cal function. Their work demonstrates the value of taking an integrated approach to cellular dynamics, and shows that even though the cell is a complex, hierarchical system, it is possible to gain insight into its functional organization using relatively simple analyses.

The stage is set for further investigation of these types of protein network. How, for example, did they evolve? Possible clues can be found in related work on the emergence of power-law distributions[6,4,9]. Such distributions will emerge if the probability that a particular node makes future connections is proportional to the number of current connections. Put another way, highly connected nodes tend to become even more connected as time goes by. What, therefore, is happening at the level of protein interactions? Certain highly connected proteins could have a special structure that enables them to bind to many different types of protein, including new ones that arise through mutation. So it may be that the proteins that make up the highly connected nodes in cellular networks share common structural features.

Modelling work[10] has shown how power-law networks can arise from simple dynamical rules on the basis of evolutionary principles. This latter study demonstrates that power-law connectivity is a property of networks that are in a state of transitory expansion, suggesting that the connectivity properties of a network are a signature of its particular evolutionary state. If this is correct, it implies the existence of networks that do not follow power laws. For example, the modelling work indicates that newly developed networks are, by nature, sparsely connected and are best described by exponential distributions. Moreover, models of this type may also be relevant to the observed power-law distributions of protein family sizes[11], in which a 'family' consists of proteins that share sequence similarity and have similar biological functions. In this context, a power-law distribution implies the existence of 'mega-families' composed of a large number of proteins that are both structurally and functionally similar.

From a biomedical standpoint, Jeong and colleagues' findings[1] suggest that it may be unwise to select a highly connected protein as a drug target, given that inactivation of the protein could prove to be fatal or highly disruptive to the cell. Accordingly, a better strategy may be to target a less well connected protein that has a similar function. In this regard, understanding the connectivity of the network could provide likely candidates through the principle of 'guilt by association' — that is, if two proteins interact with one another, they are probably involved in similar cellular functions[2,12]. ■

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1. Jeong, H., Mason, S. P., Barabási, A.-L. & Oltvai, Z. N. *Nature* **411,** 41–42 (2001).
2. Uetz, P. *et al. Nature* **403,** 623–627 (2000).
3. Xenarios, I. *et al. Nucleic Acids Res.* **28,** 289–291 (2000).
4. Barabási, A.-L. & Albert, R. *Science* **286,** 509–512 (1999).
5. Jeong, H., Tombor, B., Albert, R., Oltvai, Z. N. & Barabási, A.-L. *Nature* **407,** 651–654 (2000).
6. Albert, R., Jeong, H. & Barabási, A.-L. *Nature* **401,** 130–131 (1999).
7. Costanzo, M. C. *et al. Nucleic Acids Res.* **28,** 73–76 (2000).
8. Vogelstein, B., Lane, D. & Levine, A. J. *Nature* **408,** 307–310 (2000).
9. Simon, H. A. *Models of Man* 145 (Wiley, New York, 1957).
10. Slanina, F. & Kotrla, M. *Phys. Rev. E* **62,** 6170–6177 (2000).
11. Bader, J. S. http://xxx.lanl.gov/abs/physics/9908032
12. Oliver, S. *Nature* **403,** 601–603 (2000).

Astronomy

A new twist on neutron stars

Chris Fryer and Stan Woosley

Theory suggests that neutron stars should be born rotating rapidly, but in reality they spin more slowly. New calculations suggest that they may be slowed by the emission of exotic gravity waves.

A neutron star is like a gigantic atomic nucleus, packing more than a solar mass of neutrons inside a ball just 20 kilometres across. Neutron stars are born when the iron core of a massive star collapses violently inside a supernova[1]. Before they collapse, the inner cores of massive stars can have high angular momentum. Indeed theory suggests that neutron stars could be born rotating at near the maximum value they can endure without flying apart, 1,000 times per second. This is much faster than the spin rates

