# The Formation of Stars and Solar Systems

**edited by**

**David L. Alles**

**Western Washington University**

**e-mail: alles@biol.wwu.edu**

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Note: In PDF format most of the images in this web paper can be enlarged for greater detail.

## Introduction

"Few questions are as ancient and compelling as that of how the world beneath our feet originated. Countless societies have sought an answer, developing varied and intriguing cosmographies that, however, often reveal more about their authors than the origins of Earth.

In 1644, Rene Descartes made what can be considered the first steps toward a reasoned description of planetary origins. His view theorized that Earth and the other planets surrounding the Sun originated from a system of vortices. Over a hundred years later, Immanuel Kant in 1755 and Pierre Simon Laplace in 1796 independently formulated what would become an underlying principle of modern ideas regarding the origin of the solar system. Both of their nebular hypothesises suggested that Earth and the other planets formed contemporaneously with the Sun from a cloud of gas that collapsed due to gravity into a rotating, flattened disk of material. This picture appears to be correct.

In the past decade, almost 200 planetary systems beyond our own have been discovered, along with a multitude of embryonic, protoplanetary systems. We now have the means not only to investigate the universal origins of worlds but also to hold our own up in comparison to others.

Protoplanetary systems can be enormously complex. It naturally follows that formed planetary systems must have considerably diverse properties. No single world is likely to have an exact duplicate, either among its immediate siblings or within the myriad systems in our galaxy. Gas, microscopic dust, ices, and rocky planetesimals are drastically processed and often reprocessed en route to becoming planets. These raw ingredients drift and circulate as the protoplanetary disk and the central protostar evolve. Their cooking takes many forms, from the coagulation and fragmentation of solids to the accretion or photo-dissociation of gases. It also involves widely varying thermal and radiation environments as well as a perplexing array of possible chemical pathways. Despite this complexity, research is revealing common mechanisms. And it is probably no overstatement to say that such details ultimately relate to the origins of life itself." (excerpts from Scharf, 2006)

## Giant Molecular Clouds

Space between stars in a galaxy is nearly empty, except for a scattering of hydrogen atoms. The atoms are so far apart that, if an atom were an average- size person, each person would be separated by about 465 million miles, which is the distance between our Sun and Jupiter. These atoms are moving very fast because they are extremely hot, baked by ultraviolet radiation from stars. This makes it difficult for atoms to bond to form molecules. Those that do form don't last for long. If radiation doesn't break these molecules apart, a chance encounter with another atom will.

Some parts of space, however, are not wide open frontiers containing a few atoms. These cosmic spaces comprise dense clouds of dust and gas left over from galaxy formation. Since these clouds are cooler than most places, they are perfect breeding grounds for star birth. When the density is 1,000 times greater than what is found in normal interstellar space, many atoms combine into molecules, and the gas cloud becomes a molecular cloud. Like clouds in our sky, these molecular clouds are puffy and lumpy. Molecular clouds in our Milky Way Galaxy have diameters ranging from less than 1 light-year to about 300 light-years and contain enough gas to form from about 10 to 10 million stars like our Sun. Molecular clouds that exceed the mass of 100,000 suns are called Giant Molecular Clouds.

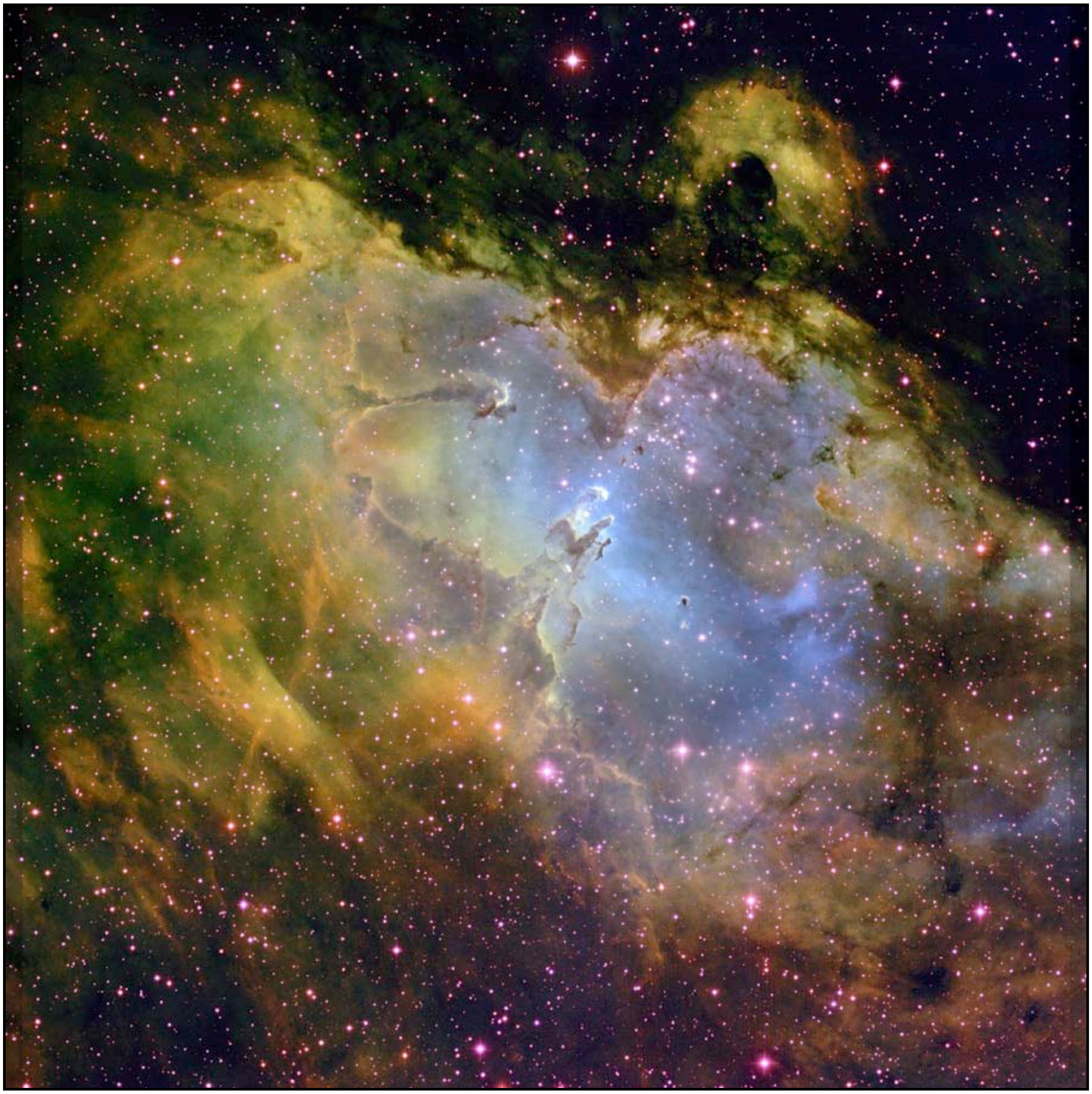
A typical full-grown spiral galaxy contains about 1,000 to 2,000 Giant Molecular Clouds and many more smaller ones. Such clouds were first discovered in our Milky Way Galaxy with radio telescopes about 25 years ago. Since the molecules in these clouds do not emit optical light, but do release light at radio wavelengths, radio telescopes are necessary to trace the molecular gas and study its physical properties. Most of this gas is very cold—about minus 440 degrees (°) Fahrenheit (F) or -262 degrees Celsius (C)—because it's shielded from ultraviolet light. Since gas is more compact in a colder climate, it is easier for gravity to collapse it to form new stars.

