

Solar Active Regions

Solar active regions form where the tops of loops of magnetic flux, shaped like the Greek letter omega (Ω), emerge into the solar atmosphere where they can be seen. These Ω loops are thought to be generated by the solar dynamo, located deep within the Sun (see DYNAMOS: SOLAR AND STELLAR). The appearance of active regions depends greatly on the radiation used to image them, as well as the angle at which they are observed. When seen projected against the dark sky at the edge of the Sun (called the LIMB), the magnetic field of an active region is traced by glowing arches of gas confined within CORONAL LOOPS (figure 1). When projected against the solar disk the appearance of active regions is much different. In hydrogen $H\alpha$, at low telescopic resolution, one sees bright SOLAR CHROMOSPHERIC PLAGE (figure 2). At higher resolution, the relatively cool (chromospheric) loops of the active region appear (figure 7). In x-rays, the much hotter (coronal) loops of the active region are seen (figure 3).

All of these active region loops, whatever their temperature, trace out magnetic field lines. Plage appears at their footpoints, where the loops pass through the chromosphere and photosphere. At one footpoint of each loop the magnetic field comes out of the Sun (north polarity), and at the other footpoint it goes back into the Sun (south polarity). Active regions are formed of many such bipolar pairs of footpoints connected by coronal loops, as if a large magnet was buried beneath the visible solar surface at the site where the active region appears.

The high density at which magnetic loops are packed together at their photospheric footpoints is the distinctive feature that makes active regions different from the surrounding *quiet* atmosphere. The effects of the magnetic field on the temperature and density structure of an active region depend on its strength, the relative fraction of the active region it fills (compared with non-magnetic regions) and its topology, i.e. how each point is connected to another. In chromospheric plage—the bright areas that can be seen in figure 2 both scattered around the quiet Sun (two examples shown) and within the active region itself—magnetic loops are packed 10–100 times more densely than in the quiet Sun. In SUNSPOTS, loops are packed so tightly that there is no significant amount of unmagnetized gas, which inhibits the flow of heat by convective motions and makes sunspots cooler and darker than their surroundings. Finally, irregular dark strands of gas called solar FILAMENTS form where the magnetic field lines dip to form valleys in the corona that can hold ionized gas (which cannot easily move across field lines) in clouds above the photosphere. Several such filaments can be seen in figure 2, both inside the active region and outside it, in the quiet solar atmosphere. When filaments are seen in profile at the solar limb, they are called SOLAR PROMINENCES.

Active regions come and go, and their lifetime depends to a large extent on their size. Active regions have no preferred size; they form a continuous distribution, with many more small ones than large ones. The smallest

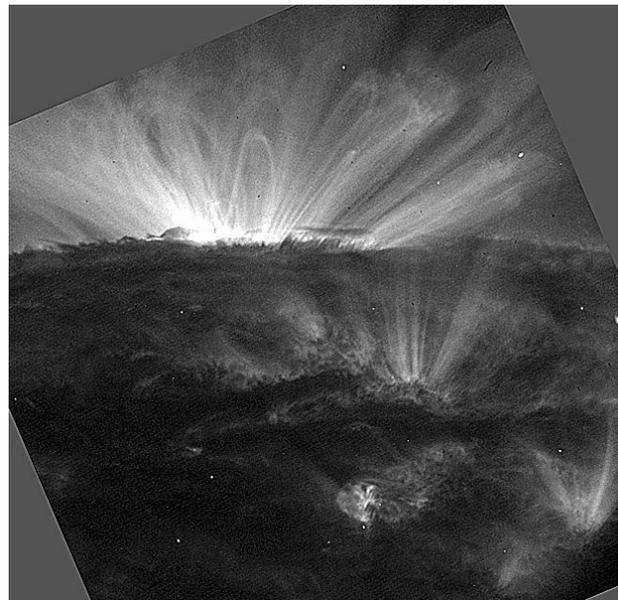


Figure 1. A small solar active region near the edge of the solar disk, seen in emission from a highly ionized Fe line emitted by gas at about 1.5×10^6 K. Photo from the NASA TRACE satellite courtesy Lockheed Martin.

