Protostars

"Stellar embryology" takes a step forward with the first detailed look at the youngest Sun-like stars

Thomas P. Greene

Anatomists have been studying the embryonic development of animals for centuries. Their detailed descriptions of tissue growth may have reached a high art, but a theoretical understanding of how the embryo undergoes its remarkable transformation from a single cell to a crying infant lags far behind. Until recently, the field of astrophysics had been struggling with a nearly opposite problem. Theoretical models of how a star forms—its embryonic development from a cold cloud of interstellar gas to a blazing furnace of nuclear fusion—had outpaced the astronomer's ability to observe the process. It's as if developmental biologists had identified the major stages in the growth of an embryo with only the crudest views of their subject.

This peculiar state of affairs in astrophysics is largely due to the reclusive nature of embryonic stars. A stellar embryo grows in a cloudy womb of molecular gas, which is so choked with dust that visible light has little hope of passing through. A view of these molecular clouds in even the largest optical telescope would reveal little more than a dark patch of sky. Observations are further hindered by the forbidding distances to the stars. The nearest region of stellar birth is more than 400 light-years away. At such distances, a prenatal star the size of our Sun is exceedingly dim.

Despite such impediments, astrophysicists have been able to piece together the broad outlines of how a low-mass (Sun-like) star forms. It's a surprisingly complex process. Although it may involve the simplest of elements and molecules, the making of a star is directed by a maelstrom of competing forces—including gravitational collapse, magnetic fields, nuclear processes, thermal pressures and fierce stellar winds—all of which wish to have their way with the unformed star. Because the interaction of these forces is not fully understood, there is much that remains mysterious about the birth of a star. How exactly does a growing star accrete matter from its surroundings, and how does the process stop? Why do stars form in the numbers and range of sizes that they do? And why do some stars form planetary systems? These are fundamental questions that cannot be answered without actually observing the process of star formation.

Fortunately, the field of stellar embryology has recently turned a corner as an observational science. Although visible light is unable to penetrate the dusty cloud that swaddles a prenatal star, the longer wavelengths of infrared radiation can easily slip through the dust and so escape the inner confines of the cloud. Such radiation has been detected for decades, but until recently infrared telescopes have lacked the sensitivity and resolution to provide detailed information about the youngest prenatal stars, the *protostars*. With the development of giant telescopes and extremely sensitive infrared detectors in the past decade, astronomers have now been able to observe these secluded stellar embryos. My colleagues and I have been among the privileged few to witness some of the earliest stirrings of a star's life.

Baby Steps to Stardom

The process of making a star begins inside enormous clouds of interstellar gas and dust that lie primarily within the plane of the Galaxy *(Figure 1)*. Consisting chiefly of molecular hydrogen (H_2), the largest of these *giant molecular clouds* may be several hundred light-years across and weigh as much as 100,000 solar masses. These clouds have an average density of about 100 H_2 molecules per cubic centimeter, but they are far from being homogeneous. Some regions may have a density of

Figure 1. Stellar embryos—protostars—lie hidden within the dust of the Rho Ophiuchi dark cloud, a star-forming region about 400 light-years away, near the common border of

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the constellations Ophiuchus and Scorpius. Optical-wavelength images, such as this one, cannot reveal these young stellar objects, but a new generation of large telescopes and sensitive infrared detectors has allowed astronomers to make detailed observations of these objects for the first time. Light from Rho Ophiuchi *(near top)*—a hot young star associated with the dark and dusty cloud—is reflected as a bluish glow. The aging red-giant star Antares *(lower left)* is not related to the star-forming region.

