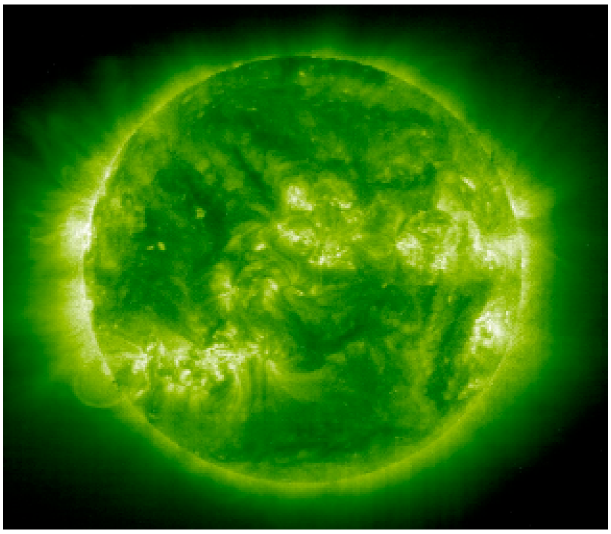
The Sun, Source of all our Energies

Rafael Bachiller

Directly or indirectly, the Sun is the source of all our energy. Solar light, assimilated in photosynthesis, is transformed into plants, and plants are the basic food of many animals. Thanks to the decomposition of plants and other living beings millions of years ago solar energy has been stored away in the form of fossil fuels (coal, oil and natural gas). The Sun is also the cause of many other energy-based phenomena on Earth, such as the wind in the atmosphere and the currents in the oceans. Nuclear energy generated on Earth originates from elements created either at the core of the Sun or at the core of some other star. Earth itself, along with other planets of the Solar System, is nothing more than a product, a "secondary" product in fact, created during the formation of the Sun.

What is the Sun? What is so special about it? How does it work? How was it formed? How long will it last? Where does its energy come from? How much energy do we receive from it?



Solar iron. This image of the Sun taken by SOHO in September 2001 shows the emission of eleven times ionised Iron atoms (known as Fe XII) which shoot across regions of the solar crown where the temperature can exceed 2 million degrees. Courtesy: SOHO (EIT consortium), ESA, NASA.

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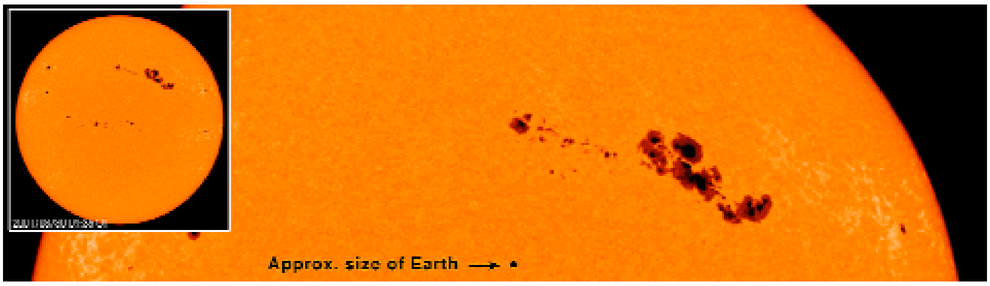

Group of sunspots observed on 30 March 2001 (near the maximum for solar activity). These sunspots caused numerous fulgurations. For the sake of comparison, the size of the Earth is indicated. Courtesy: SOHO, ESA, NASA.

A commonplace star. A unique star

The Sun is a commonplace star located in a commonplace galaxy. Technically speaking it is a G2V star. That is a quick way of saying that it is a yellow, dwarf star, with a surface temperature of around 5780 K.[1] It is essentially composed of hydrogen (74 per cent of its mass or 92 per cent of its volume) and helium (24.5 per cent of its mass or seven per cent of its volume), plus trace quantities of other elements, including iron, nickel, oxygen, silicon, sulphur, magnesium, carbon, neon, calcium, and chromium.