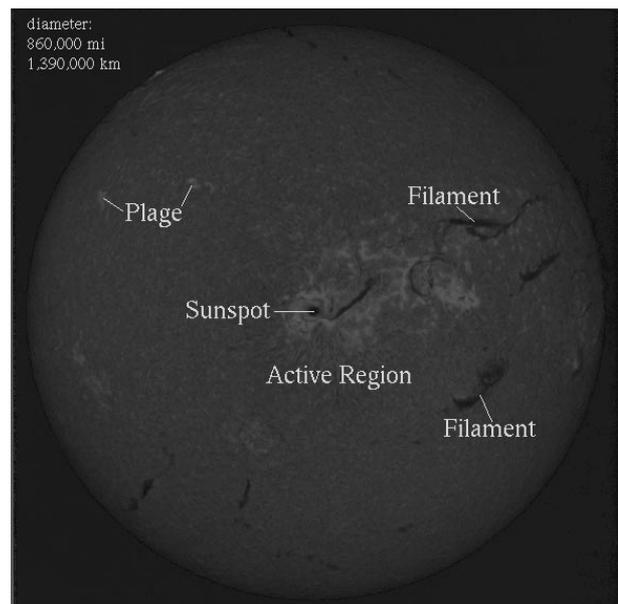


Figure 2. An image of the Sun's chromosphere in the neutral hydrogen $H\alpha$ line emitted at about 10^4 K, showing a large active region near disk center, containing sunspots, plage and filaments (labeled elsewhere on the disk). Photo courtesy the National Solar Observatory, which is supported by the US National Science Foundation.

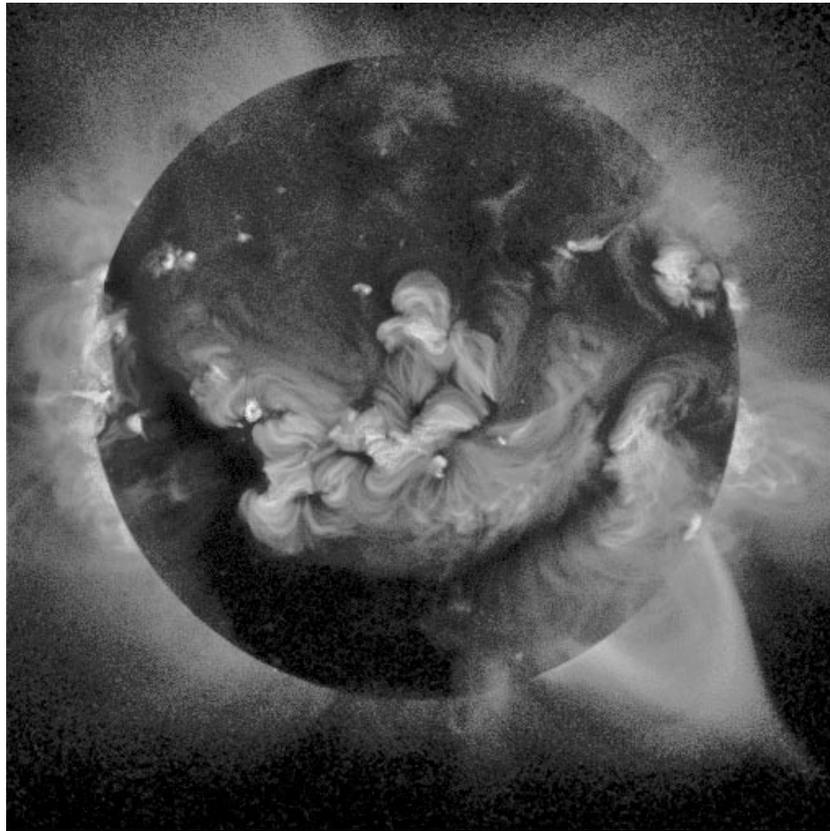


Figure 3. An x-ray image of the Sun's corona on 25 January 1992, a few years after the 1989 solar cycle maximum. Such x-rays are emitted by gas at about $(3\text{--}5) \times 10^6$ K. At mid-latitudes a huge solar activity complex, made of many solar active regions, is present. The tiny x-ray bright points seen most easily in the northern (upper) hemisphere mark the sites of ephemeral solar active regions. The prominent cusp in the lower right signals a recent coronal mass ejection. Yohkoh image courtesy L Acton, Montana State University Bozeman.

