THE BIRTH OF Binary Stars

How did so many stellar systems become guilty of duplicity?

BY
ALAN P. BOSS

As you look into the night sky, the stars overhead seem to be solitary beacons, just as our Sun is. But in reality we are frequently "seeing double," because binary stars — two stars orbiting a common center of mass — are everywhere. Although their ubiquity is not at all apparent to the unaided eye, telescopic scrutiny made the case convincing two centuries ago. In 1782 William and Caroline Herschel began systematically cataloging pairs of apparently close stars. By painstakingly measuring stellar positions over the next several decades, William Herschel proved that paired suns do exist.

Binary stars are gravitationally bound to each other and, if left undisturbed, remain joined for eternity. But how did they begin their life together? We can wonder, as Huckleberry Finn did while rafting down the Mississippi River, gazing at a sky "all speckled with stars . . . whether they was made, or only just happened." We can answer the question of origin in two distinct ways.

One approach is observational. We can look at successively younger and younger populations of stars in the hope of learning at what point binaries first become manifest. Dating this epoch is a crucial step in discriminating between the various mechanisms offered to explain why multiple-star systems exist. The second approach is to construct theoretical models to try to discern whether a particular formation mechanism has any special strengths or failings that can be used to help decide the issue.

We have reached a point where both observations and theory seem to be yielding the same answer: binary systems appear to form at the very same time that the stars themselves do, during the gravitational collapse of interstellar clouds. Thus stars are paired from the outset, and as we'll see later this realization has profound consequences for the long-term viability of any planets created in these same systems.

Old Binary Stars

The first observational step was to discover how many binary stars lurk among the Sun's closest neighbors. Nearby stars are obviously the easiest to search for such pairings. Therefore, they should yield the best statistical estimates of how frequently binaries occur among main-sequence stars in the Milky Way's disk, those with ages from about 1 to 10 billion years.

Binary stars have been discovered with orbital periods that range from a few hours for the closest pairs to millions of years for the most distant, barely bound systems. This means their separations must vary from a few stellar radii to nearly a light-year. Consequently, different observational methods must be used to find binary stars over this extended range of orbital periods.

The widest binaries, like those discovered by the Herschels, can be found by comparing images taken years or decades apart. Such comparisons demonstrate that two candidate stars are at least headed in the same direction across the sky (that is, they have a common *proper motion*) and perhaps even exhibit motion about a common center of mass. Closer-orbiting systems can be detected by the technique of speckle imaging, in which many telescopic images of the system are combined after first shifting them small distances in the plane of the image to remove the random dance induced by atmospheric turbulence. Speckle work is often done in the infrared to reveal faint, cool companions.

Systems with even smaller separations can be discerned by interferometric imaging. This technique exploits the fact that an optical system resolves finer and finer spatial detail as the diameter of its aperture increases. Interferometers combine the light from several telescopes to yield the angular resolution that would result from a single aperture equal to the widest separation of the individual telescopes. As a result, this technique can probe closely spaced stellar systems that would be otherwise unresolvable.

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Lunar occultations can also be used to detect tightly bound binary stars. An observer simply measures the amount of light from the target star as the dark edge of the Moon sweeps over it. Unless the binary star happens to be aligned so that both components disappear at the same instant, a rare event, the light diminishes in two distinct steps and thus reveals the binary nature of the target. Finally, the very closest binaries can be discovered spectroscopically, whereby spectral lines from the primary star are scrutinized for a periodic shift in wavelength. If a sizable companion is present, the primary will wobble around their common center of mass. The resulting Doppler effect creates a cyclic variation in wavelength whose period gives the unseen companion's orbital period and whose amplitude gives a lower limit on its mass.

Many astronomers have searched for binary systems among main-sequence stars, and two large-scale surveys published in 1991 and 1992 have already become classics. Well before they became famous for finding extrasolar planets, observing teams led by Michel Mayor (Geneva Observatory) and Geoffrey Marcy (San Francisco State University) spent many years searching for the low-mass stellar companions of nearby stars. The late Antoine Duquennoy and Mayor surveyed all solar-type dwarfs (spectral types *F7* through *G9*) within 72 light-years of the Sun, while Debra Fischer and Marcy studied stars with somewhat lower mass (*M* dwarfs) slightly nearer to the Sun.

