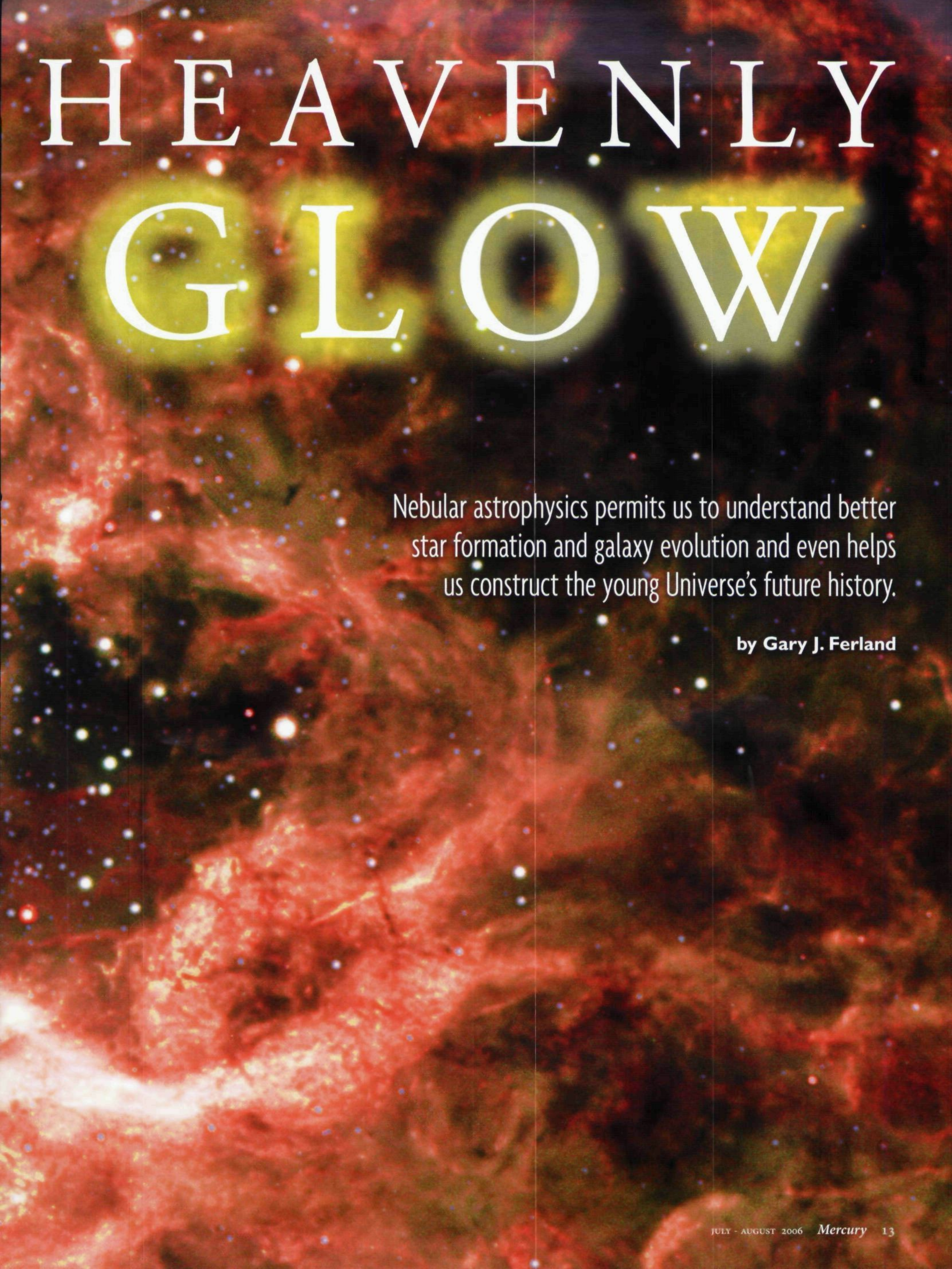
Three-color image of the Tarantula Nebula in the Large Magellanic Cloud. Image courtesy of ESO; image data were extracted from the ESO Science Archive and processed by H. Boffin (ESO).



