Chapter 2

The Solar Atmosphere

From the viewpoint of the newcomer to total solar eclipse chasing, it might be thought that the Sun simply disappears when covered by the Moon, i.e. everything goes black. However, the real beauty of the sight of an eclipsed Sun is in seeing parts of the solar atmosphere that are normally hidden. Above all, it is the solar corona that is the most awesome. While modern H-Alpha filters (see Chap. 13) can show you solar prominences on any sunny day, albeit in a weird shade of deep red, viewing the corona is still unique to total solar eclipses.

The Photosphere

Let us take a look at what our nearest star actually consists of. The brilliant solar surface which is seen when you project the Sun onto white card, or when you use, e.g. the appropriate Neutral Density 5 (1 part in 10^5 gets through with no colour bias) solar filters, is called the photosphere (a Greek-derived word meaning "sphere from which light comes"). It is tempting to think of the photosphere (Fig. 2.1) as being a solid surface below which the gaseous solar furnace resides. In fact, apart from the central core, we can realistically regard the Sun as being a huge incandescent, unbelievably hot, gas ball, up to the photosphere, at the photosphere and even beyond the photosphere. We simply see the photosphere as if it were a solid surface because it is opaque and we are looking straight through the gas that lies above it. But the Sun does not have a solid surface. It is just one big atmosphere and the parts that stretch way outside the surface-like photosphere are what we see during a total solar eclipse. If only the photosphere was transparent and astronomers could glimpse the inner machinery of the Sun! In fact, that blindingly bright impenetrable top surface is only about 400 km thick. On a globe almost 1.4 million km in diameter the photosphere is, relatively speaking, thinner than the skin of an apple. Nevertheless, it is what Earth based astronomers see and it contains the famous "rice-grain" granulation visible even in good amateur images. This granulation is the result of supersonic gas convection "bubbles", roughly 1,500 km across, bursting and cooling at the visible surface. The lines between the granules are where the cooling material sinks back down. The photosphere is not a surface in the same sense as the Earth's surface. It is merely an opaque cap on the top of the convective zone beneath. The sunspots (Fig. 2.2), so well known to all solar observers, are, perhaps surprisingly, regions on the solar surface where intense magnetic fields have reduced the energy arriving from the convective layer beneath. Sunspots are therefore considerably cooler and less

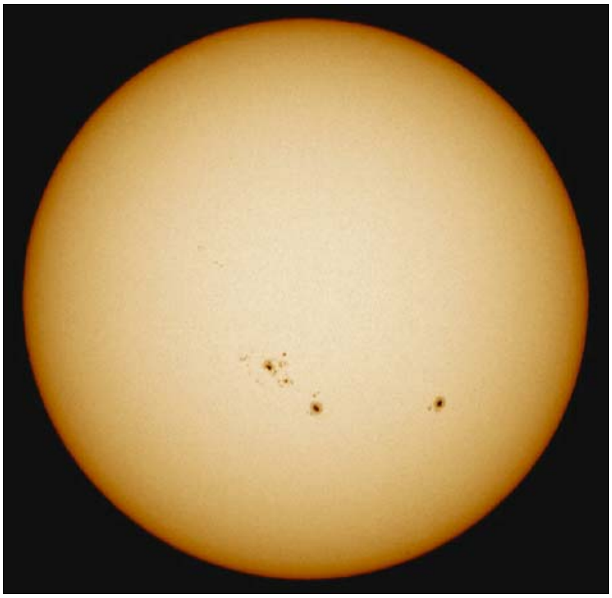

Fig. 2.1. The Sun on 21 June 2004. Vixen 80 mm f/8 Apo + Fuji S2 Pro DSLR. Baader solar filter. Image: Damian Peach