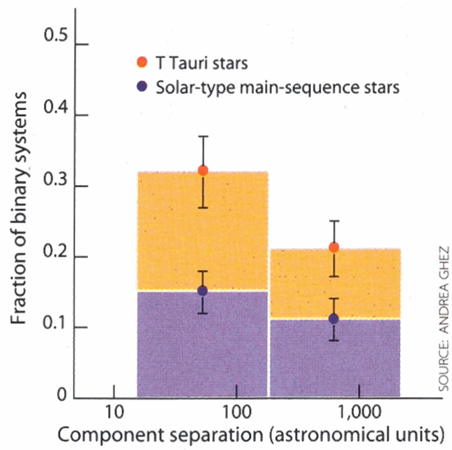
Both of these surveys yielded a similar result: about half of all nearby primary stars have a stellar companion. Some have two or even three companions, inevitably arranged in a stable hierarchical system: a close binary orbited by a distant third star, or a pair of close binaries that orbit about a common center of mass. Remarkably, the two surveys even derived very similar proportions among these types. The ratio of singles to doubles to triples to quadruples for the *G* stars is 57:38:4:1, while it is 58:33:7:1 for the *M* stars. The distributions of binary orbital periods are also very similar for the two spectral types, and highly eccentric orbits are the norm. Thus, the Duquennoy-Mayor and Fischer-Marcy findings provide the benchmarks for subsequent surveys of younger populations of stars.

Young Binary Stars

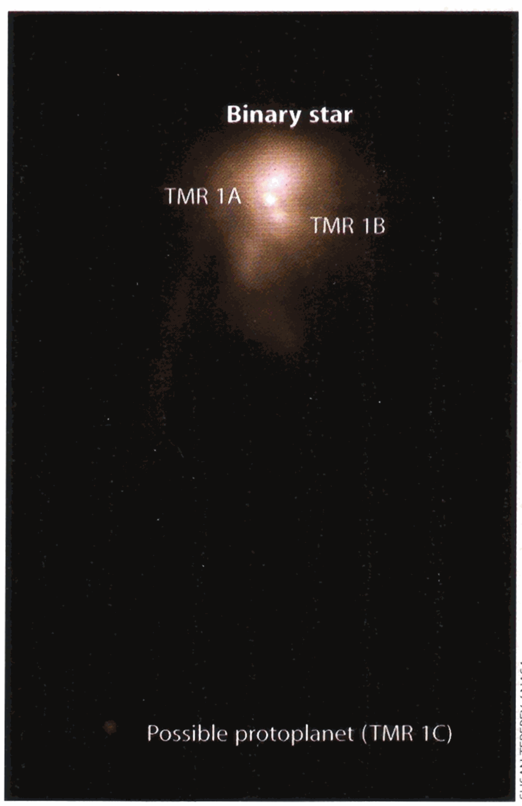
The Hyades cluster has an age of about 600 million years, considerably younger than the Sun's neighbors. Jennifer Patience and Andrea M. Ghez (University of California, Los Angeles) and their colleagues have used speckle imaging to search for binaries in the Hyades. They find that, when combined with the results of other searches, half of its stars had a companion, with the ratio of singles to binaries to triples being 59:35:6. A similar result was found for the even younger Pleiades cluster, with an age of about 100 million years, by Jérôme Bouvier and his colleagues at Grenoble Observatory. Evidently the frequency of occurrence for double stars is well established by the time they are 100 million years old.

But we can push back the epoch of binary formation much further by considering newly formed, pre-main-sequence stars, which have ages of just 1 to 10 million years. In 1993 Ghez and her colleagues used speckle imaging to search for unseen companions to young, energetic (T Tauri) stars in the Taurus-Auriga and Ophiuchus-Scorpius star-forming regions. They found that for companions with separations ranging from 16 to 252 astronomical units, the T Tauri stars in these star-forming regions have *four times* as many companions as the older, main-sequence stars do. Observing teams led by Christoph Leinert (Max Planck Institute for Astronomy, Heidelberg) and Michal Simon (State University of New York, Stony Brook) have also tallied excess binaries among T Tauri stars.

All told, binaries with separations from 15 to 1,800 a.u. are twice as likely to be found among the T Tauris as they are among main-sequence stars. This is very surprising. We had long assumed that progressively younger



