SOLAR ACTIVITY

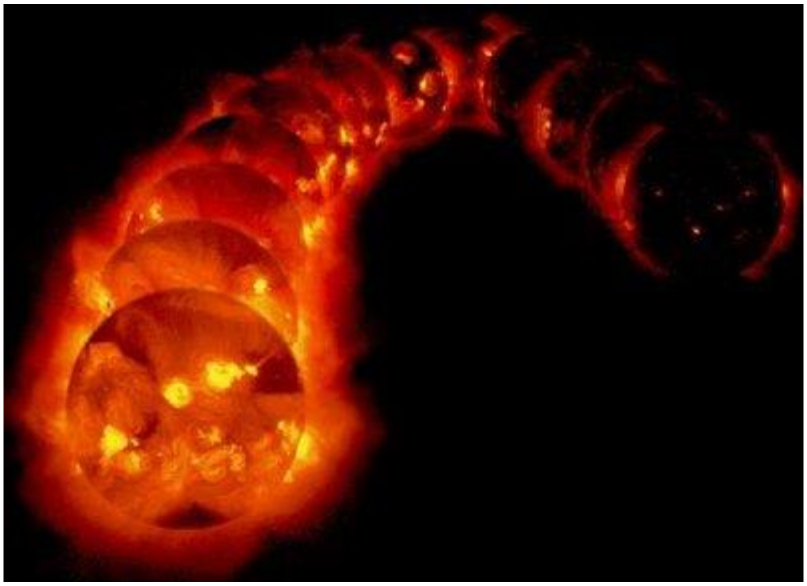

Figure 1: Soft X-ray solar cycle, showing *Yohkoh* observations ranging from 1991 (leftmost image; sunspot maximum) to 1996 (sunspot minimum).

This article briefly introduces **solar activity** (Figure 1), by which we understand the many forms of transient behavior patterns of the Sun, especially in its atmosphere, that depend upon magnetism. The source of the surface magnetism in the Sun lies in the convection zone, the layer of the solar interior just below the photosphere. The magnetic fields underlying stellar activity arise from some combination of convective flows and stellar rotation. A deep-seated dynamo mechanism produces the sunspot-scale fields, but in the quiet Sun other effects may play a role as well.

Active-plasma phenomena similar to solar ones, but often much more powerful, appear in all solar-type stars as well as recently-formed stars (T Tauri) in the process of accretion and in a variety of types of double star. A planetary magnetosphere may have similar plasma processes, such as the aurora.

Background information

The Sun

The proximity of the Sun allows us to study the details of rotation and convection at its surface, and to resolve the various forms of magnetic activity with ground-based telescopes and solar space observatories. Even better, we can sometimes actually sample solar material carried out by the solar wind into the range of *in-*

situ observations by spacecraft orbiting the Earth or elsewhere in the heliosphere. In ordinary *white light*, the solar surface reveals a statistically uniform pattern of granulation outside the magnetic active regions where sunspots appear. SinceGalileo's time, the morphology of sunspots has revealed fascinating complexities, starting of course with the (differential) solar rotation itself. The complexities became even more fascinating in the 19th century, when the 11-year solar cycle was recognized, and in the early 20th century when Hale's spectroscopic observations revealed its inherently magnetic nature. The 11-year sunspot cycle then became half of a 22-year *Hale cycle* because of the alternating hemispheric polarities.

The observed solar magnetic field

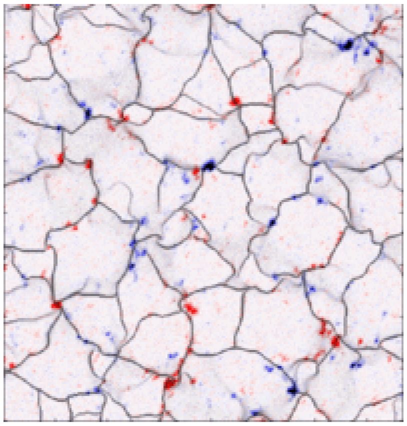

Figure 2: Analysis of SOHOmagnetic and velocity measurements in a quiet region near solar disk center. The red and blue colors show magnetic flux tubes of different polarities, and the lines show boundaries of convective cells. The images is about 180,000 km across.

