Young Stars and Their Surroundings

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As stars are created by the gravitational contraction of knots in giant interstellar clouds, they shed angular momentum and magnetic and gravitational energy in an interplay of complex circumstellar structures: swirling disks, fast collimated jets, and shock waves in the surrounding cloud. Many of these structures were inferred a decade ago from ground-based telescope observations. The high resolution of the Hubble Space Telescope and other instruments has now revealed these circumstellar regions in great detail, showing features never before imagined. In the Orion Nebula alone, examples of all types of interactions between young stars and their environment can be seen simultaneously, highlighting circumstellar dynamics in sharp relief in one of astronomy's most famous objects.

An ordinary star appears to be one of the simplest entities in nature. It is almost perfectly spherical. Light is radiated from its surface at a uniform temperature with a Planck distribution disturbed only by signature lines and discontinuities of a few elements. A solar-mass star typically remains stable for a few billion years before any noticeable changes occur. It is only upon very close examination that heterogeneous structures, such as star spots, coronas, and streams of plasma or ionized gas, appear on the surfaces of the majority of stars.

The birth sites of these stars—the dark clouds of gas and dust in the Milky Way—are far from simple in their structure and dynamics. These clouds contain regions differing by orders of magnitude in density (10^3 to 10^8 molecules cm^{-3}) and temperature (10 to 100 K) and regions with shapes ranging from spheroids to elongated tubes and fragments with turbulence, porosity, and chemical differentiation over length scales of $\sim10^{17}$ cm (*1*). Previous workers (*2*) modeled the collapse of these clouds to make new stars by assuming spherically symmetric infall and dynamics that included no interference from other stars or interaction of the parent cloud with the newly created star.

A more refined picture was developed from optical telescope observations. In the 1980s, several advances in observational techniques allowed the morphological details of circumstellar material that remains after the initial collapse of a cloud to be studied (Fig. 1). It became clear that young stars are rarely if ever surrounded by spherical envelopes of gas and dust. The most visible manifestations of the circumstellar physics are the winds and jets of gas that emerge from stars and light up the surrounding clouds. Evidence for stellar winds has accumulated for several decades (*3*), whereas the jets are a more recent discovery (*4*, *5*). Like the much larger jets seen emanating from distant quasars, gas streams away from a young star at several hundred kilometers per second, generating shock waves along its path and creating brilliant plasmas, called Herbig-Haro objects, when it plows into much denser cloud material (*6*). These objects are easy to see and were observed long before they were connected to the young stars.

As angular resolution improved and it became possible to observe young stars at infrared (IR) wavelengths, the jets were seen to emerge along the polar axes of structures called circumstellar disks that consist of gas and dust orbiting the stars in relatively thin planes. The disks surround the stars for the first few million years or so of their early life, dropping matter onto the star and pumping energy and mass into the jets (*7*). Above and below the disk planes, cloud material at much lower density continues to fall onto the disks and stars, adding mass to the disks and fuel to the winds. This complex environment gives rise to a number of important effects on the cloud. The mass outflow may often be strong enough to inhibit or substantially alter subsequent star formation in the cloud. There is no widespread agreement yet on the origin of the mass outflow, nor whether it is driven primarily by the disks or the stars. The collimation of the outflowing winds into very narrow gas jets was unexpected and remains unexplained, although there is general consensus that the mass loss itself and possibly the collimation are essential features of the birth of a new star, perhaps helping to shed angular momentum or magnetic energy stored during the cloud infall (*8*).

The disks may be the birthplaces for planetary systems, raising the possibility that systems like the one around our sun are plentiful in the galaxy. Most stars are parts of gravitationally bound binary or triple star systems, and this propensity for bonding appears to set in very early in a star's life. To search for extrasolar planets and to understand star systems, investigators are using the Hubble Space Telescope (HST) to produce images of the circumstellar regions. These observations have allowed investigators to study disks and jets and their effects on the surrounding cloud, as well as interactions among young stars as they affect their local regions and shape the course of star formation. All of