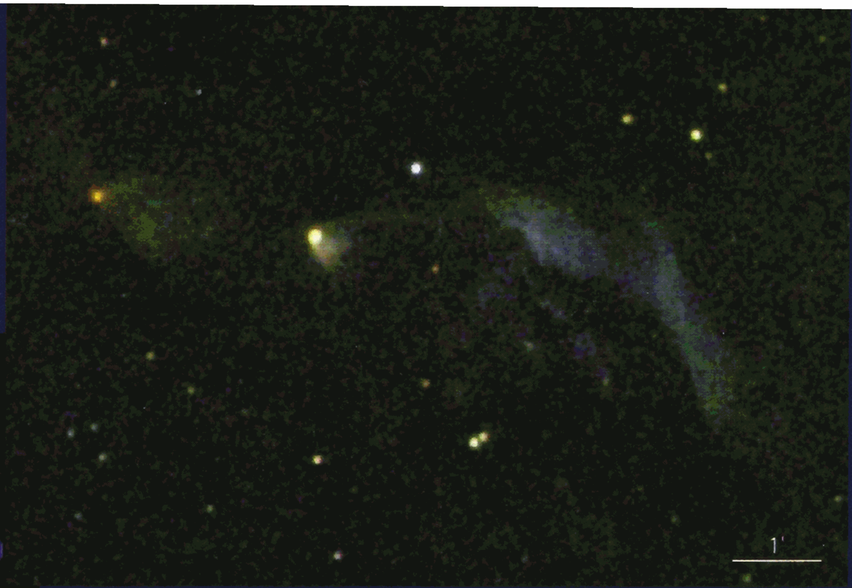
Top: **Not all binaries are created equally. Observations of five low-mass star-forming regions show that young, energetic (T Tauri) stars tend to have binary companions about twice as often as do older, solar-type stars in the Sun's neighborhood. For a select range of component separations, near 100 a.u., the disparity jumps to a factor of four.**

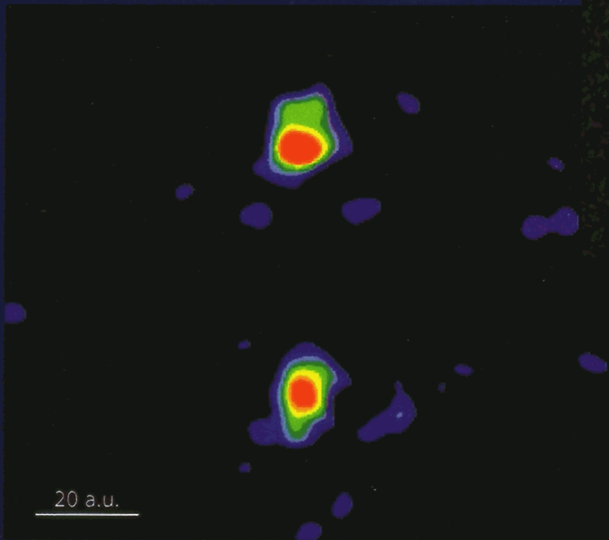


SUSAN TEREBEY / NASA

Left: **The TMR 1 protostar in Taurus is actually a binary system with a separation of about 42 astronomical units. This infrared image from the Hubble Space Telescope reveals a dim, third object, TMR 1C, that may be a large protoplanet situated about 1,400 a.u. from the binary.**

Observers are examining ever-younger stars in their pursuit of the earliest binary systems. To glimpse these new suns, observers must record them at far-infrared and submillimeter wavelengths because their dusty cocoons are opaque to visible light.





EUGENE KOPAN

LUIS RODRIGUEZ

Top: Stars only about 100,000 years old are just emerging from the dark clouds of Lynds 1551, about 450 light-years away in eastern Taurus. The yellowish smudge at center is designated IRS 5, and to its left (northeast) is L1551-NE. This false-color image is from the 2-Micron All-Sky Survey (*S&T:* August 1997, page 46).

Left: A Very Large Array radio image reveals that Lynds 1551 IRS5 harbors a binary protostar. The two components are separated by about 45 a.u., and this nascent system is accompanied by a strong bipolar outflow of high-speed matter not seen here.

populations of stars would exhibit relatively fewer binary systems. Yet the abundant multiple suns found in Taurus and Ophiuchus seem to demand that binaries are *destroyed*, not created, over time. Why is this so? One can imagine that triple- and quadruple-star systems might fly apart when they encounter other stars, but binaries should be relatively immune to such chance encounters — if one component is ejected, the invading star often takes its place in the system. Perhaps the observed winnowing of double stars over time results from binary-binary encounters, during which one system (or both) will likely lose a component.

However, not all star-forming regions show an excess of binaries. Infrared imaging studies by Monika Petr (MPIfA, Heidelberg) and her team found that the proportion of binaries in Orion's Trapezium cluster was the same as that for main-sequence stars in our interstellar neighborhood. Because most stars are believed to form in massive interstellar clouds like Orion's, rather than in lower-mass sites like that in Taurus, Petr's statistics reassure us that the wholesale destruction of binary stars need not occur. More likely, the odds of duplicity probably depend on specific properties of star-forming clouds, such as rotation rate, temperature, and magnetic-field strength.