The Sun is located some 26,000 light-years from centre of the Galaxy (which has a radius of 60,000 light-years), in a region which does not appear to contain anything special: the inner rim of the Orion Arm. The Sun moves through the Galaxy at a speed of 214 kilometres per second, which allows it to travel a light-year in distance every 1,400 years. There are around 200,000 stars in our Galaxy, the Milky Way, of which more than 100 million are of the G2 type. And although most (85 per cent) of the Milky Way stars are red dwarves, less bright than the Sun, our Sun is a million times less luminous than the most luminous stars of the Milky Way. And ours is nothing but an average galaxy in the thousand million galaxies that have been observed in the universe. Hence, from an astronomical standpoint, the Sun is a small lost star in a galaxy that does not appear to contain anything special.

But to the planet Earth and its inhabitants, the Sun is a unique star: our star. The Sun totally dominates practically all activity on Earth. During the day, the Sun makes all other celestial bodies pale into insignificance, its blinding light preventing anyone from looking at it directly. The Sun has undoubtedly been an object of curiosity and study for all civilizations. Many ancient communities regarded it as a god and dedicated monuments and observatories to its glory and study. One of the most famous is Stonehenge (Wiltshire,

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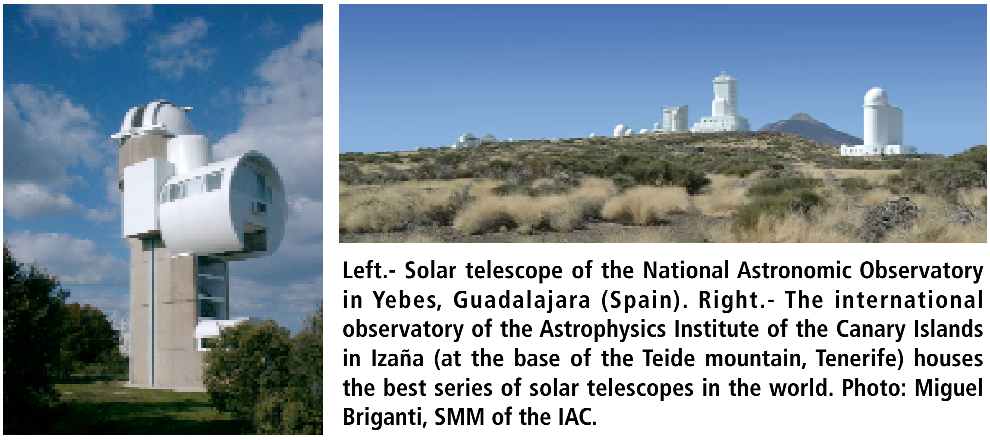
[1] Kelvin (K) is the base unit of temperature, starting with -273 degrees Celsius, absolute zero.

United Kingdom), erected between 2800 and 1500 BC. Throughout the whole world, in places such as Egypt, Greece, America, the Far East, etc, there are countless examples and curiosities which illustrate the rightful fascination with, and acknowledgement of the light and warmth provided by the Sun as a source of life and energy on Earth.

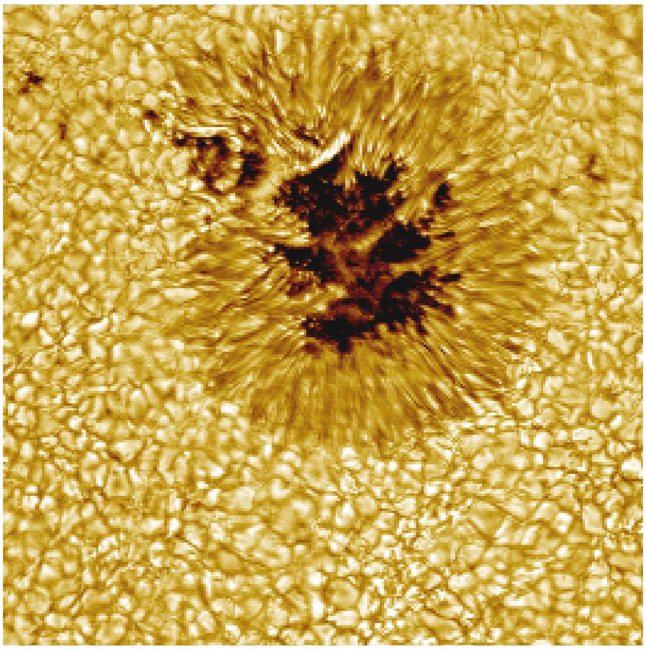
Although to astronomers the Sun seems an anodyne star, similar to so many others, it is difficult to find stars that can be considered twins of the Sun. Some astrophysical applications (calibration) consider such twins important because the Sun, although the standard for certain measurements, is too near and too bright to calibrate our instruments. Detailed studies of stars identical to the Sun have given unsatisfactory results. Until now, the stars considered most similar to the Sun are 18 Scorpii (HD142633) and HIP56984. 18 Sco is similar to the Sun in many aspects but differs in others. For example it contains an abundance of lithium three times that of the Sun. HIP56984, however, appears identical to the Sun in terms of precise measurements. This star, located some 200 light-years away from the Sun, has the same age as our star and is thus an excellent candidate on which to concentrate the search for planets similar to the Earth and for life.