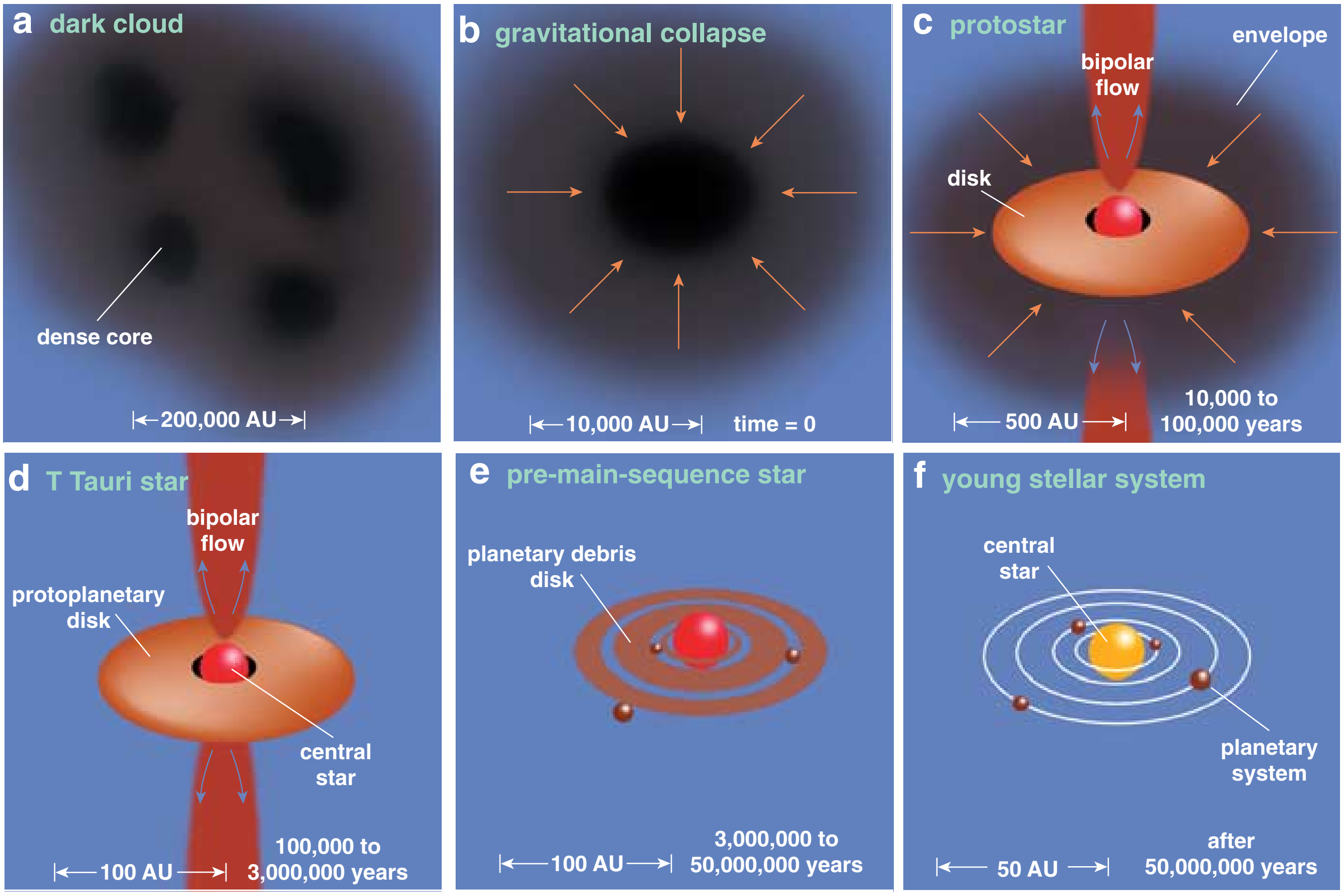

Figure 2. Early development of a young, Sun-like star can be described in a series of stages that span more than 50 million years. Star formation begins inside dark interstellar clouds containing high-density regions *(a)* that become gravitationally unstable and collapse under their own weight *(b)*. The collapsing core forms a protostar *(c)*, a phase of stellar evolution defined by the rapid accumulation of mass from a circumstellar disk and a surrounding envelope of gas and dust. As the dusty envelope dissipates, the object becomes visible at optical wavelengths for the first time as a T Tauri star *(d)*. These objects can often be recognized in telescopic images by the presence of a protoplanetary disk *(see Figure 5)*. After a few million years the dusty disk dissipates, leaving a bare pre-main-sequence star at its center *(e)*. In some instances, a debris disk with newly formed planets may continue to orbit the star. The star continues its gravitational collapse to the point where its core temperature becomes hot enough for nuclear fusion, and the object becomes a main-sequence star *(f)*. (AU = astronomical unit, the average distance between the Sun and the Earth.)

10,000 molecules or more per cubic centimeter, or more than 1,000 times the density of the most rarefied parts of the cloud. A molecular cloud may have many such dense cores (each of which may become a star), but the star-formation process is not very efficient, as a 100,000-solar-mass cloud never yields 100,000 Sun-sized stars. In fact, the conversion efficiency of cloud mass to stellar mass probably averages less than 10 percent.

Giant molecular clouds are supported against their weight by thermal pressure, turbulent gas motions and magnetic fields within, but at some point their dense cores become gravitationally unstable and begin to collapse *(Figure 2)*. The center of the collapsing core becomes a protostar, which, as the name suggests, is the first step toward stardom. The protostar's life (lasting about 100,000 years) is defined by the rapid accumulation of mass from the surrounding envelope of gas and dust *(Figure 3)*. It does so at the rate of a few millionths of a solar mass—equivalent to one Earth-sized planet—every year. Coinciding with the onset of accretion is a steady outflow of material in powerful winds that emanate from the poles of the young star. These *bipolar jets* are telltale signs of a protostellar system, and it is ironic that protostars are often detected by the jets that shed mass from the system, rather than the process of accretion *(Figure 4)*.

Throughout this period, the protostar progressively increases in density as it shrinks in size. The infalling material, which had been rotating relatively slowly around the dense core, begins to speed up as the radius of the protostar decreases. The angular momentum—which is the product of rotational velocity and radius—of the core material remains constant, so material rotates faster as it gets closer to the protostar. Slowly moving material falls directly onto the protostar, but some of the gas and dust is moving so quickly that it travels in an orbit instead. Since all of the material in the envelope surrounding the protostar rotates in the same direction, the matter falls into orbits of various sizes depending on its velocity, and so forms a *circumstellar disk*. Most matter eventually flows onto the protostar through the disk, but some of it remains in orbit. As the surrounding envelope of dust disperses, the accretion process stops, and the central globe of gas is no longer considered to be a protostar; it is now a *pre-main-sequence* (or *PMS)* star. (Protostars and PMS stars are often grouped under the term *young* *stellar objects*, which neatly includes all prenatal stars.)

The pre-main-sequence phase of evolution lasts for tens of millions of years. In its earliest phases, the first few million years or so, these objects are often called *T Tauri* stars, a name derived from the archetypical star in the constellation Taurus. Having shed their dusty envelopes, T Tauri stars are the youngest objects that can be seen with an optical telescope. They are still surrounded by a disk of dust and gas—often called a *protoplanetary disk* at this stage—and may continue to eject material in their bipolar jets. After a few million years, much of the dust and gas in the protoplanetary disk dissipates, leaving a bare PMS star in the center. In some instances, a few large bodies may continue to orbit the star in a remnant debris disk *(Figure 5)*. The planets, moons and asteroids of our solar system all had their beginnings in such a disk.

At this stage the internal structure of the star is determined by a balancing act between gravity, which compresses and heats the object, and the pressure of the gas, which acts to expand the star. The gas pressure is proportional to the star's temperature, which is only about 3,000 to 4,000 kelvins (degrees above absolute zero) in the outer regions but nearly one million kelvins in its core. This represents a dramatic increase from the frigid 10 to 20 kelvins typical of the dense cores in a molecular cloud, but one million degrees is still considered to be "cool" for a stellar core. This temperature is just hot enough to fuse a deuterium atom (hydrogen-2) and a proton into helium-3, a process that releases only a modest amount of energy.

It takes tens of millions of years, but eventually the crushing force of gravity wins the battle against the outward thermal pressure of the gas within the star. The compression of material raises the temperature of the star's interior to about 10 million kelvins—hot enough to fuse four protons into one helium-4 atom, which is the primary generator of energy within a true star. The event marks its arrival on the *main-sequence* phase of its evolution. This period of stellar evolution is extremely stable, and may last for many billions of years. Our Sun is a fine example of a main-sequence star—one that has been steadily burning hydrogen for 5 billion years, and should continue to do so for another 5 billion years. The Sun's relative stability is the key reason that creatures such as ourselves can evolve on the "debris" that continues to orbit the star after it is formed.

Youthful Energy

Our Galaxy appears to have a healthy lust for making stars, with many places that can be aptly called "stellar nurseries." Some of these nurseries may consist of merely a few young stars, whereas others may contain many hundreds. Among the more notable of these are the Orion Nebula and the star-forming clouds near the star Rho Ophiuchi. These regions have been studied for decades and have provided the observational basis for much of what we do know about the first stages of star formation.