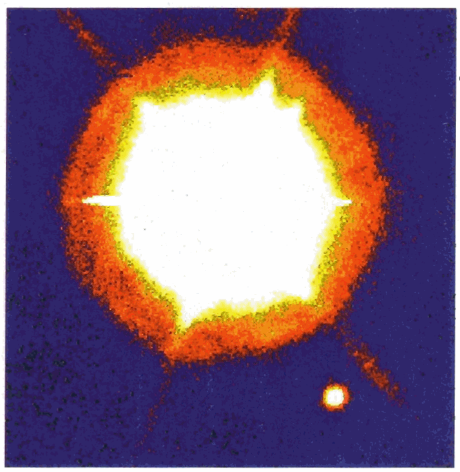
The final step in this observational hierarchy is still incomplete. Our search for binary companions must include *protostars,* stars-to-be that are still accreting gas and dust from the dense interstellar clouds in which they form. Because the dust falling onto these objects obscures our view in visible light, these searches must be performed at infrared or even longer wavelengths, at which the intervening clouds are more transparent.

Using the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) on the Hubble Space Telescope, Susan Terebey (Extrasolar Research Corporation) and her colleagues discovered an object called TMR 1 in Taurus that is actually a binary protostar with a separation of about 42 a.u. Considering the tender age of TMR 1, just a few hundred thousand years, it is clear that binary stars must form very early in protostellar evolution. Similarly, Luis F. Rodríguez and his colleagues at the National Autonomous University of Mexico have used the Very Large Array of radio telescopes to determine that the protostar at the center of Lynds 1551 IRS 5 in eastern Taurus is actually two objects, as had been suspected.

Despite these successes, binary protostars are proving difficult to detect. We cannot yet estimate how often multiple-star systems arise at this very early phase of stellar evolution. However, the detections to date suggest that binary formation has already largely occurred by this point.

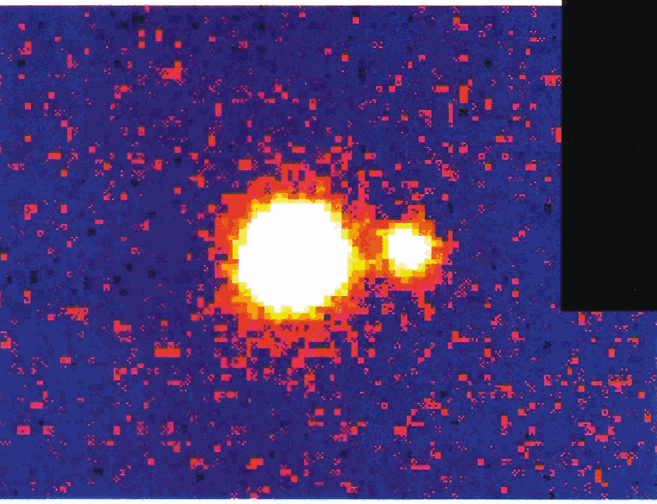
Binary Brown Dwarfs

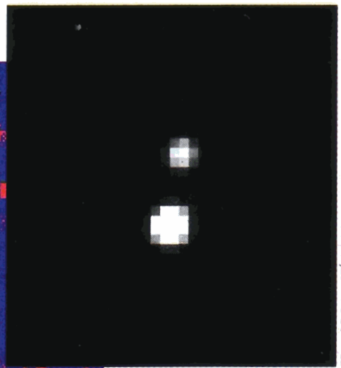
Because of continuing advances in instrumentation, very small companions — either planets or brown-dwarf stars — can now be detected around main-sequence stars. Brown dwarfs form in the same way that stars do but happen to end up with too little mass (less than about 75 times that of Jupiter) to initiate hydrogen fusion in their cores. Because



RAFAEL REBOLO

A brown dwarf (lower right) circles the nearby star G 196-3, a 12th-magnitude *M*-type red dwarf roughly 70 light-years away in Ursa Major. The pair are separated by 350 a.u. in this false-color infrared image from the Nordic Optical Telescope.





EDUARDO MARTÍN / GIBOR BASRI

Far left: **This false-color infrared image shows that the two brown dwarfs comprising the very young binary ITG 45 in Taurus are separated by about 320 a.u.**

Left: **The Pleiades cluster is host to more than young stars and wispy nebulosity. It also contains this binary brown dwarf system, known as Pl 18. Its binary nature was discovered with the Hubble Space Telescope's NICMOS infrared camera.**

hey lack a sustained source of thermonuclear energy in their cores, brown dwarfs soon fade away and after a few billion years become nearly as difficult to discover as extrasolar planets.

Brown dwarfs are hard to detect, so many nearby stars previously thought to be single may actually be binary. There is evidence that low-mass objects accompany about 10 percent of the main-sequence stars. The most spectacular example to date is a brown dwarf found paired to the nearby red star Gliese 229 by astronomers from Caltech and Johns Hopkins University in 1995 (*S&T:* January 1996, page 11). Gliese 229B weighs in at 30 to 50 Jupiter masses, typical for a brown-dwarf mass. To see it, the observers used a sophisticated detector system that simultaneously removed atmospheric distortion and most of the light from the host star. Rafael Rebolo (Astrophysical Institute of the Canaries) and others have spotted another brown dwarf, this one having about 25 Jupiter masses, circling the *M* dwarf star G 196-3.