Left.- Solar telescope of the National Astronomic Observatory in Yebes, Guadalajara (Spain). Right.- The international observatory of the Astrophysics Institute of the Canary Islands in Izaña (at the base of the Teide mountain, Tenerife) houses the best series of solar telescopes in the world. Photo: Miguel Briganti, SMM of the IAC.

Energy generation in the Sun

Contrary to what Anaxagoras believed, the Sun is not an incandescent stone, but an incandescent sphere of gas. Specifically, the core of the Sun, that is to say the part that extends from the centre to 0.2 solar radii, has an extremely high temperature (some 15 million degrees centigrade) and is in fact an immense nuclear reactor. In the Sun's central zone, hydrogen atoms fuse together to form helium atoms. Helium is a noble gas that was detected in the Sun before it was disco-



This is a high resolution image of a sunspot immersed in a granulated structure on the solar surface. Each granule is 1,000 km long and lasts some 10 minutes. These are convective gas cells that move up and down the solar surface in a movement of genuine thermal flux. Courtesy: Vacuum Tower Telescope, NSO, NOAO.

vered on Earth, which accounts for the origin of its name: from Helios, the Sun god of the Ancient Greeks. Through a series of nuclear reactions known as the p-p (proton proton) chain, every four hydrogen atoms convert to a helium one. But the conversion of hydrogen into helium destroys just a small fraction of mass (some 0.7 per cent), which converts into energy in accordance with Einstein's formula $E=m c^2$.

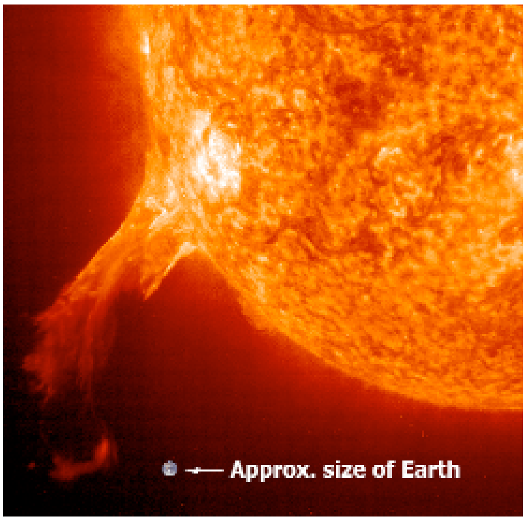
About 3.4 x 10^{38} protons are converted into helium nuclei every second, generating some 3.86 x 10^{26} watts. In other words, every second in the solar interior around 580 million tons of hydrogen gas are converted into helium, consuming some five million tons to produce 90,000 million megatons of pure energy. For the sake of comparison bear in mind that a nuclear bomb typically has several or tens of megatons of power.

The Sun, as it produces nuclear energy, becomes lighter and lighter, losing some five million tons of mass a second. In spite of this, solar luminosity remains very constant. Measurements indicate that variations in the Sun's luminosity are below one per cent (no significant variations has been noticed in the 11-year solar cycle). Although the nuclear power generated by the Sun is enormous, it should be noted that the efficiency generating energy per volume or mass is very small: just 0.3 µW/cm³ (microwatts per cubic cm), or about 6 µW/kg. For the sake of comparison, the human body produces heat at around 1.2 W/kg, which means that it is millions of times more efficient. In order to work efficiently a terrestrial nuclear fusion reactor needs to use far higher plasma temperatures than those found in the Sun's interior.