HEAVENLY GLOW

Nebular astrophysics permits us to understand better star formation and galaxy evolution and even helps us construct the young Universe's future history.

by Gary J. Ferland

In the next decade we will see the construction of ever larger telescopes, making it possible to observe carefully newly forming galaxies at the very edge of the Universe. And methods of spectroscopic analysis now being used to probe the nebulae, such as Orion or the Crab, will be used to follow the births of galaxies. Because a wealth of information can be derived from studies of hot and cold interstellar clouds, let's examine some of the basic physics that occurs in an interstellar cloud and show how such fundamental properties as the composition, temperature, or star formation rate can be determined.

Understanding our origins is one of the most fundamental questions science can answer. Today we have a fair picture of from where we came. The hydrogen in the water in our bodies was created in the Big Bang roughly 14 billion years ago. Most of the other elements were produced by nuclear reactions that occurred in stars that died before our Solar System was formed 4.6 billion years ago. The iron that gives blood its red color is created in stellar explosions called Type I supernovae when either a white dwarf or neutron star receive additional layers of material from a nearby orbiting star.

Another type of supernova, Type II, which marks the end of the lives of very massive stars, produces most of the oxygen we breathe and the carbon that is the basic unit of organic molecules. Nitrogen, the most common gas in Earth's atmosphere, is produced by stars similar to the Sun that end their lives with a short-lived stage as planetary nebulae.

In all of these stars the elements that are synthesized by nuclear processes are ejected violently when the star dies and then enter the interstellar medium—the matter between the stars. Subsequent to this mixing of the ejected elements into the interstellar medium, gravity pulls together clouds of that interstellar matter to form new stars. Earth and the Solar System formed at the end of such a series of events. It is interesting to consider, in the light of this sequence of exquisite events, that the average atom in our body has been through this cycle of star birth and death about three times.

But how do we know these things? Astronomy has a fundamental disadvantage compared with fields such as physics or biology: it is an observational, not experimental, science. All we can do is look into the cosmos and analyze the light we receive to the best of our intellectual and technological abilities. But astronomy does have a big advantage over those other sciences—it provides us a time machine.

Due to light's finite speed, we can look far into the past by looking at objects far away from Earth. The distance to a star or galaxy is often given in light-years, the distance light travels in one year. This distance also correlates with the "look-back time," how long ago the light was emitted. Consider with the following example how we can use astronomy's "time machine" to do real science:

> we see the Orion Nebula (pictured on the next page), the closest region where stars are actively forming, as it was 1500 years ago;
>
> the nearest galaxies are several million light-years away, a short time in the history of the Solar System;
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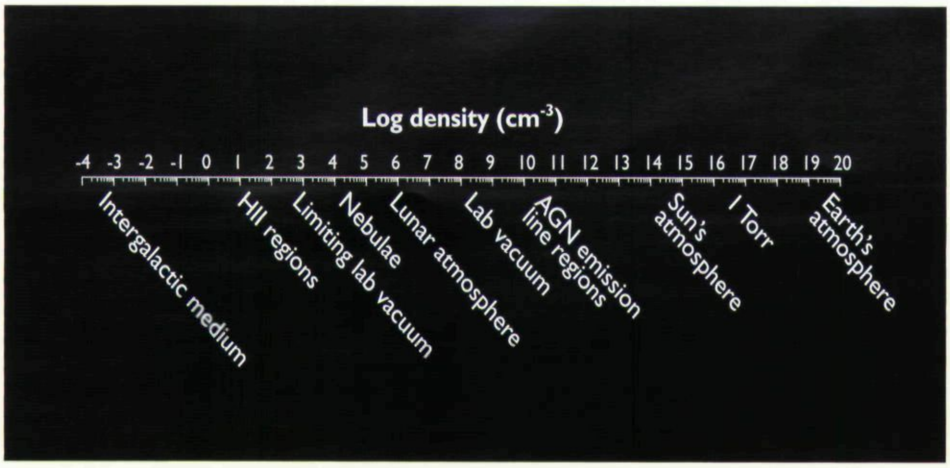
> with very large telescopes astronomers now routinely observe galaxies as they were more than 10 billion years ago, a time when the Universe was in its infancy; and
>
> by combining observations of distant galaxies with those of nearby regions like Orion, we can trace the history of the formation of stars and elements from the beginning through to today.