Ironically, the same climate that is conducive to star formation also may shut off the star birth process. The problem is heat. Young stars are very hot and can heat the molecular gas to more than 1,000° F (537° C), which is an unfavorable climate for star birth. When the temperature exceeds about 3,000° F (1648° C), the gas molecules break down into atoms.

The density of the gas can increase considerably near the centers of some Giant Molecular Clouds: Gas as dense as 1 billion molecules per cubic inch has been observed. (Though dense by astronomical standards, such gas is still 100 billion times thinner than the air we breathe here on Earth at sea level!) In such dense regions, still denser blobs of gas can condense and create new stars. Although the star formation process is not fully understood, there is observational evidence that most stars are born in the densest parts of molecular clouds.

What happens when stars begin forming in Giant Molecular Clouds depends on the environment. Under normal conditions in the Milky Way and in most other present-day spiral galaxies, star birth will stop after a relatively small number of stars have been born. That's because the stellar nursery is blown away by some of the newly formed stars. The hottest of these heat the surrounding molecular gas, break up its molecules, and drive the gas away. As the celestial smog of gas and dust clears, the previously hidden young stars become visible, and the molecular cloud and its star-birthing capability cease to exist. In 1995 the Hubble Space Telescope revealed such an emerging stellar nursery in the three gaseous pillars of the Eagle Nebula (M16).

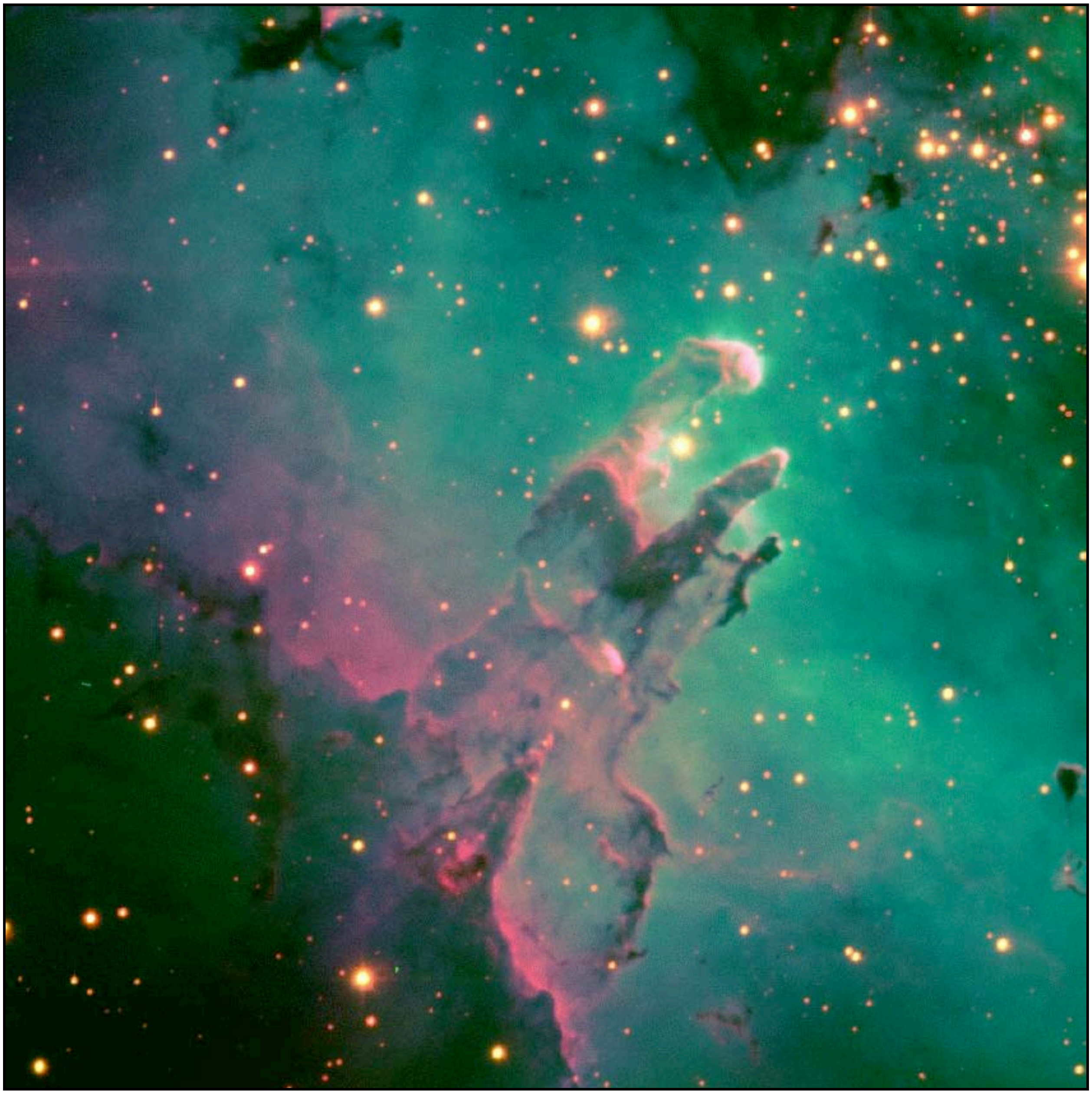
Web Reference
http://hubblesite.org/newscenter/archive/1995/44/



The Giant Molecular Cloud shown above is the Eagle Nebula (M16) a nearby star-forming region 7,000 light years away in the constellation Serpens.