ones that can be observed depend on telescope resolution, and presumably there are many still smaller ones that have not been resolved. In the photosphere the largest and most long-lived active regions have areas in the range 50–100 000 Mm^2 , which is only 1–2% of the surface area of the Sun, but about 100–200 times greater than that of the Earth. The x-ray image shown in figure 3 illustrates the extreme range of sizes seen in the solar corona. The smallest active regions, and also the most short lived, are called ephemeral solar active regions, which are often only a few thousand km across. Several tiny x-ray bright points, which mark the sites of ephemeral solar active regions, can be seen in the northern hemisphere of the image in figure 3 (see SOLAR CORONA: X-RAY BRIGHT POINTS; SOLAR ACTIVE REGIONS: EPHEMERAL). The active regions in which phenomena such as SOLAR FLARES and sunspots occur typically fall in the size range from 10 000 to 100 000 km, and live for a month or two (one or two solar rotations). Many such active regions can be seen in figure 3. It happens that, at the time of this image, more were located in the southern hemisphere than in the northern, but that is not a general rule. At the extreme end of the distribution of sizes and lifetimes are SOLAR ACTIVITY COMPLEXES, which are made up of several

active regions. The interconnected active regions at and below the center of the solar image in figure 3 collectively form such a complex of activity.

Active regions have several interesting properties, which vary either on the 22 yr SOLAR CYCLE or the 11 yr sunspot cycle. Very few active regions, or the sunspots they contain, are present at sunspot minimum—sometimes, none at all. In contrast, near sunspot maximum, it is not unusual to find five to ten active regions on the hemisphere visible from Earth. Their emergence frequency varies by about a factor of 8, in phase with the sunspot cycle. On the other hand, the shape of the size distribution of regions does not change significantly from minimum to maximum.

The orientation of the magnetic polarity pair in active regions, with respect to the direction of solar rotation (from left to right, solar east to west, if north is up), follows what is called the Hale–Nicholson polarity law during the solar cycle. As can be seen in figure 4 one magnetic polarity tends to predominate at the leading (right) edge of all active regions in one hemisphere, whereas the opposite polarity predominates at the leading edge in the other

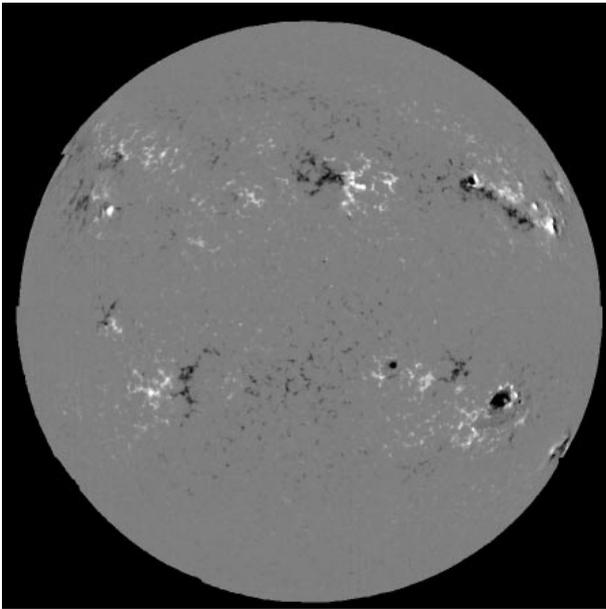


Figure 4. Solar magnetogram, 19 February 1999 at 15:17 UT. Photo courtesy the National Solar Observatory, Kitt Peak, which is supported by the US National Science Foundation.

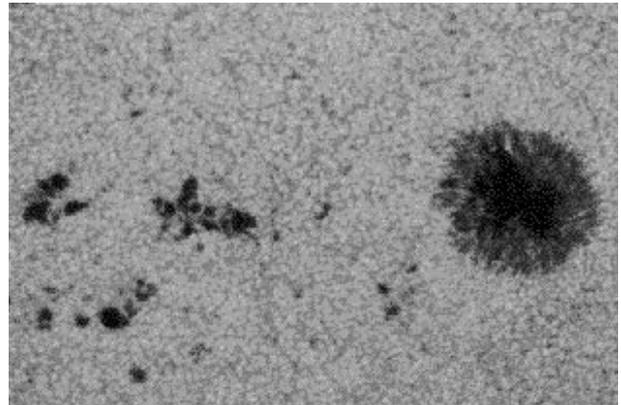


Figure 5. Sunspots are the most prominent feature of active regions in the photosphere, as seen in ordinary visible light. Photo courtesy the National Solar Observatory, Kitt Peak, which is supported by the US National Science Foundation.

hemisphere. The polarity that dominates in a given hemisphere reverses every 11 yr, repeating with the 22 yr period of the solar cycle. Interestingly, the Hale–Nicholson polarity law is only an approximation, and many regions are exceptions. These exceptions are attributed to kinks in Ω loops and buffeting of them by convective motions.

