Neutron stars

How pulsars get their spins

Adam Burrows

A supernova explosion announces the spectacular death of a star heavier than about eight solar masses. Its brightness can rival that of its host galaxy, and its total explosion energy is a prodigious 10^{51} ergs. The usual residue of such an explosion, a neutron star, is no less extreme an animal. With a density that of the atomic nucleus, these stars the size of a city are observed to be rotating with periods from milliseconds to seconds, and travelling at up to 1,500 km s^{-1} (Fig. 1, overleaf). Radio pulsars are neutron stars, and as such have been studied for 30 years. Approximately 10^3 of probably 10^5 radio pulsars in the Galaxy have been discovered (among perhaps 10^8 neutron stars). Their masses, magnetic fields, spin periods, spin-down rates, and proper motions across the sky are catalogued, and theories for their emission are devised. But the origin of these basic pulsar parameters has all but been ignored as untestable. On page 139 of this issue[1], Spruit and Phinney attempt to bridge the gap between the supernova and pulsar communities with a provocative thesis.

Taking a lead from the suggestion[2] that a 'kick' from an asymmetrical supernova could exert a torque on a nascent neutron star, they posit a unified theory of pulsar spins, kicks and magnetic fields. First, they suggest that magnetic fields in massive stars couple core and mantle strongly enough to leave the pre-supernova core in solid-body rotation. Such initial magnetic fields indeed yield neutron stars with fields of 10^{12} gauss, as seen in radio pulsars. But the core would rotate far too slowly (with a period of ~100 seconds) to leave young neutron stars spinning as fast as they do. So Spruit and Phinney propose that the mechanism that gives the neutron star its linear kick may also generate its spin.

Second, the authors show that a series of random impulses naturally yields a quantitative connection between spin and kick magnitudes, and at the same time partially decorrelates spin and transverse proper motion vectors and magnitudes. A single kick would produce a spin perpendicular to the velocity change, and so give a strong correlation between spin and apparent motion on the sky — which radio pulsar data do not show. Many randomly placed kicks, perhaps from a convecting supernova explosion, would not cause the same problem.

Evidence that neutron stars experience a net kick at birth has been mounting for years. Pulsars are the fastest population in the Galaxy[3], with an average velocity of ~450 km s^{-1}. Such speeds are far larger than any orbital motion left over from birth in a binary. In the pulsar binaries, PSR J0045–7319 and PSR1913+16, the spin axes and the orbital axes are misaligned, suggesting that the explosions that created the pulsars were not spherical (ref. 4, and I. Wasserman, J. Cordes and D. Chernoff, personal communication). In fact, for the former the orbital motion seems retrograde relative to the spin[5] — the explosion may have kicked the pulsar backwards! The young supernova remnant Cassiopeia A, formed in about AD 1680, has calcium, sulphur and oxygen element distributions that are clumped and have gross back–front asymmetry[6] — no simple shells are seen. Many other supernova remnants, such as N132D and SN0540–69.3, have velocities[7] relative to the local interstellar medium of up to 900 km s^{-1}. The supernova SN1987A is a case study in asphericity: its X-ray, gamma-ray and optical fluxes and light curves require that shards of the radioactive isotope ^{56}Ni were flung far from the core in which they were created; the infrared line profiles of its oxygen, iron, cobalt, nickel and hydrogen are ragged and show a pronounced red–blue asymmetry; its light is polarized (something a sphere cannot accomplish); and Hubble Space Telescope pictures of its inner debris[8] reveal large clumps and hint at a preferred expansion direction.

Finally, SN1997X is one of the most intriguing recent finds. This is a so-called type-Ic supernova, thought to be the explosion of the bare carbon/oxygen core of a massive star that has been stripped of its envelope. SN1997X has the greatest optical polarization of any known supernova (L. Wang, personal communication), which implies that supernova cores, and explosions, are asymmetrical.

All in all, it seems clear that neutron stars can be given a hefty extra kick at birth, and that asymmetries in the supernova explosion are implicated. How might these asymmetries arise? No doubt, instabilities in the outer envelopes of supernova progenitors make debris clouds clumpy and mixed. The observation of hydrogen deep in SN1987A's ejecta strongly suggests the work of such mantle instabilities. But overall, the data — particularly for the heavier elements produced in the inner core — point to asymmetries in the central engine of the explosion.