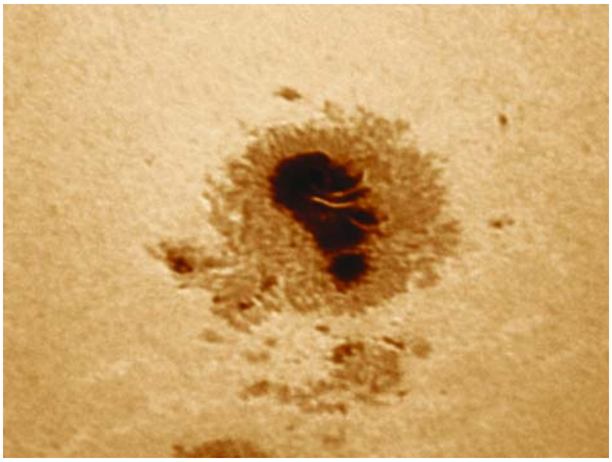

Fig. 2.2. A large sunspot on 17 July 2004. Vixen 80 mm f/8 Apo at f/45 + Atik 1HS webcam. Baader solar filter. Processed with Registax. Image: Damian Peach

bright than the rest of the visible solar surface, and their darkest parts represent the coolest and most magnetically active areas. Sunspots and the effects they generate are just like bar magnets and iron filings in those early physics lessons at school. They group together in twos, one with a positive polarity and the other with a negative polarity, usually in an east–west pairing. Magnetic arches join the two sunspots and the solar equivalent of the bar magnet's iron filings manifest themselves as so-called prominences when the Sun's rotation takes them to the solar limb. When viewed from above, i.e. in the centre of the solar disc, they appear as dark, snake-like filaments at the hydrogen-alpha wavelength.

Prominences

Prominences at the solar limb, especially when the Sun is very active, can be truly spectacular (see Chap. 11 for eclipse images of prominences). The largest prominence ever recorded was on 4 June 1946. The photographs of this event, recorded at the Climax Observatory in Colorado, amazed the scientific world. That prominence was known as the Grandaddy prominence and it extended 200,000 km above the solar surface and stretched across more than half a million kilometres of the solar limb. Such prominences are extremely rare and so the chances of a really large one being visible during the few minutes of totality at a total solar eclipse are very slim. Nevertheless, at the total solar eclipse of 29 May 1919, famous for its role in proving Einstein's theory that gravity bends light, a superb prominence was photographed by the British Eclipse Expedition led by Arthur Eddington at Principe Island (in the Gulf of Guinea, off the west coast of Africa). While not as spectacular as the awesome Grandaddy prominence of 1946 it was an awesome prominence to be seen at a total solar eclipse and nothing larger has been seen at an eclipse since. The 1919 prominence towered some 100,000 km above the solar surface. What a sight that must have been! Large solar prominences tend to occur more when the Sun is very active and Sunspot numbers are high. As we shall see shortly, the Sun has a 11-year period of activity.

Vassenius, the Swedish observer, may have been the first to describe the appearance of prominences in any detail, during a total solar eclipse in 1733. However, the observer, Captain Stannyan, observing from Berne in Switzerland, may have seen prominences 27 years earlier. When John Flamsteed presented a report of the 1706 total solar eclipse to the Royal Society, he mentioned Captain Stannyan's observations, in particular, his comment: "The Sun getting out of his eclipse was preceded by a blood-red streak of light from its left limb, which continued not longer than six or seven seconds of time." Flamsteed's comments on this observation were: "The captain is the first man I ever heard of that took notice of a red streak of light preceding the emersion of the Sun's body from a total eclipse. And I take notice of it to you because it infers that the Moon has an atmosphere." However, speaking as someone who has witnessed five totalities it sounds to me as if Stannyan may well have been describing the Sun's chromosphere (described shortly), as that also could be described as a red streak emerging for a few seconds before the solar photosphere. Vassenius, possibly influenced by the ideas of the time (and maybe even Flamsteed's comments of 27 years earlier) thought the prominences were a lunar phenomenon too. After the August 1868 eclipse, Lockyer (England) and Janssen (France) worked out on how to observe them spectroscopically, even when an eclipse was not in progress.

Although the sunspots, visible in white light, are cooler than the surrounding photosphere they are still very hot and as bright as an arc lamp, in real terms. Their darkness is just a relative effect. The temperature of the photosphere is typically about 5,800 K compared to around 3,500 K for a sunspot. The region surrounding a sunspot can appear bright, especially when a spot is near the solar limb, as seen in white light. These regions are called faculae. In narrow-band H-Alpha filters large regions of the solar disc, surrounding sunspots, can appear white; these features are called plages and are in the thin layer just above the photosphere called the chromosphere (shown in Fig. 2.3).

