The Winds of Starbirth

Stellar winds may play a crucial role in the formation of sun-like stars

By IVARS PETERSON

In the Milky Way, stars form within dusty, dense clumps of material scattered throughout gigantic clouds of molecular hydrogen. Drawn together by gravity, this cold gas and the accompanying dust gather into huge balls that eventually become dense enough at their cores to initiate nuclear fusion.

But this simple, serene picture belies the true fury of starbirth. Recent observations reveal an intriguing pattern of violent, high-speed discharges, in which nascent stars apparently eject vast quantities of material even as they amass gas and dust (SN: 7/8/89, p.20; 7/22/89, p.55).

The paradoxical idea that an embryonic star somehow both attracts and expels material puzzles astronomers. How can a star form while it's suffering a heavy mass loss?

"The answer to this question holds the key to understanding the basic physics of star formation," assert Charles J. Lada of the University of Arizona in Tucson and Frank H. Shu of the University of California, Berkeley, in the May 4 SCIENCE.

Energetic outflows from newborn stars are crucial for completion of the star-formation process, they argue. Such discharges may even explain two long-debated astrophysical questions: why sun-like stars have masses that fall within a particular range and why only a small fraction of a molecular cloud collapses into stars. In the SCIENCE paper, Lada and Shu outline their star-formation theory, which includes a vital role for stellar "winds."

The majority of stars in the Milky Way form within giant molecular clouds. Typically, these clouds have masses greater than 100,000 times that of the sun, spread across areas more than 400 light-years wide. Composed largely of molecular hydrogen, they also contain a sprinkling of dust and a variety of other simple molecules. Such clouds rank among the coldest objects in the universe, with gas temperatures rarely exceeding 10 kelvins.

Radio-wave observations reveal that molecular clouds tend toward lumpiness, showing dense knots and numerous filaments. It is within these denser regions, representing 1 to 10 percent of the cloud's total mass, that stars actually form.

Magnetic fields permeating the clouds also play an important role in starbirth. They appear strong enough to delay gravitational collapse, cutting the rate of star formation to one-half or one-third the rate expected based on cloud dynamics. This balance between magnetic repulsion and gravitational attraction keeps a cloud stable for periods ranging from 10 million to 100 million years.

According to the Lada-Shu scenario, a cloud starts to contract when its magnetic field, by slowly diffusing away, weakens sufficiently to let gravity win the war between the cosmic forces. The cloud's core gradually grows denser as it draws together material. Eventually, the material becomes so thick that it traps light, and no internally generated visible radiation can penetrate the gloom. It develops a dense core with an ill-defined surface, and the resulting "protostar" continues to grow as more matter rains down from the remainder of the molecular cloud.

"To form an object like a star, one has to gather material over very large distances," Shu says. However, not all matter falls directly toward the core. Material initially moving at a right angle to the direction of fall would tend to spiral in. Thus, some material would miss the core and end up in a flattened rotating disk girdling the central body.

Gas spiraling in from the disk to the surface would carry with it angular momentum, which would cause the protostar to spin faster and faster. The embryonic star would quickly end up spinning so fast that it would reach the point at which it flies apart. That sets a strict limit on how large the burgeoning star could grow — unless the star has some way to shed its excess angular momentum.

That's where stellar winds and molecular outflows may enter the picture. The observation of supersonic, expanding flows of molecular gas within clouds where stars are forming was one of the more startling and unexpected astronomical discoveries of the early 1980s. Astronomers have now identified more than 100 of these flows, almost all of them apparently originating in the vicinity of newborn stars. Many of these relatively thin, outwardly moving shells of material appear as two separate lobes, often more or less on diametrically opposite sides of their apparent source.

Such outflows involve too much mass — typically 0.1 to 100 solar masses — to come directly from a protostar. Instead, they appear to consist of molecular gas caught up in and pushed by extremely powerful winds emanating from the protostar's poles.

"What you see in molecular form is the swept-up material," Shu says. "The stellar wind itself presumably comes off at a much higher speed, and in a few cases, we know that this wind consists of neutral atomic hydrogen."