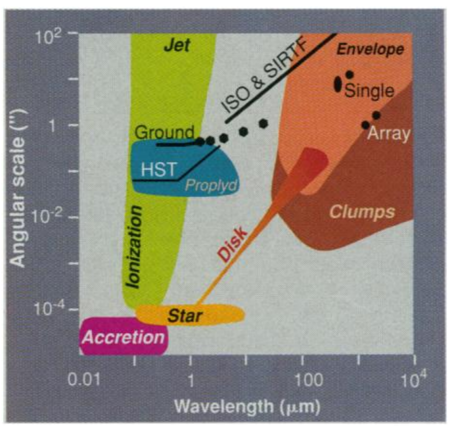

Fig. 1. This diagram shows the major structures currently known around young stars and outlines the angular scales and wavelengths at which they are most likely to be observed in the closest star formation regions 500 light years away. The observation wavelength is mainly determined by the temperatures of the region: Ionized gas in the jets and accretion shocks near the star emit primarily at UV and visible wavelengths. The stars are a few thousand kelvin, emitting mainly at visible and near-IR wavelengths, and the clouds are cold, emitting primarily at submillimeter wavelengths and longer. The disks have regions with a range of temperatures from a few thousand kelvin near the stars down to a few tens of kelvins in the outermost parts, several tens of astronomical units from the stars. The protoplanetary disk (proplyd) region was identified by the HST through high-resolution optical images and was unanticipated before being observed. Other areas of the diagram without labeled structures, such as the lower right, may contain structures that will be identified only with new telescopes. Structures that are unresolved, such as circumstellar disks observed at far-IR wavelengths, may nevertheless yield information about their structure through their spectral energy distributions. ISO, Infrared Space Observatory; SIRTF, Space Infrared Telescopic Facility.

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these phenomena can be observed in the Orion Nebula, which is one of the best known celestial objects (9).

Circumstellar Disks

The onset of the collapse of an interstellar cloud begins when enough material has accumulated in a small region so that thermal and magnetic pressure can no longer support the weight of the cloud against gravitational implosion. The initiation can be more complicated, such as when collapse is triggered by the sudden removal of a supporting force, such as a magnetic field, or by an increase in an external force, such as a passing shock wave (10). In any case, the events leading up to collapse are sufficiently complicated that the cloud always has some small, net, randomly oriented angular momentum before collapse. This net angular momentum is typically two orders of magnitude greater than that which a star can have without breaking apart. For a cloud to collapse to create an isolated star, it must rid itself of over 99% of its angular momentum during the process of collapse or manage to put it into orbiting material. The high–angular momentum material in the cloud winds up in a plane oriented perpendicular to the net angular momentum vector of the original cloud, creating a circumstellar disk. Just as Jupiter can contain most of the solar system's angular momentum although it has only one thousandth of the sun's mass, so very little material is needed in the disk to accommodate the cloud angular momentum, so long as the disk extends a large distance from the star. A typical young star will have a radius of 1.5×10^{11} cm, about 0.01 astronomical units (AU), whereas a typical disk will extend to orbital radii of 100 to 1000 AU, safely satisfying the large distance requirement.

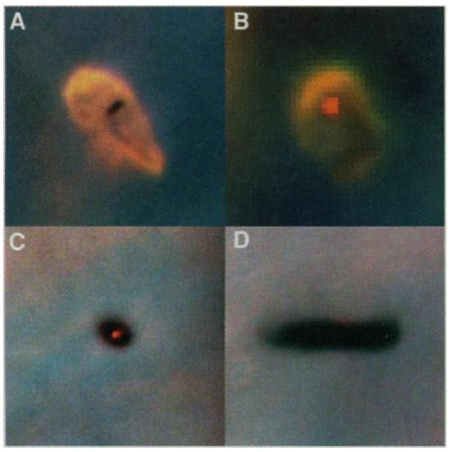

Fig. 2. HST views of four young stars in the Orion Nebula, representing a range of locations and orientations. The upper panels show stars and their circumstellar clouds that are close to hot stars that photoionize the outer parts of the clouds and render them bright. The small dark disk in the top left panel (Ori 182-413) is viewed edge-on, and the star is obscured. In the top right panel (Ori 206-446), the disk is almost face-on and the star is easily visible. The lower panels show two young stars that are shielded from photoionization, leaving their circumstallar disks visible in silhouette against the background nebula. The right-hand object (Ori 114-426) is viewed almost edge-on, whereas the left-hand object (Ori 183-405) is seen from an oblique angle. Each panel shows a region 1600 AU (20 times the diameter of Pluto's orbit) on a side.