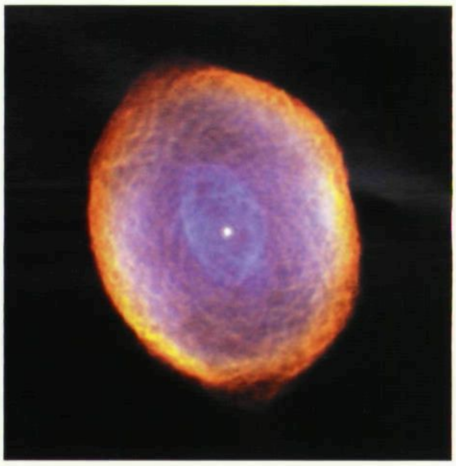
Astronomers are then, by necessity, great experts at "remote sensing." We are constantly developing or refining methods to reap the greatest possible amount of information from the light we receive. And while pictures of planets and galaxies can be stunning and almost qualify as art in their own right, the greatest amount of information by far comes from spectroscopy, the detailed study of the types of light emitted by an object. Let us now trace the formation of stars and the elements, beginning in the here and now and reaching out across the cosmos to early times. Most often our understanding is going to be the result of the analysis of a spectrum of some kind.

William J. Henney's composite of an optical image of the Orion H II region in the center and a radio image showing the distribution of carbon monoxide molecules in red. The stars that power the Orion Nebula were born in the molecular cloud. Their starlight powers the H II region. Optical image obtained as part of the Two Micron All Sky Survey (2MASS), a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. The CO image is derived from Plume *et al.* (*ApJ* 539, L133).

The Orion Nebula as seen in a recently released Hubble Space Telescope image. The gas glows because of the effects of light from the stars near the center of the brightest parts of the Nebula. Image courtesy of the Neubla. Image courtesy of NASA, ESA, M. Robberto (STScI/ESA) and the Hubble Space Telescope Orion Treasury Project Team.



A comparison of the gas densities of terrestrial and cosmic environments. Illustration by T. Ford with data courtesy of the author.



A planetary nebula represents the final stage in the evolution of a star similar to our Sun. The star at the center of IC 418, the Spirograph Nebula, was a red giant a few thousand years ago, but then ejected its outer layers into space to form the nebula, which has now expanded to a diameter of about 0.1 light-year. Image courtesy of NASA and the Hubble Heritage Team (STScI/AURA).

Stars Here and Now

Stars form in molecular clouds, regions of the interstellar medium where gas and dust are shielded from the energetic radiation that permeates much of the cosmos. Consider the relatively nearby Orion complex shown on page 14. The figure is a composite of images made with different types of telescopes that detect different wavelengths of light. The molecular cloud, seen in light emitted by carbon monoxide, is shown in red. And somewhat similar to raindrops forming in a thundercloud, condensations of gas within this molecular cloud pull together into clumps because of gravity. These clumps may eventually become stars and their planetary systems. This process can form hundreds or even thousands of stars at one time—stars form with a a broad range of masses, extending from roughly a tenth the mass of the Sun all the way up to stars with a hundred times the Sun's mass.

Named the Helix Nebula, this planetary nebula was ejected from the faint star in the center roughly 10,000 years ago. Visible in the inset image are dense, cold, clumps of molecular material that are roughly the size of the Solar System. Light from the cooling dead star heats and ionizes the side of the clump facing the star, driving "comet tails" away from the star. It is possible that these clumps survive passage into the interstellar medium and form seeds of dense molecular material for the next generations of solar systems. Both images courtesy of NASA and STScI/AURA.