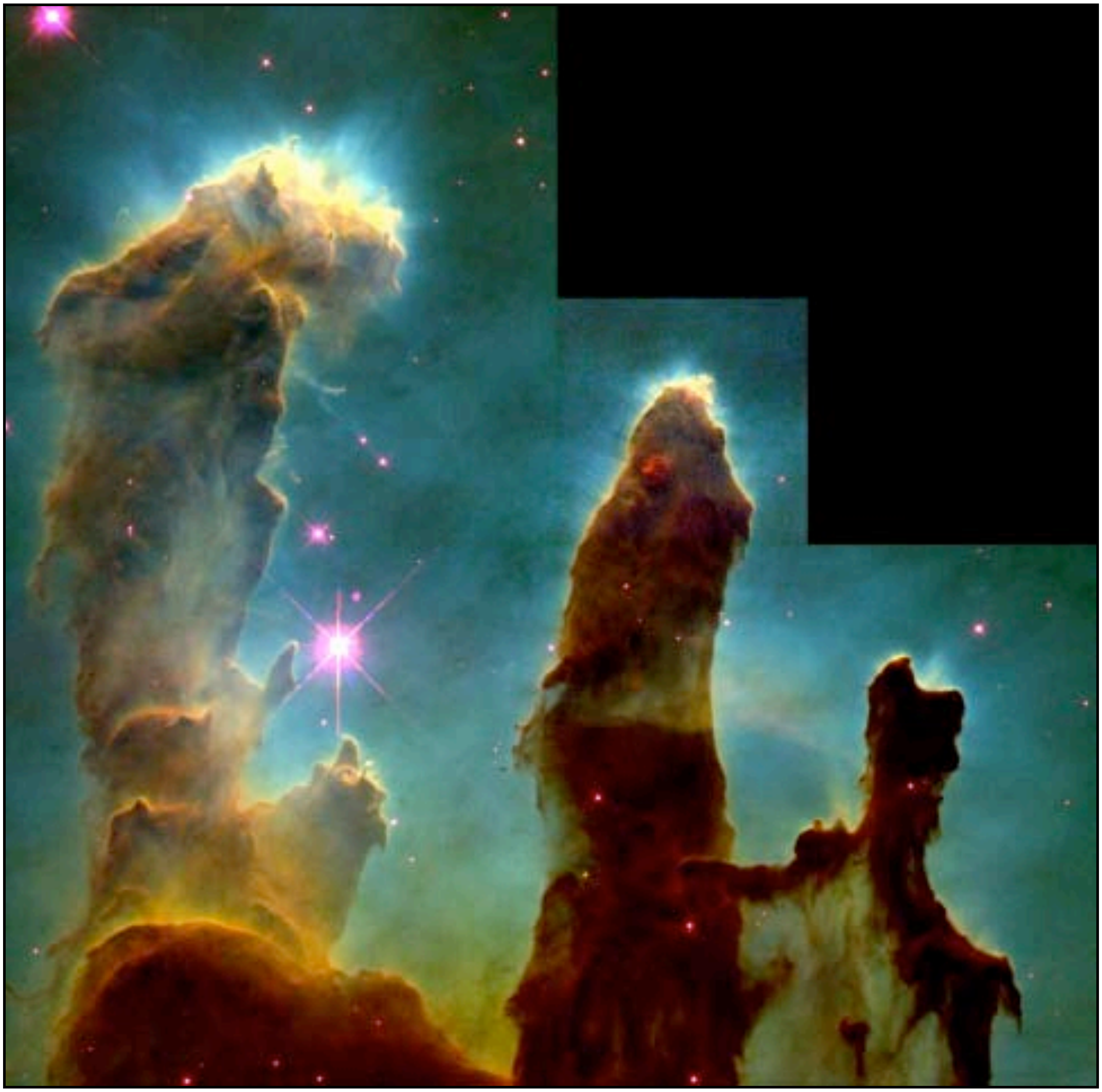
(Image credit: T. A. Rector & B. A. Wolpa)

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap020611.html



This image shows the massive star forming region in the Eagle Nebula known as the "pillars of creation".

(Image credit: Paul Scowen)



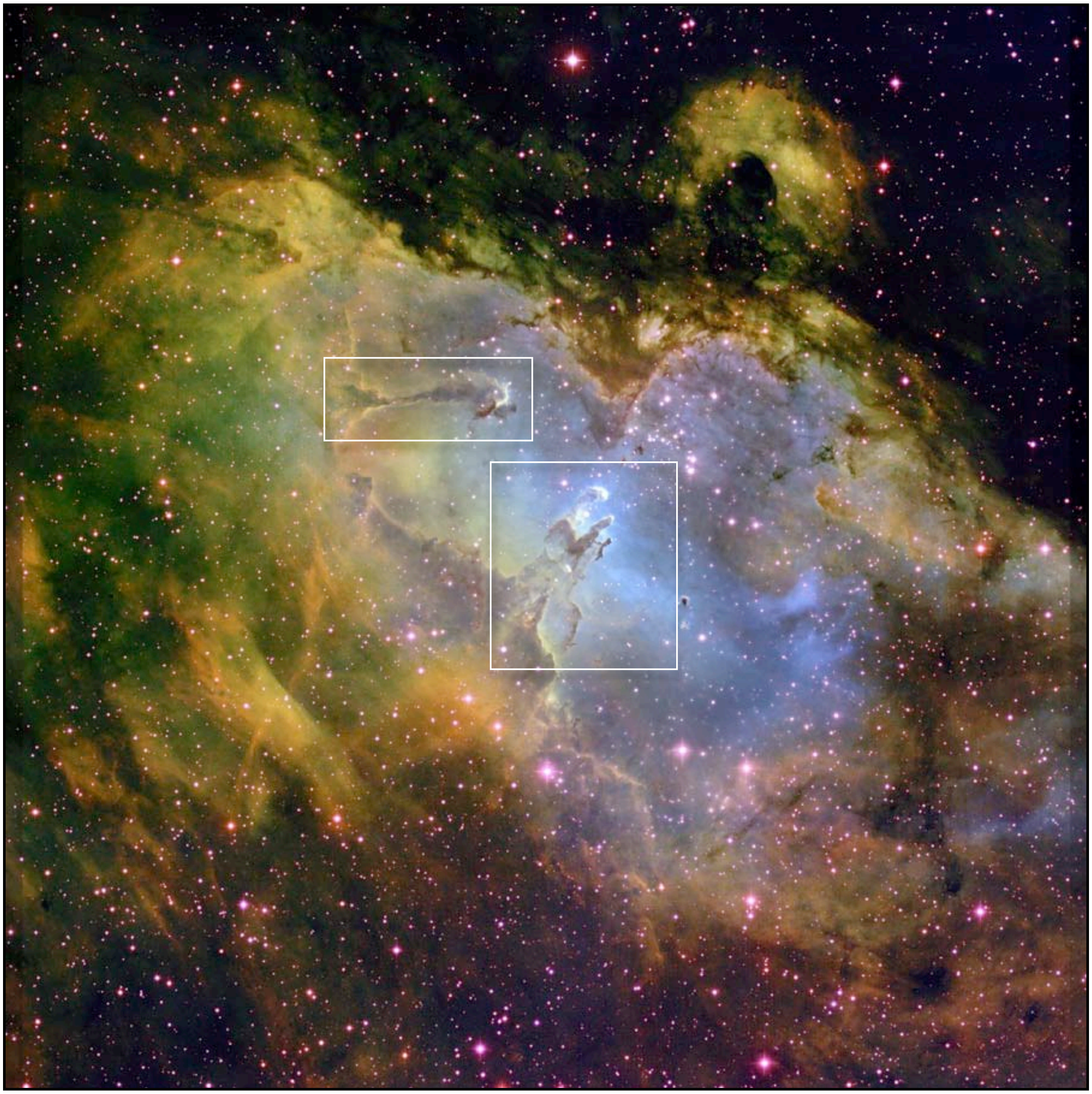
This stunning Hubble Space Telescope (HST) image of the "pillars of creation" was taken by Jeff Hester and Paul Scowen of Arizona State University. From their common base these pillars of gas rise approximately 1.02 light years or 9.7 trillion kilometers.