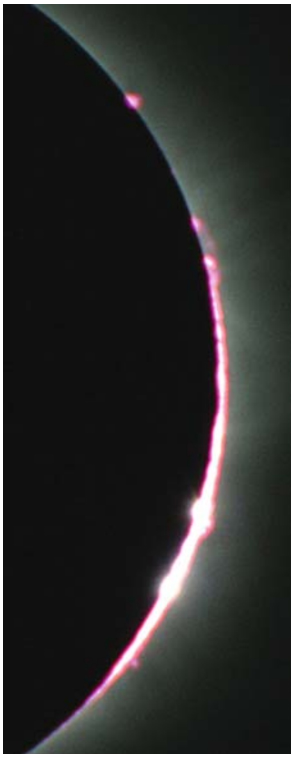

Fig. 2.3. The solar chromosphere is briefly visible at second and third contacts during total solar eclipses. This image (1/500 at ISO 400) was taken at third contact on 29 March 2006 using a Canon 300D digital SLR and Celestron C90 (90 mm aperture f/11). Image: M. Mobberley

The Chromosphere and Spectral Lines

Features in the chromosphere can be observed at deep red hydrogen-alpha wavelengths (6,563 Å) or in the violet wavelengths of singly ionised calcium (3,933 and 3,967 Å). In passing I would just like to digress and clear up a point here that confuses many non-physicists. You may well ask, "What the hell has calcium got to do with the Sun?" Looking at the Sun at the wavelength of hydrogen-alpha seems quite reasonable; after all, the Sun consists mainly of hydrogen. But I think most people will automatically associate calcium with teeth, bones and milk. So what on Earth is that element's connection with the Sun! Although most amateur astronomers have some appreciation of the fact that elements can be identified as vertical lines in a star's spectrum, a brief explanation of the origin of spectral lines may not be inappropriate at this point. A bright hot star emits radiation across the electromagnetic spectrum, and when an optical prism, a diffraction grating or even raindrops are used to disperse the light into its component colours, we see the standard rainbow colours from red to violet. However, when the light in question has passed through a gas on its way to us, photons may be absorbed by electrons orbiting the atomic nuclei in the gas and the electrons will then jump up a discrete orbit level as they absorb photons. This absorption leads to dark lines appearing at discrete wavelengths in the spectrum. If I want to be totally accurate here I would have to admit that when photons are absorbed and an electron moves to a new energy level, the electron eventually returns to its original level, re-emitting a photon. So you might think the effect would cancel out. In fact, because the photons can be re-emitted in any direction but were absorbed while heading straight for us, there is a net dimming of the overall light, i.e. the dark absorption line.

The opposite effect occurs when the gas is being excited by some energy input. In this case the electrons may jump down a discrete orbit level as they emit photons. This emission leads to bright lines appearing in the spectrum. The well-known Balmer series of hydrogen atom orbit transitions give rise to lines in the visible part of the spectrum and correspond to electron transitions between the second orbit level and higher orbit levels. It was only with the development of quantum physics and probabilities that the discrete allowable orbits were fully understood.

Using narrow-band filters to study the Sun at specific wavelengths shares the above principles. At the frequencies corresponding to these orbit transitions a great detail of contrast can be seen and, depending on the frequency, a different layer of the star's atmosphere can be studied. Of course, if an orbit transition results in absorption or emission outside the waveband that our eyes are sensitive to then we cannot see it. The same applies to CCD detectors although their spectral range is slightly wider than that of the eye. It just turns out that the corresponding hydrogen-alpha and calcium wavelengths are the two frequencies for our Sun that are within that region. However, you may still have some suspicions about calcium, despite what I have just said. After all, it surely cannot be a major constituent of the solar atmosphere. Dead right! In fact, there is estimated to be almost half a million times more hydrogen than calcium in the Sun. However, the strength of absorption by a certain element is dependent not only on the amount of a particular element but also on its absorption efficiency. Hydrogen has low-absorption efficiency (dependent on electron availability and the likelihood of absorption when a photon whizzes by), whereas calcium has a very high absorption efficiency and the line(s) produced are still within the human visual range, although well into the violet region.

Anyway, just to repeat my sentence of a while back, features in the chromosphere can be observed at deep-red hydrogen-alpha wavelengths (6,563 Å) or in the violet wavelengths of singly ionised calcium (3,933 and 3,967 Å). Today, narrow-band filters revealing only these wavelengths are well within the financial reach of the keen amateur.