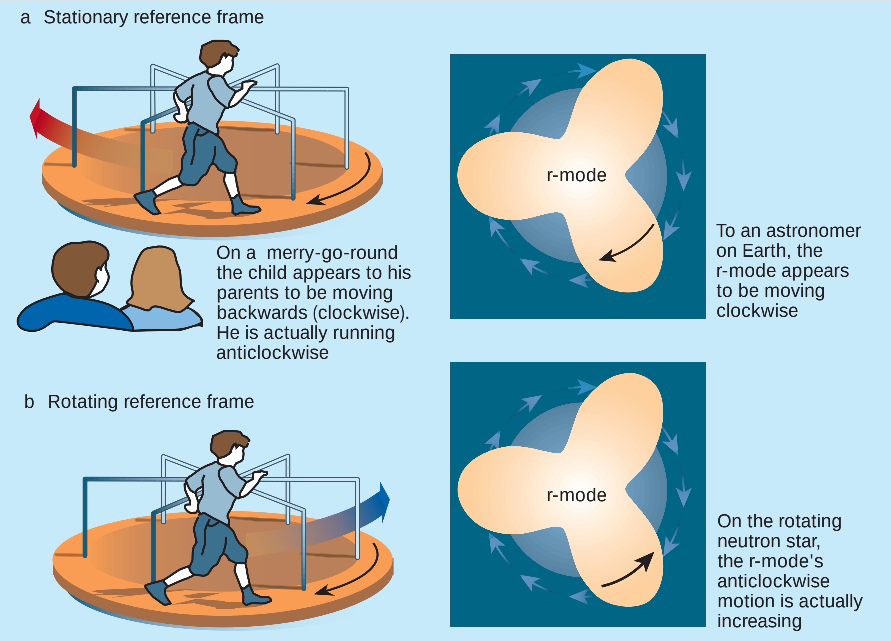


Figure 1 **Rotating neutron stars and gravity waves. The growth of r-modes can be understood through an analogy with a child running anticlockwise on a clockwise-spinning merry-go-round.** a, **If the child is running slower than the merry-go-round is spinning, he appears to his parents sitting on a nearby bench to be moving clockwise (although slower than the merry-go-round). In the case of a spinning neutron star, an r-mode moving slowly in the opposite direction to the spinning neutron star will appear to an observer on Earth in the 'stationary reference frame' to be moving with the spin of the neutron star. The gravitational waves created by the current variations of the r-mode carry away angular momentum, causing the r-mode to slow down in the observer's stationary frame.** b, **In the rotating reference frame of the merry-go-round, the child is running in the opposite direction to that of the spinning merry-go-round. When the child runs faster in this frame, he appears to slow down in the stationary reference frame of his parents. Similarly, when the r-mode emits gravitational waves and slows down in the stationary reference frame of the observer, the r-mode velocity in the rotating reference frame of the neutron star is actually accelerating, causing the r-mode amplitude to grow. As the amplitude grows, more gravitational waves are emitted, leading to a runaway process. New calculations[2,3] show that this process may be responsible for slowing down rapidly spinning neutron stars.**

observed for rotating neutron stars — also known as pulsars — and indicates that angular momentum must have been removed somewhere along the way. But when, how and by how much? In two papers appearing in *Physical Review Letters*, Stergioulas and Font[2] and Lindblom *et al.*[3] provide support for the idea that neutron stars are slowed, at least in part, by the emission of gravity waves.

Single pulsars, typically observed 1,000 years or more after their birth, rotate relatively slowly, just 30 times per second for the pulsar in the Crab Nebula. Although faster, literally, than the blink of an eye, this is a snail's pace compared with the maximum value. So why do pulsars rotate at this slower, seemingly arbitrary value? Two possibilities emerge. Either they were born rotating slowly, or they were born rotating much faster but radiated away their excess rotational energy shortly after birth. The key issues here are the spin frequency of a neutron star when it is first born, and whether that neutron star will emit copious gravitational radiation.

Theory is, at the moment, unable to discriminate between these two possibilities. For a neutron star to be born rotating slowly, angular momentum must be removed from the spinning iron core before it collapses. Calculations[4] of the effects that might transport angular momentum in massive stars — friction, convection, circulation and the like, but ignoring magnetic fields — still allow a neutron star to be born spinning at nearly 1,000 times per second. Other calculations that crudely attempt to include the effects of magnetic forces[5] predict, with great uncertainty, a larger effect and a very slowly rotating neutron star.

Given this uncertainty, astronomers have assumed values of the spin frequency appropriate to their tastes. Those needing enough rotation to explain gamma-ray bursts by the creation of disks around collapsed stellar cores[6] or very luminous pulsars[7] assume high spin frequencies of around 1,000 times per second. So do those who want rotation to be important in supernova models, especially those desirous of the large gravitational radiation signature that comes from a highly deformed, rapidly rotating neutron star. On the other hand, those seeking a simpler life and not wanting to include rotation in their supernova models adopt the slow value.

The alternative explanation for slow spin frequencies is that the neutron star is in fact born rotating with a spin frequency near 1,000 times per second, but radiates away the excess rotational energy as light or gravity waves. If this energy were emitted through a pulsar mechanism, it would drastically affect the explosion energy and emission from the supernova remnant. Observations of supernovae and young supernova remnants seem to rule this option out. Although not all astronomers agree[7], it seems that, if neutron stars born rotating rapidly are to be slowed, gravitational radiation must do the job. Gravitational waves are ripples in the fabric of space–time that were predicted by Einstein's theory of general relativity but that are normally too weak to be detected directly. Could young neutron stars be spinning fast enough to produce detectable gravity waves? And will such radiation significantly slow the rotation of the star?

