The Formation of Substellar Objects Induced by the Collision of Protostellar Disks

D. N. C. Lin, G. Laughlin,* P. Bodenheimer, M. Różyczka

Simulations of a close encounter between two protostars, each surrounded by a relatively massive disk, resulted in the ejection of some of the disk material into a tidal tail. A portion of the tail condensed into an object with a mass in the range of 5 to 10 jovian masses. This mechanism may explain the existence of the single objects of substellar mass that have recently been discovered.

Tidally interacting or merging galaxies show extended filamentary structures (*1*). The tails of galaxy NGC 7252, which is thought to be a merger product (*2*), are excellent examples of these filamentary structures. In such tails, self-gravitational fragmentation and condensation are thought to account for the observed overabundance of dwarf galaxies along the structures (*3*). Numerical simulations of galactic encounters not only reproduce the observed structures but also provide evidence that self-gravitating condensations can indeed form in the tails (*4*). Here, we suggest that similar processes can occur on a much smaller scale through the tidal interaction of two very young stars with disks and that the resulting condensations could be identified with single brown dwarfs, such as those recently discovered in the Pleiades (*5*).

To explain the origin of the solar system, Buffon postulated in 1745 that planets may have condensed from a stream of gas that was torn from the sun by a passing celestial body in the course of a near collision (*6*). The original version of this scenario has been challenged on the grounds that hot stellar material would expand and disperse rather than condense into planets. However, most young stars have large surrounding disks, so encounters between them can be frequent and close enough to induce impacts that are similar to those observed in interacting galaxies. The gas torn out of these disks is much colder than the stellar material. Previous work indicates that the most interesting consequences of such encounters are (i) the formation of a binary system by capture (*7*) or (ii) gravitational fragmentation in the disks, resulting in the formation of additional stars or substellar objects (*8, 9*). In particular, noncoplanar disk-disk encounters (*9*) result in the formation of tidal arms and substellar condensations in the vicinity of the protostars themselves.

We hypothesize that encounters may have yet another outcome: Extended filaments may develop, and condensed objects may form within them, unbound to and at a large distance from the protostars. To check this hypothesis, we performed a numerical simulation of an encounter between two protostars. For the initial conditions, we adopted a model of a protostar with a surrounding disk, which was broadly similar to the conditions that resulted from the collapse of a rotating fragment in a molecular cloud (*10*). In the 40,000 years after the onset of the collapse, a central star of 0.6 $M_\odot$ ($M_\odot$ represents the mass of the sun) is formed along with a disk, close to hydrostatic equilibrium, of radius 250 astronomical units (AU) and mass 0.4 $M_\odot$. The disk temperatures and densities vary between 200 and 20 K and 10^{-12} and 10^{-15} g cm^{-3}, respectively, over the radius range of 5 to 250 AU. The disk is stable against spontaneous fragmentation as a result of the shear associated with its differential rotation. The evolution of the disks was computed with a three-dimensional smoothed particle-hydrodynamics scheme (*11*), in which the outer 0.2 $M_\odot$ of gas (lying in the radius range of 100 to 250 AU) of each disk was modeled by 8000 particles of identical mass. A variable smoothing length was employed (*12*) in such a way that the 50 nearest neighboring particles were used to produce density and pressure estimates. The inner high-density (<250 AU) regions of the disks were assumed to evolve adiabatically. In the optically thin regions beyond 250 AU, however, the molecular hydrogen gas was assumed to be isothermal with a temperature of 10 K because of the relatively short cooling time scale (*13*). The disks were likely to be immersed in remnants of the molecular cloud core or cores from which they formed and to have associated bipolar outflows. In our simulation, these features were not taken into account because of their low density compared with that of the disks.