Circumstellar disks are commonly found around young stars. The interstellar dust particles in the original cloud are efficient at absorbing visible stellar radiation and reradiating the energy at IR wavelengths. It is often sufficient just to detect the IR radiation and identify the spectral characteristics to determine that a star has a disk, and this is the method used to survey many hundreds of stars to determine the frequency of disk formation (11, 12). Estimates of the fraction of young stars with disks range from a low of about 10% to a high of 100%, depending on the methods used to select the sample, with the larger percentage being favored by studies of dense clusters from which many stars originate (13). In theory, all young stars should have either a circumstellar disk or a companion to take up the cloud angular momentum. Observationally, disks and companion stars are common, and young binary systems often have disks surrounding one or both stars as well (14).

It is possible to directly observe flattened distributions of gas or dust in special cases with the most modern telescopes. The HST has identified a few tens of disks this way (15) (Fig. 2), as have radio astronomers looking at molecular radiation from the outer parts of the disks, using interferometric arrays of millimeter-wavelength telescopes (16).

One of the exciting revelations of the past few years is the realization that many of these disks have the right physical characteristics to spawn planets (17, 18). Disks with these characteristics are so common that one can reasonably argue that planets are common around all stars, resulting naturally from the coagulation of material within the circumstellar disks. The many recent discoveries of extrasolar planets lend credence to this idea and open up a new dimension in the study of the disks (19).

In addition to providing a reservoir for angular momentum and potential birthsites for planets, the disks are way stations for matter that will eventually fall onto the star. Mutual interactions among the orbiting particles lead to a slow spiraling of material through the disks onto the star. This accretion of matter releases energy. The release of energy heats the star and the disk and is believed to provide the ultimate source of power for the jets that so commonly accompany star formation. In all cases in which they have both been observed (20), the jets emerge along the axis of the disk perpendicular to the orbital plane. Despite the lack of agreement on how this mass loss process occurs in detail, almost all theorists agree that the disks and stars are threaded by magnetic fields, which were present in the original cloud, and that their dynamo forces are responsible for generating and collimating the outflowing winds. Migration of matter through the disk onto the star and the corresponding release of gravitational energy somehow trigger the winds and jets.

Winds, Jets, and Their Manifestations

Stars do not just accrete matter, they also spew it out, generating winds that flow away from the star-disk system into the surrounding cloud. Winds were first detected two decades ago with ultraviolet (UV) spectrographs, millimeter-wavelength telescopes, and powerful charge-coupled devices. These winds are intimately connected with the continuing infall and accretion of matter onto the star, the mass loss rate rising in proportion to the accretion rate and disappearing when the disks dissipate after a few million years (21). Winds from young stars typically shed matter at rates between 10^{-8} and 10^{-5} $M_\odot$ year^{-1} (solar masses per year), in stark contrast with the solar wind, which flows out at a rate of 10^{-14} $M_\odot$ year^{-1}. A portion of the outflow is collimated into tiny opening angles, giving the appearance of a nozzle channeling matter into the surrounding cloud, which is unusual because special conditions must be required to produce this directed flow. This collimated outflow is called a jet.

Visible manifestations of these outflows are the Herbig-Haro (HH) objects (6), which are localized regions of hot plasma glowing in the midst of an otherwise cold, neutral cloud. HH objects, named for the astronomers who defined them as a class before it was known how they were powered, are ionized by shock waves created as stellar winds plow into dense cloud gas (5). It is now possible to observe thin jets from young stars terminating in HH objects, leading to the suggestion that it is the jets, moving at several hundred kilometers per second, that provide the energy for the shock waves and concomitant ionization (22, 23). Radiative cooling of the shock-heated gas produces a rich spectrum that is used to derive the temperature, density, and relative abundances of the atoms and ions in the heated regions.

It is more difficult to observe the jets because little of their bulk energy is released internally to excite atoms and molecules. Collisions with the surrounding gas radiate enough energy to trace the course of the jet, but they are faint and require sensitive detectors to be observed (Fig. 3). Images of jets show hydrodynamic instabilities and structures along their lengths, which indicate episodic mass loss producing a series of shock waves (*24*). These episodic mass ejections have corresponding periods of increased mass accretion onto the parent star, as seen in the bizarre star FU Ori (*25*).