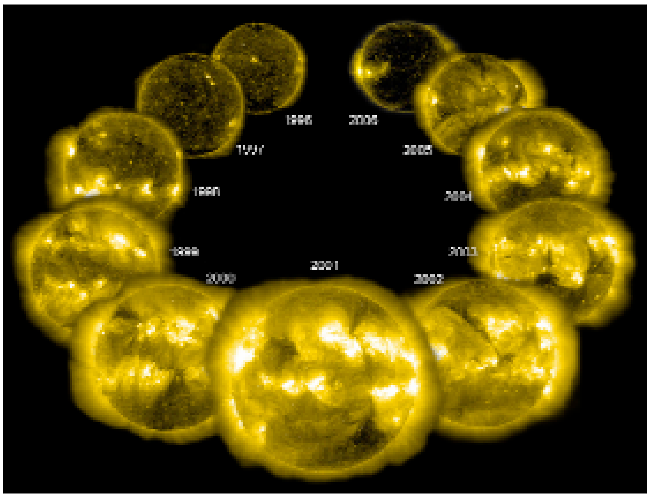
As a result of the deficit of mass which takes place during the transformation of hydrogen into helium, the nuclear reactions generate high-energy radiation. The photons of which this radiation is composed are absorbed and then re-emitted several times along the trajectory they follow from the centre of the Sun. The travel time of the radiation across the densest part of the Sun (between 0.2 and 0.7 solar radii) is estimated as ranging between 10,000 and 200,000 years. This area is known as the *radiative zone*, because energy is transmitted through it via successive absorptions and re-emissions of the radiation. However, at a distance of some 0.7 solar radii from the core, the density and temperature are not sufficiently high to continue the transfer of energy via radiation. This area is where thermal convection begins: the hot – less dense – material emerges on to the surface and cools down before it plunges back downward to the base of the convection zone. Great convective cells are formed which can be observed as the granulated structure of the solar surface. The photosphere, or visible surface of the Sun, is the layer in which photons find the free space to travel. It is about 100 kilometres thick, has a temperature of about 6,000 K, and a relatively low density of some 10^{23} particles per cubic centimetre, about 1 per cent of the particle density of Earth's atmosphere at sea level. Above the photosphere there is a thin gas known as *solar atmosphere*, which is composed of various layers: the chromosphere (inner layer), the corona, and the heliosphere (outer layer).

Spots and fulgurations

The ionised material that circulates around the solar globe forms a complicated network of electric currents that are, in turn, the source of magnetic fields. The rotation and upward and downward movements of the convection serve to compress the magnetic lines at certain points and elongate them in others. Sometimes these magnetic lines cross the surface of the Sun, forming loops in which the lines of force emerge in an area of positive polarity and submerge in another area of negative polarity. Due to the



Solar protuberance observed in 2002 by the SOHO space telescope in ultraviolet radiation emitted by the helium atoms. For the sake of comparison, the size of the Earth is indicated. Courtesy SOHO (EIT consortium), ESA, NASA.



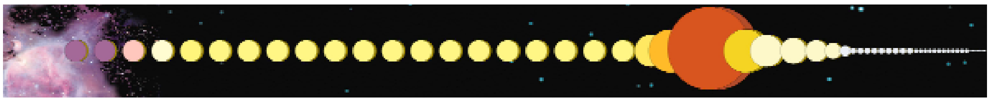
The SOHO space telescope, in orbit around the Sun, took images of our star during one of its 11-year complete cycles of activity. The last maximum period of activity was in 2001, while 1996 and 2007 were minima. These images were taken in the ultraviolet extreme, where the contrast between maxima and minima is most accentuated. Courtesy: SOHO (EIT consortium), ESA and NASA.

effects of the magnetic fields, these regions are colder and thus darker, appearing as spots in the photosphere. The darkest part of these spots typically has a temperature of around 4,200 K (as opposed to the 5,800 K of the photosphere). Sunspots usually appear in pairs (a positive one alongside a negative one) and in groups, and often remain visible for several weeks. Naturally, sunspots are an easy and direct way to measure solar activity. The simplest way of estimating and noting down this activity is via the Wolf number: an expression that combines the number of individual spots and the number of spot groupings.

The number of sunspots (the Wolf number) has been measured without interruption since the start of the 18th century, but there are now estimates as to how the number of sunspots has varied over the past 10,000 years. It has been observed that solar activity periodically passes through maximum and minimum levels. The duration of this main cycle is 11 years, but there is also another long term cycle of 80 years. However, the effects that these cycles have on the Sun's total luminosity are very small. The fluctuations in intensity are barely one per thousand, so the effects on Earth are likewise considered of little importance, although the matter is the subject of further study.

