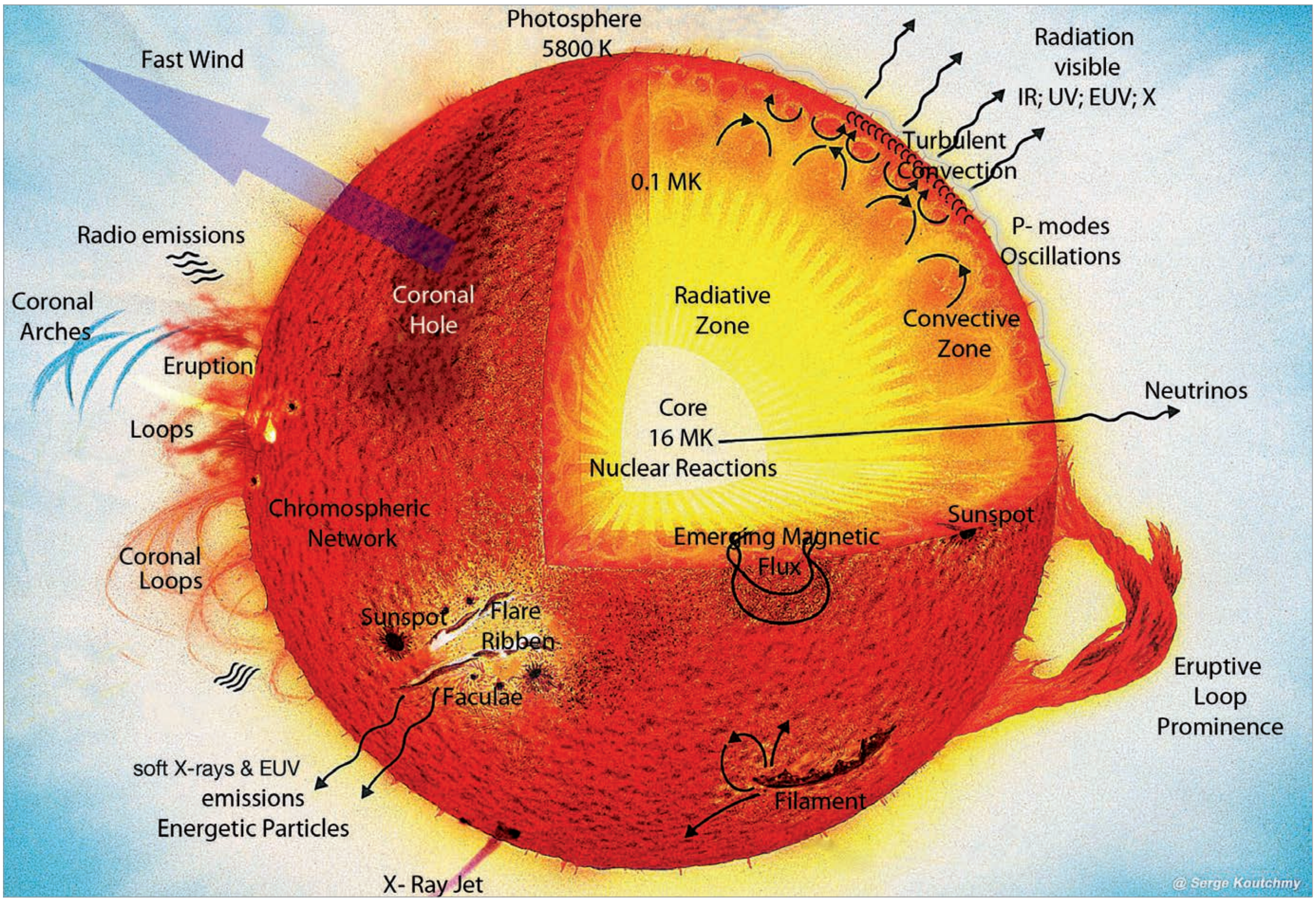
- *The photosphere, in yellow, full of granules bursting out of the surface.*
- *The mesospheric region, in orange, lying at the minimum of temperature level (around 500 km). This layer has abundant "low FIP" (First Ionization Potential), which are elements like FeII, BaII, TiII, MgII, etc., which have a first potential of ionization lower than 10 eV and which get ionized inside this layer. The most abundant high FIP elements, like hydrogen and helium, stay in a neutral state and will only be ionized at a higher level because of the increase in temperature whose origin is still unknown.*
- *The chromosphere, where the temperature increases and where the magnetic field of the chromospheric network emerges, is in yellow then in green. The magnetic field is filling the whole space. The lines of forces spread horizontally at around 1000 km marking the level of the magnetic "canopy". At the bottom of the chromosphere, the different layers become heterogeneous (they are crossed by cooler and denser fibrils, in red) and more dynamic (oscillations and shocks).*
- *At a higher altitude, up to around 5000 km, the tenuous envelop of the chromosphere is crossed by numerous and more dense spicules (in red) propelled upward by thermomagnetic forces overcoming the gravity force. Still higher, rarer macro-spicules (giant spicules with temperature close to 100 000 K) can develop in an even more tenuous corona (light blue) where the temperature reaches one million K and more, without anyone knowing the reason why.*
- *Finally, downward speeds, possibly implying the condensation of coronal ionized gas, are spectroscopically observed at the bottom of the corona (the so-called transition region), when at the same time X-EUV photons and energetic electrons flux coming from the surrounding corona are spilling over the surface.*