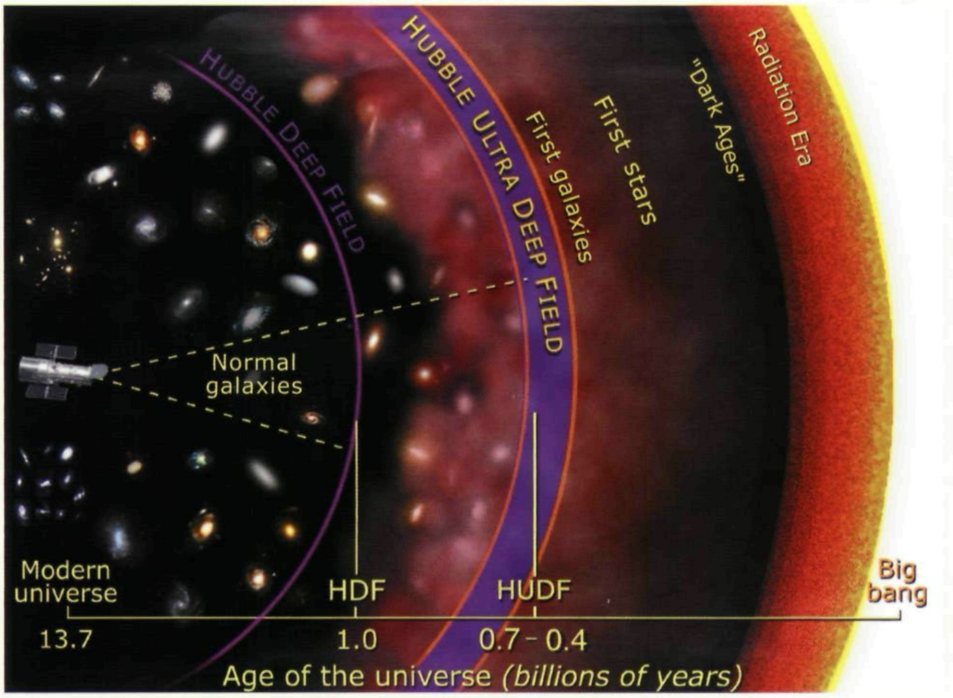
We notice the most massive stars because they are the hottest and brightest. Being more massive, they have more fuel, but their luminosity—the rate at which they emit energy and use up their fuel—can be a million times larger than that of our Sun. The result is that these largest stars have relatively short lifetimes, less than a few million years, and they do not live long enough to stray far from their birthplaces. Hot bright stars, therefore, are often found near the molecular clouds where they were born.

The glowing gas we see as the Orion Nebula in the central illustration on page 14 and shown in greater detail in a recently released Hubble Space Telescope image on page 15, is produced when starlight from the Trapezium cluster (the stars near the center of the second illustration) strikes the outer layers of the molecular cloud. Starlight heats the gas and causes it to glow.

Spectral Matters

Let's examine the spectrum of the Orion Nebula (see "Orion's Light Fantastic" on

In this detail view of the Hubble Ultra Deep Field are several very young galaxies. The bright point with a cross is a star within our own galaxy. Nearly all other sources present are young galaxies in the process of formation, and their irregular shapes betray their youth—they have not yet had time to settle down into the regular shapes we see today. Image courtesy of NASA, ESA, S. Beckwith (STScI), and the HUDF Team.



Deep exposures of the Universe by modern telescopes—examples include the Hubble Space Telescope's Hubble Deep Field (HDF), Hubble Deep Field South (HDFS), and the recent Hubble Ultra Deep Field (HUDF)—permit astronomers to fashion its history of star formation and element creation. Illustration courtesy of NASA and A. Feild (STScI).

page 17), which was collected when a spectrometer, the device that splits the light we receive into its constituent colors, was pointed at the Nebula's region near the Trapezium cluster. The horizontal axis gives the light's wavelength, measured in Ångstroms—equal to 10^{-10} of a meter and abbreviated as Å—and the vertical axis shows the intensity, or brightness of light at various wavelengths. Red light has a wavelength of roughly 6000 Å; blue light, roughly 4000 Å. Most of the types of light shown in the figure cannot be seen by the human eye. In fact, Earth's atmosphere blocks light with wavelengths shorter than approximately 3000 Å, and this part of the spectrum as shown was taken with the Hubble Space Telescope.

The gas in the Orion Nebula is constantly recombining, converting ions into atoms, and cooling, as energy is converted into forbidden-line radiation. Were no source of heat and ionization present, the bright H II region (so named because all of the hydrogen in the region is ionized; compare to, say, H I, which is neutral hydrogen, or Fe VII, which denotes iron that has had six electrons removed) in the image on page 15 would become cold, neutral, and dark in a few centuries. The Nebula's luminosity is powered by the radiation field due to the brightest stars visible in the image.