Another phenomenon associated with that of sunspots is that of the immense protuberances that emerge from the solar surface. These are

Representation of the evolution of the Sun, from its formation in an interstellar cloud, passing through the main sequence phase - in which it currents finds itself, and in which it will spend most of its life - up until its transformation into a red giant and its subsequent decline into a white dwarf (drawing by F. Martín, Observatorio Astronómico Nacional).

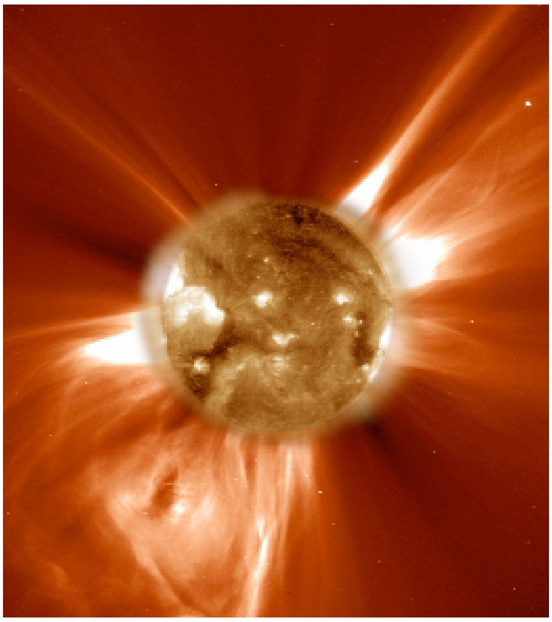


columns of ionised material of a very high temperature (deep red in colour) that can reach close to a million kilometres in height. Due to the effects of magnetic fields, these protuberances often curl to form arcs or loops above the sunspots that can last several days.

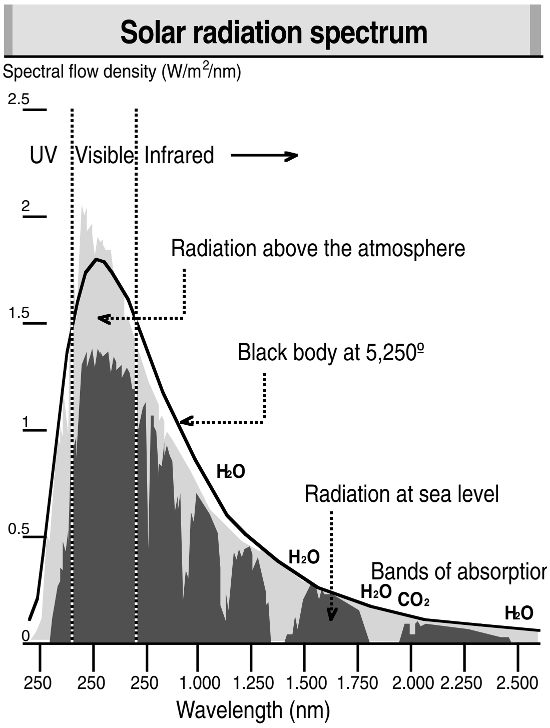
The instabilities of the magnetic fields can cause huge explosions in the photosphere. These explosions, known as fulgurations, provoke an intense emission of X-rays and gamma rays and the ejection of a wind of very high energy particles. When this rain of particles reaches the Earth a few hours later a series of truly awesome phenomena occur: telecommunications can become altered due to the effect in the upper layers of the atmosphere. Disturbances in the terrestrial magnetic fields, can disorientate our measuring instruments (compasses and similar devices) and even carrier pigeons. This interaction of solar ejections and terrestrial magnetic fields also causes the so-called aurora borealis phenomenon.