The PMS stars were among the first

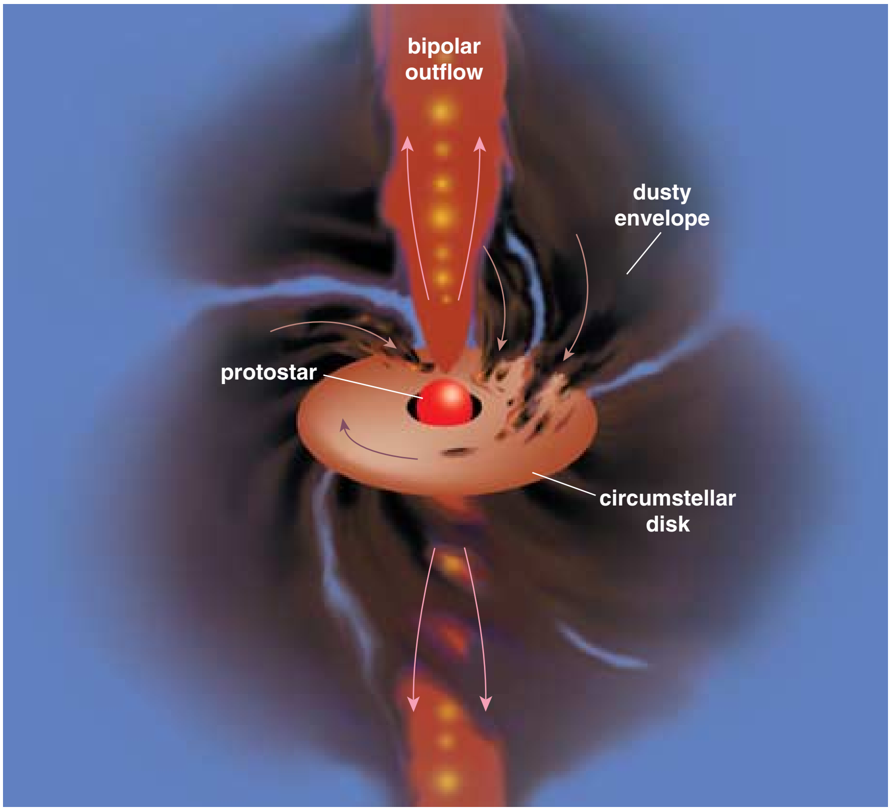

Figure 3. Protostars accumulate mass from a surrounding envelope of dust by way of a circumstellar disk that orbits the young object. Most of the energy the protostar radiates comes from this accretion process, which typically ends after about 100,000 years, as the object approaches its final mass. Powerful winds, which appear to be linked to the accretion process, emanate from the poles of the star, expelling some of the envelope's mass. These bipolar jets are often evident in telescopic images *(see Figure 4)*.

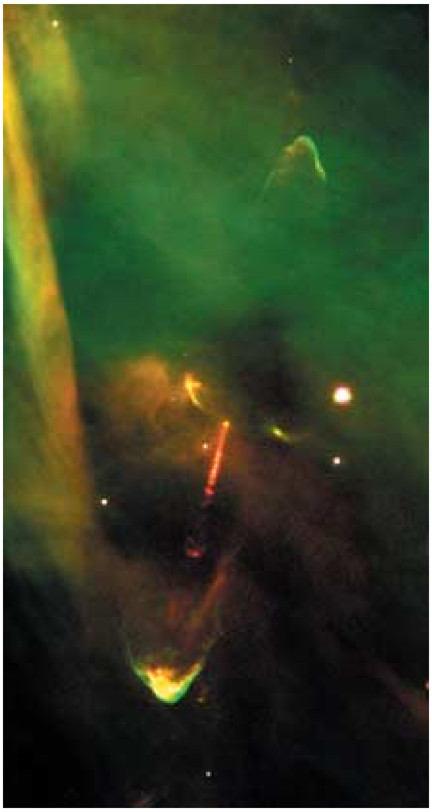
Courtesy of the European Southern Observatory

Figure 4. Herbig-Haro 34, a young stellar object, exposes one of its bipolar jets *(red streak)*, which emanates from the central star. Two bow-shaped regions *(upper right and lower left)* show where the jets collide with the interstellar medium.