Each star, together with the inner 100 AU of its disk, is represented by a single massive particle. They are initially on a marginally bound elliptical orbit with a period of 64,000 years. The orbital angular momentum vector is parallel to the initial spin vector of one disk (around star A) and perpendicular to that of the other (around star B). The periastron passage occurs at time $t = 0$, with a stellar separation of 300 AU. Numerical computation begins at $t = -611$ years (Fig. 1a). At $t = 820$ years, a tidal tail, containing a few percent of the entire system mass, is drawn from disk A to a distance of ~1000 AU (Fig. 1b). Segments of the tail essentially move together, resulting in a much reduced shear compared with the shear throughout the disk; also, disk material, initially at 20 K, cools to 10 K in the tail. Consequently, at $t = 1774$ years (Fig. 1c), the tidal tail becomes gravitationally unstable and forms a collapsing fragment of ~7 M_J (M_J represents jovian mass). This mass is comparable to the characteristic Jeans mass (*14*), given the density of the filament. At $t = 2251$ years (Fig. 1d), a self-gravitating substellar object is formed, traveling away from the center of mass at 2.2 km s^{-1} (a sufficient velocity to escape the system).

The initial disk model was selected as a result of several lower resolution simulations, in which the radial surface density profile of the disk was varied. A relatively flat profile was used; if the profile is more centrally concentrated, the fragment forms closer to the base of the tidal tail.

The object may continue to accrete particles with similar velocities in its vicinity. However, its growth is limited by the diverging flow pattern along the tail (Fig. 2). The radial velocities along the filament are roughly proportional to the distance from the center of mass, a result which has been established in the case of galactic encounters (*15*). Thus, the end of the tail beyond the condensed object may disperse before the rest of the tail.

The simulation was terminated at the point where the collapse had led the object into an opaque high-density state. Given the relatively smooth velocity field, we estimated that the filament would survive as a coherent entity for several thousand years. These time scales and the properties of the system may, of course, be modified with different assumptions regarding stellar masses, periastron distance, or disk orientation.

The subsequent evolution of the object was analyzed numerically by the solution of the standard equations of stellar structure under the assumption of spherical symmetry (*16*). Objects with mass $M = 5$ and 10 M_J were considered, starting at radii of 50 and 100 AU (the Jeans length), respectively. After a brief hydrodynamic collapse, the objects reach hydrostatic equilibrium with radii $R \approx 30$ to 40 AU. Subsequently, they undergo contraction on the Kelvin-Helmholtz time scale [~$0.25G\,M^2/RL$, where G is the gravitational constant and typi-

D. N. C. Lin and P. Bodenheimer, University of California/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA. G. Laughlin, Department of Astronomy, University of California, Berkeley, CA 94720, USA. M. Różyczka, Nicholas Copernicus Astronomical Center, ulitsa Bartycka 18, 00-716 Warszawa, Poland.

*To whom correspondence should be addressed. E-mail: gpl@astro.berkeley.edu

cal luminosity $L = 4 \times 10^{-4}$ and $5 \times 10^{-5}\ L_\odot$ ($L_\odot$ represents the luminosity of the sun) for the models of 10 and 5 M_J, respectively]. The contraction continues, with surface temperatures $T_{\mathrm{eff}} \approx 10$ to 60 K, until the central temperature reaches 2000 K, where the molecular hydrogen dissociates, inducing a second collapse phase. The radii at the onset of the second collapse are 0.5 and 1 AU for 5 and 10 M_J, respectively, and the contraction times to this point are 3.8×10^4 and 9×10^3 years, respectively. Thereafter, hydrostatic equilibrium is quickly reestablished (*17*) with radii of the order of 10^{10} cm, and the standard evolutionary tracks (*18, 19*) apply. On the basis of these models and the Kelvin-Helmholtz formula, we infer that on the dispersal time scale ($\sim 5 \times 10^3$ years) of the filament, objects in the mass range $<15\ M_J$ remain in the suspended cold giant state, whereas those $>15\ M_J$ will have undergone the second collapse.

