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DAVID ALEXANDER* AND LOREN W. ACTON**

# The active Sun

*Following the sun we left the old world* – Christopher Columbus

The title of this chapter presupposes that there exists a Sun that is Non-active or Quiet. Modern research, however, is discovering more and more that there is no such thing as a perfectly placid Sun. Activity occurs on all scales at all times in the solar atmosphere. As solar instrumentation improves, the subsequent advances in our knowledge of what physics controls this continuous activity will lead to a better understanding of how stars like the Sun work. Ever since Fabricius and Galileo first confirmed that sunspots were solar phenomena, the nature of our nearest star has been a subject of scientific investigation. The culmination of this line of inquiry is the present-day field of solar physics, the goal of which is to investigate the constantly changing Sun. Solar activity in all of its myriad forms, from cyclical variations of the whole Sun to small-scale transient phenomena, is ubiquitous in solar research. Improved instruments now demonstrate that even the quiet Sun is far more dynamic than once thought. The intrinsic variablity of the Sun provides a touchstone to the intricate workings of stars. In this chapter we will explore the active Sun and examine how our knowledge of this dynamic star has blossomed in this *Century of Space Science*.

An important early tool in the exploration of solar activity was the solar eclipse. The popular attraction of eclipses remains strong today but their scientific value has steadily declined since the invention of the coronagraph by French astronomer Bernard Lyot in 1930. The eclipse expeditions of the late nineteenth and early twentieth centuries are a testimony to the dedication of early solar astronomers. The word "expedition" itself conjures up the effort involved in observing an eclipse since, more often than not, the eclipse was best observed from a remote and inhospitable part of the planet. Despite all of the hardships, the astronomer was often rewarded with wonderful scientific data and occasionally an important discovery. Eclipse observations provided a strong foundation for the subsequent research into solar activity.

Eclipses always yielded spectacular displays in the darkened sky, but until 1836 the coronal phenomena observed were thought to originate on the Moon or even in the Earth's atmosphere and, therefore, merited little scientific interest. The last four decades of the nineteenth century, however, were witness to many discoveries which laid the foundation for the study of solar activity in the solar corona. Eclipse data, in particular, were responsible for a number of these discoveries and significantly advanced our knowledge of the Sun and its behavior: the solar origin of prominences (1860; Pietro Secchi, Warren De La Rue), the discovery of helium (1868; Jules Janssen), the existence of a chromosphere (1870; Charles Augustus Young), the unequivocal identification of the corona as solar (1871; Jules Janssen), and the relation between sunspot cycle and corona (1878; Jules Janssen). The eclipse of 1878 was particularly interesting as it occurred during solar minimum and exhibited a corona with a marked equatorial extension (in contrast with the nearly circular corona observed in 1871). It was noted that the coronal streamers, as the extensions off each limb were called, had a strong resemblance to magnetic lines of force and it was proposed that the Sun must, in fact, be a large magnet (Frank Bigelow in 1889 and Störmer in 1911). Subsequently in 1912,

* Lockheed-Martin Solar and Astrophysics Lab, Palo Alto, CA, USA
** Montana State University, Bozeman, MT, USA

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Henri Deslandres suggested that the forms and motions of prominences seen during solar eclipse appeared to be influenced by a solar magnetic field. The link between magnetic field and the emitting plasma on the Sun was beginning to take shape.

The key to understanding solar activity is the Sun's ever-changing magnetic field. It is now virtually certain that all solar activity, and perhaps the solar atmosphere itself, is there because of solar magnetism. However, it is only in this last century that the fundamental importance of the magnetic field for solar phenomena has been realized. The epochal discovery of magnetic fields on the Sun by American astronomer George Ellery Hale in 1908 signalled the birth of modern solar physics. This realization led to fundamental progress in our understanding of many physical processes occurring on the Sun and set the foundation for most of the solar physics advances in the modern age. The discovery of solar magnetism arose out of Hale's supposition that the distinctive alignments of penumbral filaments in sunspots bore a remarkable resemblance to the iron filing patterns formed around the poles of a bar magnet. To test his hypothesis Hale looked for the line splittings expected from the newly-discovered Zeeman effect: the first application of this in astronomy. Using the spectrograph at the recently completed solar tower telescope at Mount Wilson, Hale was immediately rewarded with a clear line-triplet indicating the presence of a strong magnetic field.

The study of the Sun's magnetic field was limited to strong-field regions, such as those of sunspots, until the invention of the solar magnetograph in 1952 (see Figure 1). Harold Babcock and his son Horace used the first ever solar magnetograph to discover that the magnetic field existed outside of sunspots and was, in fact, distributed across the whole solar surface. The solar magnetograph, refinements of which are now used in virtually every major solar observatory in the world (there is even one currently in space), introduced an improvement of about two orders of magnitude in the sensitivity of magnetic field measurements over the contemporary visual or photographic techniques. Without these observational breakthroughs we would know very little of what turned out to be the active Sun.