The solar latitude at which active regions emerge varies from about 60° at the start of each sunspot cycle to very close to the equator at its end almost 11 yr later. The regions that emerge at high latitudes early in the solar cycle tend to be very small—not large enough to contain sunspots, which tend not to be seen in regions above 30° or so. As the cycle goes on, the latitude of emergence proceeds toward the equator, and the size of the active regions tend to increase. This tendency for active regions to emerge at progressively lower latitudes as the sunspot cycle progresses is called Spörer’s law. There is also a tendency for the smaller regions to be spread out more in latitude of emergence, which may be attributed to greater buffeting by convection.

The spots on the leading edge of active regions tend to be closer to the equator than those that follow, so the axes of the active regions appear to be tilted with respect to the equator. Several clearly tilted regions appear in figure 4; in the north, white polarity leads and tends to be closer to the equator, and in the south, black polarity plays that role. When enough regions are studied, it becomes clear that this tilt depends on latitude, being only about $1\text{--}2^\circ$ near the equator, but increasing to $5\text{--}8^\circ$ at latitude 25° . The flux in the leading part of active regions also tends to be concentrated in fewer larger spots than the following part (see figure 4, lower right quadrant, and figure 5). This

morphology has been ascribed to the dynamics of gases in flux loops as they rise through the convection zone and expand. Gas tends to flow toward the following leg of the Ω loop, increasing its cross-section. This reduces the field strength in the following leg, making it more easily shredded into smaller strands by convection.

The rope-like magnetic field structures of active regions in the northern hemisphere tend to be twisted weakly in a left-handed sense, and those in the southern, right-handed. As a result, coronal loops in the south tend to be shaped like an S, and those in the north, the mirror image of an S. These properties, and some of the other properties described above, are thought to be determined by the forces felt by convection zone flux tubes (see SOLAR INTERIOR: CONVECTION ZONE FLUX TUBES). The fields of active regions are twisted by motions of the rising gas, which tend to rotate in opposite directions in the two hemispheres under the influence of the Coriolis force. As well, they are buffeted by strong turbulence. The same tendencies of tilt and asymmetry seen in active regions appear in emerging magnetic flux tubes (see SOLAR INTERIOR: EMERGING MAGNETIC FLUX TUBES) that have just appeared in the atmosphere after their journey through the convection zone.

Active regions are sites of strong heating of the outermost solar atmosphere (corona). Hence, active regions are much brighter than their surroundings in coronal x-ray images (figure 3). Active regions are filled with coronal loops, which outline magnetic field lines along which the ionized coronal plasma is forced to move. In active regions, magnetic fields are very strong, ranging from roughly 1000 to 3000 G. These fields are about 10 000 times stronger than the 0.3 G field of the Earth at the equator. In a mature active region, the amount of magnetic flux (the product of the strength of the magnetic field and the area it covers) ranges from 10^{19} to 5×10^{22} Mx. These magnetic fields carry currents—as much as 10^{12} A. In comparison, a 100 W light bulb carries a current of about 1 A. Nevertheless, it is not understood just how the vast

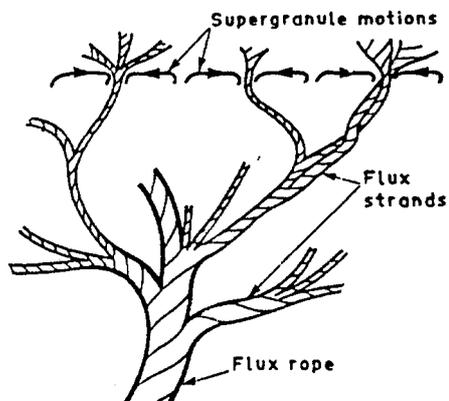


Figure 6. The tree-like structure of an active region thought to exist below the photosphere. Adapted from a figure by J H Piddington.

amounts of energy contained in these currents is converted into coronal heating, solar flares or coronal mass ejections (see SOLAR CORONAL MASS EJECTION).