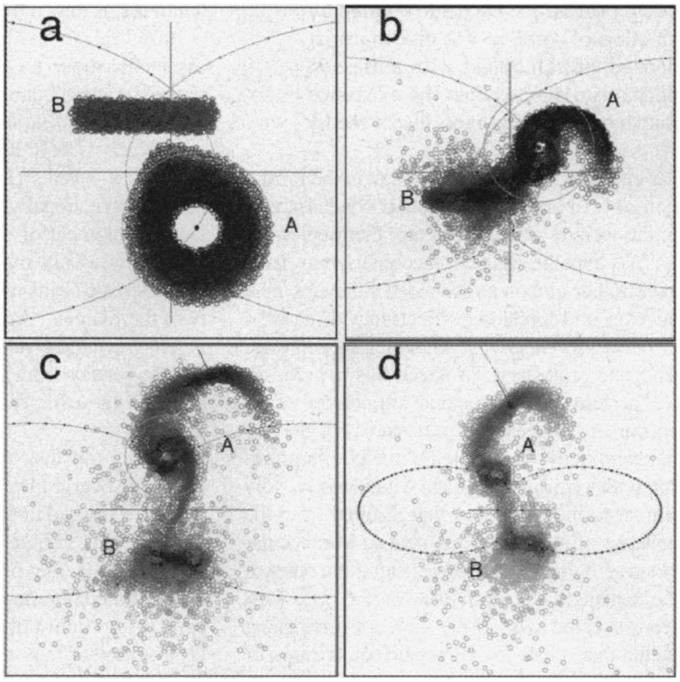

Fig. 1. A prograde close passage between two protostar/disk systems (A and B). Snapshots of the material distribution, projected onto the orbital plane, are plotted for four different times: **(a)** −661, **(b)** 820, **(c)** 1774, and **(d)** 2251 years relative to the moment of periastron. In (d), part of the tidal tail has collapsed into a 7 M_J object. Its approximate future orbit, obtained from a simple three-body integration, is indicated. In (a) through (d), the cross hairs marking the center of mass have a length of 1000 AU. The small dots along the orbital paths mark 1000-year intervals. The density ρ at each particle location is indicated by shading. Gray circles correspond to $\rho < 10^{-17}$ g cm^{-3}. Particles located in regions of density $\rho > 10^{-14}$ g cm^{-3} are shown as solid dots. The circle surrounding star A encloses a region with a radius of 250 AU, outside of which an isothermal equation of state is used.

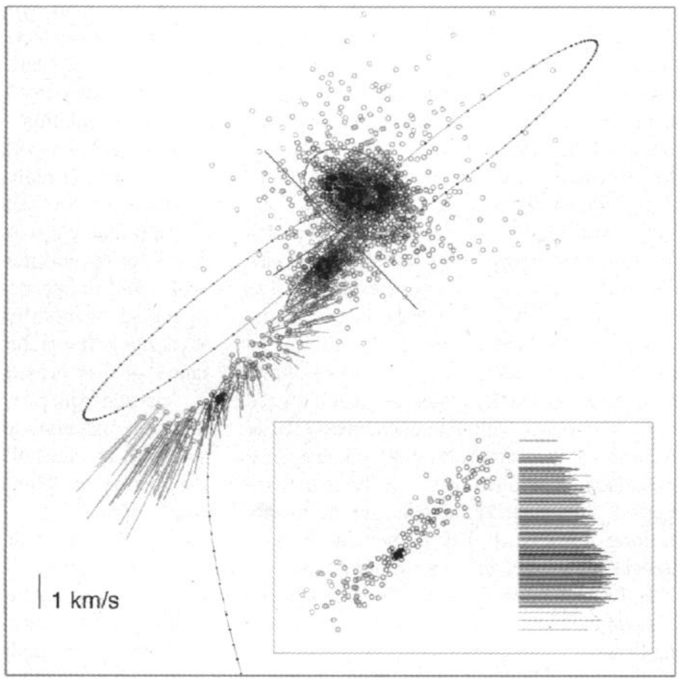

Fig. 2. A view of the system at $t = 2251$ years relative to the moment of periastron. Two thousand particles were used to produce this plot. The Euler viewing angles ($\phi = 120°$, $\theta = 235°$, and $\psi = 150°$) were chosen to provide a direct comparison between the numerical results and the Hubble Space Telescope image of the TMR-1 complex. The tangential velocities of the particles along the tidal tail are shown with lines whose lengths are scaled to their values. The future trajectory of the condensed object is indicated. In the inset diagram, the radial velocities of approach are plotted for the particles in the tail. All remaining symbols have the same meaning as in Fig. 1.