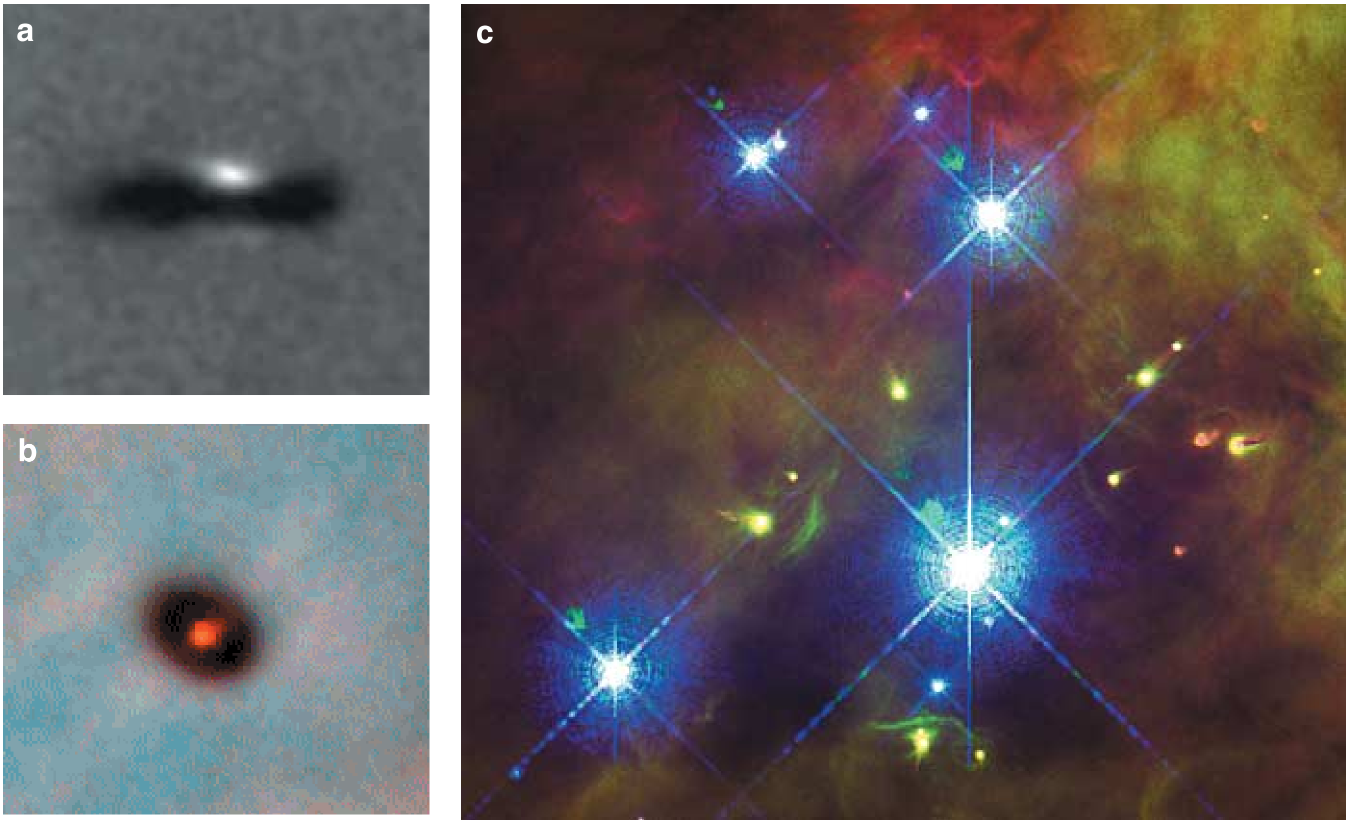

Figure 5. Protoplanetary disks (or proplyds), seen on edge *(a)* or face on *(b)*, can be found in images of star-forming regions. These dust-filled disks may evolve to form planetary systems, but some recent images of the trapezium in Orion *(c)* suggest that strong winds from energetic neighboring stars may destroy the proplyds *(yellow tear drops pointing in the direction of the wind)* before the planetary systems form. (*A* and *B* courtesy of Mark McCaughrean, C. Robert O'Dell and NASA. *C* courtesy of John Bally, David Devine, Ralph Sutherland and NASA.)

young stellar objects to be observed, which is not surprising given that many of them are optically visible. In the 1950s, Merle Walker, then at the Mount Wilson and Palomar Observatories, noticed that some stars in the vicinity of dark clouds were intrinsically brighter (more *luminous)* than their main-sequence counterparts of the same temperature. Since an object's luminosity is proportional to its radius *(R)* and temperature *(T)*, in the relation R^2T^4, it was apparent that these objects were larger than the main-sequence stars. This is precisely what theoreticians had predicted for a PMS star that was still in the process of contracting.

Protostars were not discovered until the pioneering infrared surveys of the 1960s and 1970s, which found several candidates embedded deep within the dark clouds. Space-based observations later showed that protostars are up to 10 times more luminous than PMS

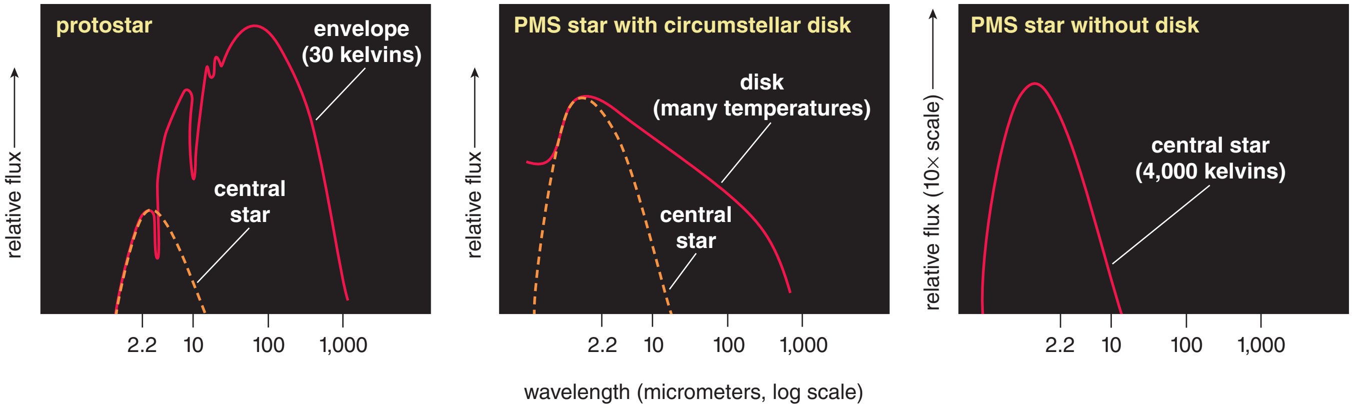

Figure 6. Spectral energy distributions at infrared wavelengths can reveal different classes of young stellar objects. The key to the identification is the relation between wavelength and temperature, with longer wavelengths corresponding to cooler temperatures. Protostars *(left)* emit a broad band of infrared energy, with a peak near 100 micrometers, which emanates from the cold envelope of material surrounding the star. A circumstellar disk is recognized as a broad range of emissions that decrease in strength at cooler temperatures *(middle)*, corresponding to a range of distances from the central pre-main-sequence (PMS) star. A bare PMS star is recognized by a relatively narrow peak near 2 micrometers *(right)*, which corresponds to a temperature of about 4,000 kelvins. (Adapted from the work of Charles Lada and others.)

stars. But since protostars are not much bigger than PMS stars, it suggested that they had an extra source of energy that was contributing to the protostar's luminosity.

In the decades that followed, astronomers refined their observations of young stellar objects. Such studies included the object's *spectral energy distribution*—the amount of energy the object releases over a range of wavelengths (especially in the infrared part of the spectrum). As it happens, measurements of an object's spectral energy distribution are surprisingly informative.

In particular, the shape of the distribution reveals the evolutionary stage of the object *(Figure 6)*. Since the various components of the object—the central star, the dusty envelope and the circumstellar disk—each have different temperatures, the amount of infrared radiation the object emits at a particular wavelength tells us which components are present. The spectral energy distribution of a protostar, for example, is dominated by an infrared emission near 100 micrometers, which represents the radiation from the large outer reaches of its chilly (30-kelvin) envelope. The presence of the envelope also explains why protostars are more luminous than PMS stars: Matter from the envelope is still falling onto the protostar. As the material slams into the protostar's surface, its gravitational energy is converted to thermal energy—the source of the infrared radiation.