Solar magnetism is mainly observed via the Zeeman splitting of the photospheric Fraunhofer lines. With modern observations this provides vector information (via use of the full Stokes parameters) of the emissions, and in principle one can use this information as the basis for an extrapolation into the chromosphere and corona. Valuable supplemental information is now arriving via other techniques, specifically centimeter-wavelength radio spectroscopy, ultraviolet and X-ray image morphology, and direct coronal Zeeman measurements. These measurements generally show quiet-Sun fields to be concentrated in the network boundaries and vertices, with a large amount of the flux in roughly vertical flux tubes having $|\mathbf{B}|$ of order 0.1 T. Much of this flux returns to the photosphere on relatively small height scales, but a substantial fraction penetrates into the corona and even into the solar wind if originating in a coronal hole.

Active-region magnetic fields have different properties. Sunspots have even stronger fields, as large as 0.5 T and with much larger surface areas (sunspot umbrae may have areas 10^{4-5} larger than those of the intense flux tubes in the quiet Sun). Accordingly they transmit much more stress locally into the corona, resulting (empirically) in the active-region concentrations of heating seen in X-ray images. The active-region flux concentrations can also be observed to emerge bodily from the interior via buoyant motions, which can be interpreted theoretically in terms of an upward Poynting flux, which transports a part of the solar luminosity up to the photosphere and then through it.

Large-scale solar activity

Morphology

Stellar magnetism results from the convective and rotational velocity fields working on the ionized medium. These rather simple flow fields produce surprisingly coherent patterns of magnetism, including the solar cycle itself, Maunder's *butterfly diagram*, and other more exotic orderings. The sunspots appear at middle to low latitudes. As shown by coronal imaging, these complex magnetic fields simplify to become bipolar and radial at the base of the solar wind. In between the photosphere and the solar wind, the coronal magnetic field - although sustaining some currents - can be determined fairly well from a scalar potential function via mapping from the photospheric Zeeman-splitting observations.

On the largest scales the corona evolves slowly, while on the smallest scales there is a continual flickering of activity that involves energy release leading to heating and plasma injection. Although there are cold inclusions (filaments; see below), the bulk of the coronal volume has temperatures of order 1-3 x 10^6 K. The corona forms a concentric shell of low plasma beta, with its outer boundary defined by the solar-wind flow. Large-area coronal holes occur, as marked by electron temperatures below 10^6 K and by the inference of open field lines. These are especially prominent at the poles during sunspot minima, but open field lines can occur even within active regions.

Flares and coronal mass ejections

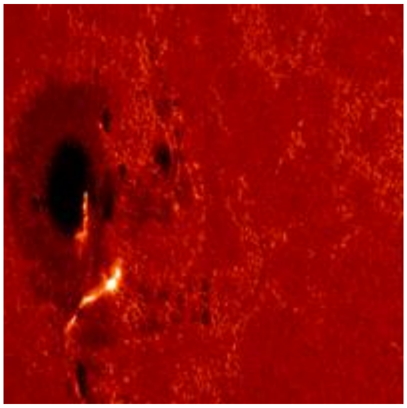

Figure 3: Solar flare observed theHinode spacecraft in the photospheric G band.

A solar flare consists of a sudden increase in the solar luminosity, together with associated phenomena. By general agreement such a phenomenon results from the unstable release of energy that had been slowly accumulated as magnetic stress in the coronal volume. Observed in soft X-rays, a flaring magnetic loop may have a fast risetime (down to a few sec, but not well characterized observationally yet) and a much slower decay time (e-folding time for temperature decrease of order an hour in extreme cases). At the time of the initial energy release, termed the *impulsive phase*, a broad array of non-thermal emissions spreads across essentially the whole electromagnetic spectrum. These reflect strong non-thermal particle acceleration, which dominates the flare energy release. During the impulsive phase a large mass of new material from the lower atmosphere is injected into coronal magnetic loop structures. The *gradual phase* consists of the processes, notably soft X-ray emission, involved with the cooling of this material. Figure 3 shows a solar flare observed by the Hinode spacecraft, which carries the first high-resolution solar telescope in space. This image is in the Fraunhofer G-band, which forms mainly in the photosphere. Accordingly one can see faculae and network signatures, as well as the large sunspot group. The elongated G-band brightenings are the *flare ribbons*, which mark the footpoints of coronal magnetic flux tubes containing hot, dense plasma visible most easily in soft (few keV) X-radiation.