A possible example of a disk-disk encounter is the binary protostellar system TMR-1, located in the Taurus star-forming region at about 140 pc from the sun. The components of this system, with a projected separation of 45 AU, are heavily embedded in a dusty envelope and have a total luminosity of 2.8 $L_\odot$. A bright long filament, observed in the near-infrared (IR) spectrum, extends in a southeasterly direction from the binary system out to a distance of about 1300 AU (*20*). TMR-1 has an associated bipolar outflow, detected in CO, whose direction may be close to that of the filament but is not well determined by existing observations (*21*). Just beyond the end of the filament (*20*) is a condensed object known as TMR-1C, which is claimed to be a protoplanet. Its projected separation from the binary is about 1400 AU. If TMR-1C were at the same distance from the sun as TMR-1, its luminosity would be about 1/10,000 of the solar value, and its inferred mass would be substellar. Its surface temperature is not well determined from existing IR photometry, because of the unknown extinction in the region.

The radiation from TMR-1C could be explained by our model in two different ways. First, its reported near-IR luminosity may be attributed to the light of TMR-1, which was scattered from a $5 M_J$ protoplanet with an age of $\sim 1.5 \times 10^3$ years, $T_{\mathrm{eff}} = 9$ K, and $R = 15$ AU; other masses are also allowed at different ages. Second, the estimate of the contraction time of a 20 M_J object is 2500 years. Shortly after collapse (*19*), such an object has $\log L/L_\odot = -2.35$, $T_{\mathrm{eff}} = 2900$ K, and $R = 1.6 \times 10^{10}$ cm. The radiative properties of the protoplanetary condensation in the filament could also be matched to those observed for TMR-1C if the object is heavily obscured. Our model also allows for predictions concerning the dynamics of the system. The expected radial and tangential velocities are 2.2 and 0.7 km s^{-1}, respectively (Fig. 2).

However, because it has not been established that TMR-1C is at the same distance as the binary TMR-1, the explanation of its origin on the basis of the disk-disk encounter scenario must be viewed with some caution. Alternatively, TMR-1C may be a substellar object that had formed in the original disk during the encounter and was ejected along with the filament. In this case, the object, even with a relatively low mass, would have time to undergo the second collapse. Indeed, previous work (*9*) on the encounters of stellar disks shows that fragmentation can be induced within or near the disks themselves. Finally, TMR-1C could be a background star.

In summary, we find that an encounter between two protostars with masses comparable to that of the sun, each having a massive disk, can result in the ejection of a tidal filament of length ≈1000 AU, in which an unbound substellar object forms with characteristic mass 10 M_J. Such objects could be the progenitors of single brown dwarfs, several of which have been found in the Pleiades cluster (*5*).

A more speculative application would be the TMR-1 complex. In this case, we predict the following: (i) The luminosity of the filament arises mainly from the scattered light of TMR-1. (ii) The IR signature of TMR-1C may be due to scattering or extinction, which could be differentiated by future spectroscopic observations. (iii) TMR-1C recedes from TMR-1 in a direction offset from the long axis of the filament at a velocity on the order of 2 km s^{-1}. The proper motion would be ~1 km s^{-1}. Characteristic filament velocities would be in the same range.

Finally, we stress that the formation of substellar objects along tidal filaments requires the protostars to have massive disks. Such disks evolve rapidly, so these events must occur during the earliest phase of protostellar evolution. The Taurus region, where TMR-1 resides, has a modest number of protostars per unit of volume, and the probability of an encounter with the parameters of the simulation is only 1 part in 10,000. Furthermore, the encounter is observable for only a few thousand years, which is only 1% of the typical protostellar lifetime of 2×10^5 to 5×10^5 years. However, in the much denser Orion Trapezium cluster, or in the Rho Ophiuchi star-forming region, such encounters may be quite frequent.