In contrast, the spectral energy distribution of a PMS star with a circumstellar disk is dominated by the central star, with a peak emission near 2 micrometers. The disk itself shows up as a broad range of emissions, especially at longer wavelengths, representing the various temperatures of the disk (which decrease with distance from the central star). In the absence of the dusty envelope, the accretionary process has slowed to a trickle, if anything at all, in the PMS star.

As valuable as these measurements have been to our understanding of star formation, they only scratch the surface when it comes to revealing the physical properties of the young stars themselves. A much better probe is a star's true spectrum, which shows atomic and molecular absorption lines *(Figure 8)*. Such spectra reveal the identity of the elements and molecules present in the star's atmosphere, as well as provide an accurate reading of its temperature, its radius and its rate of rotation.

Modern telescopes and infrared detectors have been able to show the absorption lines in the spectra of some young stars still embedded in dark clouds. These turn out to be PMS stars, which are very similar to their optical counterparts, except that they are still hidden in the dust. However, there are a number of young stars in the dark clouds that do not show strong spectral absorption features. The spectral energy

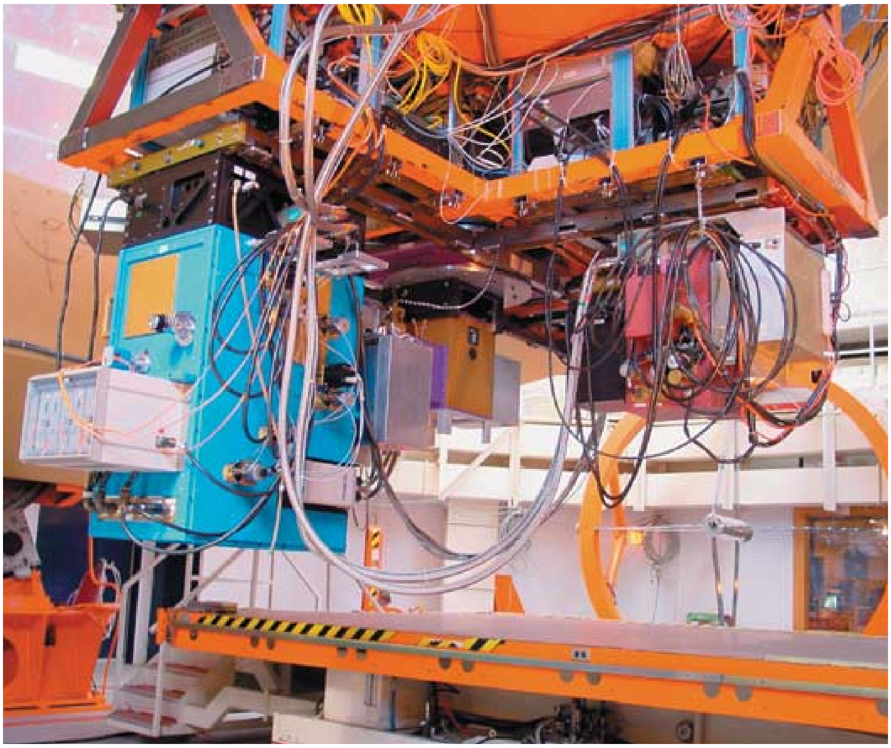

Figure 7. Highly sensitive infrared spectrographs, such as the SpeX *(blue box)* and CSHELL *(red box)* instruments at NASA's Infrared Telescope Facility on Mauna Kea, allow astronomers to measure the atomic spectra of protostars for the first time. Here the spectrographs are attached to the bottom of the 3-meter IRTF reflector telescope. (Image courtesy of the IRTF staff.)

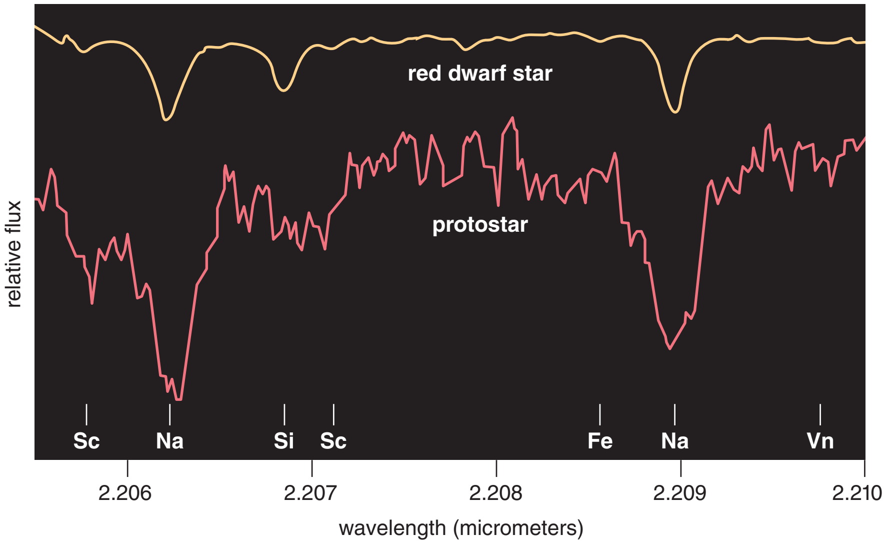

Figure 8. Atomic spectrum of a protostar can be matched to a "normal" star such as a red dwarf, a relatively small, cool star. The absorption line in a spectrum reveals the elements and molecules in the protostar's atmosphere, and can be used to deduce the star's temperature, radius and rate of rotation. The data were collected with CSHELL *(see Figure 7)*.