Diagram: Serge Koutchmy (Institut d'Astrophysique de Paris - CNRS and Sorbonne University).

In reality the solar activity is incessant, the most clear proofs being the **violent eruptions, active regions and fast wind flows from the polar coronal holes.** As for now, we do not understand everything about this activity, even if we guess that magnetism, at work in all these forms of activity, is an endless source of energetic phenomena in every cosmic plasma, including the Sun and its corona.
Soon after SOHO, an ambitious 10 billion dollar space program was launched by NASA, meeting some somewhat ancestral needs, in particular to explore aspects of the Sun-Earth system that directly affect life and society. Called "Living With a Star" (LWS), this program is still running today. Its extension beyond 2020 is bitterly discussed today, in particular because of the competition with the conquest of Mars and with exoplanets research projects. Several new solar missions have already been launched under the LWS program and the Japanese and European space agencies became part of them.



4 *Deconvoluted image obtained by the SOT telescope of the HINODE mission during the 2012 Venus transit in front of the solar disk (angular diameter of Venus is around 60"). The filter used is centered on the violet CaII H line (0.4 nm bandwidth) and allows to study the spicules at the solar limb. The resolution of the processed image is close to 0.15 arcsecond over the whole field, thanks to the absence of turbulence in space. The fringe of the spicules forest asks for a separate processing to resolve each structure. This image is the first one showing the atmosphere of Venus visible all around the planet disk, with the famous luminous arc visible outside the solar disk. This faint arc, which was claimed to be visually observed by M. Lomonossov during the 1761 transit, is the result of the refraction and scattering of the solar rays through the higher layers of the venusian atmosphere. On the solar disk, the structures close to the limb are reminiscences of the inverse granulation (see figure 3). The Gibbs effect, an artifact produced by a too strong deconvolution, is well contained here, proof is the absence of signal on the disk of the planet. Images by H. Goodarzi and S. Koutchmy (2016) used to calculate the PSF (Point Spread Function) of the telescope in order to study sunspots, solar limb profile, faculae and granulation.*