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap970119.html

This close-up of the gas clouds in the Eagle Nebula was released on the 15th anniversary of the Hubble telescope. The soaring tower of dust and gas above is 9.5 light-years or about 90 trillion kilometers high, about twice the distance from our Sun to the next nearest star.

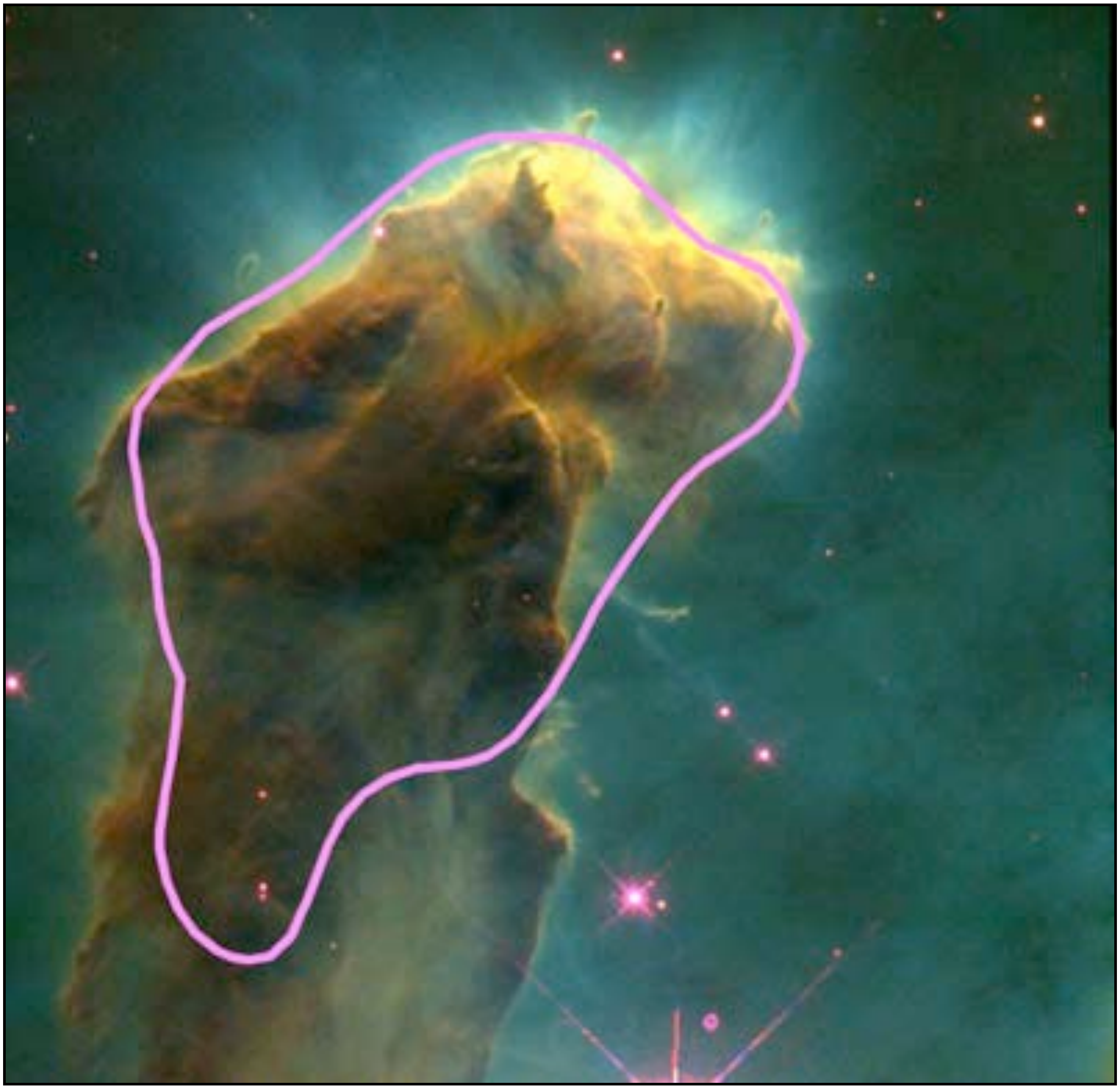
Web Reference

http://hubblesite.org/newscenter/newsdesk/archive/releases/2005/12/



The white boxes above show the relative position of the 1995 Hubble image of the three pillars to the 2004 Hubble image of the gas plume.

Hubble images gives a clear look at what happens as a torrent of ultraviolet light from nearby young, hot stars heats the gas along the surface of the pillars, "boiling it away" into interstellar space—a process called "photo evaporation". In the Eagle Nebula the ultraviolet light is uncovering the denser protoplanetary disks or “proplyds” that surround stars that were forming inside the gigantic gas columns. Both terms refer to condensed regions of gas where individual stars, and possibly planets, form that are undergoing intense radiation from nearby massive stars.



Shown above is the region of active star formation at the top of the far left pillar of the "pillars of creation". Some of these proplyds of gas appear as nothing but tiny bumps on the surface of the columns. Others have been uncovered more completely, and now resemble "fingers" of gas protruding from the larger cloud. Some proplyds of gas have pinched off completely from the larger column from which they emerged, and now look like teardrops in space.

Web Reference
http://hubblesite.org/newscenter/archive/1995/44/image/b

Above is a teardrop shaped proplyd, in the Orion Nebula.

(Image courtesy of NASA)

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap010504.html

For a long time astronomers have speculated about what processes control the sizes of stars—about why stars are the sizes that they are. Striking pictures taken by Jeff Hester and co-investigators resolve the evaporating gaseous globules at the tip of finger-like features protruding from monstrous columns of cold gas and dust in the Eagle Nebula (also called M16 for the 16th object in the Messier catalog). The columns—dubbed "pillars of creation"—protrude from the wall of a vast cloud of molecular hydrogen, like stalagmites rising above the floor of a cavern. Inside the gaseous towers, which are light-years long, the interstellar gas is dense enough to collapse under its own weight, forming young stars that continue to grow as they accumulate more and more mass from their surroundings.

Ultimately, photo evaporation inhibits the further growth of the embryonic stars by dispersing the cloud of gas they were "feeding" from. It’s believed that the stars in M16 were continuing to grow as more and more gas fell onto them, right up until the moment that they were cut off from that surrounding material by photo evaporation.

It’s also speculated that photo evaporation might actually inhibit the formation of planets around such stars. It is not at all clear from the new data that the stars in M16 have reached the point where they have formed the disks that go on to become solar systems, and if these disks haven't formed by this point, they never will.

This process is markedly different from the process that governs the sizes of stars forming in isolation. Some astronomers believe that, left to its own devices, a star will continue to grow until it nears the point where nuclear fusion begins in its interior. When this happens, the star begins to blow a strong "wind" that clears away the residual material. Hubble has imaged this process in detail in so-called Herbig-Haro objects.