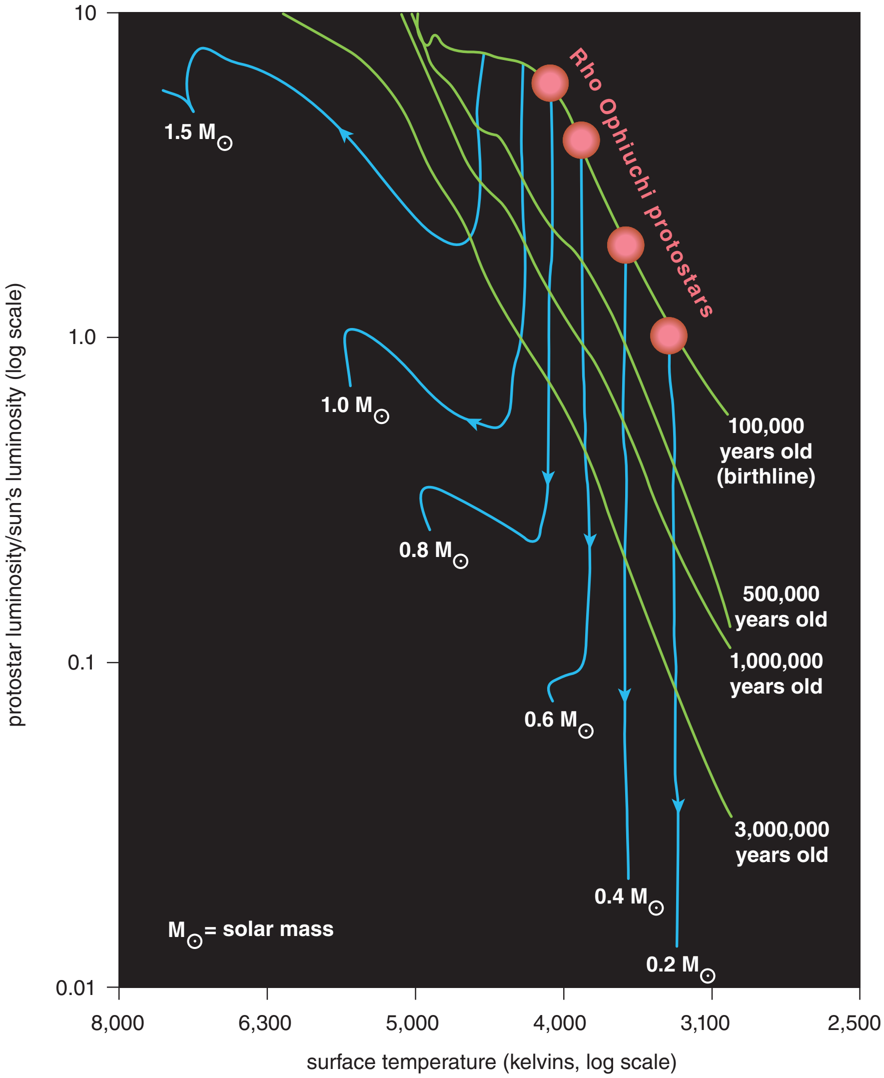

Figure 9. Hertzsprung-Russell diagram reveals the evolutionary course of a star based on its mass *(blue lines)*. A cohort of stars that were born together move as a wave through time *(green lines)*. The protostars of the Rho Ophiuchi dark cloud define the *birthline* for low-mass stars, and thus represent the youngest stars ever plotted on such a graph. Here only the first few million years of evolution are shown, even though most low-mass stars have lifetimes measured in billions of years. The early evolution of our Sun is represented by a young stellar object of 1.0 solar mass.

distributions of these objects suggest that they are protostars, and they offer a special challenge for stellar spectroscopy.

Playing Peek-a-Boo with Protostars

It's been said that protostars are the "Holy Grail" of infrared astronomy, and this statement pretty much sums up the difficulty of the pursuit. The dust that surrounds a protostar dims its visible light by a factor of one billion, and even its near-infrared emissions (wavelengths around 2 micrometers) are dimmed by a factor of 10. Much of this dust is very close to the star (about 5 stellar diameters away), and is heated to a temperature of nearly 1,500 kelvins by the star's radiation and the energy liberated by matter falling in from the envelope and disk. The glow of the warm dust usually emits several times as much near-infrared radiation as the central star itself. The protostar is effectively washed out—or *veiled*—by its surroundings. What is an infrared astronomer to do?

The solution lies in bigger telescopes and extremely sensitive infrared detectors. Fortunately, such equipment now exists. Three of the more powerful infrared telescopes are located atop Mauna Kea on the big island of Hawaii: the 3-meter NASA Infrared Telescope Facility (IRTF), the 3.8-meter United Kingdom Infrared Telescope and the giant 10-meter Keck II telescope. These telescopes collect infrared radiation with their large primary mirrors, which focus the light into spectrographs. These spectrographs use large diffraction gratings to disperse the light (into its component wavelengths), which is then focused again onto sophisticated infrared detector arrays *(Figure 7)*. The optics and the detectors must be cooled to as low as 30 kelvins (with liquid nitrogen and mechanical coolers) to prevent the infrared radiation of the instruments from overpowering the faint signals from the young stars.

Charles Lada, of the Smithsonian Astrophysical Observatory, and I have recently used the IRTF and Keck telescopes to make the first detections of infrared absorption lines in Sun-like protostars. The task required a large amount of observing time (about a week per year) to build up a sufficient signal. So far we have recorded about a dozen high-resolution spectra of strongly veiled protostars in the dark clouds near Rho Ophiuchi.

Interestingly, the atomic spectra of these objects are similar to main-sequence stars that are very cool—except that their absorption features are much weaker. (Main-sequence stars such as red dwarfs can have very cool surfaces, even though their core temperatures are hot enough for thermonuclear fusion.) We interpret this to mean that the protostars have surface temperatures that are similar to the cool stars, about 3,500 to 4,000 kelvins. This is about the same as the PMS stars in the same clouds, which have temperatures as high as 4,500 kelvins. We need more observations to see whether there are truly any significant differences in the temperatures or sizes of these young stars.

We have also quantified the veiling of these protostars by measuring the depth of their absorption lines relative to main-sequence stars and PMS stars of equivalent temperatures. At wavelengths of about 2 micrometers, some of the veiling is as much as three times brighter than the star itself! We think this "excess" emission is caused by the active accretion of material either onto the protostar or within its circumstellar disk. In some instances the veiling is even greater than a threefold brightness of the central star. We interpret this higher level of veiling as the accretion of matter from the circumstellar envelope.

By subtracting the excess emissions we can also determine how much infrared radiation comes from the central star itself. This allows us to estimate the protostar's intrinsic brightness, which reveals a luminosity comparable to the PMS stars in the same cloud. This suggests that protostars and PMS stars are about the same size. These measures of the protostar's luminosity may appear to be in slight conflict with their spectral energy distributions, which indicate that protostars are several times brighter than PMS stars. However, the spectral energy distributions of the protostars also include the accretion of matter onto their central stars, a process that releases gravitational energy.