Active regions—photosphere to corona

Active regions extend from below photosphere far into the corona. The physical conditions change dramatically over this range. In and below the photosphere, the gas is so dense that its turbulent motions push the magnetic fields around. Such motions serve to break up the magnetic fields into bits and pieces outside active regions, as well as to concentrate magnetid fields in individual dark sunspots and SUNSPOT PORES within them. Active regions are surrounded by brighter granular areas which are almost field free (figure 5). As one goes higher in the solar atmosphere, the density of the gas falls off more rapidly than the strength of the magnetic field. In and above the chromosphere, the magnetic field can no longer be forced to move by the flow of the gas, and it spreads out to fill all space. Hence, the appearance of active regions is much different in the photosphere, where kinetic and thermal terms dominate the energy budget, from in the chromosphere and corona, where the magnetic field is more important.

At some depth below the visible surface convection zone flux ropes are shredded into smaller strands, as envisioned in figure 6. Motions within granules, supergranules and perhaps even larger structures (see SOLAR PHOTOSPHERE: GRANULATION; SUPERGRANULATION) push these strands around to form the sunspots and pores of an active region, such as those shown in figure 5. Our present knowledge of the subphotospheric structure of active regions is fuzzy, since the techniques of helioseismology that tell us about this structure do not have high enough spatial resolution. The main reason for believing that the structure has such form is the appearance of the active region in the photosphere shown in figure 5. This appearance typically evolves from many tiny pores early

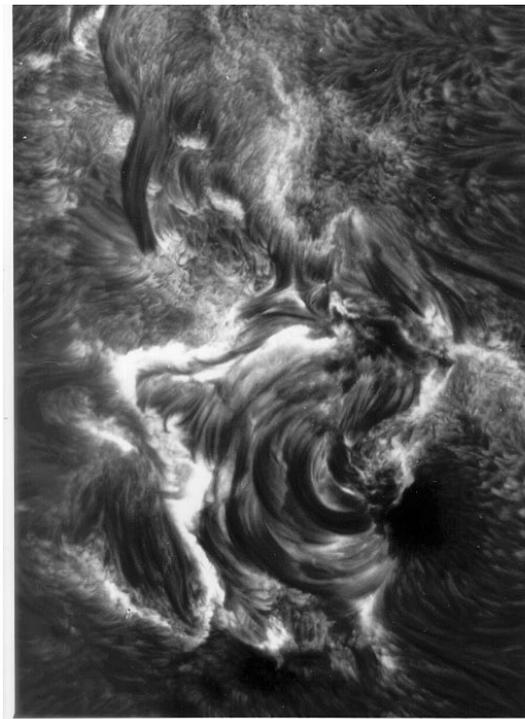


Figure 7. The graceful structures of an active region in the chromosphere, consisting of loops and swirls connecting magnetic features in the underlying photosphere. Sunspots, as they appear in the chromosphere, can be seen in the lower part of the active region. Photo courtesy R Muller, Pic du Midi Observatory.

in the region's life to large spots (in the leading polarity) when it is fully developed. This is understood as the consequence of the gradual rising and emergence of the tree-like structure of figure 6.

In the chromosphere, imaged in the hydrogen $H\alpha$ line in figure 7, the structure of the active region consists primarily of magnetic loops, which are the continuation of the flux strands into the upper atmosphere from below. Such loops show up in a hydrogen $H\alpha$ image only where the atmospheric conditions are just right for hydrogen gas to be partially ionized. The temperature in this part of an active region is typically about 10^4 K, and extends a few thousand km above the photosphere. The important aspect of such $H\alpha$ images is that the structures seen in them outline the magnetic field, since the ionized gas must follow magnetic field lines. Generally, $H\alpha$ images are more useful for revealing the connections of the magnetic field than for measuring the temperature or density of the gas—brightness in an $H\alpha$ image has little to do with these thermodynamic variables. An exception is at the footpoints of hot coronal loops, visible in x-rays and not in $H\alpha$. Their presence in the corona, overlying the chromosphere, is reflected in the very bright areas that wind through the lower left-hand part of figure 7. In these regions the chromosphere is unusually hot and dense