Several hundred HH objects are now known. They are common because young stars are normally surrounded by residual material, and jets from young stars may be the rule rather than the exception. In a case in which the star is buried inside its molecular cloud, the jets give rise to flows of molecular material seen only with radio and IR telescopes (*26*), whereas stars near the surface suffer less extinction and give rise to optically visible shocked material. It is still not known whether jets are natural by-products of all newly formed stars. There is evidence that mass loss starts when a star is still heavily shrouded by placental cloud material in the infall phase. Because jets are visible as a result of their interactions with ambient material, their appearance depends on the distribution of this material. As new ways of detecting mass loss have been introduced, such as IR emission lines, far-IR thermal emission, or submillimeter lines of rotational excited molecules, the fraction of stars exhibiting jets has increased, which suggests that mass loss is an integral part of early stellar evolution.

Just as a disk can provide a reservoir for angular momentum during the initial buildup of a star, so the winds are thought to provide an outlet for angular momentum and energy as matter accretes from the disk onto the star. The regulation of the angular momentum at the star-disk interface most likely determines the stellar rotation rate. Stellar rotation rates vary regularly among different masses of stars and at different stages during their pre–main sequence evolution (*27*). If the disks, jets, and stars are linked dynamically, these seemingly disparate phenomena may provide clues about the detailed processes occurring during star formation.

The Orion Nebula as a Cradle for Star Formation

Just below the Milky Way in the constellation of Orion, masquerading as the middle star in the sword, is the Orion Nebula. It is bright enough to be seen with the naked eye but can be appreciated only with a telescope. The eye is captured by the four bright stars, the Trapezium, in the center of a glowing multicolored nebula. The nebula is a large, nearly empty region bounded by ionized gas at a temperature near 10^4 K. The nebula is, in turn, embedded in a dense molecular cloud of neutral gas and dust. The cloud wraps around the front of the nebula, creating a veil in front of it; we see around and partially through this veil, and the variations in transparency create a rich series of dark and light regions at visible wavelengths (*28*).

The nebula is ionized by UV light emitted from the brightest of the Trapezium stars, θ^1C Ori, whose surface temperature is about 40,000 K and therefore produces many energetic photons (>13.6 eV) capable of stripping the electrons from hydrogen atoms. θ^1C is 30 times as massive and 300,000 times as luminous as the sun. At any one time, only about 1 $M_\odot$ of nebular material is photoionized. It is glowing and evaporating away from the dense surface layer of the molecular cloud but is being continuously replaced by material from that cloud, a reservoir of ~100,000 $M_\odot$ of hydrogen.

The immediate surroundings of the Trapezium contain more than 700 stars that constitute the eponymous Trapezium Cluster. They are so closely packed that the density of stars reaches 1500 per cubic light year (*29*), almost 500,000 times the average star density in the neighborhood of the sun. Many stars are born in clusters like that in Orion. They disperse as they age, and the evidence of the early clustering is lost after a few tens of millions of years or so. But the high density of stars and gas during the early stages of a star's life means that interactions among the stars, whether gravitational or through the radiation and winds put out by the massive stars in particular, probably affect their stellar characteristics later on. And the harsh environment of the nebula affects the disks and envelopes that typically accompany a newly born star through gravitational stripping of outer material and ablation by photoionization (*30*).

When a cluster is young, most of the stars seen are still evolving rapidly and collapsing slowly, and have not reached the stable configuration they will retain for several billion years—the main sequence. As young stars collapse, their luminosity wanes at almost constant temperature, the temperature depending mainly on the stellar mass. The rate of these