The temperatures and luminosities of the protostars can also be converted to estimates of their ages and their masses. Theorists generally model the evolution of PMS stars, but are now beginning to consider the effects of accretion so that their models can be applied to protostars. This was recently done by several independent groups of astrophysicists, including three Italian theorists, Francesco Palla, Francesca D'Antona and Italo Mazzitelli, as well as Steven Stahler of the University of California, Berkeley, and Isabelle Baraffe and Lionel Siess of France. Their sophisticated calculations allow us to place the protostars on a temperature-luminosity—or Hertzsprung-Russell (H-R)—diagram for the first time ever *(Figure 9)*. This is no small accomplishment, since the H-R diagram is the key to providing the age and mass of a star.

All of the protostars in the plotted sample come from the same dark cloud near Rho Ophiuchi. They appear to be very young, effectively defining the observational *birthline* where stars first appear on the H-R diagram, and all appear to be lightweights of about 0.5 solar mass. Similarly, PMS stars in the same cloud appear to span a range of masses with a peak near 0.5 solar mass. The masses of protostars and PMS stars are generally expected to be similar because the protostars should have accreted nearly all of their final mass at this stage of their evolution. However, many more protostars will have to be studied to determine whether there is a significant difference between their masses and those of PMS stars.

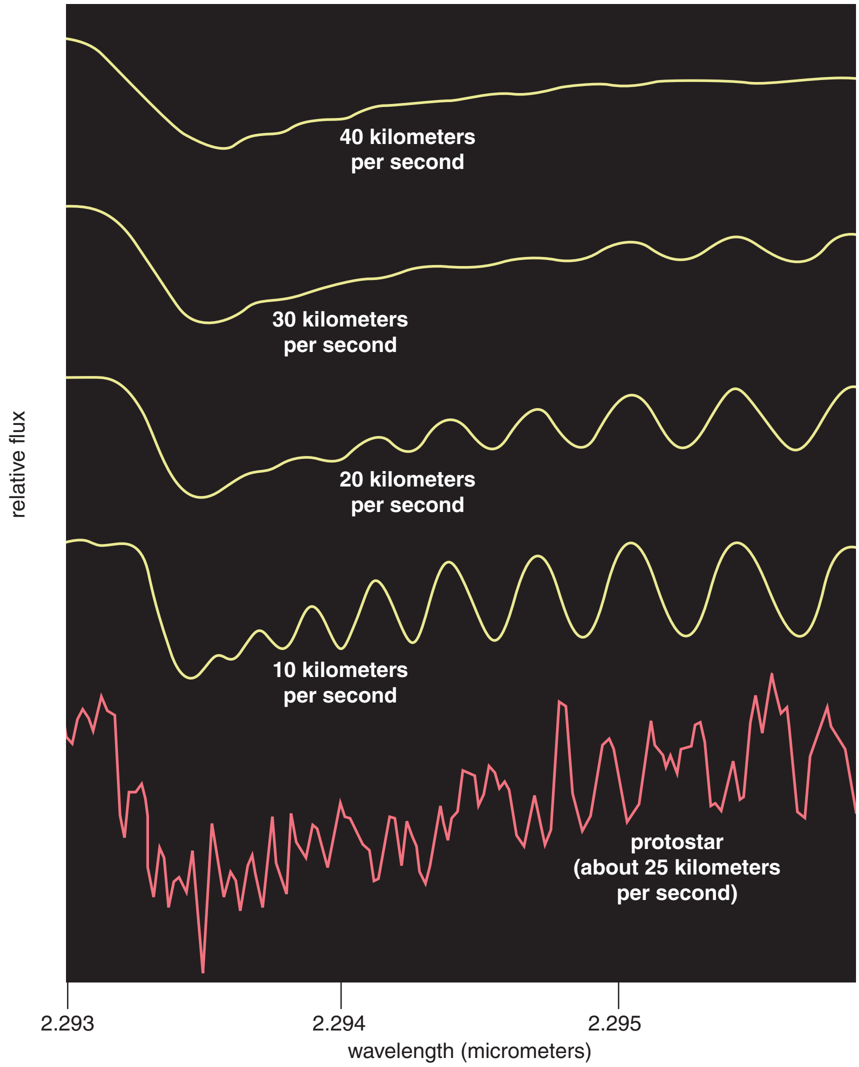

Figure 10. Stellar rotation can be measured by the absorption-line spectrum of the carbon monoxide molecule in a protostar's atmosphere. A computer compares a protostar's noisy spectrum *(red line)* to the shapes of synthetic spectra *(yellow lines)* from objects with different rotation velocities.

Spinning in the Cradle

Among the more interesting physical properties that absorption-line spectra allow us to measure is the star's rate of rotation. All stars spin on their axes, a quality that is believed to be inherited from the rotation of the dense core as it collapses in the prenatal dark cloud. Our Sun has a rotation period of about 26 days, which corresponds to a velocity of about 2 kilometers per second at its equator. This actually corresponds to a tiny fraction (one percent) of the angular momentum in our solar system, even though the Sun contains the bulk of the system's mass. Instead, most of the solar system's angular momentum lies in the planets, especially Jupiter and Saturn. One of the mysteries of solar-system formation is how the bulk of the mass gets concentrated in the center, while almost all of the angular momentum is transferred to the periphery. One road to answering this question is to observe how the rate of rotation changes during the early stages of a star's formation.