Solar physics research was, literally, taken to new heights by the advent of observations from space. The age of space astronomy has its roots in the flight of a captured World War II German V2 rocket on 10 October 1946 from White Sands Missile Range in New Mexico. This rocket, carrying instruments to observe for the first time the far ultraviolet spectrum of the Sun, reached an altitude of 90 km above the Earth's surface. However, despite the increasing sophistication of rocket-borne experiments in the following decade and a half, discoveries were hampered by the very short flight durations attainable by these sounding rockets.

In March of 1953 the National Academy of Sciences appointed a National Committee to oversee US participation

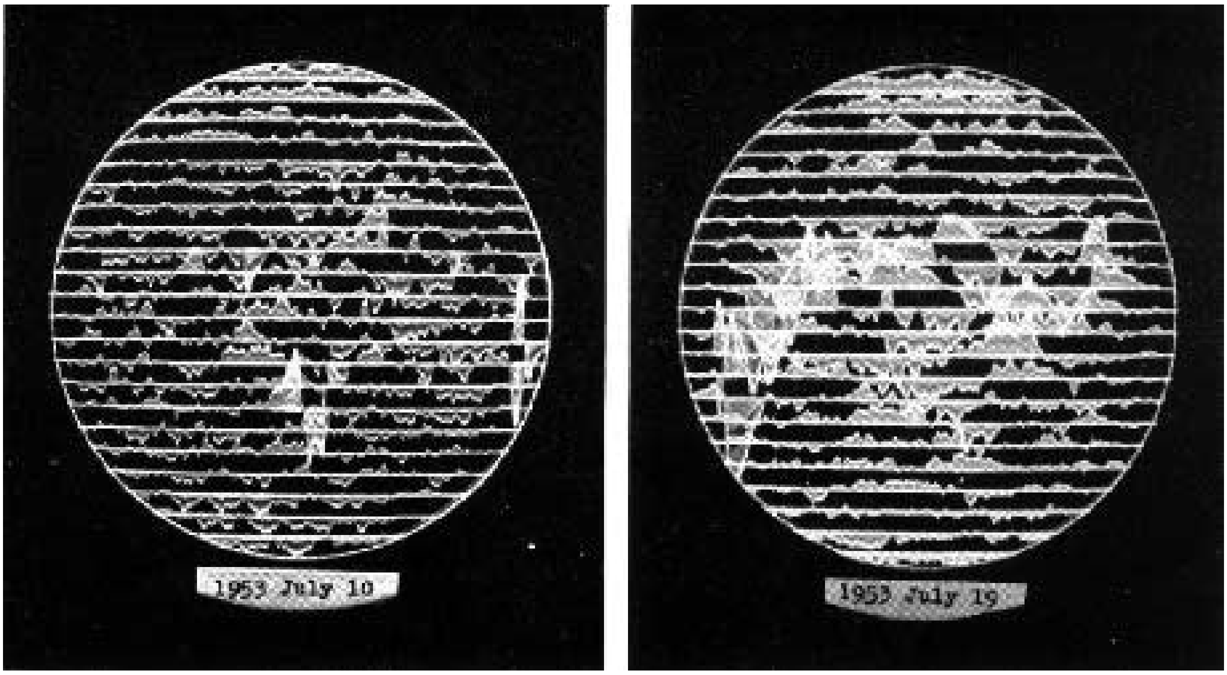


**Figure 1** Two of the original magnetograms of the Sun taken with the Babcock magnetograph in July 1953. (Reproduced with permission of H.W. Babcock and the American Astronomical Society.)

in the International Geophysical Year (IGY), a comprehensive series of global geophysical activities set up by the International Council of Scientific Unions the previous year. The IGY spanned 1957–58 and included investigations into solar activity and the upper atmosphere of the Earth. In connection with the upper atmosphere research, the USA undertook to develop an orbiting satellite program.

The advent of orbiting satellites opened the way for continuous solar observations at wavelengths unattainable from the Earth. A series of eight satellites known as the Orbiting Solar Observatories provided much of the space-based solar observations through the 1960s, although the OSO satellites were modest in size with relatively small instruments. Solar physics received an enormous boost in 1973 when NASA launched the Skylab space-station mission (Figure 2). Skylab allowed long-focal-length solar telescopes to be flown in space for the first time and the commensurate improvement in observations was so great that the data are still being used today.

In terms of versatility and reliability, the performance of the Skylab telescopes and instruments exceeded the highest aspirations of astronomers at the time. Skylab made a number of important discoveries which significantly enhanced our knowledge of solar activity and which changed the nature of solar physics research permanently. In the almost three decades since the launch of Skylab many solar observatories have been placed in space, each making a step towards a better understanding of the Sun. The physics and phenomena we will discuss here depend heavily on results from these space missions and the legacy left by sounding rockets, OSO, and Skylab.

Much of this chapter will center on what we have learned about the Sun through advances in our knowledge of the magnetic field, its variability, and its interaction with the solar plasma. While this is of intrinsic interest to the solar physics community, the problem posed by the observed magnetic activity of the Sun is of fundamental importance to all of astrophysics. Activity is observed in many distant stars and galaxies. However, the proximity of the Sun makes it the only star whose activity can be seen in enough detail to guide us toward an understanding. Naturally, to do justice to a century of research would tax even the space limitations of a single dedicated volume. To confine such a task to a single chapter necessitates a more circumspect approach. We attempt to highlight the major discoveries which have led us to where we are today in our

**Figure 2** The Skylab space station seen from Skylab 4. (Reproduced with permission of Skylab, NASA.)

understanding of solar activity and to describe the phenomena which best exemplify solar variability.