Stellar wind plays an important role in the Lada-Shu scenario because it provides a way for a star to rid itself of extra angular momentum. "We can't form objects like stars without throwing some fraction of them back out," Shu says. Such discharges allow the process of star formation to continue to its conclusion.

The precise nature of the engine that drives the intense neutral wind remains unclear. Shu suggests that a rapidly rotating star with a modest magnetic field could act like a propeller, whipping ionized material and accompanying neutral gas near the star's surface into a wind. "The tricky part is to explain why this kind of process ends up collimating the wind so that it begins to flow parallel to [the star's] rotation axis," Shu says.

One controversial aspect of Shu's wind-generating mechanism concerns the origin of the star's magnetic field. He suggests that the start of nuclear fusion at the protostar's core would produce convection currents, which in turn could generate a magnetic field large enough to drive a stellar wind.

The high rotation rate necessary for wind generation by this mechanism may represent another weakness in the proposed mechanism. Astronomers have discovered that young stars old enough to have sloughed off their dusty blankets appear to rotate quite slowly. That means the protostar must somehow lose a lot of angular momentum during the last stage of its evolution into a full-fledged, optically visible star.

"It certainly is not at all well understood what goes on," says Richard B. Larson of Yale University in New Haven, Conn. "Presently, there's just a black box in the region where the star and the disk interact. Nobody knows what goes on in that black box. All we know is that material comes out of it at high speeds along the polar, or rotation, axis."

The notion of stellar winds associated with newborn stars – whatever their origin – provides a plausible, though controversial, explanation for why all the mass of a molecular cloud doesn't collapse into stars. "Only about 1 percent of the raw material in these molecular clouds ever actually makes it into stars during the lifetimes that these clouds exist," Lada says.

Stellar winds and the resulting molecular outflows are collectively powerful enough to generate sufficient turbulence to keep the whole cloud from collapsing, Lada and Shu say. The winds may also blow away most of the excess material surrounding a protostar, stopping the accretion process and finally allowing the fledgling star to emerge from its dusty cocoon. "The winds wreak havoc and stir up the surrounding material enough that it prevents further star formation," Lada says.

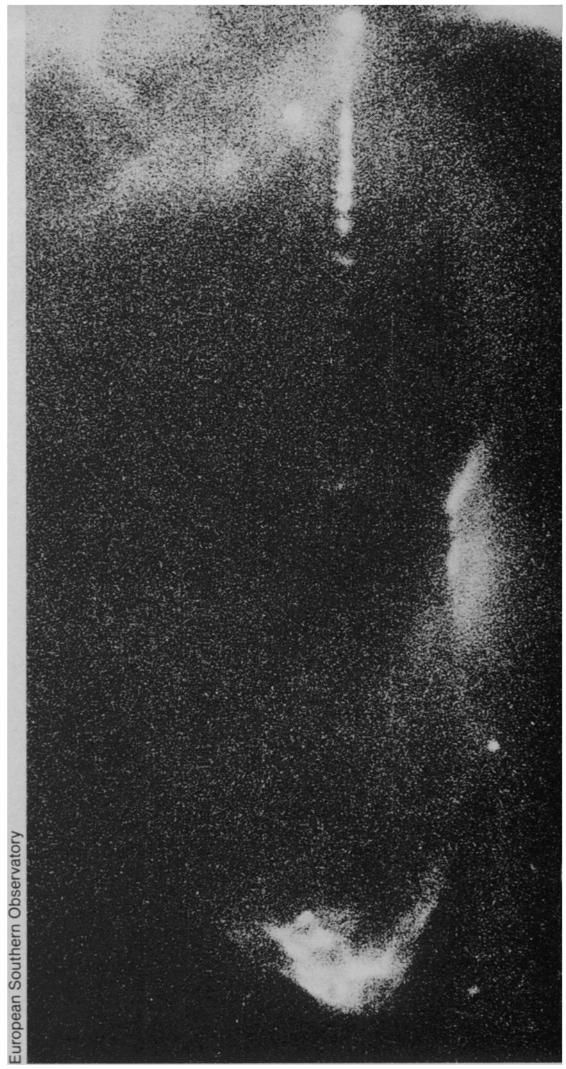
By clearing away surrounding gas and dust, the stellar wind in effect sets a limit on how massive the star can get. In other words, the wind determines the final mass of the forming star, Lada and Shu say.