## Herbig-Haro Objects

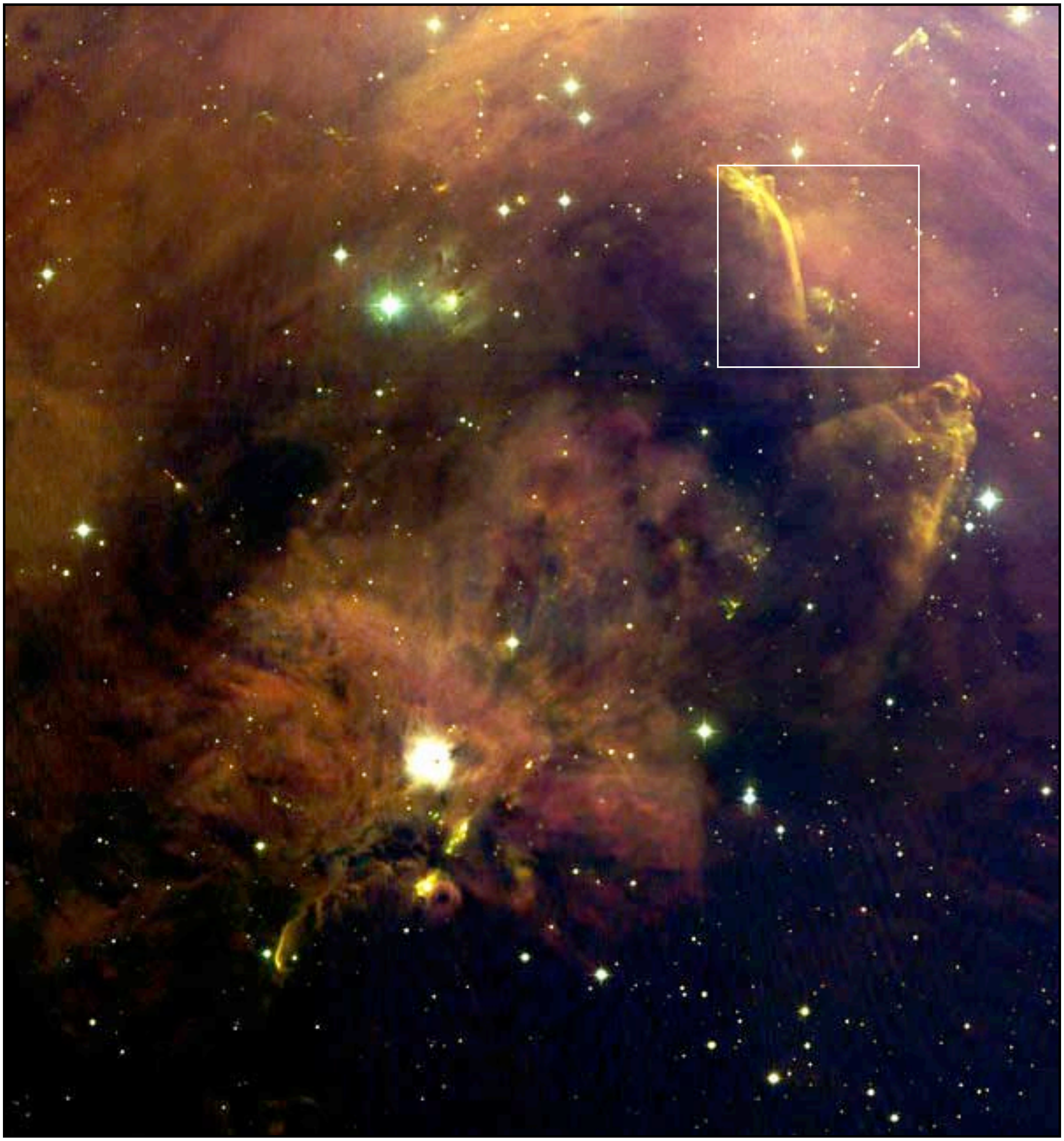
In the early 1950's, American astronomer George Herbig and Mexican astronomer Guillermo Haro independently catalogued several enigmatic "clots" of gas in the Orion nebula that have since been called Herbig-Haro objects. It is only in the last 20 years, however, that the true nature of these objects, and their role in the star formation process, has been understood.

Careful study showed that many of the Herbig-Haro objects represent portions of high-speed jets streaming away from nascent stars or protostars. Later workers have shown that the large range of energetic conditions involved requires bow shocks and other complex features to form.

By the early 1980s, several Herbig-Haro (HH) objects were shown to be tight collimated jets of partially ionized plasma moving away from young stars. Many individual HH objects consist of separate knots or bow shocks. Others consist of highly linear chains of jets. Most show evidence of being a part of or caused by a highly collimated flow from a young star. Today there are nearly 300 Herbig-Haro objects that have been identified by astronomers.

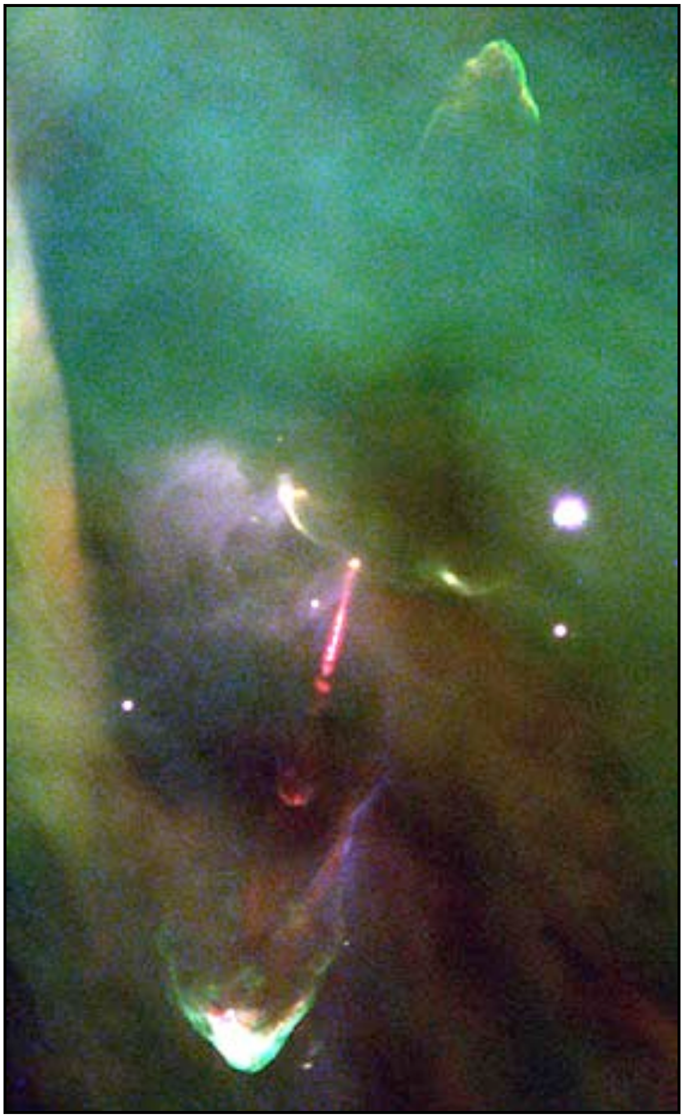
This European Southern Observatory (ESO) image shows the young object Herbig-Haro 34 (HH-34), now in the protostar stage of evolution. HH-34 is located at a distance of ~ 1,500 light-years, near the famous Orion Nebula, one of the most productive star-birth regions known. Note also the enigmatic "waterfall" to the upper left, a feature that is still unexplained.