5 *Highly schematic representation of the known internal structure of the Sun, with the main structures and phenomena observed on its surface and beyond. Neither intensities nor colors nor scales are respected in this attempt to draw a synthetic representation. Labels are related to features or process rather well described in the scientific literature. The granulation and the chromospheric spicules can't be represented at this scale (see figure 3). Prominences and filaments are relatively cold elements (partially ionized hydrogen and helium) immersed in the surrounding hot corona. In these regions, loops and coronal enhancements (see figure 2) are even hotter and accordingly produce extreme ultraviolet radiation (EUV) and even much X-rays and radio emissions. Sunspots come isolated or in groups to form an active region that, while evolving, eventually produces flares (strong eruptive EUV, X, gamma, radio emissions), which can be preceded by eruptions (abrupt displacement, instability and ejection) of cool matter which becomes ionized and produces coronal mass ejections (CMEs) in the surrounding corona. Diagram: Serge Koutchmy.*

Thus, the STEREO mission launched in 2006, composed of two twin probes with onboard coronagraphs and EUV imagers similar to those of SOHO. Placed into orbits around the Sun that cause them to respectively pull farther ahead of and fall gradually behind the Earth, they provide a stereoscopic vision of the solar activity from its surface to far away in its outer atmosphere (HI images). The numerous images recorded are under studies. The STEREO probes have already completed half a revolution around the Sun, but one of them unfortunately broke down when it was passing behind the Sun. The other probe keeps on sending images that, when compared to those taken by the satellites around the Earth, allow a better monitoring of the activity of the solar atmosphere and up to the interplanetary medium.

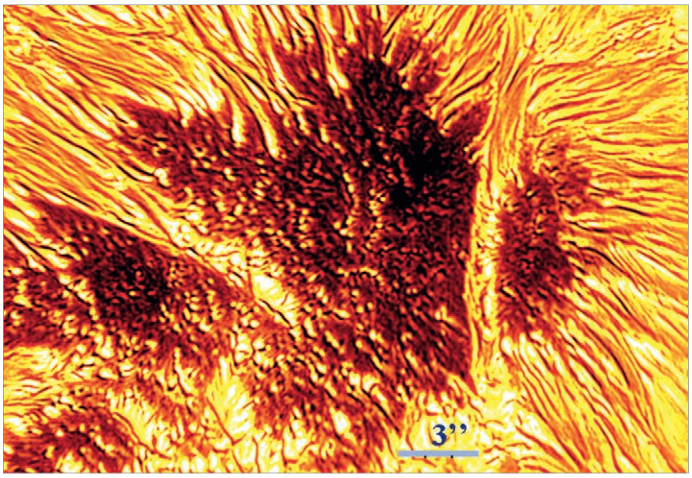
But predicting solar flares and eruptions requires a much more advanced monitoring in term of spatial and temporal resolution. It was the goal of SDO mission (Solar Dynamics Observatory) launched in 2010, which was made possible thanks to huge technological advances in the steps of some very successful experiences by SOHO. It is currently the American flagship of the solar observatories in polar orbit. SDO is a full package satellite mission whose description would deserve an extended report given its many facets. Only spectroscopy is missing.

Meanwhile in 2013, a smaller mission, IRIS (Interface Region Imaging Spectrograph), was put into orbit, with a spectrograph able to monitor narrow fields of the transition region and the chromosphere at very high spatial (1/3 arcsec) and temporal (1 s) resolution.

SDO also provides 4K full-disk images in ten different EUV wavelengths with 0.7 arcsec/pixel scale at 10 s interval (AIA images), and full-disk magnetograms at 1 arcsec resolution (HMI images). These images show the continuous evolution of each and every detail from the surface of the Sun, the numerous successive layers of the solar atmosphere, and up to the corona, with all the complexity imposed by the emergence, then the dominance, of the magnetic field at all scales, field induced by millions of local dynamos phenomena operating on the whole surface. And this is of course without taking into account sunspots and active regions deeply anchored in the atmosphere, creating majestic magnetic edifices, although often unstable inside the corona, including surface distortions resulting from the differential rotation. Eruptive events, called solar flares, burst into the corona just near the surface (see figure 5). Finally, the physics of the "X jets" discovered by YOHKOH, in complement with the macro-spicules observed by SKYLAB (the former "spikes" visible on images of total eclipses) and the "tornado" phenomenon very recently revealed by the AIA images of SDO, is beginning to be uncovered and keeps on feeding the research of the physicists.