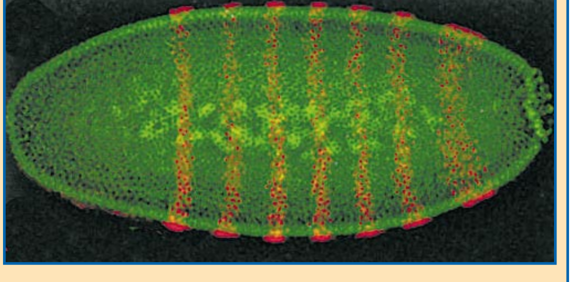
This is where the latest results[2,3] come in. They provide the first three-dimensional simulations of a process responsible for generating gravity waves in neutron stars, and show that it can become strong enough to slow the rotation. A rapidly rotating neutron star produces fluid motions or currents, called r-modes, which are similar to hurricanes or ocean currents on the Earth. These currents produce gravitational waves. The strength of the gravitational radiation depends on the maximum amplitude of the r-mode, which in turn depends on the competition between viscous effects that damp the flow, and driving forces that strive to increase it. The r-modes in neutron stars are driven to larger amplitudes by the same gravitational waves that they produce.

How does this positive feedback work? One way to view it is to consider an r-mode propagating on the surface of the neutron star in a direction opposite to the neutron star's spin (Fig. 1). If the r-mode is moving more slowly than this spin, it will appear to an astronomer observing from a safe distance above the star surface to move in the same direction as the neutron star (albeit slower). The gravitational waves produced by the velocity perturbations of the r-mode carry angular momentum away from the r-modes and, to the stationary astronomer, the emission of these gravitational waves appears to make the r-mode move slower. But on the rotating neutron star the already negative velocity of the r-mode becomes more negative and its magnitude (that is, its velocity amplitude) grows.

As the amplitude of the r-mode grows, its gravitational radiation increases, causing a runaway instability. Andersson[8] and Friedman and Morsink[9] first showed by calculation that this instability does indeed occur in neutron stars. How much it actually grows depends on the angular momentum lost through gravitational radiation, which increases rapidly with neutron star spin, and the strength of the opposing viscous forces. The viscosity is highly dependent on the temperature of the neutron star, reaching

Cell biology

Asymmetry in action



G. S. WILKIE & I. DAVIS

The tops and bottoms of cells generally differ in shape and structure, as well as in their protein components. In embryos, such asymmetry is crucial in establishing the pattern of cells and tissues that will make up the adult organism. One way in which the asymmetric distribution of proteins is achieved is through their encoding messenger RNAs. Take, for example, the early fruitfly embryo, pictured here. Some mRNAs (red) form stripes along the top (apical part) of the monolayer of cells that constitutes this stage of development. Others are found at the bottom. Two groups, writing in *Cell*, now delve deeper into the asymmetric distribution of RNA in fruitflies.

Andrew J. Simmonds and colleagues (*Cell* **105,** 197–207; 2001) show that the mRNA encoding a signalling protein, Wingless, is concentrated at the apical side of certain cells. Wingless is involved in many embryonic patterning processes, and, as Simmonds *et al.* show, if its mRNA is not distributed correctly the protein does not function properly. The authors also identify the 'address labels' in the mRNA that are crucial for its distribution.

Meanwhile, Gavin S. Wilkie and Ilan Davis (**105,** 209–219; 2001) have traced the journey of some apical mRNAs from where they are produced to their final destination. They find, first, that all mRNAs diffuse at random from their source in the nucleus. In other words, apical mRNAs do not necessarily leave the nucleus on the apical side.

Instead, once outside the nucleus, particles containing the apical mRNAs make their way rapidly towards the apical part of the cell. These particles are now transported specifically in the right direction — rather than, for example, diffusing randomly throughout the cell and becoming anchored only in the apical part. They are probably transported along microtubule-based tracks, with a motor protein known as dynein acting as the transport vehicle. It remains to be seen, however, how the address labels in the mRNAs connect with this transport machinery. **Amanda Tromans** a minimum just above 1 billion kelvin. So r-modes are most important for rapidly spinning, hot neutron stars. Such conditions could be produced either by the formation of a young hot neutron star in a supernova explosion, or in binary systems in which the neutron star accretes material from a binary companion. If r-mode amplitudes become large under these conditions, the neutron star will emit nearly all of its rotational energy as gravitational waves.