The generation of the magnetic field in the interior of the Sun is the subject of a different chapter of this volume (Chapter 44) but its importance for the observed phenomena which have driven solar research over this last century provides us with a natural starting point for our discussion into the activity of the Sun. The solar dynamo is the machine that is responsible for this magnetism and whose most evident manifestation is the solar cycle.

## THE CYCLICAL SUN

*With orb and cycle girds the starry throng* – Wordsworth

Some two hundred years after the death of Galileo, a pronounced quasi-regular period was discovered in the number of sunspots by a German apothecary and amateur astronomer, Heinrich Schwabe, in 1843. This period demonstrated that the Sun had an 11-year cycle of activity which had been repeated, with a couple of important interruptions, for about 250 years. It may seem surprising that it took approximately two centuries for this pattern to become apparent. However, it should be pointed out that the cyclical pattern in the sunspot behavior is most clearly recognizable after considerable averaging. Indeed, the oft-quoted cycle of about 11 years is far from regular, in either duration or form. Lengths of cycles vary from a minimum of about 8 to a maximum of about 15 years, the long-term average being about 11.1 years. While the solar cycle is a discovery of the nineteenth century, it has had a profound effect on the solar physics of the twentieth century, driving much of the advances in our current understanding of the Sun.

Essentially all solar phenomena exhibit 11-year cycles, including radiative outputs, particle and plasma emissions, interior oscillations, and perhaps even fundamental processes in the Sun's nuclear burning core. Diverse solar parameters such as the integrated X-ray emission, UV irradiance, and solar radio flux record this variability over wide ranging spectral and temporal scales. Like the sunspot number, the total radiative output and the entire solar spectrum exhibit pronounced quasi-11-year and 27-day cycles, linking all aspects of solar radiation variability to a common source: the magnetic activity of the Sun. The 27-day period corresponds to solar rotation. Detailed investigation of this activity led Hale to discover, in 1913, that a predominance of major spot groups exhibited a very distinctive pattern. He found that the preceding and following polarities were opposite in the northern and southern hemispheres and, more importantly, that this pattern was reversed from one 11-year cycle to the next. This ultimately led Hale to conclude (with Seth Barnes Nicholson some 25 years later) that the magnetic cycle of the Sun must have a duration of 22 years.

The variability best quantified observationally is that of the Sun's total (spectrally integrated) radiative output. The extremely small amplitude of this variability was undetectable until the development of radiometers of sufficient sensitivity in the 1970s. Overlapping cross-calibrated measurements made by active cavity radiometers since November 1978 compose a total irradiance database with sufficient long-term precision to identify an 11-year total irradiance cycle of about 0.1% amplitude during solar cycles 21 and 22 (1976–1986 and 1986–1996, respectively), in phase with solar activity. Although these variations in solar luminosity seem quite small they are of the same order of magnitude as the longer period insolation change that give rise to major ice ages. However, to date it has not been fully determined whether cyclical changes in the Sun's radiative output have a marked effect on the Earth's climate or not.

While the spectrally integrated solar output provides the best measure of the solar variability, specific wavelengths can provide some insight into the nature and cause of the variability. A prime example of this is the variation in the X-ray irradiance over the course of a solar cycle. The Soft X-ray Telescope (SXT) on board the Yohkoh spacecraft has demonstrated a variation by as much as a factor of 40–50 from solar maximum to solar minimum in the wavelength range 3–60 Å, which is to be compared with that seen at shorter wavelengths by the (Geostationary Operational Environmental Satellite (GOES) series of satellites (1–8 Å) of about a factor of 80–100. The advantage of modern grazing (and, more recently, normal) incidence optics at X-ray wavelengths is that the imaging allows us to determine the role played by different solar phenomena in the solar variability. The SXT has shown that the whole corona participates in the solar cycle not just the most active parts (see Figures 3 and 4).

The solar activity cycle is variable in several aspects. One obvious signature of this variability has shown up in the last century. The most recent series of solar maxima, spanning 30–40 years, exhibited the largest minimum to maximum amplitudes in the 400-year record, suggesting that the overall activity level is at a historical high. (At the time of writing, Cycle 23 appears to have entered its declining phase after peaking in March 2001 with a maximum which was significantly lower than early predictions.) There are some rules, however, that apply to the vast majority of sunspots, demonstrating large-scale patterns in the activity cycle, which reveal fundamental properties of the magnetic structure below the atmosphere. Studies of the active Sun can therefore complement the recent advances in helio-seismology (see Chapter 44) by providing important clues to the working of the solar dynamo.

Understanding the solar dynamo and its observational effects is now a full-time occupation for an increasing number of solar scientists. A network of ground stations (called GONG, the Global Oscillation Network Group) and a

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