Perhaps the best place to find a brown dwarf is in orbit around *another* brown dwarf, because stars tend to have companions with masses not too different from their own. The problem is to find one or the other of them in the first place. Surveys of nearby star clusters have begun to turn up brown dwarfs by the handful, and some of these have already been discovered to be binary systems. The relatively youthful Pleiades are an obvious place to try to catch brown dwarfs before they have a chance to cool to the point of invisibility.

One of the first suspected brown dwarfs, Pleiades 15 (Pl 15), also appears to be the first brown-dwarf binary. Gibor Basri (University of California, Berkeley) and Eduardo L. Martín (Astrophysical Institute of the Canaries) found that Pl 15 has a double-lined spectrum. By disentangling the twinned spectral lines, these observers find that the pair twirl around one another with a weeks-long period, indicating the close pairing of

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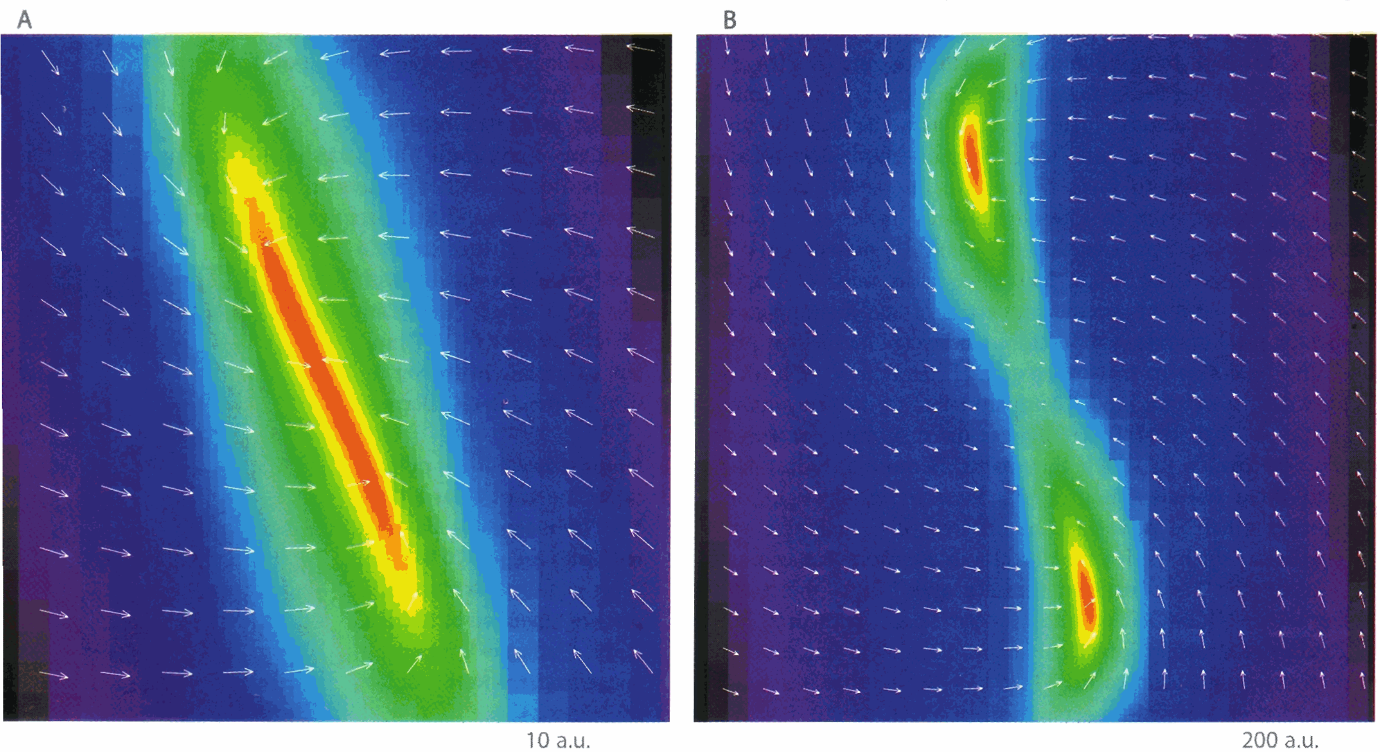
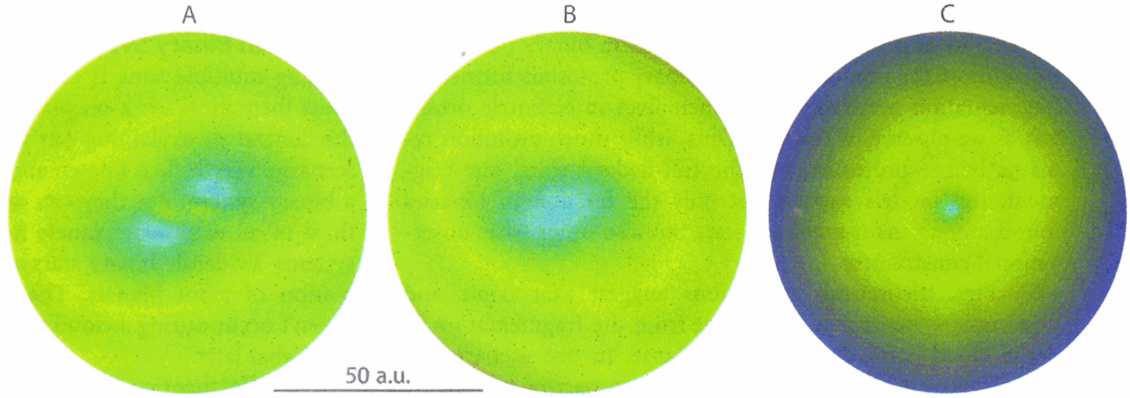