If stellar winds determine stellar masses, and if the startup of nuclear fusion indirectly generates the winds, then star formation would automatically regulate itself, Shu says. That may be why, when gravitational collapse proceeds, the resulting objects inevitably halt their growth at just the right size to sustain nuclear fusion.

"A cloud is just trying to make the biggest object it can, and that's a very big object when one tries to make a whole molecular cloud into a condensed object," Shu says. "But in fact, at some point, which is related to the fact that stars are capable of thermonuclear fusion, they turn on a wind and prevent themselves from getting too bloated."

Theoretical calculations indicate that, for embryonic stars accumulating mass at a reasonable rate, nuclear fusion of deuterium can start when the star's mass reaches a few tenths of a solar mass. And that matches observations of nearby star-forming regions, which suggest that the most common outcome of the birthing process is a star with about half the sun's mass.

"The fact that star formation ends at least in part through the action of a stellar wind is a very important concept," says Fred Adams of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass. "It says that the stars themselves partly determine their own masses through the action of these winds."



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A long, narrow jet, originating at a young star (top), points toward a small nebula where the jet apparently rams into the surrounding interstellar cloud (bottom).

But these ideas remain speculative. "It's not at all clear exactly how and even whether [these outflows and winds] play a major role in setting stellar masses," Larson says. "Nobody can challenge that there's an effect, but I have reservations about whether they're the only thing or even the main thing that terminates the growth of an embryonic star and determines how much mass this star is going to end up with. My view is that the masses of stars are related to, if not determined by, the properties of the clouds out of which stars form."

"The problem," says Adams, "is that we still don't have a complete theory that tells us what mass of star will form out of a cloud. Even though we know the winds play a major role, we still can't calculate in a definitive manner what the mass of the star that's forming will be."

And other gaps punctuate the theory. "We have discovered and recognized the importance of energetic outflows for the stellar formation process, yet we do not understand how they are generated, when they are ignited, and how long they last," Lada and Shu admit in their report. "We still have no idea how outflows and other processes actually interact to produce the observed spectrum of stellar masses in the galaxy."

Furthermore, although observers have seen evidence for outflows of various kinds, no one has unambiguously observed material falling onto an embryonic star, which should be happening if the star is truly still forming. And no one has caught a molecular cloud in the act of collapsing.

"At a certain point, the central star generates winds," Larson says. "The trouble is it's still pretty vague what that certain point is."

Says Lada, "The most critical measurement that needs to be made is that of actually detecting material falling in. If we're right, there has to be material falling in."

In their scenario, Lada and Shu focus on the formation of a single, low-mass star from a small molecular cloud. But that's only the first step toward the development of a general theory of star formation.

"It's an idealized model that postulates almost static conditions of perfect symmetry and so on, and doesn't consider the possible effects of vigorous turbulence or interaction with nearby stars," Larson says.

Many other questions remain unanswered. How do pairs of orbiting stars form? What triggers bursts of star formation, which produce large, tight clusters of stars? How do stars much more massive than the sun come into being? How did the very first stars form?

"The origin of stars represents one of the most fundamental problems of contemporary astrophysics," Lada and Shu write. "Although considerable progress has been made in star-formation research during the last 15 years, we are still far from a solution to this fundamental astrophysical problem."

But observations are getting better, especially with the arrival of large ground-based arrays of infrared sensors, which can penetrate the blanket of dust hiding a star's early days.

"One result of this advance in knowledge is that we are now beginning to appreciate just how rich and complex the physics of stellar creation really is," Lada and Shu say. "Indeed, if we have learned anything, it is that star formation is a much more mysterious process than anyone had expected even as late as 15 years ago." □