Formation, evolution and death of the Sun

The Sun is a third-generation star that was formed some 4,600 million years ago, that is, when the universe was around 9,000 years old (it is currently 13,600 million years old). The most advanced theories on stellar formation teach us that the Sun was formed in a particularly dense region of an interstellar cloud. There are myriad such clouds in the Milky Way composed of gas and dust (particles of material in solid state). The force of gravity (the weight of the cloud itself) caused the cloud to contract at a specific moment. In order to reach the typical densities observed in stars, an interstellar cloud needs to contract by a factor of 10^{20}. If the initial cloud were more or less spherical, the radius of the sphere would need to have become a million times



Ejections from the active surface of the Sun observed by SOHO in 2002. The light of the solar disc has been blocked (via a sort of artificial eclipse) and its image replaced by an ultraviolet image taken at the same time. The ejections rise up from the crown forming immense filaments and loops that end up having serious effects on Earth. Courtesy: SOHO, ESA, NASA.



The solar radiation spectrum that reaches the upper part of the earth's atmosphere is similar to that of a black body at 5,250° C (the average temperature on the solar surface). After the dispersion and absorptions that occur in the atmosphere, the radiation that reaches sea level is highly diminished in the ultraviolet (below 400 nanometres) and has an excess of blue (responsible for the colour of the "sky"). The different gases in the atmosphere (molecular oxygen, water, carbon dioxide, etc.) create bands of absorptions in the infrared (between 750 and 2500 nanometres).

smaller in its process of formation into the Sun.

The force of gravity is thus the motor of stellar formation, the cause of the high densities reached in the core of the Sun, and the mechanism via which the nuclear reactions are unchained therein. During the gravitational collapse the part of the material that is moved by a small rotation does not fall directly on to the proto-Sun, but rather it forms a disk which rotates around the central object. In the same way as a skater moves faster and faster as he tucks in his arms, the material in this disk accelerates the speed of its rotation as it nears the centre. As time passes, the material in this disk builds up with solid objects (planetesimals), which combine into larger objects to form a series of planets: the Solar System.

In a star such as the Sun, it is estimated that after around 30 million years of gradual contraction, the temperature and core density reach the required values for nuclear fusion to begin (the conversion of hydrogen into helium). The start of this fusion marks the beginning of the mature phase, which astronomers refer to as the start of the main sequence. This phase of maturity will be the longest in the life of the star, since the hydrogen (70 per cent of the total mass) is sufficient to feed the nuclear reactor for 10,000 million years. But once this fuel runs out, the Sun needs to go through some drastic structural readjustments before becoming a red giant (a huge, bright star that is also relatively unstable). After a new, but short, phase of stability in which helium acts as the nuclear fuel to counteract the force of gravity via its conversion into carbon, the Sun will succumb to gravity and convert itself into a white dwarf star that is practically inert, and will lose a fair proportion of its mass during these processes (in the form of various explosions and ejections).

The solar constant

The energy emitted by the Sun as a result of the nuclear activity in its core is something more than optical light. The spectrum (distribution in frequencies) of solar radiation is similar to that of a black-body (an ideal that absorbs all incoming radiation without reflecting anything, an ideal source of thermal radiation), at an average temperature of 5,250 K. As a result, there is as much energy released by the Sun in the optic as in rest of the spectrum (mainly the near infra red with a small contribution in the ultra violet).

The power of electromagnetic solar radiation per surface unit that reaches the Earth's atmosphere, on average throughout the year, is around 1,366 W/m2 (watts per square meter of surface perpendicular to the rays of the Sun). This amount is referred to as the solar constant. Sometimes it is expressed as 1.96 Ly/min (where Ly stands for 1 langley, that is, one calorie per square centimetre). Annual insolation (accumulated in one year) reaches a value of some 280,000 Ly, and when the attenuation of the atmosphere is taken into account, this value converts itself into approximately 150,000 Ly. These numbers, which are purely astronomical in origin, are those used to calculate the size and performance of solar energy plants. Together with the performance of the solar panels, the local insolation values are those that determine the final output of a solar energy plant.

We have seen how the Sun will unavoidably succumb to gravity when its nuclear fuel runs out and convert itself into a practically inert star, a white dwarf. During the final stages of its life, successive explosions and ejection processes will lead to a large portion of the Sun being projected into space. Once returned to the Galaxy's interstellar clouds, this material is ideal for the formation of new stars. In time these interstellar clouds will contract and repeat the complex process of stellar formation to create a new generation of suns (as we have mentioned, our Sun is itself a third-generation star). This is the great cosmic cycle via which stars are born, evolve, die and are reborn. The death of stars, when a large part of stellar material is ejected into space, in turn brings with it the possible birth of new stars.