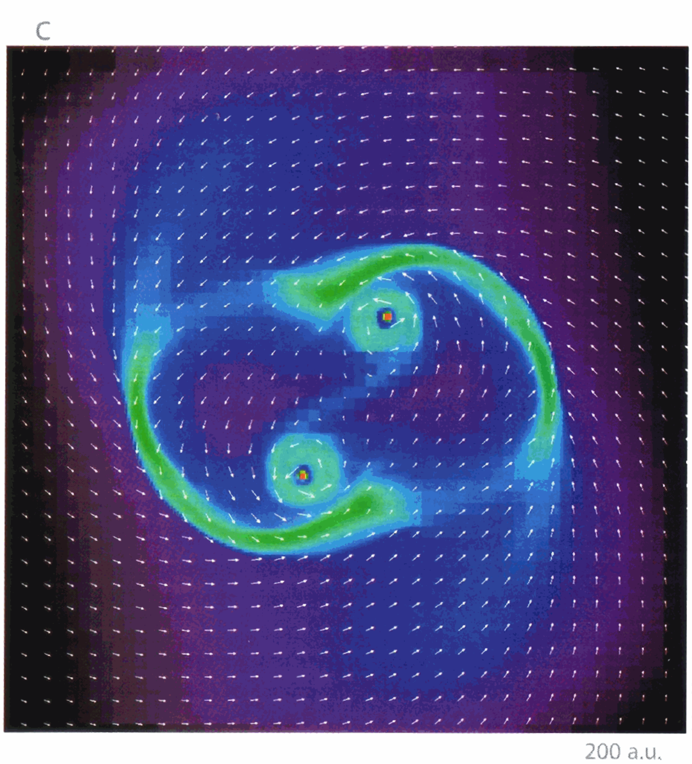
Theoretical modeling shows that as the initial rotation rate of a dense, magnetic, interstellar cloud core drops (from *A* to *B* to *C*) the outcome of the cloud's collapse changes from a binary protostar to a single protostar. Light blue marks the highest-density regions. Courtesy Alan P. Boss.

objects with about 65 Jupiter masses each. Basri, Martín, and their colleagues have turned up another such binary in the Pleiades, Pl 18, with a separation of 42 a.u.

The search for binary brown dwarfs can be pushed to even younger populations than those in the Pleiades. Several such pairs have been detected in the Taurus star-forming region by Motohide Tamura (National Astronomical Observatory, Japan) and his colleagues, who used an infrared imager with the Hale 5-meter telescope. The brown dwarfs of ITG 45 are so young, about 1 million years old, that they appear to be still accreting gas from their placental cloud cores.

Fragmentation Calculations

We no longer doubt that binary protostars are prevalent and that pairings occur with roughly the same frequency for old stars, young clusters of stars, and newly formed stars. But at what point is their fate cast? Apparently it must take place prior to the protostar phase, during the gravitational contraction of dense interstellar clouds. The culmination of this process is a rapid collapse lasting some 100,000 years or less. Richard B. Larson (Yale University) calculated the first detailed models of collapsing interstellar clouds in the late 1960s. He suggested that rapidly rotating clouds would collapse to form rings, which might then break up into binary or multiple protostars.



RICHARD KLEIN / ROBERT FISHER / CHRISTOPHER MCKEE

The breakup or division that can occur during a cloud's collapse is termed *fragmentation,* and devising models of just how and when dense cloud cores do so has become a minor theoretical industry. These calculations involve complex equations of compressible-gas hydrodynamics and self-gravitation, in three spatial dimensions (3-D) and in time. It's a formidable task that calls for a numerical solution, that is, the aid of a fast computer.