Web Reference
http://www.eso.org/outreach/press-rel/pr-1999/pr-17-99.html

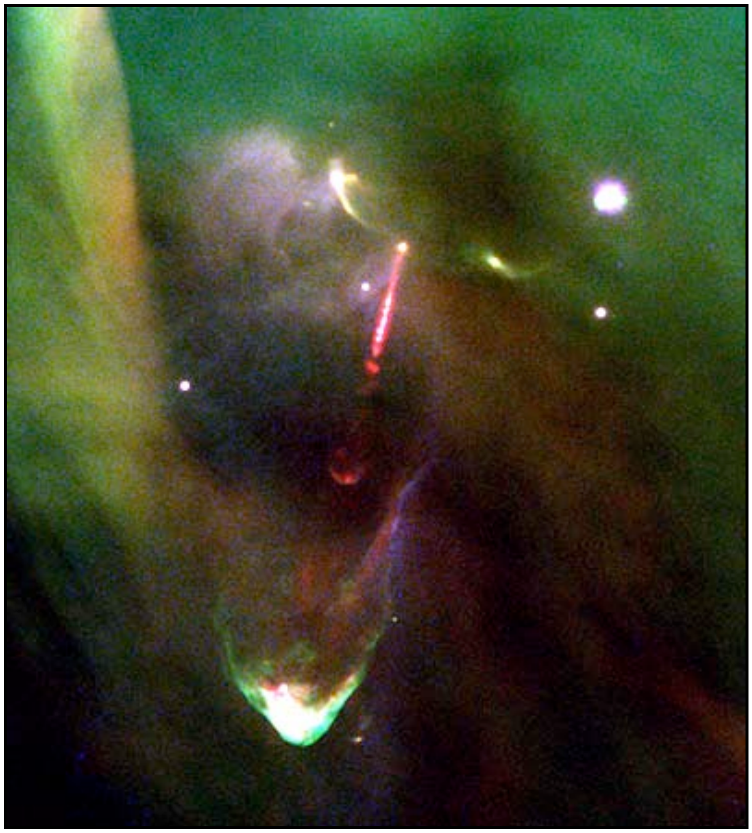


This spectacular panorama of star formation is located about two degrees south of the Orion Nebula, where a surviving portion of one of Orion's giant molecular clouds, known as Orion A, is continuing to spawn new stars. The white box above shows the location of HH-34 as shown in the previous image.

Web Reference
http://www.noao.edu/outreach/latest/

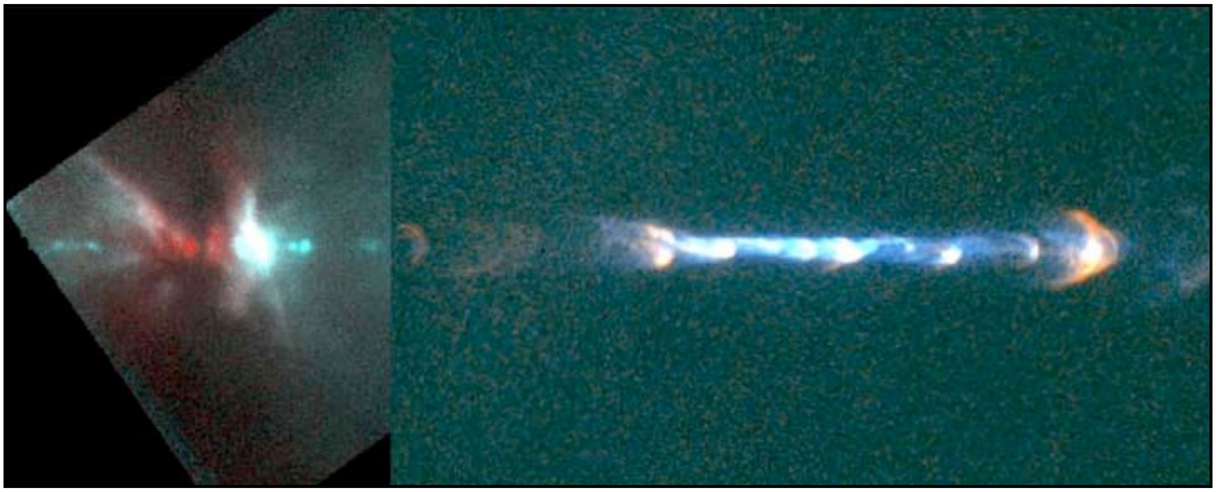


This object has a remarkable and very complicated appearance that includes two opposite jets that ram into the surrounding interstellar matter. This structure is produced by a machine-gun-like blast of "bullets" of dense gas ejected from the star at high velocities (approaching 250 km/sec). This seems to indicate that the star experiences episodic "outbursts" when large chunks of material fall onto it from a surrounding disk.



Material falling onto a star creates a jet when some of it is heated and blasted along a path that follows the star's rotation axis, like an axle through a wheel. Jets may assist star formation by carrying away excess angular momentum that otherwise would prevent material from reaching the star.

These images offer clues to events that occurred in our solar system when the Sun was born 4.5 billion years ago. Because all the planets lie in the same plane and orbit the Sun in the same direction, astronomers believe that Earth and the other eight planets condensed out of a circumstellar disk similar to HH-34. According to this theory, when the Sun ignited it blew away the remaining disk, but not before the planets had formed. A disk appears to be the natural outcome when a slowly rotating cloud of gas collapses under the force of gravity.