References and Notes

1. A. Toomre and J. Toomre, *Astrophys. J.* **178**, 623 (1972).
2. F. Schweizer, in *The Structure and Properties of Nearby Galaxies*, E. M. Berkhijsen and R. Wielebinsky, Eds. (Reidel, Dordrecht, Netherlands, 1978), pp. 279–285.
3. F. Zwicky, *Ergeb. Exakten Naturwiss.* **29**, 344 (1956); S. D. Hunsberger, J. C. Charlton, D. Zaritsky, *Astrophys. J.* **462**, 50 (1996); A. D. Glenn, S. D. Hunsberger, J. C. Charlton, R. B. Ciardullo, D. Zaritsky, *Bull. Am. Astron. Soc.* **29**, 1379 (1997).
4. J. E. Hibbard and J. C. Mihos, *Astron. J.* **110**, 140 (1995); J. E. Barnes and L. Hernquist, *Nature* **360**, 715 (1992); B. G. Elmegreen, M. Kaufman, M. Thomasen, *Astrophys. J.* **412**, 90 (1993).
5. M. R. Zapatero Osorio *et al.*, in *Brown Dwarfs and Extrasolar Planets*, R. Rebolo, E. L. Martin, M. R. Zapatero Osorio, Eds. (Astronomical Society of the Pacific, San Francisco, CA, 1998), pp. 51–60.
6. Several versions of the encounter theory of the origin of the planets exist in the literature [G. L. L. Comte de Buffon, *De la Formation des Planétes* (Paris, 1745; reprinted in *Oeuvres Complets* (Adolf Deros, Brussels, 1852), vol. 1, pp. 120–140; J. H. Jeans, *Mem. R. Astron. Soc.* **62**, 1 (1917); T. C. Chamberlain, *Astrophys. J.* **14**, 17 (1901); M. M. Woolfson, in *The Origin of the Solar System—The Capture Theory*, S. F. Dermott, Ed. (Wiley, New York, 1989), pp. 15–21]. The argument against the hypothesis was presented by L. Spitzer [*Astrophys. J.* **90**, 675 (1939)].
7. C. J. Clarke and J. E. Pringle, *Mon. Not. R. Astron. Soc.* **249**, 584 (1991); R. B. Larson, in *Physical Processes in Fragmentation and Star Formation*, R. Capuzzo-Dolcetta, C. Chiosi, A. DiFazio, Eds. (Kluwer, Dordrecht, Netherlands, 1990), p. 389.
8. I. Bonnell, J.-P. Arcoragi, H. Martel, P. Bastien, *Astrophys. J.* **400**, 579 (1992).
9. S. J. Watkins, A. S. Bhattal, H. M. J. Boffin, N. Francis, A. P. Whitworth, *Mon. Not. R. Astron. Soc.*, in press.
10. G. Laughlin and P. Bodenheimer, *Astrophys. J.* **436**, 335 (1994).
11. L. Hernquist and N. Katz, *Astrophys. J. Suppl. Ser.* **70**, 419 (1989).
12. The particles were treated as point masses in the calculation of the gravity. A continuous density distribution was obtained by averaging the smoothed contributions of a specified number of neighboring particles. The smoothing length is thus inversely proportional to the local density.
13. A. P. Whitworth and C. J. Clarke, *Mon. Not. R. Astron. Soc.* **291**, 578 (1997).
14. At a given density and temperature, the Jeans mass is the minimum mass required for an object to collapse under self-gravity in the presence of opposing gas pressure gradients.
15. D. N. C. Lin and D. Lynden-Bell, *ibid.* **198**, 707 (1982).
16. P. Bodenheimer and J. B. Pollack, *Icarus* **67**, 391 (1986); J. B. Pollack *et al.*, *ibid.* **124**, 62 (1996).
17. P. Bodenheimer, A. S. Grossman, W. M. DeCampli, G. Marcy, J. B. Pollack, *ibid.* **41**, 293 (1980).
18. A. Burrows *et al.*, *Astrophys. J.* **491**, 856 (1997).
19. F. D'Antona and I. Mazzitelli, *Astrophys. J. Suppl. Ser.* **90**, 467 (1994).
20. S. Terebey, D. Van Buren, T. Hancock, D. L. Padgett, M. Brundage, *Bull. Am. Astron. Soc.* **30**, 933 (1998).
21. S. Terebey, C. A. Beichman, T. N. Gautier, J. J. Hester, *Astrophys. J.* **362**, L63 (1990); M. R. Hogerheijde, E. F. van Dishoeck, G. A. Blake, H. J. van Langevelde, *ibid.* **502**, 315 (1998).