The astonishing computing power now available has allowed fragmentation simulations to advance well beyond the rather crude 3-D calculations that I was involved with two decades ago. Instead of treating the cloud as a three-dimensional grid of cells, some modern-day computer simulations can represent the gas by a gridless collection of interacting idealized particles. This approach, known as *smoothed-particle hydrodynamics* or SPH, is particularly well suited to fluid media (like a collapsing interstellar cloud) and to simulations involving fragmentation or fracture. Ian Bonnell (Institute of Astronomy, England) and Matthew Bate (MPIfA, Heidelberg) have been leaders in the SPH effort. Recently, a powerful new grid-based code has been developed by a group at the University of California, Berkeley. The Berkeley code solves the 3-D equations in a way that inserts extra grid points where needed for enhanced resolution, a crucial issue when an interstellar cloud collapses to a size perhaps one-millionth of its initial radius.

The success of any of these theoretical models depends on knowing the properties of dense clouds on the verge of collapse. These clouds rotate at different rates, are centrally condensed, and have prolate shapes somewhat like footballs. They are supported in part by magnetic fields and partially by pressure from hot gases. Magnetic fields control the early phases of a cloud's contraction, but once they begin to leak out of the cloud by a process called ambipolar diffusion (in which ions and field lines move past the neutral gas), a rapid collapse ensues.

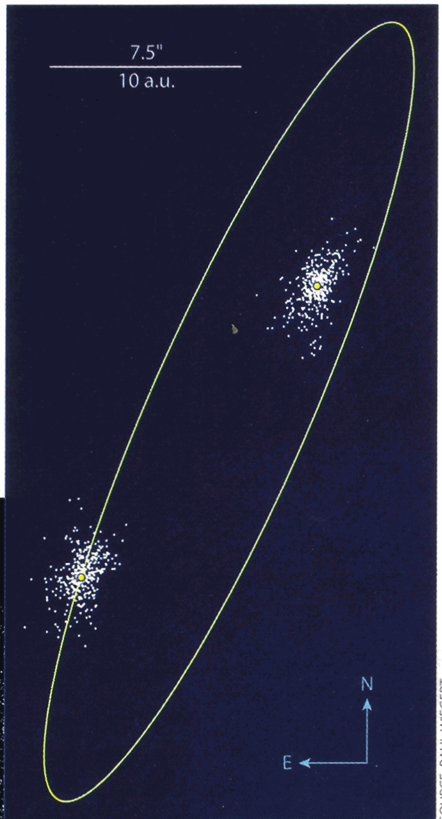
Given these initial conditions, theoretical models of collapsing magnetic clouds show that fragmentation into binary protostars is possible provided that the systems revolve relatively fast, in roughly two million years or less. Slower-rotating clouds lead only to single protostars. As it turns out, about half of the observed dense cloud cores rotate faster than this

Three state-of-the-art computer simulations of protostellar formation. Regions of highest mass are colored red, and arrows depict the flow of matter within the surrounding cloud. *(A)* A narrow filament results from the collapse of a centrally condensed cloud whose temperature remains constant. *(B)* Two narrow filaments occur when the cloud has uniform density and a constant temperature. *(C)* A binary system, complete with circumstellar disks, occurs when a uniformly dense cloud heats up as it collapses.

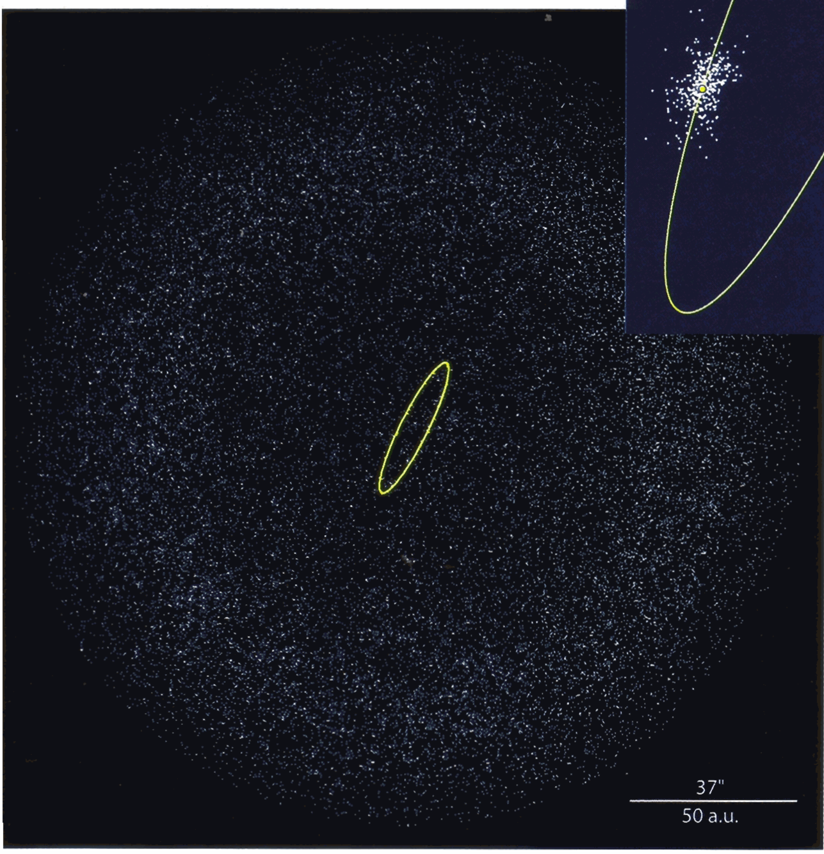
critical rate and so will likely go on to form binary protostars. In addition, the models show that binary protostars formed by fragmentation inevitably begin their lives in eccentric orbits, just as we observe in real life. Thus, while much evolution remains before protostars become full-fledged stars, our fragmentation models explain not only the fraction of binaries found among main-sequence stars but also other basic observational constraints.