The chromosphere (from the Greek *chromos* meaning colour) lies immediately above the Sun's visible surface (the photosphere). Even with appropriate filters it is not normally visible to observers but, at total solar eclipses it is visible for a matter of seconds just after the last brilliant point of the photosphere disappears (second contact) and just before it reappears (i.e. just before the so-called "diamond ring" effect at third contact). Visually it has a vivid pinky red colour and appears as a dramatic curved line just above the lunar limb at the point where the photosphere will emerge. The chromosphere has a depth of about 2,500 km so it is considerably thicker than the photosphere although still only a skin on the apple. Ultra-high resolution images at hydrogen-alpha wavelengths show that the outer edge of the chromosphere, when looked at from a shallow angle, i.e. the foreshortened limb view, resembles a spiky mountain range. Indeed, the spiked extensions are actually called spicules. These spicules are short-lived jets of gas (they only live for a matter of 5 or 10 min), travelling out from the main body of the chromosphere. They can shoot up to more than 10 km in height (so the mountain peak analogy is valid) and then fall back to the average chromosphere surface, just a few minutes later. In the best images they resemble mountains of iron filings on a sheet of paper with a bar magnet underneath. Indeed, solar physicists think that the spicules may be involved in conveying magnetic fields out from the Sun to heat the next region of the solar atmosphere, the corona.

The Solar Corona

Unlike the photosphere and the chromosphere the solar corona (Fig. 2.4) is not limited to a thin skin-like surface on top of the seething cauldron of energy, we call the Sun. The corona extends to millions of kilometres into space and is the most awesome sight to behold during the totality phase of a solar eclipse. I have heard the black disc, nestling within the electric blue corona, described as looking like the eye of God. (In case you are getting confused, the different components of the Sun are labelled in Fig. 2.5.) While the Sun does not have a solid surface, and even the white-light visible photosphere is really gaseous, the corona actually does look gaseous when viewed at totality. Most first-time eclipse watchers, technically known as "eclipse virgins", are amazed at the brightness of the inner corona. My first

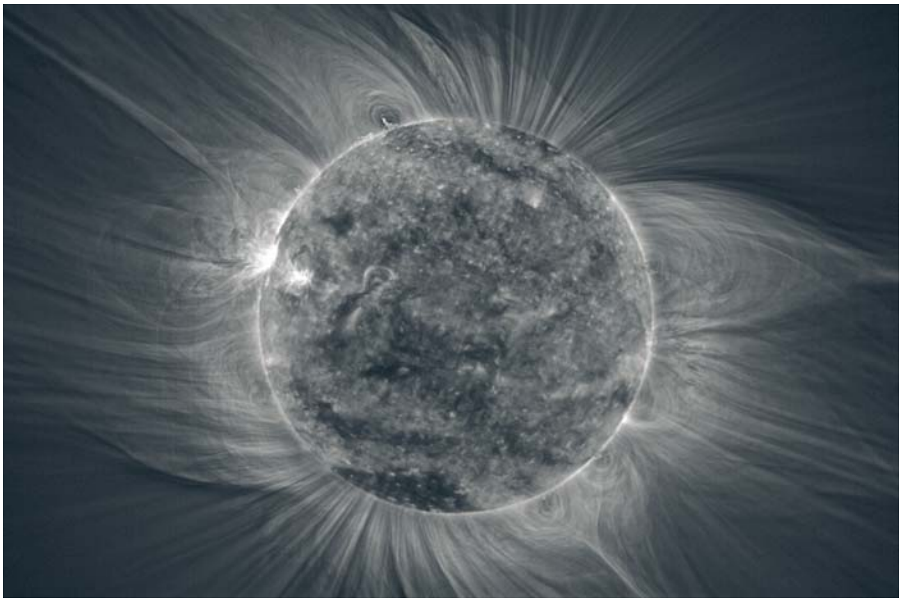

Fig. 2.4. This is a composite of the solar corona and disc at the time of the 29 March 2006 total solar eclipse. It is probably very similar to the visible appearance which would be seen if it was possible to completely switch off the dazzling solar photospheric radiation. The image was created from a series of fine eclipse images by Peter Aniol, expertly processed by Miloslav Drückmuller. The black disc of the Moon has been replaced by a SOHO EIT 17.1 nm image (Fe IX/X) taken 20 min after the eclipse images were taken in Libya. The corona images from Libya were taken with a 100 mm aperture f/8.2 Takahashi ED refractor with a 2x converter, giving f/16.4. A Canon EOS 5D II digital SLR at 100 ISO was used for the 60 exposures which ranged from 1/1000 to 4 s © 2006 Miloslav Druckmüller, Peter Aniol, ESA/NASA.