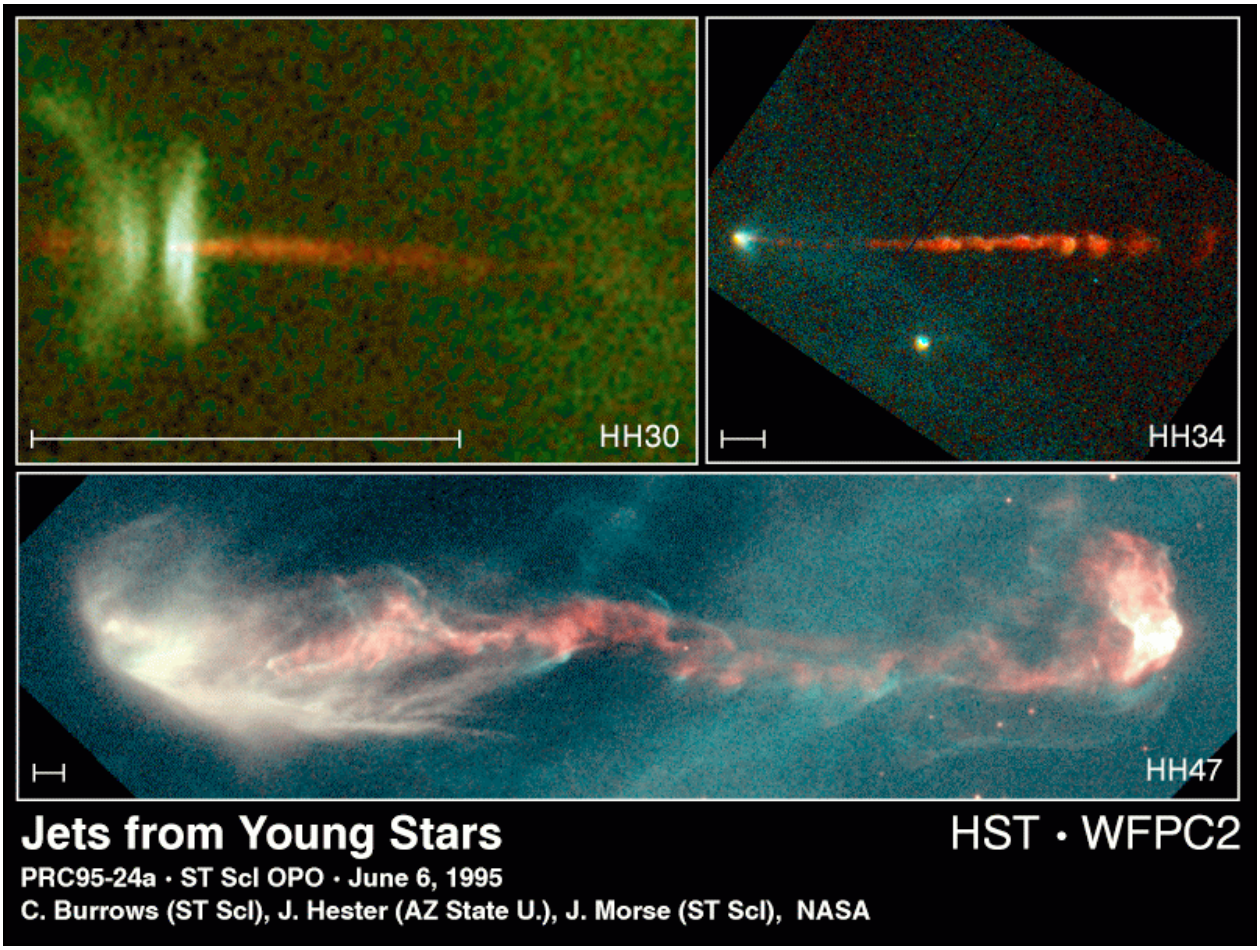
**Hubble Space Telescope image of HH-111**

Stellar jets are analogous to giant lawn sprinklers. Whether a sprinkler whirls, pulses or oscillates, it offers insights into how its tiny mechanism works. Likewise stellar jets, billions or trillions of miles long offer some clues to what's happening close into a star at scales of only millions of miles, which are below even the Hubble telescope's ability to resolve detail.

Hubble images show that a jet comes from close-in to a star rather than the surrounding disk of material. Material either at or near the star is heated and blasted into space, where it travels for billions of miles before colliding with interstellar material.

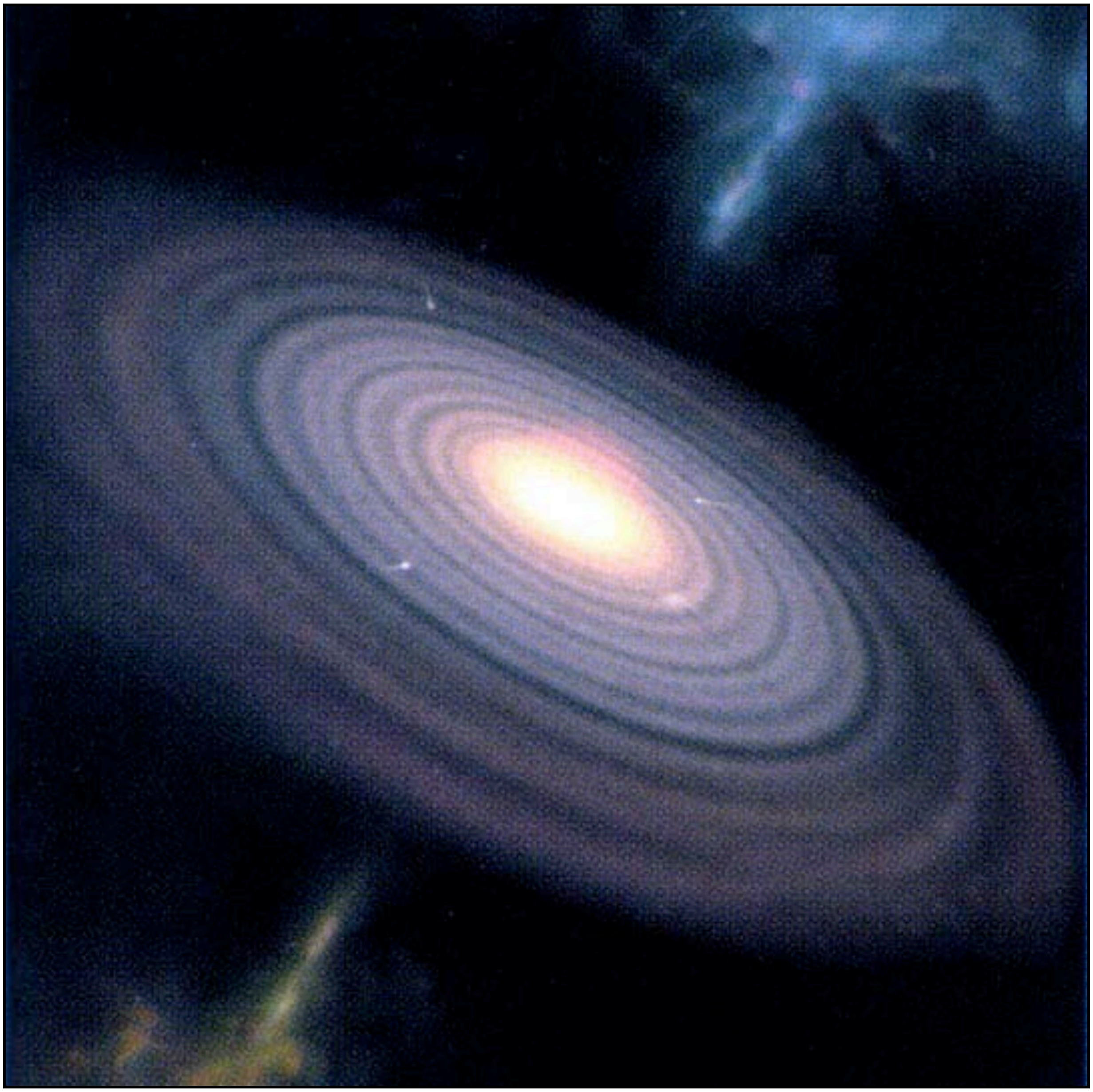
The Hubble pictures increase the mystery as to how jets are confined into a thin beam. These pictures tend to rule out the earlier notion that a disk was needed to form a nozzle for collimating the jets, much like a garden hose nozzle squeezes water to a narrow stream. One theoretical possibility is that magnetic fields in the disk might focus the gas into narrow beams, but there is as yet no direct observational evidence that magnetic fields are important.