Very hot stars emit most of their light at wavelengths even shorter than those shown in the spectrum of the Orion Nebula. These photons have enough energy to tear an electron free from a hydrogen atom in a process named photoionization. Thus stripped to its essentials, the energy in the light we see in the colorful image of the Nebula was originally produced by nuclear reactions within the Nebula's stars and emitted as starlight, which subsequently ionized the nebular gas and produced the emission-line spectrum.

Complications to this scenario are introduced by the extremely low density of the gas. The Orion Nebula is dense by H II region standards, but in the plot showing common terrestrial and cosmic environments on a pressure/density scale (page 16), we see that it is a great challenge to build as

The Hubble Ultra Deep Field is the culmination image of a one-million-second exposure of a tiny part of the Universe by the Hubble Space Telescope. Visible in this image that was released in 2004 are numerous, small, faint, and irregularly shaped galaxies that existed when the Universe was less than a billion years old. They will eventually merge and form larger galaxies of today like our Milky Way Galaxy. Image courtesy of NASA, ESA, S. Beckwith (STScI), and the HUDF Team.

complete a vacuum in an Earth-bound laboratory as that in Orion. Indeed, most nebulae have densities significantly lower than that of the Moon's atmosphere and are often even lower than the best vacuum that can be produced here on Earth.

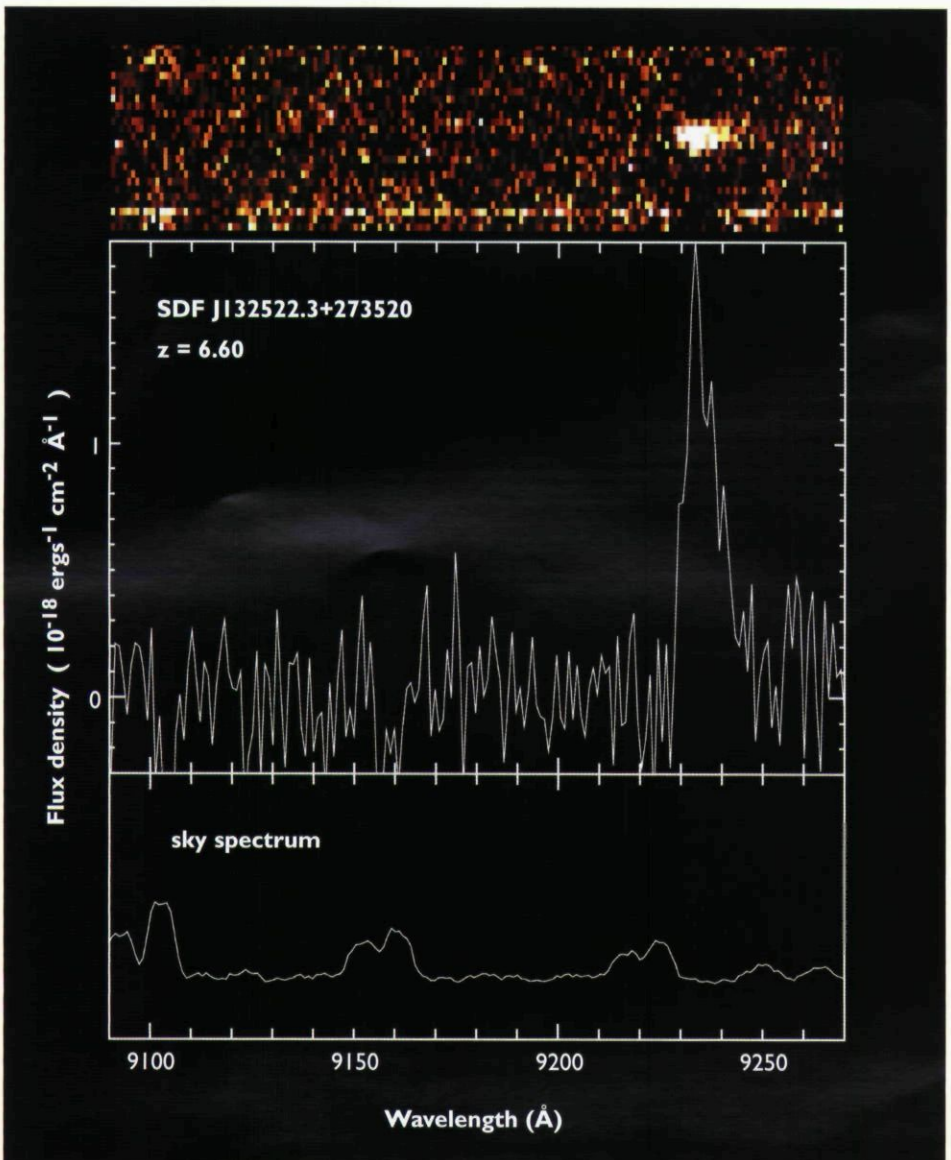
This low density introduces several complications, mainly because collisions between various constituents are slow and relatively infrequent. And, because a variety of processes determine the properties of the gas, simple concepts like temperature can lose their meaning. Consider the life history of a hydrogen atom within the Orion H II region. An atom survives, on average, for a few days before being photoionized by starlight. The atom's electron is torn free and becomes a "free," or unbound electron. Every few weeks it strikes an atom of a heavier element, most likely oxygen, leading to the forbidden lines that appear in the Nebula's spectrum. After a few years, the free electron will pass close enough to a proton to be captured into an orbit. It remains in larger (lower-energy) orbits for, on average, a fraction of a millionth of a second, emitting the recombination lines we see in the spectrum as it moves to lower orbits, eventually arriving back to the lowest, ground-state orbit. The process beings again with the absorption of another stellar photon.