22. This work was supported in part by NSF grant AST-9618548; in part by the NASA Origins Program under grant NAG5-4277; and in part by a NASA astrophysics theory program, which supports a joint Center for Star Formation Studies at NASA/Ames Research Center, University of California at Berkeley, and University of California at Santa Cruz. We thank N. Turner for useful discussions.

15 June 1998; accepted 12 August 1998

Bax and Adenine Nucleotide Translocator Cooperate in the Mitochondrial Control of Apoptosis

Isabel Marzo,* Catherine Brenner,* Naoufal Zamzami, Juliane M. Jürgensmeier, Santos A. Susin, Helena L. A. Vieira, Marie-Christine Prévost, Zhihua Xie, Shigemi Matsuyama, John C. Reed, Guido Kroemer†

The proapoptotic Bax protein induces cell death by acting on mitochondria. Bax binds to the permeability transition pore complex (PTPC), a composite proteaceous channel that is involved in the regulation of mitochondrial membrane permeability. Immunodepletion of Bax from PTPC or purification of PTPC from Bax-deficient mice yielded a PTPC that could not permeabilize membranes in response to atractyloside, a proapoptotic ligand of the adenine nucleotide translocator (ANT). Bax and ANT coimmunoprecipitated and interacted in the yeast two-hybrid system. Ectopic expression of Bax induced cell death in wild-type but not in ANT-deficient yeast. Recombinant Bax and purified ANT, but neither of them alone, efficiently formed atractyloside-responsive channels in artificial membranes. Hence, the proapoptotic molecule Bax and the constitutive mitochondrial protein ANT cooperate within the PTPC to increase mitochondrial membrane permeability and to trigger cell death.

Pro- and antiapoptotic members of the Bcl-2 family have pleiotropic effects on caspase activation cascades regulated by the apoptosome, on cellular redox potentials, and on the barrier function of mitochondrial membranes (*1–9*). The proapoptotic protein Bax redistributes to and acts on mitochondria to induce cell death (*6–9*). Bax induces all mitochondrial hallmarks of apoptosis when overexpressed in cells, including the dissipation of the mitochondrial inner transmembrane potential ($\Delta\Psi_m$) (*1*) and the release of cytochrome c through the outer mitochondrial membrane (*6–9*).

These effects of Bax are the same as those of agents that open the permeability transition (PT) pore, a structure involved in the control of apoptosis (*2*). Accordingly, recombinant Bax (*10*) and atractyloside (Atr)—a PT pore–

I. Marzo, N. Zamzami, S. A. Susin, H. L. A. Vieira, G. Kroemer, CNRS, UPR 420, 19 rue Guy Môquet, F-94801 Villejuif, France. C. Brenner, CNRS, UPR 420, 19 rue Guy Môquet, F-94801 Villejuif, France, and CNRS, UPRES-A6022, Université de Technologie de Compiègne, F-60200 Compiègne, France. J. M. Jürgensmeier, Z. Xie, S. Matsuyama, J. C. Reed, Burnham Institute, 10901 North Torrey Pines Road, La Jolla, CA 92037, USA. M.-C. Prévost, Unité d'Oncologie Virale, Institut Pasteur, 28 rue du Docteur Roux, F-75724 Paris Cedex 15, France.

*These authors contributed equally to this report.
†To whom correspondence should be addressed. E-mail: kroemer@infobiogen.fr