These images are solving the puzzle of a unique beaded structure in the jets, first detected from the ground but never fully understood. Many astronomers thought that the knots were the result of interactions of the jet with the gas that the jet is passing through, while others thought that the knots were due to 'sputtering' of the central engine. We now know that the knots are the result of sputtering. This conclusion is based on Hubble images which show the beads are real clumps of gas plowing through space like a string of motor boats.




The jet's clumpy structure is like a stockbroker's ticker tape; they represent a recorded history of events that occurred close to the star. The spacing of the clumps in the jet reveals that variations are occurring on several time scales close to the star where the jet originates. Like a "put-put" motor, variations every 20 to 30 years create the strings of blobs we see. However, every few hundred years or so, a large amplitude variation generates a "whopper" of a knot, which evolves into one of the major bow-shaped shock waves. Other Hubble views reveal new blobs may be ejected every few months. If the circumstellar disk drives the jet then the clumpiness of the jet provides an indirect measure of irregularities in the disk.

Web Reference
http://hubblesite.org/newscenter/archive/1995/24/



**Circumstellar Disk of Star Formation**

A star forms through the gravitational collapse of a vast cloud of interstellar hydrogen. According to theory, and confirmed by previous Hubble pictures, a dusty disk forms around the newborn star. As material falls onto the star, some of it can be heated and ejected along the star's spin axis as opposing jets. These jets of hot gas blaze for a relatively short period of the star's life, less than 100,000 years. However, that brief activity can predestine the star's evolution, since the final mass of a star determines its longevity, temperature, and ultimate fate.

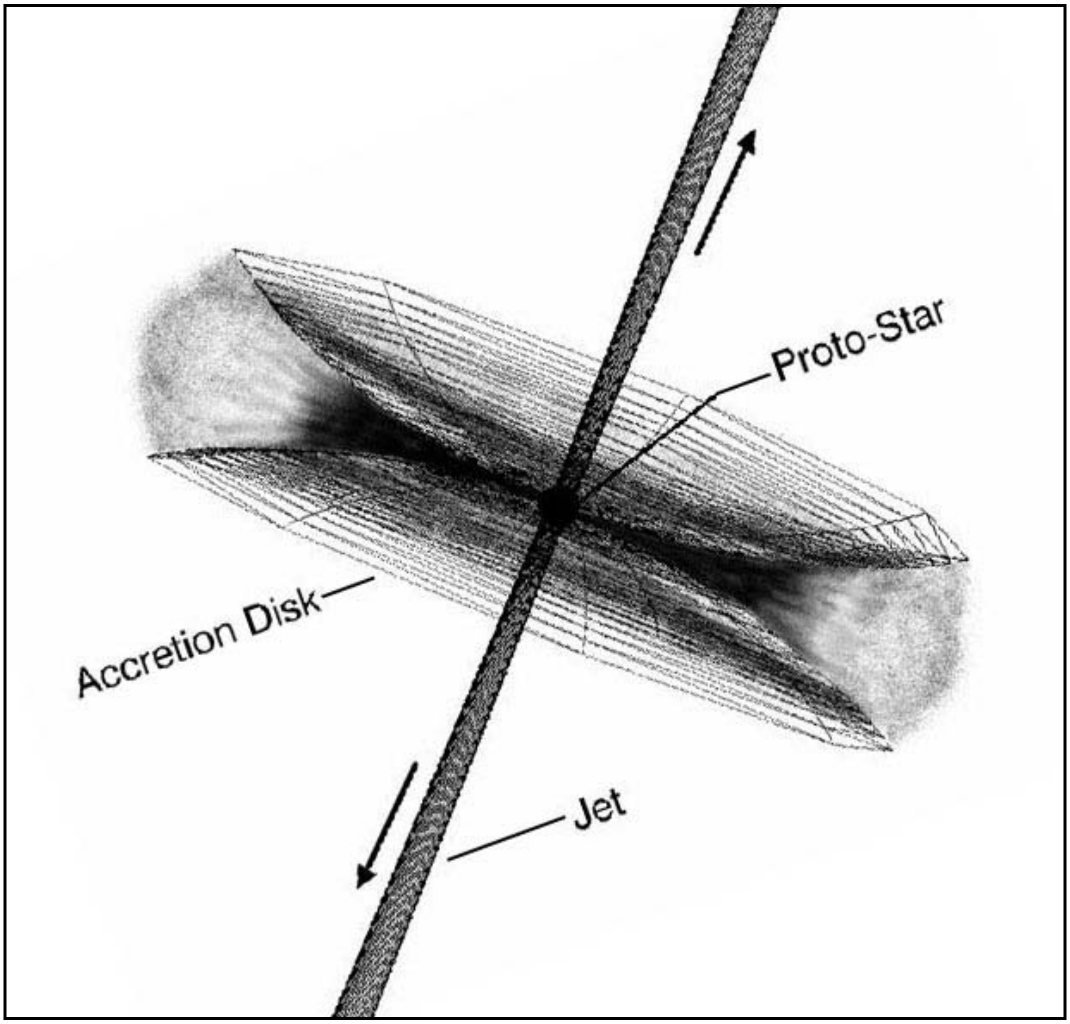



**Diagram of Circumstellar Disk and Jets**

The jet might carry away a significant fraction of the material falling in toward the star, and, like a hose's water stream plowing into sand, sweeps out a cavity around the star that prevents additional gas from falling onto the circumstellar disk. The disk can be seen to "flare" away from the star. (It is thicker at larger distances from the star.) This behavior can be understood because it takes material farther out in the disk longer to settle to the disk midplane.

(Figure courtesy of NASA)

**A dusty beginning.** As comets streak by, a small, scarred planetesimal (foreground) forms from the dust encircling a young sun.

**The Early Solar System**

When the star becomes hot enough it will stop accreting material and blow away much of the disk—but perhaps not before planets have formed around the star. The generally accepted theory for the creation of our solar system is that it formed from a disk, and that the orbits of the planet are the "skeletal" remnant of the disk. It also explains why the planets all orbit the Sun in the same direction and roughly the same plane.

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Cosmological Evolution
http://fire.biol.wwu.edu/trent/alles/Cosmic_Evolution_index.html

Alles Introductory Biology Lecture: *Cosmological Evolution*
http://fire.biol.wwu.edu/trent/alles/101Lectures_Index.html

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