Nearby star-forming regions like that in Orion provide a laboratory where we can develop the tools needed to understand their spectra and measure the current composition of the interstellar medium. By comparing different H II regions we can follow the slow buildup of elements like carbon and oxygen as successive generations of stars create new elements by nuclear processes and eject them into the interstellar medium. We can also deduce the rate at which stars form in the following manner: theoretical models of massive stars—the hottest, shortest-lived stars and those responsible for the high-energy photons that produce H II regions—predict both their lifetime and how much energy each radiates. With these data and the total number of stars in the cluster, we determine the number of hot stars needed to reproduce the observed emission and the star formation rate. The result of this modeling and ciphering is that roughly four solar masses of interstellar matter is converted into stars each year in our Galaxy, and roughly 90% of the available interstellar medium has already been used to create stars.

Death and Transformation

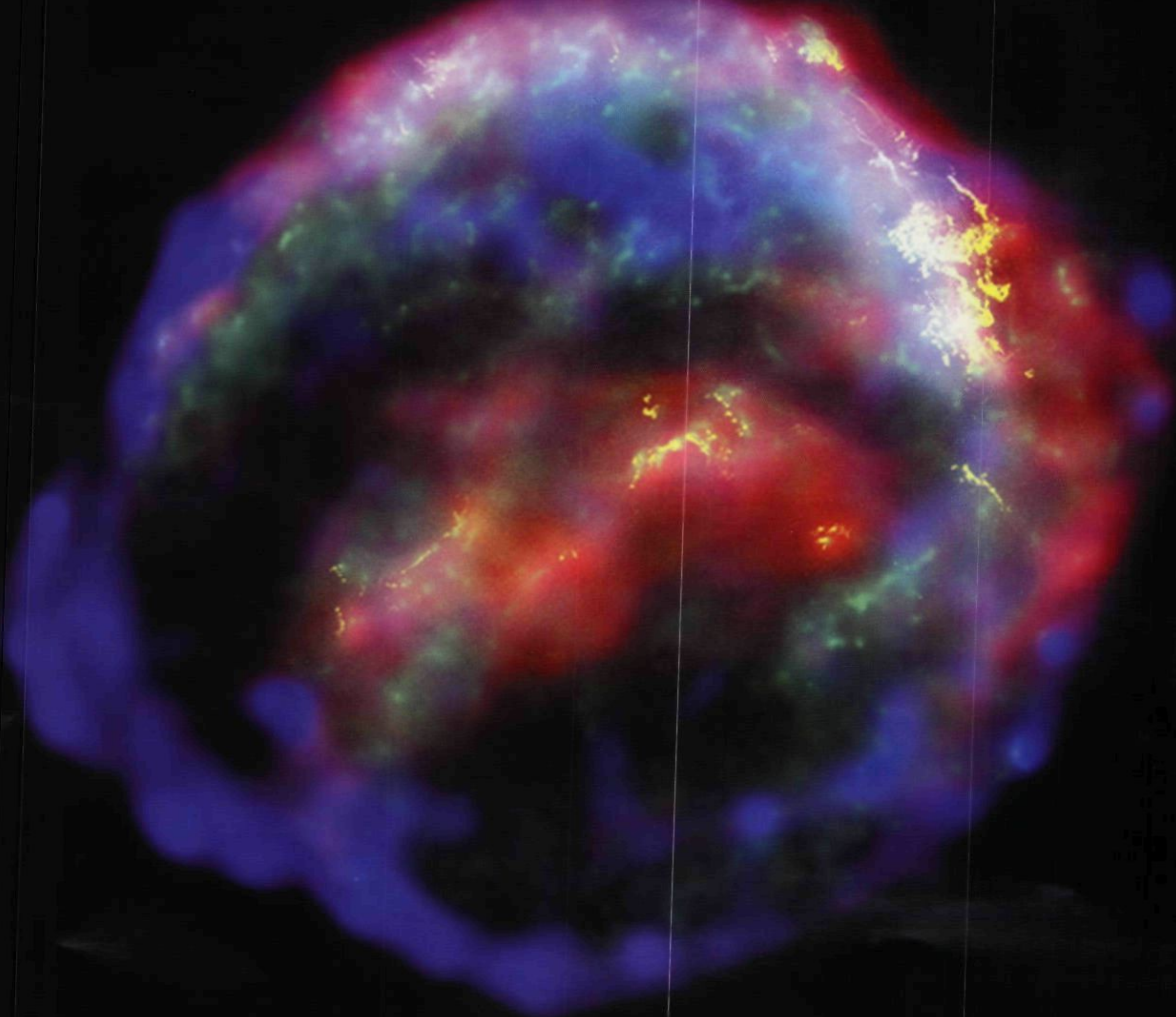
A similar analysis of nebulae produced as stars die reveals how stars create the heavy elements that make life possible. Stars like the Sun end their lives after they have converted, first, all of the hydrogen in their cores into helium, and, second, all of the core helium into carbon and oxygen. The star becomes a red giant and eventually, through processes that are not now understood, forms a planetary nebula—like, for example, the Spirograph Nebula on page 16—and ejects its outer layers into the interstellar medium. Our Sun is roughly half way through its life and will produce a planetary nebula in about five billion years.