The key to measuring a protostar's rotation is the carbon monoxide molecule. At a wavelength of about 2.3 micrometers, the absorption line of carbon monoxide has detailed structure that is very sensitive to the rotation of the protostar, but is not altered by the star's other physical properties *(Figure 10)*. By comparing the observed shapes of this feature to synthetic spectra with different rotation velocities we can determine the object's rate of rotation. Actually, what we do measure is the object's *projected* rotation velocity. Since we don't know the exact alignment of the object's axis to our line of sight, we are not getting a full measure of the object's rate of rotation. Even so, this information is ex-

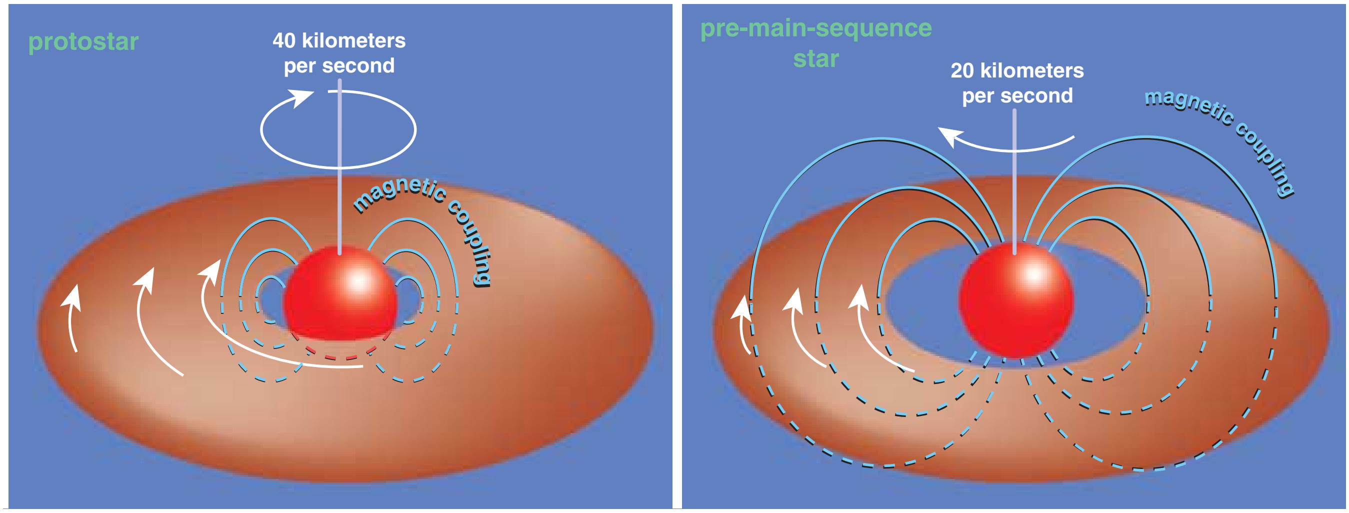

Figure 11. **Protostars rotate more rapidly than pre-main-sequence stars, suggesting that young stellar objects slow down as they age. One theory holds that protostars and pre-main-sequence stars are coupled to different parts of the disks that surround them. Since the inner region of a circumstellar disk rotates more quickly than the outer region, theorists argue that protostars may be closely coupled to the inner parts of their disks, perhaps because they are still accreting matter from the disks. If so, then the inner edge of a protostar's disk would also be about four times closer to its central star than is the disk of a pre-main-sequence star.**

tremely valuable because the orientation of these objects should be more or less random with respect to the Earth.

The results are intriguing. Nearly all of the protostars that we observed are rotating quickly, with projected velocities greater than 20 kilometers per second. On the other hand, most PMS stars with circumstellar disks are rotating slowly, with projected velocities less than 20 kilometers per second. What accounts for the differences in rotation velocities?

Several theorists have shown that the rotation velocity of a young star can be controlled by its circumstellar disk through the star's magnetic field. If this process occurs in both types of young stellar object, it means that the protostars must be coupled to regions of their disks that are spinning faster than those of PMS stars *(Figure 11)*. Since Kepler's third law dictates that the circumstellar material that orbits a star most quickly must be closest to the star, our results suggest that protostars are coupled to nearby parts of their disks. This may arise because protostars are still accreting large amounts of matter directly from their disks. Or it may be that the accreting matter carries a substantial angular momentum, which "spins up" the protostars.

In contrast, PMS stars are no longer accreting much matter and instead may have experienced some braking. "Disk braking" is thought to be produced by ionized gas in the circumstellar disk which tugs on the star's magnetic field, slowing the spinning star. The phenomenon can be likened to pulling on a sticky wad of bubble gum that is attached to a spinning baseball. The ball may not stop spinning, but it will slow down. Whatever the mechanism, our results suggest that the transition from protostar to PMS star involves a drop in rotational velocity and a coincident drop in angular momentum.

The absorption-line spectra also reveal some other interesting phenomena involving the accretion process. When we look at an object's spectrum we must distinguish whether it arises from the atmosphere of the central star or from its circumstellar disk. Since the accretion process will make the disk hot and relatively dense, it should have its own emission spectrum and absorption lines. Fortunately, the physical differences between the disk and the star help us to discriminate between their spectra. The disk is less dense than the star, so its gas is under less pressure, which means that certain elements will have different levels of ionization (which are apparent in the spectrum). Moreover, disks rotate at different speeds at each radial distance, whereas stars rotate essentially as a solid body. These physical differences translate into substantial differences in the relative strengths of the absorption lines and the velocity profiles of the carbon monoxide features.

The spectral features of nearly all protostars that my colleagues and I have studied clearly indicate that they arise from the stars' atmospheres and not their circumstellar disks. However, we have found a handful of young stars that intermittently show disk-like features. They turn out to be *FU Orionis variables,* which also show large, episodic changes in their luminosity. One possible explanation for this puzzling observation is that the FU Orionis protostars accrete material through their disks in brief spurts. Most of the time they would be in low-accretion states, during which they would show star-like spectral features. Occasionally, however, they would undergo periods of high accretion, when their luminosity increases and their spectra become dominated by disk-like features. This idea, largely championed by Lee Hartmann of the Smithsonian Astrophysical Observatory, is currently the best explanation out there.

Might all protostars go through an FU Orionis phase? So far the infrared spectra of protostars and hundreds of PMS stars show little or no evidence of FU Orionis-like features. If the FU Orionis phase of evolution were common to all young stars, one would expect at least a few of these stars to show some evidence of accretionary spurts. Perhaps the FU Orionis stars are merely freaks.

Conclusion

Many of the protostars that we've observed in the infrared won't be seen in visible light for another hundred-thousand years or more. Yet we now have a fair gauge of the qualities that astronomers seek to measure for true stars: their luminosities, sizes, ages, masses, rates of rotation and the presence of circumstellar matter. It is merely a beginning. There is much that remains unanswered, and many more dark clouds must be probed for protostars. Nevertheless, even the early anatomists began their studies of embryonic development with modest descriptions. Perhaps someday the science of stellar embryology may too describe the process of star formation in fine detail.

Acknowledgment

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