PERSPECTIVES: BROWN DWARFS

Failed Stars or Overachieving Planets?

I. Neill Reid

Among the most recent astronomical discoveries is a new binary star system with the mildly obscure name of LHS 2397a, found by Laird Close and coworkers with the Gemini-North 8-m telescope on Mauna Kea (*1*). The separation between the two components is only three times Earth's distance from the Sun. The brighter star is well known as one of the lowest mass stars in the immediate solar neighborhood, with a mass less than one-tenth that of the Sun. The newly identified companion is more than an order of magnitude fainter and is probably a brown dwarf.

With masses below ~0.075 solar masses, brown dwarfs do not generate sufficient energy during their formation to ignite hydrogen fusion. Without a long-lived central energy source, these "failed stars" disappear from view on (astronomically) rapid time scales of a few hundred million years.

Brown dwarfs eluded detection for many years, but many examples are now known. LHS 2397a is the latest in a series of discoveries of low-mass binaries derived from high-resolution ground-based (*2, 3*) and space-based (*4, 5*) imaging of low-mass stars and brown dwarfs. Observations of those binary systems offer the prospect of gaining deeper insight into one of the most complex questions in astrophysics: How do stars and brown dwarfs form?

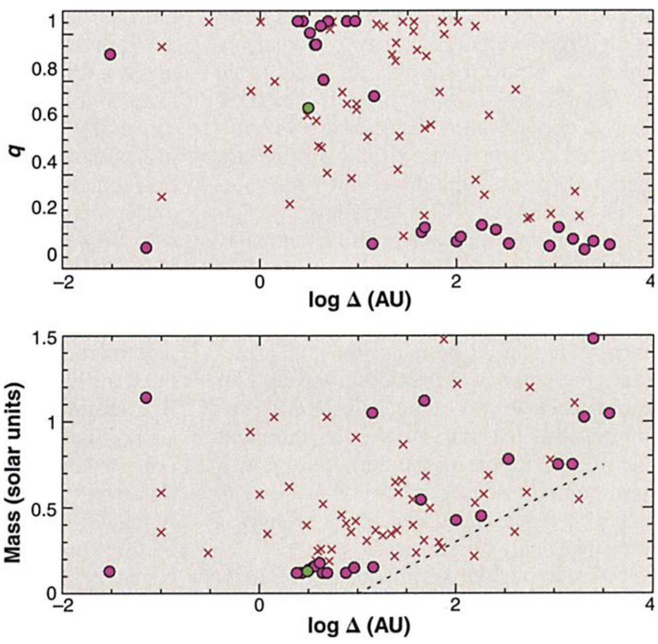
Star formation occurs in dense molecular clouds. Over the last decade, considerable progress has been made in identifying the processes that govern the formation and evolution of individual stars and in elucidating the roles of circumstellar disks, shocks, accretion, magnetic fields, and high-velocity bipolar jets. However, reliable methods for predicting ensemble properties—including the relative numbers of stars with different masses, the fraction of binary and multiple systems, and the mass ratios and separations of objects in these systems—are still lacking. Knowledge of these properties is crucial for predicting the likely prevalence of planetary systems.

What we know about star formation is still based primarily on observations. First, we know that the number of low-mass (below 1 solar mass) stars varies approximately inversely with mass, a dependence that may flatten to some extent in the brown dwarf regime. More than 80% of stars are less massive than the Sun, and brown dwarfs are probably almost as common as stars (*6*). At masses higher than the Sun's, the mass function is steeper, varying roughly with the reciprocal of the square of the mass.

Second, we know that the fraction of binary and multiple systems falls from ~70% in solar-type stars to ~30% in lower mass, cooler (*7*) stars. We know that the binary fraction is even higher for young stars in low-density star-forming regions, such as the Taurus clouds, but we do not yet have good statistics for denser star-forming regions, such as the more distant Orion nebula, where the majority of stars are thought to form.

Finally, we know from radial velocity surveys of extrasolar planets that brown dwarfs are rare as close companions to solar-type stars. However, they are not uncommon at large [>100 astronomical units (AU)] separations (*8*).