We are getting more and more aware that hidden mechanisms, operating at small scales still unattainable to observation, are playing a fundamental role. They are often described as magnetic reconnections, without any obvious or definitive diagnostics being offered to the observer, because those are dissipating electric currents that escape from investigations. Only numerous theoretical studies, often supported by numerical simulations, can guess their importance and maybe their topology. Singular neutral points, shears and counter-flows can for example be evoked.

To even further improve the resolution of solar images, on an ad hoc basis, some EUV experiments are being developed today but this is really not enough. Geophysicists have been long benefitting from *in situ* measurements that provide them with precious data that fortunately give substance to those ideas of magnetic reconnections in non-collisional plasma. Europe, Japan, Russia, China, India and the United States have desired for a long time new missions to respond to this need for *in situ* measurements closer to the Sun. Improvements will come from the development of interplanetary probes able to get closer to the Sun for a better viewing, in a progressive manner because of the orbital constraints and solar heat, thanks to the deployment of a thermal shield and a new source of power. One of these solar probes, resulting from more than 40 years of studies, was launched in 2018 by the NASA. It was named "Parker Solar Probe" to honor the great 20th century solar physicist, still active today. After 2020, another more ambitious probe will be launched by the NASA and the ESA, and followed by others. The interplanetary region closer to the Sun will be better analyzed but, apart from a new point of view brought by an angle of viewing above the plane of the ecliptic, and without any unexpected findings on the polar regions of the Sun, the knowledge of the solar disk will not be profoundly modified. So we must go back to traditional ground-based methods for new breakthrough improvements, thanks to larger telescopes and to more extended diagnostics including in the synoptic domain (a synoptic map identifies the various phenomena visible on the solar disk at a given time).



6 *One of the best images ever taken showing the umbra of a sunspot obtained with a near-IR TiO filter used at prime focus of the 1.6 m Goode Solar Telescope of BBSO. The TiO molecule absorbs some of the light from the deep solar atmosphere resulting in an increased contrast in comparison to images taken in the continuum. As of early 2020, the 1.6 m NST is the biggest solar telescope in operation. It is equipped with an advanced adaptive optics system. The original image covers a field larger than shown here. The smallest structures are in the range of 0.1 arcsec or even less (see scale bar). In the umbra, the bright structures tend to gather in groups or along alignments which, thanks to the temporal variations analysis revealing proper motions, gives clues about the role of the omnipresent and vertical magnetic field inside the umbra. In the penumbra and in light bridges like the one on the right, the magnetic field is almost horizontal.*

Image taken from the post-processed observations on May 22nd, 2013, archives of the Big Bear Solar Observatory in California USA.

Ground-based observation of the Sun

Radio telescopes can only be developed on the ground. Long-baseline radio interferometers installed in high altitude sites (especially ALMA, Atacama Millimeter/sub millimeter Array) brought new light on the chromosphere and the lower corona with an excellent resolution.

For this reason, we must keep in mind that ground-based observations are and remain necessary. Space experiments are not long lasting, aging more quickly than ground experiments because of the intense solar radiation and the omnipresent cosmic rays inside the heliosphere. They can also fail prematurely because of problems in orbital maneuvers. Finally, the cost of one kilogram of equipment put into orbit is very high, not to mention the associated operation cost.

Solar telescopes of large diameter (with a primary mirror > 1 m) are already being developed on the ground, and thanks to the progress of adaptive optics (AO) and to modern control and monitoring systems, the resolution reaches records close to 0.1 arc second (see figure 6). This is the case of the 1.6-m Goode telescope, installed at the Big Bear Observatory in California (BBSO). It is equipped with an AO system whose 357 actuators control a deformable mirror compensating the wave front errors due to turbulence at a frequency close to 2000 Hz.