The large r-mode amplitudes predicted by Stergioulas and Font[2] and Lindblom *et al.*[3] would make supernovae a strong source of gravitational radiation, and would provide a way of removing 90% of the rotational energy found in newly formed neutron stars within hours of the explosion that formed them. These numerical calculations give us our first glimpse of how much r-mode amplitudes can grow when they become unstable. Some uncertainties remain over the strength of the damping viscosity[10], but the calculations show that the r-mode instability and its accompanying gravitational radiation must be included in models of neutron stars. The large amplitude of the instability also implies that there is a potentially detectable gravitational radiation signal, a boon for those seeking to observe gravity waves. ■

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1. Burrows, A. *Nature* **403,** 727–733 (2000).
2. Stergioulas, N. & Font, J. A. *Phys. Rev. Lett.* **86,** 1148–1151 (2001).
3. Lindblom, L., Tohline, J. E. & Vallisneri, M. *Phys. Rev. Lett.* **86,** 1152–1155 (2001).
4. Heger, A., Langer, N. & Woosley, S. E. *Astrophys. J.* **528,** 368–396 (2000).
5. Spruit, H. C. & Phinney, E. S. *Nature* **393,** 139–141 (1998).
6. MacFadyen, A. & Woosley, S. E. *Astrophys. J.* **524,** 262–289 (1999).
7. Wheeler, J. C., Yi, I., Hoeflich, P. & Wang, L. *Astrophys. J.* **537,** 810–823 (2000).
8. Andersson, N. *Astrophys. J.* **502,** 708–713 (1998).
9. Friedman, J. L. & Morsink, S. M. *Astrophys. J.* **502,** 714–720 (1998).
10. Jones, P. B. *Phys. Rev. Lett.* **86,** 1384–1387 (2001).

Evolutionary biology

Hybrid costs avoided

Dennis Hasselquist

The offspring of a mating between two different species are often infertile, or almost so. But it seems that some birds can avoid this apparent cost of hybridization.

The question of how new species arise has fascinated evolutionary biologists since Darwin's time. How do species diverge, and what happens when two recently diverged species come into contact, with the risk that they will mate, producing 'hybrid' offspring? In vertebrates, speciation is rarely observed — even rapid speciation is likely to proceed too slowly to be studied in a researcher's lifetime, let alone in the period covered by a normal grant. By contrast, the effects of hybridization can be investigated in wild vertebrates, but such studies are rare. Hence the importance of the work of Veen and colleagues, who, as they describe on page 45 of this issue[1], have been looking at hybridization between two closely related bird species — pied and collared flycatchers. Their study is significant because it is based on a unique and impressively large data set, taken from two different sites (in Sweden and the Czech Republic) over 20 years. This wealth of information allows the authors to unravel some interesting ways in which the birds avoid the apparent costs of hybridization.

When individuals from two different species mate, the offspring may be viable but the effects on their ability to reproduce (and on viability in later generations) are usually severe[2]. There are exceptions, such as Darwin's finches on the Galapagos Islands[3], but the birds studied by Veen *et al.*[1] certainly suffer adverse consequences. When pied and collared flycatchers mate with each other, the first-generation female offspring tend to be almost completely sterile. (The fitness of first-generation males, by contrast, is similar or only slightly less than that of 'pure' males from each species.) Given these facts, one might predict that heterospecific pairs (that is, pairs that consist of a pied and a collared flycatcher) would have greatly reduced reproductive output in the long term. However, Veen *et al.*'s sophisticated analyses[1] reveal some fascinating, and unexpected, patterns.

Males of the two species are distinctly different in songs, calls and coloration (Fig. 1), so it is presumably easy for females to tell them apart[4]. Despite this, pairings between pied males and collared females were much more common than would be expected by chance — particularly given that collared flycatchers outnumber their pied counterparts by 9 to 1 in the sites studied. One might think that the costs of heterospecific pairings, in terms of reproductive output, would be great, but Veen *et al.* show that it was not disadvantageous for collared females to choose pied males. The apparent costs of such pairings are lessened in several ways.

First, heterospecific pairs produced more fledglings than pure collared pairs late in the breeding season. Like many birds, pure collared flycatcher pairs fare best if they mate as early as possible in the season. But pairs of collared females and pied males have peak performance later on. All of this suggests that late-arriving collared females might do best to mate with pied males.

Second, for some heterospecific pairs, not all offspring are actually hybrids. Veen *et al.* find that many of the young raised by collared females with pied males were in fact sired by collared males. Whether this is because 'extra-pair' mating is more common for heterospecific pairs, or because the sperm of collared males win out over the sperm of pied males, remains unknown. Finally, collared females that had mated with pied males produced significantly more male than female offspring. In other words, the balance was skewed in favour of the sex of hybrid that suffered fewer effects. These three mechanisms cancelled out the apparent detrimental effects of hybridization between collared females and pied males. Indeed, the

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Figure 1 **Mingling without costs: collared (left) and pied flycatchers.**