When these results are combined with the recent detections of low-mass binary systems, two interesting correlations stand out (see the figure). First, there is an apparent preference for equal-mass systems at small separation, particularly among low-mass binaries. One might suspect a selection effect (equal-luminosity companions are easier to detect); however, recent simulations indicate that systems with mass ratios $q > 0.4$ would be detectable (*9*). Second, there is a clear trend of decreasing maximum separation with decreasing total mass—a trend that runs contrary to any selection effect, because wider systems are easier to find.



Up close and far away. (Upper panel) Mass ratio (q) as a function of separation for nearby binary systems within ~100 light years of the Sun. The separation is given in units of the Earth-Sun separation (AU). Solid points mark data for low-mass binaries with LHS 2397a identified in green. **(Lower panel)** Observed separation as a function of the total mass of the system.

Star formation theory must explain these observations. Past analyses have tended to fixate on the Jeans mass, the minimum mass required for a core to collapse gravitationally and initiate star formation. Averaged over a molecular cloud, this parameter has a value of ~1 solar mass. Molecular clouds are, however, an extremely turbulent environment, and dealing with average properties is somewhat akin to considering spherical cows.

Recently, simulations have been developed that are capable of dealing in sufficient detail with such complex hydrodynamical phenomena. Bate *et al.* (*10*) have succeeded in generating a mini-cluster of stars and brown dwarfs from a molecular cloud of 50 solar masses. Most of the brown dwarfs in this simulation form by fragmentation in circumstellar disks (as planets do), rather than as separate cloud cores (as stars do). Such a process may well have dire effects for the formation of "normal" planets in those disks. Gravitational interactions eject both "stellar" and "planetary" brown dwarfs from the cloud before accretion pushes their mass over the stellar threshold.

Reipurth and Clarke (*11*) have also suggested that brown dwarfs are stellar embryos, ripped untimely from the womb. Crucially, all of the planetary brown dwarfs should be single; any stellar brown dwarf binaries must have small separation to survive the dynamical stress of ejection. Thus, if Bate *et al.* are correct, most brown dwarfs are indeed

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"Wandering companionless/Among the stars that have a different birth" (12).

How does the model match the observations? The predominance of tightly bound, small-separation binaries at low masses agrees well with predictions. Indeed, the overall trend with total mass suggests a phenomenon related to gravitational binding energy. However, and this is where LHS 2397a and its ilk are important, so far there is no indication of the sharp decrease in binary frequency at the lowest masses that would be expected if most brown dwarfs are planetary and thus single. Observations indicate that luminous [that is, young (7)] brown dwarfs occur at a frequency of 20% or more, rather than the predicted <5%.

For the moment, therefore, the more radical suggestion that most brown dwarfs form as planets do, rather than as stars do, remains unsupported observationally. A definitive answer requires further observations of larger numbers of fainter, low-mass brown dwarfs, currently possible only with the Hubble Space Telescope.

References and Notes

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7. Stars and brown dwarfs are classified according to their temperature. The Sun, a G dwarf, has a temperature of 5500 K. M, L, and T are the coolest classes. M dwarfs have temperatures in the range 4000 to 2100 K, with masses below ~0.5 solar masses; L dwarfs fall between 2100 and 1300 K; T dwarfs are cooler still. For stars, lower temperature equates to lower mass. Brown dwarfs are initially class M, but they evolve rapidly through L to T. Almost all late-type (cool) M dwarfs are low-mass stars, as are many early-type L dwarfs, but the majority of late-type L dwarfs and all T dwarfs are substellar-mass brown dwarfs.
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PERSPECTIVES: ATOM OPTICS