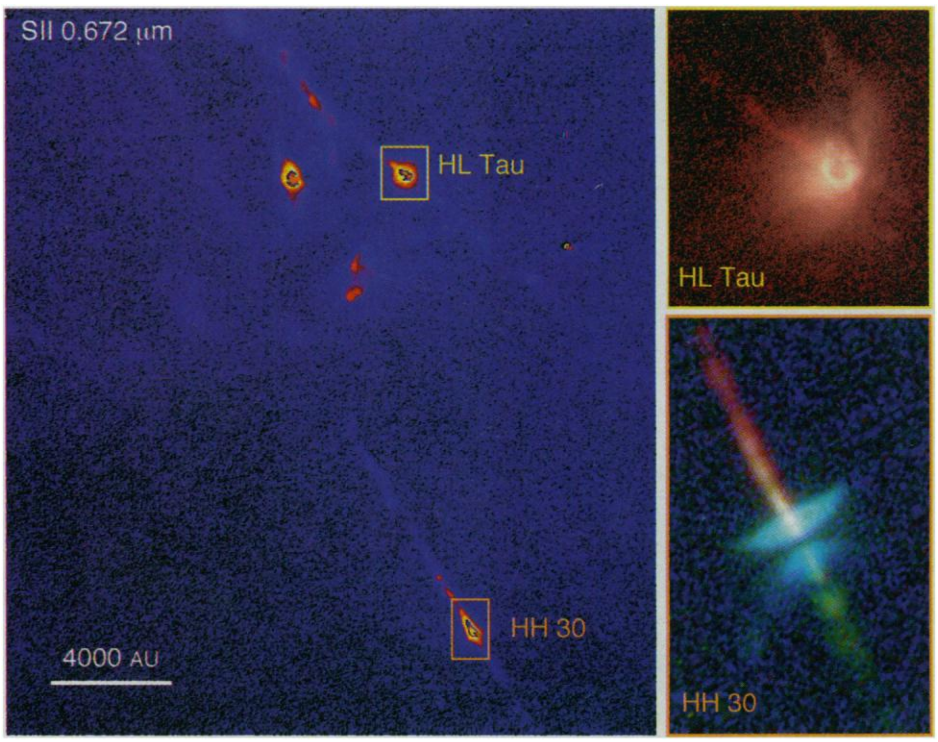

Fig. 3. The left-hand image is a 0.3–light year region around the young stars HL Tauri and HH 30 as seen in the light of singly ionized sulfur emission. The false color image is saturated to highlight the long collimated jets from these two stars (*20*). The right-hand side shows two high-resolution HST images of HL Tauri and HH 30 (*42*); the images are composites of emission line and continuum images from the HST. The red-line emission shows the ionized gas in the jets, and the blue continuum shows light scattered by dust particles near the disks surrounding the stars. These smaller images show a region 500 AU across.

changes can be calculated and compared with observations of the luminosity and temperature of the stars to determine their ages. The Trapezium Cluster is about 1 million years old, as young as the traceable precursors of modern mankind (*31*, *32*).

Circumstellar material around the cool lower-mass stars near the Trapezium is subject to the same process of photoionization that creates the nebula. The tenuous envelopes and circumstellar disks should be ionized on the side facing θ^1C; the hot plasma will glow visibly as it evaporates away from the star. There were hints of such objects in early images of Orion in visible light and at radio wavelengths, but these were not distinct enough to allow them to be clearly identified with circumstellar gas (*33*).

With 10 times the resolution of ground-based optical images, the HST was able to identify these ionized envelopes in Orion (*34*). There are many such objects, exhibiting a wide variety of forms, such as bright cusps facing θ^1C and tails created by the stellar wind from the star (Fig. 4). The longevity of these ionized envelopes and disks and their large number demonstrate that the circumstellar matter is prolific and robust. It is possible to estimate the probability that young stars have circumstellar material just by counting the ionized envelopes as a fraction of the stars in the nebula.

Fig. 4. HST views of two regions in the Orion Nebula, revealing the stripping of material from the circumstellar clouds near θ^1C Ori (top panel), which lies just off the right-hand side of the middle of the image, and the interaction of the general stellar wind off Ori 114-426 as it creates shocks in the ambient gas of the nebula (lower panel). In both cases, the images show a region about 0.15 light year on a side.

Not only does θ^1C fortuitously light up circumstellar regions that would otherwise be difficult to observe directly, it also produces the nebula, which is a bright screen against which circumstellar disks may be seen in silhouette if they are far enough in front of the nebula to escape the ionizing radiation from θ^1C (Fig. 4). Seven small, elongated dark objects blocking the light from the ionized nebula have been observed, and they provide the most direct estimate of the sizes and shapes of the circumstellar disks that surround young stars (*35*).

Silhouettes of the disks show typical sizes of several hundred astronomical units, which is a few times the size of the solar system. The appearance of the objects depends on their orientation. Those viewed nearly edge-on appear as flattened, albeit puffed-up, disks. If the disk is viewed at its equator, the central star is obscured. Intermediate stages show a variety of ellipses, exactly as would be expected if the underlying structure is circular but flat and viewed at an angle.

It takes very little dust in the disks to completely extinguish the background nebular emission. Thus, the silhouettes give little information about the mass of these disks, because as little as one Earth mass spread out around the stars is sufficient to completely block the visible light. One object that is well resolved, Ori 114-426, has at least one Jupiter-mass of material, 2.2×10^{-3} $M_{\odot}$, but these lower limits are generally less than disk masses calculated by other means (*11*). These limits are also less than the disk mass necessary to sustain the inferred photoevaporation of the gas. Although it has been argued that these disks are short-lived and evaporate quickly (*36*), their presence so close to θ^1C indicates that they are resilient. Thus, it is impossible to determine whether the disks have enough material to create planetary systems like our own, although they all have enough matter to create terrestrial-like planets (*37*).