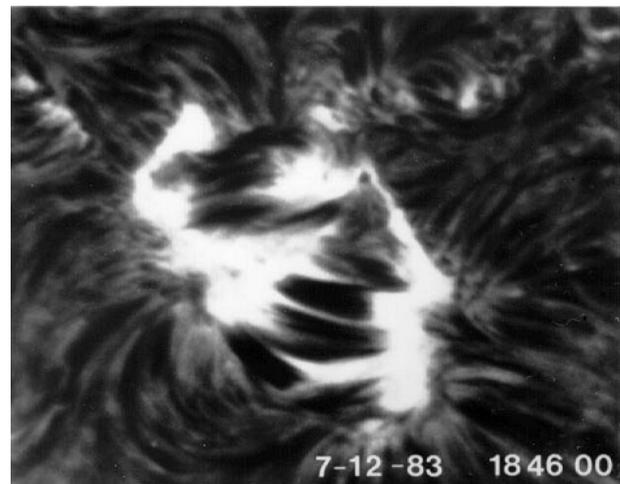
because the overlying arcade of coronal loops that has its footpoints there is also hot and dense. Such active region coronal loops, those with temperatures of several times 10^6 K, appear prominently bright in each of the many active regions in figure 3. Other loops, somewhat cooler, appear in images made in light from spectral lines radiated by ions formed at lower temperatures around 10^6 K, such as that of figure 1.

Evolution of active regions

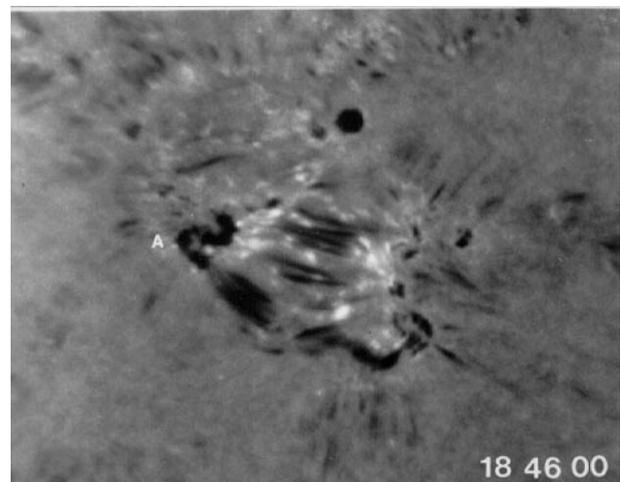
Active regions are born when strands of magnetic flux emerge into the visible atmosphere from the solar interior. Sometimes flux continues to emerge for as long as 5–7 days, and the active region grows to large size; at the other extreme, flux stops emerging so quickly that observers never even notice the small active region before it vanishes. The shape and brightness of the region depend on both the rate and location of emergence of this new flux and the manner in which it reconnects with the pre-existing magnetic fields. After a lifetime that varies up to a few months, the active region is gradually dispersed by convective motions differential rotation, meridional motion, and magnetic reconnection.

The first indication of an emerging active region is the appearance of bright chromospheric plage in $H\alpha$ and tiny sunspot pores in visible light. Pores of opposite magnetic polarity are soon seen to be connected by chromospheric loops called arch filaments, which appear as dark linear features in line-center $H\alpha$ images. The curvature of these features, which are the projections of three-dimensional arches, depends on the angle with which they are viewed. An arcade of several such arch filaments, with bright chromospheric plage at their ends, can be seen in figure 8 (top). These arch filaments are the portions of strands of magnetic flux that are just now emerging into the visible atmosphere, and the pores seen in figure 8 (middle) are the cross-section of these strands where they pass through the photosphere. The image in figure 8 (middle) is made in the blue wing of the $H\alpha$ line. The chromosphere at this wavelength is transparent when no line-of-sight motions are present, allowing the pores in the underlying photosphere to be seen clearly. However, at the tops of arch filaments, absorption can be seen, as a consequence of Doppler blueshift from their rising motion.