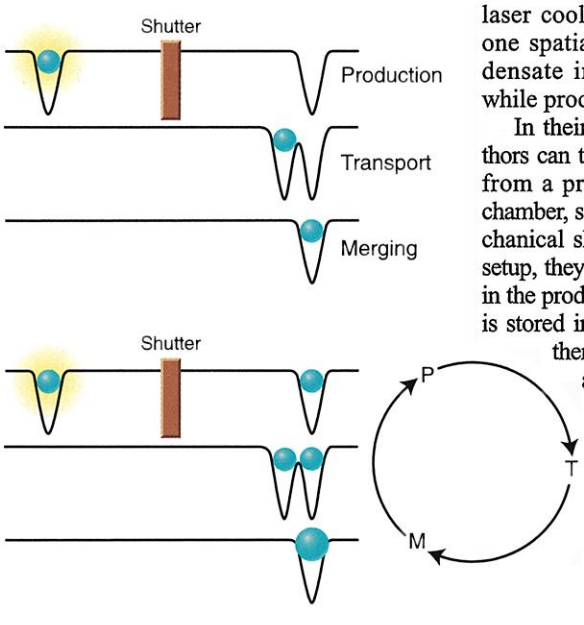
Continuous Progress on Atom Lasers

Tilman Pfau

In 1960, Theodore Maiman demonstrated the first pulsed optical laser, using a synthetic ruby crystal as the laser active material and a flash lamp to achieve population inversion by optical pumping. Just 6 months later, Ali Javan invented the first continuous optical laser. In his HeNe gas laser, collisions of electrically excited He atoms with ground state Ne atoms produced the inversion required for continuous laser operation. Just 1 day after its realization, the laser was used to transmit a telephone call. Similar lasers are still widely used, with applications ranging from precision spectroscopy to material processing.

Today, optical lasers abound, and the sights have been set on atom lasers, which exploit the wave properties of matter. In a gas, individual atoms are usually in distinct states of motion, whereas atom laser operation requires them all to be in the same state. This is achieved in a Bose-Einstein condensate (BEC), in which many atoms are trapped in the minimum energy quantum state (*1*). After experiments demonstrated the phase coherence of these giant matter waves (*2*), the atom traps were combined with controllable leaks to release a coherent beam of atoms from the trapped condensate. Pulsed atom lasers comparable to q-switched (*3*) and mode-locked lasers (*4*) were reported. But it proved difficult to move from pulsed to continuous operation. Improving control over the leaks delivered atom laser beams for up to 100 ms from a single condensate (*5*), but replenishing the reservoir was a major obstacle in moving from pulsed to continuous operation.

Many sophisticated ways to achieve continuous pumping of atom resonators have been discussed (*6–9*). Most of these ideas are based on optical pumping between various internal and external states of the atoms. However, none of them could demonstrate high enough pump rates to overcome the intrinsic losses and achieve laser action. The main problem is that reabsorption of the scattered photons by neighboring atoms gives rise to a loss mechanism that cannot be overcome by the gain due to the pump.



Condensate on demand. Bose-condensed atoms are now available in a continuous reservoir of atoms. Losses due to background gas collisions are compensated by replenishing the reservoir with condensed atoms from a production chamber. The condensates are transported, trapped, and merged with optical tweezers.

The step that seemed straightforward in the case of optical lasers, from pulsed to continuous pumping and operation, thus remained beyond reach for atom lasers. Even 7 years after the first BEC experiments, no true analog of a continuous laser has been reported.

Chikkatur *et al.* have now resolved the quest for a continuously operating reservoir of condensed atoms with a surprisingly simple concept (see page 2193 of this issue) (*10*). Instead of combining laser cooling and storage of the BEC in one spatial location, they store the condensate in a separate vacuum chamber while producing another one.

In their sophisticated apparatus, the authors can transport a condensate over 30 cm from a production chamber to a storage chamber, separated from the former by a mechanical shutter (see the figure). With this setup, they can produce a second condensate in the production chamber while the first one is stored in the dark storage chamber. They then move the second one to the storage chamber, where they merge the two condensates. This sequence can be repeated many times, providing a continuous reservoir of condensed atoms.

Through spatial separation, the authors avoid the inevitable destruction of the reservoir of condensed atoms through absorption of scattered light in the production chamber. Although the pumping mechanism is still pulsed, its repetition rate is faster than the decay time of the resonator. It can therefore

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