Supernova theorists have not been napping, and over the past decade have determined that supernova cores are indeed grossly unstable to convective instabilities[2,9,10]. Between the 'bounce' (when some material falls in and effectively bounces off

Entomology

Beauty and the beetle

Coloured beetles are of two basic types. Some have a layer of pigment in their exoskeleton (pigmentary colours), while others rely on the interaction of light with features in their integument (structural colours). These structurally reflecting colours can be very different — *Calloodes grayanus* (pictured right), for example, appears a weak green in colour, whereas *Anoplognathus parvulus* is a strong metallic gold. How are these different colours produced?

Writing in the *Journal of Experimental Biology* (201, 1307–1313; 1998), Andrew R. Parker and colleagues provide the answer. In both cases, the structural colour arises from so-called 'multilayer reflectors' — layers of a transparent material separated by layers with a different refractive index. Reflected beams from all of the layers interfere, and when this interference is constructive for a particular wavelength of light, that colour is observed.

But the similarity ends there. Parker *et al.* have found that the *C. grayanus* reflector is composed of regularly spaced layers of the same optical thickness, overlaid by an irregular transparent layer that scatters light. The resulting reflection is diffuse, appearing the same when viewed from any direction; this green colour seems to provide excellent camouflage against a leafy background.

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The layers that make up the *A. parvulus* reflector, however, decrease in spacing (and consequently in optical thickness) with depth in the structure. The resulting metallic gold colour can be seen only from certain directions, but it makes *A. parvulus* very conspicuous nonetheless, perhaps allowing it to be recognized by members of the same species. Unfortunately, its striking vesture could also mark it as a tasty morsel for predators.

Alison Mitchell

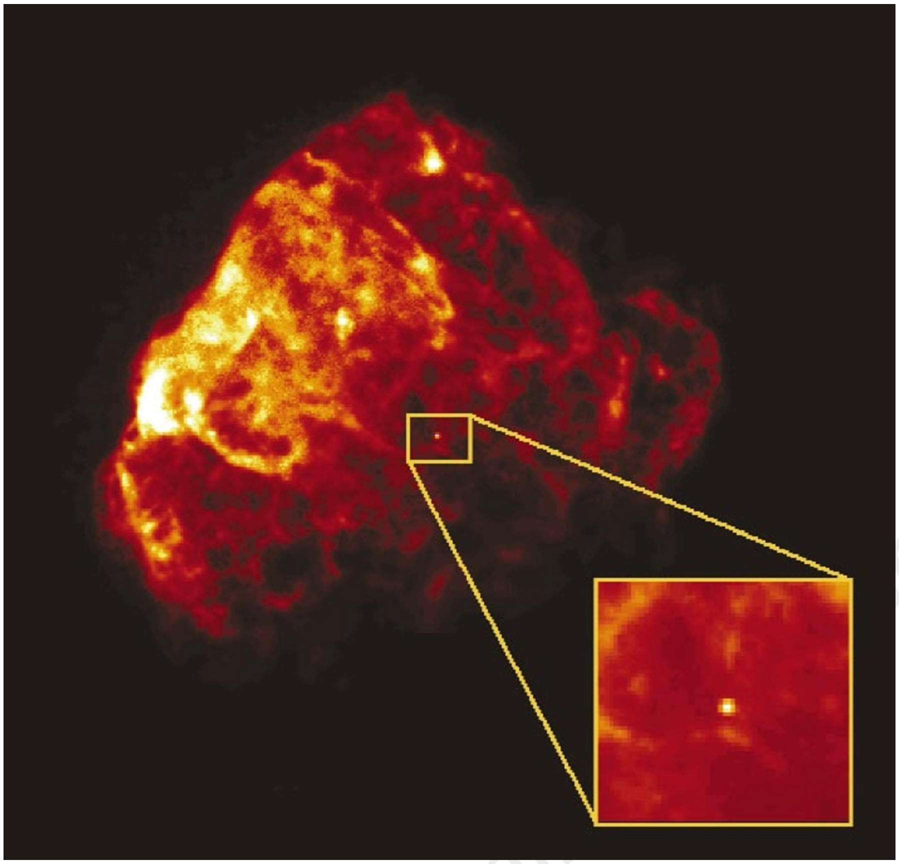

Figure 1 **The 3,700-year-old supernova remnant Puppis A, imaged in X-rays by the satellite Rosat. The bright spot has been interpreted as its neutron star, even though no pulsations are seen, because it has a large ratio of X-ray to optical emission. Its inferred transverse speed is ~1,000 km s^{-1}. Interestingly, the spot is on the opposite side to the fast, oxygen-rich knots, as one might expect in some models of neutron-star recoil during a supernova explosion.**