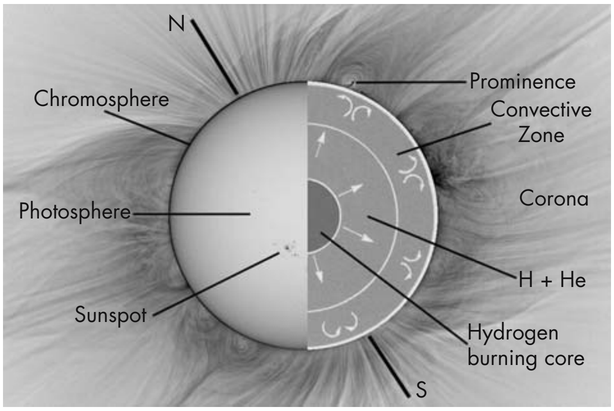

Fig. 2.5. The Sun and its internal and external components, a labelled composite of Figs. 2.1 and 2.3. Nuclear reactions on an enormous scale take place in the centre of the Sun, the core of which is thought to be at a temperature of some 15 million Kelvin. Energy flows out from the centre and supports the enormous mass of the outer layers. Just below the visible surface lies the convective zone. The blindingly brilliant yellow surface which we see (when filtered by 100,000 times with safe solar filters) is called the photosphere and is often peppered with sunspots, especially near solar maximum. Above the photosphere is the thin chromosphere seen at total solar eclipses at second and third contacts (see Fig. 2.4). The photosphere has a temperature of roughly 5,500 K. Prominences arching above the limb of the Sun can be seen at total eclipses or when using suitable hydrogen-alpha filters. Stretching out from the Sun and only visible at total solar eclipses is the tenuous solar corona which has the mind-boggling temperature of 1 million Kelvin.