Further, theoretical calculations suggest that triple and quadruple systems may also result from the fragmentation of dense cloud cores during their collapse. In one scenario, an initially prolate cloud contracts to form a narrow bar, which then breaks up along its length into a number of protostars. This initial alignment could quickly evolve into a stable hierarchical arrangement of single and binary objects, similar to that observed in multiple-star systems. Fragmentation also tends to produce clumps of roughly equal mass, though this may be an artifact of modeling the collapse of initially symmetric clouds. In reality, dense molecular clouds may be much more irregular in shape and hence produce forming clumps with a range of masses.

Science-fiction aficionados, take heart: planets could be quite common in double-star systems. These computer simulations show that planets will be stable around the double suns Alpha Centauri, either very close to each star *(right)* or in a distant "planet cloud" *(below)*. In the latter plot the sharp outer boundary is an artifact of the model — in reality planets could orbit the Alpha Centauri binary to much greater distances.



SOURCE: PAUL WIEGERT



SOURCE: PAUL WIEGERT

Planets in Binary Systems

Forging multiple suns is one thing, but what about planets? Most theoretical work on planet formation has been done in the context of explaining our own solar system, a single-star scenario. Very little is known about how planets would arise in a binary system. But they can and do occur, because about a third of all extrasolar planets found to date reside in binary systems. Evidently binary stars are quite hospitable to the formation of giant planets. The creation of planets probably doesn't occur during a cloud's collapse to protostars but rather somewhat later.

Naturally, theorists have wondered for decades what life on a world with two suns would be like. (Science-fiction legends Isaac Asimov and Robert Silverberg took this multiple-star notion to the extreme — a planet in a six-sun system — in their classic, *Nightfall.*) We *do* know which planetary orbits would be stable, however, so we can rule out certain orbital configurations, such as those with radii comparable to the distance between the component stars.

New computer simulations by Matthew J. Holman (Harvard-Smithsonian Center for Astrophysics) and Paul A. Wiegert (York University) have refined where planets should and should not be found in a binary system. As they report in the January 1999 issue of the *Astronomical Journal,* planets remain in long-term stable orbits if they either occupy an orbit close to one member of the binary or reside a great distance beyond the coupled suns (effectively orbiting their center of mass). The exact zones of orbital stability are defined by what Holman and Wiegert term a *critical semimajor axis,* which typically is 10 to 30 percent of the distance between the binary's stars. This value is relatively unaffected by the ratio of the stars' masses, but it varies dramatically if the stars orbit one another in circular or highly eccentric orbits.

As an aside, Holman and Wiegert ask, "If our own solar system had a solar-mass companion in an eccentric orbit, how large would its semimajor axis need to be for the Sun's planets (excluding Pluto) to survive?" The answer, they find, depends on the companion's orbital inclination. A second sun orbiting near the ecliptic would have to remain at least 400 a.u. away on average. For an over-the-top orbit inclined 75° or more, the standoff distance is more like 1,000 a.u.

Even though it's now relatively easy to simulate what can happen in a multiple-star system once it forms, our models have a way to go before we'll fully understand how planets get into a binary bind in the first place. But we theorists are not disheartened. To the contrary, we are ready to take up the challenge. Our exploration of the "binary universe" is just getting under way.

ALAN P. BOSS *is an astrophysicist at the Carnegie Institution of Washington, in Washington, D.C. He is the author of* Looking for Earths: The Race to Find New Solar Systems *(Wiley, 1998).*