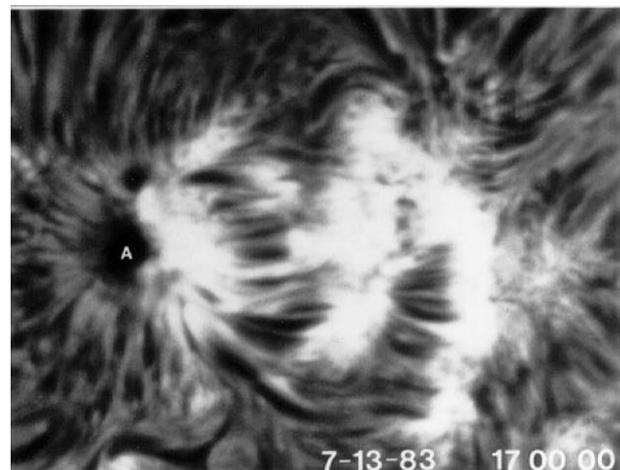
As flux continues to emerge in an active region, pores and small spots tend to coalesce into larger spots, implying that the thinnest flux strands in figure 6 are now above the photosphere, and larger strands of the lower part of the flux rope are now emerging. As long as flux emergence continues, arch filaments can be seen. Often new flux emerges amidst old flux, so only part of the region shows obvious arch filaments, as in the lower part of the region shown in figure 8 (top, middle). The distance separating the opposite-polarity spots of the active region increases. This growth of the active region shown in figure 8 can clearly be seen by comparing the bottom panel of the figure with the two above it, taken a day earlier. Bright loops of comparable size (not shown) can often be seen in x-rays,



(a)



(b)



(c)

Figure 8. An emerging flux region: (top) early stages, $H\alpha$ line center; (middle) early stages, $H\alpha$ blue wing; (bottom) 1 day later, $H\alpha$ line center. Courtesy H Zirin, Big Bear Solar Observatory.

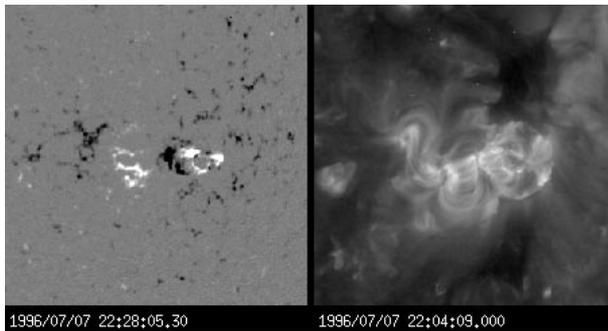


Figure 9. Co-aligned images of the photospheric magnetic field (left) and coronal loops (right) in an active region that has reconnected with its surroundings. Courtesy B Thompson, NASA/ESA Solar and Heliospheric Observatory.

overlying the chromospheric arch filament system seen in $H\alpha$.

The next phase of the development of an active region is the reconnection of the magnetic fields of the bipole with the ambient fields into which it has emerged. The structure that forms as a result of this reconnection is shown in figure 9, in which a small active region is seen in projection on the solar disk. To understand that structure, it is useful to compare the co-aligned photospheric magnetic field map (left) and projected coronal loop image (right). The polarities in the magnetic field map (toward and away from the viewer) are indicated by black and white; where the field is weak, the map is gray. Note that a strong and compact bipole is present just to the right of the center of the map—black on the left, white on the right. The coronal image shows that the black and white regions of the magnetogram are connected to one another, as one would expect from an emerging bipole. However, there are also prominent connections of the bipole to surrounding regions, forming a structure variously called a pinwheel, anemone or fountain. These loops are formed by reconnection of the bipole, after its emergence, with its surroundings.

The lifetime of active regions, the period for which they can be seen to be bipolar, has no unique or typical value. The most short-lived regions, called ephemeral active regions, and the most long-lived complexes, in which one active region may emerge within another, are discussed elsewhere. Ordinary active regions, as seen on these pages, live from a few days to a few months. The end of the lives is determined by the dispersal of their magnetic flux by convective motions, differential rotation, meridional flows and magnetic reconnection. Bits of magnetic flux break off from the edge of a decaying active region, like icebergs from a glacier. Such moving magnetic features often produce surges as they reconnect with surrounding flux of opposite polarity. Those bits of flux that do not reconnect nearby may be transported great distances. Typically an irregular diagonal streak of such magnetic debris may be seen poleward of decaying

active regions. Evidence of such dispersed flux can be seen faintly above some of the northern-hemisphere regions, and below some of the southern-hemisphere regions, in figure 4. Ultimately all such flux reconnects and flows out in the solar wind; new flux in emerging active regions replaces it, and the Sun moves on to its next 22 yr cycle.

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