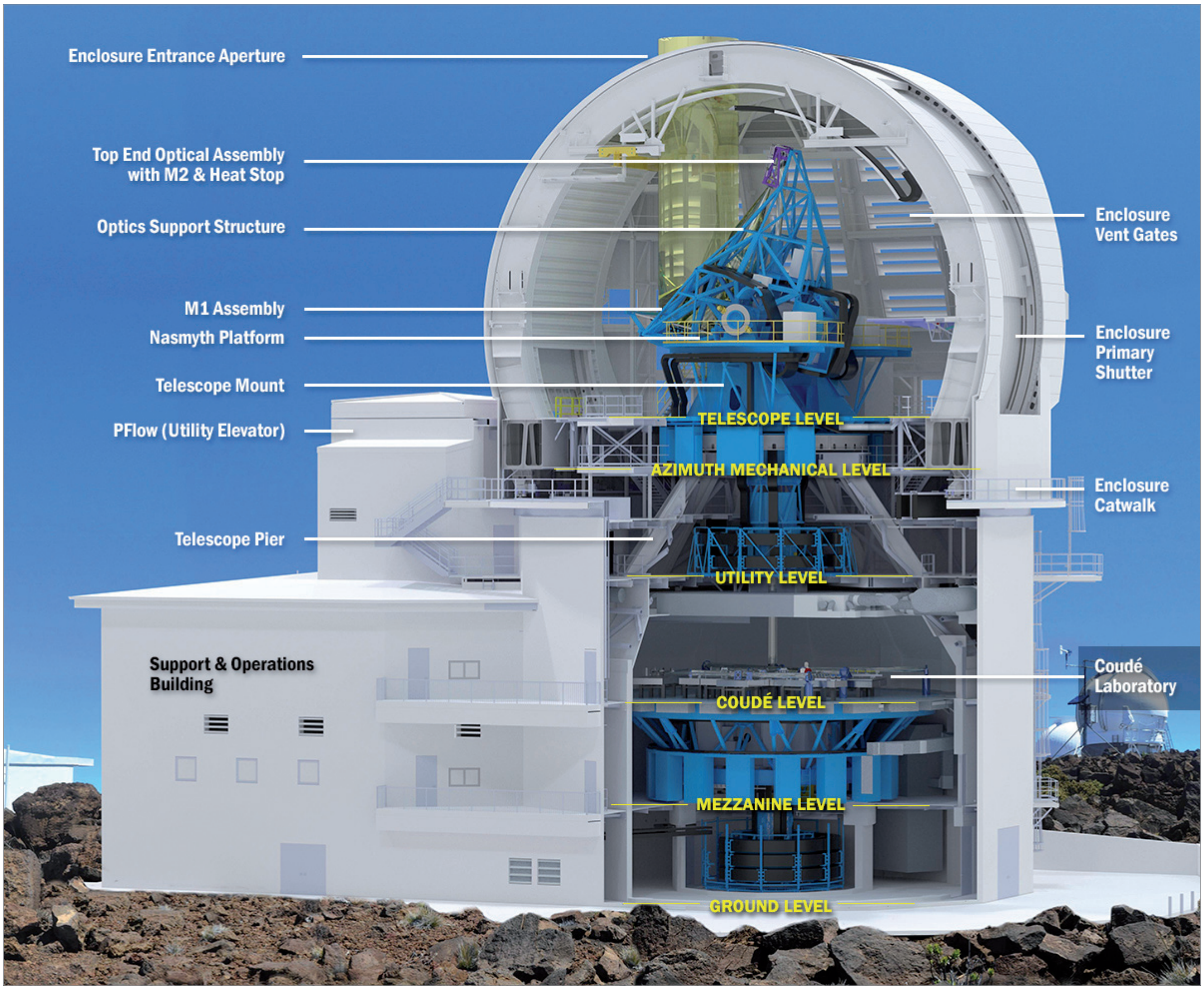
In the Canary Islands, German scientists have installed the 1.5 m GREGOR solar telescope also equipped with an AO system. Some excellent images are beginning to be released and new phenomena are being discovered at the smallest scale, including in the Hα line. Even if the turbulence is not fully corrected, the tremendous flux of photons available at the focus of the telescope makes it possible to operate very quickly and repeatedly, even after the spectral dispersion of light from very small areas of the solar disk. This allows to process hundreds of quasi-monochromatic images per second with a good signal to noise ratio (SNR), as are doing many amateurs. The SNR is fundamental in improving the resolution, but the residual distortion in the images limits the performance to relatively small fields on the Sun.