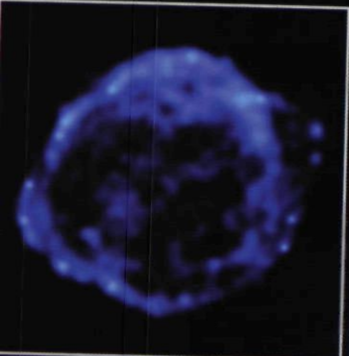
The nearest planetary nebula is the Helix Nebula, shown on page 16. The faint star visible in the center is the core of the star that ejected the nebula roughly 10,000 years ago. The core is far hotter than the stars that power H II regions but is small, with a diameter similar to that of Earth. The same photoionization process we encounter in regions of star birth occurs here, in regions of star death. The emission-line spectrum of the Helix reveals that the nebula has less oxygen than the local interstellar medium: this



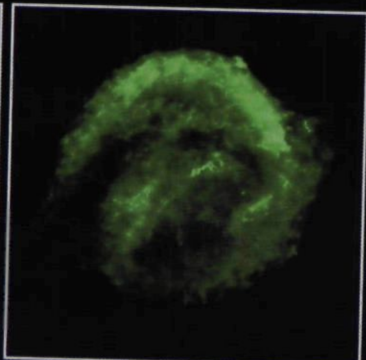
Part of the spectrum of one of the highest redshift galaxies. The strong emission line is a recombination line of hydrogen with a laboratory, or "rest," wavelength of 1216 Å. The expansion of the Universe has shifted the line's wavelength from the ultraviolet into the infrared. Spectrum and illustration courtesy of Y. Taniguchi.

Three of NASA's Great Observatories—the Hubble Space Telescope, the Spitzer Space Telescope, and the Chandra X-ray Observatory—joined forces to probe the expanding remains of a supernova. Now known as Kepler's supernova remnant, this object was first seen 400 years ago by sky watchers, including famous astronomer Johannes Kepler. Illustration and images courtesy of NASA, ESA, JHU, R. Sankrit, and W. Blair.