Disks are prevalent among the stars in the Orion cluster. Different estimates of the fraction of stars with disks among those that are clearly part of the cluster range from 0.5 to 1, with the higher value applying to the cluster core (*31*, *37*), where membership is easiest to ascertain. Although a much smaller fraction of the stars identified in x-ray surveys have disks (*38*), there is considerable dispute about their age and membership, and we believe that the high fractions are indicative of the frequency with which stars are born with circumstellar material.

The disks in the nebula, and by inference in the rest of the region, must persist for at least a million years. The nebula itself is about this old, and the circumstellar material around the low-mass stars must have been present at its creation. Disk lifetimes of more than 10^6 years have been derived for other star formation clusters, most notably in the Taurus-Auriga dark clouds (*11*, *39*); Orion, which is more typical of the environment where most young stars are born, looks very similar (*40*).

We have touched on only a few of the many new aspects of circumstellar physics revealed by the new telescopes, particularly the HST. Physical models of the nebulas, the distribution and properties of binary star systems, the presence of brown dwarf stars, and the physics of the bright boundaries between the jets and the clouds provide enough material for separate articles (*25*, *41*). The advances in the understanding of stellar birth that have been brought about by these new telescopes are manifold and continue to make the last half of the 20th century one of the most exciting and prolific periods of scientific exploration in history.

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Nucleosynthesis in Stars: Recent Developments

David Arnett and Grant Bazan

The development of new observational, experimental, and computational technologies is changing our understanding of the origins of the elements by thermonuclear burning in stars. Gamma-ray lines from newly made radioactive nuclei have been identified using instruments onboard low-Earth orbiting satellites. Grains in meteorites have isotopic anomalies which suggest that the grains were put together in a stellar explosion such as a supernova. Computer simulations allow such anomalies to be used to probe how these events happen. The simulations are being independently tested by experiments with high-energy density lasers. These developments are beginning to provide a quantitative diagnostic of galactic evolution, and of the epoch of formation of the first stars and galaxies.

Four decades ago the seminal idea that essentially all of the elements were made by thermonuclear burning in stars (stellar nucleosynthesis) was codified (*1*, *2*). Later, astronomical observations (*3*, *4*) suggested (*3*) that the elements were formed by some other process early in cosmological history, perhaps in the Big Bang itself. Ironically, existing analyses on Xe (*5*) and Ne (*6*) in meteorites suggested that the elements were formed by ongoing stellar nucleosynthesis, but this data was not considered by (*3*) and (*4*). The notion of ongoing stellar nucleosynthesis was difficult to prove. To understand the context, consider this sketch of the history of matter (*7*). First, the Big Bang produces a bland distribution of nuclei: H, D, ^{3}He, ^{4}He, and traces of Li, Be, and B isotopes. This is followed by a poorly understood epoch in which the first stars and galaxies form. Massive stars burn quickly and brightly and become unstable. The most massive stars explode as supernovae (SNe), ejecting newly synthesized elements from C to U; less massive stars enrich the surrounding gas less dramatically. The ejected elements are incorporated into new generations of stars, and eventually into planets and other objects.

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Today the nature of the debate is different because advances in astronomical instruments has improved and extended the observational field of view. Charge-coupled devices (CCDs), with higher sensitivity and linearity, have replaced photographic plates. Telescopes in orbit, which surmount the pernicious veil of atmosphere, show wavelengths not visible from the ground. We now can observe essentially the whole electromagnetic spectrum, from gamma rays to radio waves.

For most of their lives, stars are spherical to a good first approximation. The star is divided into many (hundreds to thousands) spherical shells and in this "onion skin" model, each shell is assumed to be chemically homogeneous, with heterogeneity allowed only between shells. Many problems have been solved using this model (*7*). One reason the spherical approximation works is because stars usually evolve slowly, and eventually settle down to this symmetrical form. But as stars become unstable late in their life, this is no longer true. Unstable stars are complex, asymmetric, rapidly varying objects. This is the epoch at which stars eject their nucleosynthesis products. The need to compute not only the evolutionary changes in the spherical shells, but also for "cells" in longitude and latitude within these shells, presents a computational challenge. Fortunately, the new generation of massively parallel computers is powerful enough to allow such demanding