glimpse of it was for a split second at the 1991 total solar eclipse in Hawaii. Essentially, I was clouded out, *but* as the cloud thinned for a split second there was the merest fleeting glimpse of a dark circle surrounded by a white ring. That was all I saw, but my immediate (and absurd) instinct was "they've got it wrong, this is an annular eclipse!" Admittedly, I was viewing the eclipse through cloud, but I was confused by the bright ring around the Moon. Even the inner corona only glows at a level of a million-fold below that of the solar surface but this is bright enough for it to dazzle like the full Moon. The corona is bright because it, or rather the free electrons within it, scatters the intense light of the Sun. Obviously, its intensity fades as one moves further from the blindingly bright photosphere, but even the human eye can trace the solar corona out to a distance of four or five solar radii beyond the lunar limb. In fact, the most tenuous extremes of the solar corona spread throughout the solar system. Astronomers call the point where our Sun's solar wind hits the cooler background of the interstellar medium, the heliopause and this is currently estimated to lie about 23 billion km from the Sun. Of course, the corona we see at a total solar eclipse is only a few million kilometres from the Sun. Its intricate gossamer structure is, once again, all tied up with the intense solar magnetic fields. It may come as something of a surprise to learn that the corona has a very high temperature, much higher in fact than the photosphere and chromosphere. This seems at odds with common sense. How can a tenuous region of gas so far from the solar centre have a higher temperature than the actual solar surface? It is important to remember here that there is a huge difference between the definition of temperature and heat capacity in the physical world. The temperature of a gas is determined by its average kinetic energy; in other words, the speed that the particles are moving is critical. Indeed, the kinetic energy is proportional to the speed of the particles squared. Gas at a low temperature will not have the energy to stray far from the immense gravitation at the surface of the Sun. So the very fact that we can trace the corona out to great distances tells us that the particles are moving at huge speeds and therefore are, by definition, at a very high temperature. In fact, the temperature of the corona is a staggering one million degrees, more than two orders of magnitude than that of the visible photosphere. In passing, it is worth mentioning that physicists and solar astronomers, even up to the Second World War, were so confused by the spectrum of the solar corona that they thought it might be made of a new element, coronium. It was only when Edlén and Grotrian proved that the coronal emission lines were caused by ordinary elements deprived of a dozen or so electrons per atom that coronium was resigned to history. Why were they deprived of so many electrons? Well, simply because at a million degrees, many electrons escape from their atoms and electrons in the corona are moving so quickly that they will dislodge other electrons from their atoms when they collide. The corona is at such a high temperature that it actually emits most of its energy as X-rays, i.e. high-energy photons. This is why instruments onboard the highly successful SOHO spacecraft (http://sohowww.nascom.nasa.gov/) were designed to observe the Sun in X-rays. But even though the temperature of the corona has been verified by various scientific methods, the reason it is at a million degrees, more than 100-fold higher temperature than the photosphere and chromosphere beneath it, is still puzzling solar physicists. After all, the heat is generated inside the Sun. So, instinctively, one might quite reasonably expect the solar atmosphere to get cooler as one moves further out. The best theory is that intense and changing magnetic fields are responsible for the coronal heating. However, pinning down the precise mechanisms responsible is very difficult. One possibility is that the turbulent magnetic fields rising from beneath the photosphere might generate electric currents that flow through the corona like a battery connected to a thin piece of wire. But one thing is certain: The temperature of the corona is not due to heat rising from the solar surface. The corona is so tenuous that the vast majority of the Sun's light and heat just pass straight through it. So, at a total solar eclipse, what we are seeing when we look at the subtle and complex patterns in the electric blue corona is a tiny fraction of a percentage of the light from the Sun scattered in our direction by the coronal electrons. The intricate patterns are formed by the intense magnetic fields in the region of the Sun. The corona nearest the lunar limb is dazzlingly bright, simply because of its very close proximity to the intensely bright photosphere, but as we move outwards the corona dims and we can see the delicate structure within it. At around five solar radii from the Sun the features get increasingly subtle as the corona merges into the twilight sky seen at total solar eclipses. In fact, as we have seen, the corona extends much further than this if you have sensitive enough X-ray instrumentation to detect it.

The 11-Year Cycle

Although the shape of the solar corona is different at every eclipse, it does tend to have a different general shape depending on whether the Sun is at the peak of its 11-year activity cycle or at the solar minimum point. Solar maxima, when the Sun is very active and has hods of Sunspots on its face, occurred in 1906/1907, 1917, 1928, 1937, 1947, 1957/1958, 1968/1969, 1979/1980, 1990/1991 and 2000/2001. The period of 11 years is not all that regular though, which, personally, has always seemed a bit worrying to me. I guess my simple mind just expects something as huge and essential to life as the Sun to be a bit more trustworthy. There was a 17-year period between the solar maxima of 1788 and 1805 and just over 7 years between the maxima of 1829/1830 and 1837. However, in the twentieth century the most extreme variation was the 9 years from 1928 to 1937. Solar minima occur, not surprisingly, about midway between the maxima. At the start of a new solar cycle, i.e. just after the minimum, the first sunspots appear at latitudes of roughly between 30° and 45° (both sides of the solar equator). Eventually, spots occur nearer to the equatorial regions and the average sunspot latitude at maximum is about 15°. The spots then die out, before they reach the equator and even as the last spots disappear the higher latitude spots of the old cycle begin. The whole cycle can be illustrated nicely with a so-called "Butterfly Diagram", invented by Maunder in 1904. Of course, during totality, the Sunspots can never be seen. However, during the partial phases it is always nice to have a few big sunspots to measure the Moon's progress across the disc with reference to.

The number of sunspots on the disc is the white light solar observer's indicator of where we are in the solar activity cycle. It is also an indicator of how the magnetic activity is taking place over the solar surface. However, for eclipse chasers the shape of the corona is usually a very reliable indicator of solar activity too. At solar maximum the corona extends all around the solar disc, at every angle, from the sun's poles through the solar equator. But there are usually no ultra-long thin coronal streamers. Conversely, at solar minimum, there tend to be wide, long, and obvious east–west streamers, i.e. streaming out in a long thin plane parallel to the solar equator. The corona is no less spectacular at solar minimum, it just looks as if all the magnetic energy is being funnelled into making the equatorial streamers.

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