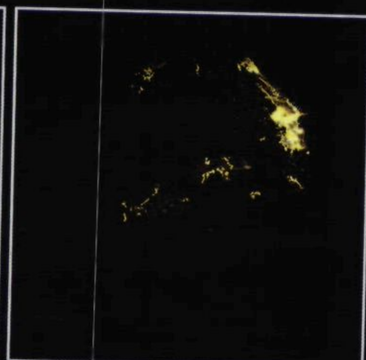




CHANDRA X-RAY
(HIGH ENERGY)



CHANDRA X-RAY
(LOW ENERGY)



HUBBLE OPTICAL

SPITZER INFRARED

reflects the composition of the interstellar medium when the star was born billions of years ago. Further, there is more nitrogen here than in the interstellar medium, showing that this element was created by the star. Small comet-like condensations are visible in outer regions of the Nebula (detail in the figure on page 16); these form small molecular clouds, although the details of how this happens are not understood. It is possible that these knots survive migration into the interstellar medium and help seed the Galaxy with sites where complex chemistry can occur.

Stars considerably more massive than the Sun can create elements with many more protons than carbon. These stars end their lives as supernovae—catastrophic explosions that destroy the stars and create many of the heavy elements like iron. Consider the Crab Nebula, the remnant of a supernova that occurred in 1054 of the Common Era, in the Hubble Space Telescope image on this page. Detailed spectral analysis shows that the Nebula's diffuse blue light is emitted by very high-speed electrons that have been accelerated by the rapidly spinning neutron star produced by the explosion. The filaments are photoionized by this light and their spectra reveal that the gas is enriched in elements produced by the explosion. Supernova remnants can be studied with other wavelengths of light, too. The illustration on page 21 shows the remnant of the supernova Johannes Kepler observed in 1604 in x rays, visible light, and infrared light. That different elements emit different forms of x rays makes it possible to map the composition of the material blown off in the explosion. Besides being the source of many of the common heavy elements here on Earth, supernovae are bright enough to be seen from far away—so bright, in fact, that supernovae are used to measure distances to remote galaxies. This process of using remote supernovae as distance indicators is what led astronomers in 1998 to the realization that the expansion of the Universe is accelerating.

The Crab Nebula was produced in a supernova explosion that occurred in 1054 C.E. These events are the most violent stellar explosions and produce many of the heavy elements that make life possible. Image courtesy of NASA, ESA, and J. Hester.

Star and Element Formation Across Time

Distant and faint galaxies can be detected using the world's largest telescopes. The Hubble Space Telescope's Ultra Deep Field, shown on page 19, is the result of a very long exposure and reveals a host of galaxies that are too faint to be seen with most ground-based telescopes. The galaxies are at a range of distances with the most distant being well over 10 billion light-years away. Those far-flung galaxies, which we see at a time before the formation of our Milky Way Galaxy, are often small and irregularly shaped. These small galaxies will eventually merge and form larger galaxies like our own.

It will soon be possible to apply our understanding of molecular clouds, H II regions, and star formation to objects at cosmological distances and to test our theories with these very young and distant galaxies. Most of the galaxies visible in the Ultra Deep Field are too faint for their spectra to be obtained. But new generations of larger telescopes will make this possible.

As an intriguing example, the illustration on page 20 shows part of a spectrum of one of the most distant galaxies yet taken. The strong emission line is a recombination line of hydrogen: this line has a "rest wavelength," one when no Doppler shift is present, of 1216 Ångstroms, placing it to the far left in spectrum on page 17. The expansion of the Universe has shifted the line's wavelength from the ultraviolet into the infrared. Incredible as it may seem, the light in this spectrum last touched matter when the Universe was only a few hundred million years old; and it can reveal what was taking place in the young Universe as the first galaxies formed. Our best evidence is that young proto-galaxies experienced a period of very rapid star formation as gravity pulled interstellar matter together.

The next generations of even larger ground- and space-based telescopes will make it possible to detect many more lines in the spectra of distant, and young, galaxies. With such observations of the stars and nebular gas in those galaxies, we will be able to quantify the steps in the formation of the first generations of stars in a young and evolving universe, leading to the birth of our own Galaxy. And we will come to a better understanding of how the chemical elements came to fill out the periodic table of elements.

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