Media:Solar_activity_flare_med.mov
The movie to the right shows the full time development of a powerful impulsive flare of January 20, 2005, as observed in the EUV by TRACE and in soft (red) and hard (blue) X-rays by RHESSI. The total elapsed time is 1.5 hours, and the EUV image quality fluctuates. In the movie sequence one can see the formation of ribbons, as in the example of Figure 3, together with hints of the presence of coronal magnetic loops connecting them, and filled with hot plasma as the result of the flare. The *solar cosmic rays* and high-energy neutrons produced by this event penetrated to ground level on Earth, a rare phenomenon associated with the most energetic events.

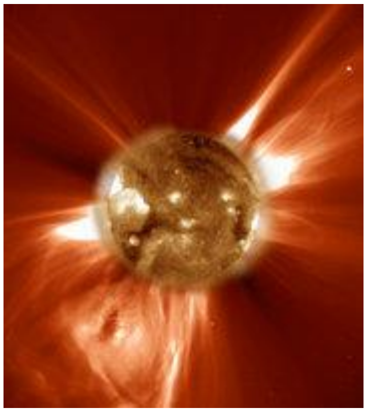

Figure 4: Coronal mass ejection observed by the SOHOspacecraft via its coronagraph and EUV imager.

A coronal mass ejection (CME) typically accompanies the most energetic flare events.Figure 4 (left) shows this in a composite image that incorporates both a coronagraph view (scattered light from above the limb) and a direct view (emission at high temperatures) of the corona. The flare and CME phenomena are to some extent independent, in the sense that weaker flares tend not to have CMEs, and that large-scale CMEs can take place with only weak flare effects. The CME has the appearance of expanding magnetic flux tubes that entrain plasma and eject it into the solar wind. The expanded flux tubes can achieve large enough radial distances that they may be considered *open* and support solar-wind flow. Further extensive particle acceleration may result from large-scale collisionless shock waves associated with the ejecta (see below).

Filament eruptions

Filaments are elongated coronal features composed of relatively dense material at chromospheric temperatures. They are identified with quiescentprominences at the limb, against the disk they are seen in absorption, and on the limb in emission. They reside in filament channels, which consist of elongated, nearly horizontal, and slightly twisted flux tubes. The filament channels and the filaments they support have many interesting properties; they can form in the quiet Sun even at high heliographic latitudes. They may erupt, and this often leads to a CME and to an associated flare-like structure of enormous scale (of order a solar radius) best visible in soft X-ray images or in chromospheric lines. The classical CME morphology has a three-part structure: a bright front, a dark cavity (identifiable with the pre-eruption filament channel), and some filament material embedded in the cavity.

Jets

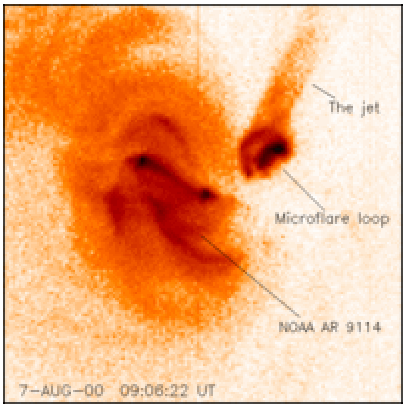

Figure 5: Soft X-ray observation from the *Yohkoh* satellite.

In addition to flares and CMEs, soft X-ray observations of the solar corona reveal the existence of *jets* on large as well as small scales.Figure 5shows an excellent example. The motions in the jets appear to be parallel flows of plasma along the magnetic field, with apparent speeds of order 10^3 km/s. The association of of X-ray jets with meter-wave type III radio bursts, which are due to weakly relativistic electrons that may be subsequently observed far out in the solar wind, establishes that in many cases these jet fields mark *open* field lines. Invariably a compact flaring loop structure appears at the base of a jet, strongly suggesting an interaction between closed and open magnetic field systems involving magnetic flux transfer across the separatrix between the two systems. Figure 1 shows another excellent example of a jet, to be seen in the NW (upper right) quadrant of the first image.

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