As for the observation of the solar corona, the situation is not as idyllic. Improvements are still possible by going into longer wavelengths in the infrared, as for night-time observations. This is partly the bet made by the developers of the largest solar telescope ever built, the DKIST (Daniel K. Inouye Solar Telescope, named after the deceased Hawaiian senator who was instrumental in the development of the project on the island of Haleakala, Hawaii). This telescope is now the flagship of solar astronomy, with its 4-m aperture primary mirror, its "off-axis" configuration favorable to solar corona observation thanks to its low level of stray light due to the absence of central obstruction, its dome designed to reduce turbulence and finally an impressive suite of focal instruments. The long list of institutions and universities taking part to the development of the instrumentation is a testimony of the high expectations put in this new solar investigation tool (figure 7). Other less ambitious projects of ground-based solar observatories are being developed throughout the world, in Europe, China and India.

Of note is the GONG (Global Oscillations Network Group) international network of small telescopes spread around the globe that has been operated successfully for many years. The associated database works as a virtual observatory managed by the National Solar Observatory (Tucson, USA), where full-disk Hα images and magnetograms taken every 1 min can be accessed by the solar community at the click of a mouse. Incidentally, the resolution is not as good as that reached today by amateurs, as the images of this book will show. It is planned to improve its performances (SPRING project).

The amateur world

The amateur world has become very active. Impressive results have now been achieved, as evidenced by this book. This traces back to a tradition deeply rooted in the history of solar physics, as exemplified by one of the major discoveries of solar physics of the 19th century, the **11-year** periodicity of solar activity. This achievement was the feat of an amateur, Heinrich Schwabe, pharmacist at Dessau, from more than 15 years of diligent sunspots observations, in search of the transits of the Vulcan planet across the solar disk. The elusive planet was supposedly disturbing the secular orbit of Mercury. Later, A. Einstein would find a much more rational explanation but this is another story!



7 *The 4-m DKIST solar telescope of the National Solar Observatory (NSF-USA). The telescope was commisioned in late 2019. It is located on top of the Haleakala summit, Island of Maui, Hawaii. It is the largest solar telescope ever built. The dome is designed to reduce the local diurnal turbulence and to favor laminar surface flow. Several floors can be identified on this exploded view, with the off-axis low stray-light level telescope at center, in blue with its altazimuth mount. The telescope is equipped with a state-of-the-art adaptive optics system and five first light instruments including the IR coronagraphic mode of observations. Image: NSO/AURA/NSF.*

Challenging professionals and amateurs seems by the way pointless. What is important is to find personal satisfaction and enjoyment in the long days dedicated to the study of the Sun, which also means using the right equipment to match one’s ambitions. This book, "Solar Astronomy", dedicated to this discipline by Christian Viladrich and his co-authors perfectly fits into this logic. No doubt it will offer new "solar satisfactions" to a public wondering every day about the fate of our star and its ups and downs, so much it contains descriptions, suggestions, interpretations and answers. It has been possible to gather and highlight complementary and extended skills in this undertaking. All the credit comes back to Christian who reveals through this adventure the extent of his knowledge as a skilled amateur, dedicated so long to observation, in addition to his qualities of organizer and manager endowed with teaching skills. What a superb work!

Serge Koutchmy
Emeritus Research Director
Institut d’Astrophysique de Paris, CNRS and Sorbonne University
J. Janssen Medal of the Académie des Sciences (1994), Medal of the CNES (1983)
and Janssen prize of the French Astronomical Society (SAF, 1998)