the surface of the forming neutron star) and the explosion, there is a delay while the outward-moving shock wave travels through the star. During this 100 to 1,000 milliseconds, the core is strongly convective, boiling and churning at sonic speeds (~3×10^4 km s^{-1}). Any slight asymmetry in collapse can amplify this jostling, and result in vigorous kicks and torques to the residue that can be either systematic or random[11].

Whatever the details, it would seem odd if the nascent neutron star were not left with a net recoil and spin, although it is not known whether pulsar speeds as high as 1,500 km s^{-1} can be reached through this mechanism. But asymmetries in the matter distribution may also cause asymmetries in the emission of neutrinos, which carry away most of the binding energy of the neutron star (around 3×10^{53} ergs). Amazingly, a net angular asymmetry in the neutrino radiation of only 1% would give the residue a recoil of 300 km s^{-1}. Not surprisingly, many theorists have concentrated on producing such a neutrino asymmetry, invoking anisotropic accretion, exotic neutrino-flavour physics, or the influence of strong magnetic fields on neutrino cross-sections and transport. The last is particularly interesting, but generally requires[12] magnetic fields of 10^{14} to 10^{16} gauss, far larger than the average pulsar surface field of 10^{12} gauss. Perhaps the pre-explosion convective motions themselves can generate the required fields by dynamo action.

It is now reasonable to imagine a theory that unifies the spins and velocities of neutron stars, the anisotropies observed in supernova ejecta, and stellar collapse and explosion. To date, dialogue between the pulsar and the supernova communities has been rare — but the paper by Spruit and Phinney is a good conversational gambit. □

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Daedalus

Deceptive appearances

Few women have ever been satisfied with their figures. Hence the foundation-garment industry. Perhaps its peak was the late nineteenth century, when the fashionable Victorian young lady seems to have carried nearly as much rigging as a sailing ship.

Since then, elasticated undergarments have grown simpler and less fashionable. Modern women are urged to perfect their figures by diet and exercise. This state of affairs is not an improvement — elastic at least worked. So Daedalus is studying the basics of the technology.

Tensioned clothing cannot truly shape; it can only squeeze. The natural resulting cross-sections are circles or arcs of circles. The human figure, however, tends to have elliptical or ovoid cross-sections. To impose such shapes, a garment needs not tightness, but directional rigidity.

So DREADCO corsetières are devising fabrics woven, not of fibres which can only carry tension, but of micro-girders which can resist bending. These tiny I-beams have polyimide compression faces, carbon fibre tension faces, and thermoplastic central webs. As with some steel girders, they are initially made in T-section, with a sawtooth vertical web. When two such sections are welded together by their tooth points, the resulting I-beam has diamond-shaped holes along its web. The warp and weft half-girders of the new fabric are laid on a shaped former, the corresponding top half-girders are brought down on them, and all the welds are made at once by a fast-set adhesive. Warp and weft micro-girders thus pass through each other's web holes. They can move angularly against each other, giving the new fabric the soft 'drape' of cloth. But it has a definite shape derived from its former; and will impose that shape, subtly but firmly, on the wearer.

Until the complex micro-engineering of production has been optimized, DREADCO's 'Shapers' will be vastly expensive. In the fashion trade, fortunately, this is not necessarily a disadvantage, especially for such a revolutionary product. Instead of merely squeezing the wearer at one point and displacing the tissue elsewhere, they will truly shape her figure. Thin and seemingly insubstantial, they will flatten an excessive stomach without cramping the rest of the waist, and will form thighs, buttocks and breasts into pert, becoming contours without even feeling tight. Even if quite overweight, the happy wearer will still display a perfect figure, but slightly scaled up.

David Jones