Bull. Astr. Soc. India (2001) **29**, 283–287

Neutron stars : Seen my way

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Abstract. An unconventional survey is presented of the observable properties of neutron stars and of all astrophysical phenomena possibly related to them, such as their pulsing, clock irregularities, bursting, flickering, and occasional super-Eddington brightness, the generation of cosmic rays, of gamma-ray bursts, of jets, and of synchrotron nebulae, their birth, and their occasional transient appearance as 'supersoft' X-ray sources. The msec pulsars are argued to be born fast, the black-hole candidates to be neutron stars inside of massive disks, and the gamma-ray bursts to be sparks from dense 'blades' accreting spasmodically onto the surfaces of (generally old) neutron stars within $\lesssim 0.3$ Kpc from the Sun. Supernovae – the likely birth events of neutron stars – are thick-walled explosions, not to be described by Sedov-Taylor waves, which illuminate their gaseous environs via collisions of their 'splinters'.

Key words : neutron stars, accretors, ejectors, pulsars, timing noise, coherent emission, gamma-ray bursters, cosmic-ray boosters, BH candidates, jet sources, supernovae.

1. Neutron stars and their models of detection

Neutron stars are thought to have the following properties (Kundt 1998a, b; Becker & Pavlov 2000) : Mass determinations are all consistent with $M = (1.4 \pm 0.2)\ M_\odot$, moments of inertia I with $I \approx M R^2/3 \approx 10^{45} g cm^2$ (from spindown power), radii $R = 10^{6\pm0.3} cm$ (from X-ray fluxes), magnetic moments $\mu := BR^3 = 10^{31\pm1} G cm^3$ (from wind strengths), and surface temperatures $T_s \lesssim 10^{6.2}\ K$ with somewhat hotter polar caps, $Tp \lesssim 10^{6.5} K$. Here I have ignored the possibility of surface field strengths above $10^{14} G$ as proposed by Thompson & Duncan (1996) for so-called magnetars which I consider unrealistic. These properties are thought to apply to all neutron stars, whose various modes of occurrence will not be listed and discussed.

1. Pulsars : Pulsars are defined as periodical radio sources, with periods $\lesssim 10 s$, emitting intensity spikes at radio frequencies. More than $N = 10^3$ are presently known, but the plot N versus distance shows that we lose completeness already near 0.1 Kpc; we have detected less than 1% of them. Their spectral powers νS_ν peak at gamma-ray energies, between 10^{21} and 10^{25}Hz ($10^{0.6}$ MeV and $10^{1.6}$GeV), with an integrated power which may or may not be comparable

to the spindown power. (Note that published spectra tend to leave out the factor 4π in the radiated power $L = 4\pi S d^2$, assuming strong beaming, an omission which cannot apply to all pulsars). Pulsars should therefore be thought of as gamma-ray pulsars.

Statistically, pulsars do not get older than $10^{6.4}$ *yr*, as is shown by the histogram N versus log (τ), $\tau := P/2\dot{P} \geq$ pulsar age. The Galaxy should be full of extinct pulsars, of spin periods $\gtrsim$ 5s. – The histogram of pulse periods is 2-humped, with the so-called msec pulsars between ms and 10 ms and with the 'ordinary' pulsars between 0.1s and 10s. Yet the 'bridge' region, between 0.01s and 0.1s, contains at least 12 pulsars, and there is no criterion where to put a cut between the two subsets. The literature assumes that the msec pulsars are 'recycled', i.e. spun up by accretion. This assumption ignores braking torques during the proposed spinup. It also ignores the absence of progenitor systems, i.e. binary X-ray pulsars which would spin up monotonically throughout at least some Gyr. For these and other reasons, I prefer to think that the msec pulsars have been born fast and that they have comparable ages to the ordinary pulsars; cf. Cowsik et al. (1984).

Dipole magnetic fields in (fluid) neutron stars would be unstable towards a splitting in the middle and transition into a quadrupole configuration, on a dynamic timescale, unless they were toroidally bandaged during the supernova explosion. The bandage creates large odd-order multipoles, perhaps as shown in Fig. 1 (from Chang); cf. Krolik (1991).

2. Accretors : Accreting neutron stars are observed as X-ray sources, called of high/low mass according to the mass of their mass-donating companion. They can be distinguished from accreting white dwarfs by their much smaller (10^{-6}) moments of intertia – hence faster period fluctuations – and by their higher luminosities at comparable feeding rates. They can pulse, when accreting to their polar caps (instead of equatorial rings, via heavy 'blades' in the orbit plane), and burst due to nuclear explosions of the accreted fuel (type I), or due to clumpy accretion (type II). And they flicker due to unsteady accretion.

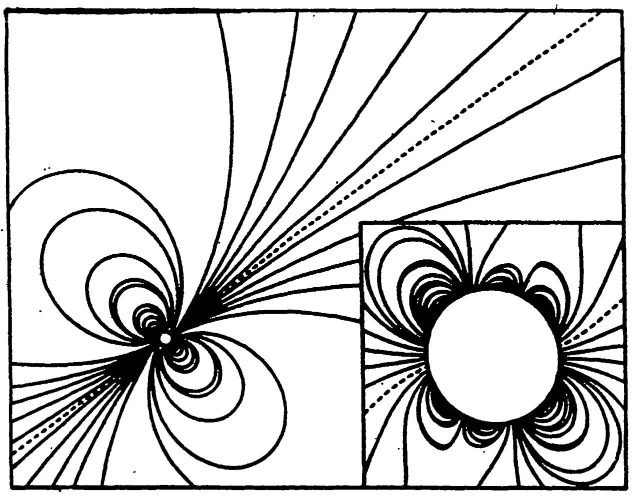

Figure 1. Bandaged magnetic dipole, considered a fair approximation to a pulsar magnetosphere. The inset at lower right enlarges its inner part.

There is the impressive subclass of accretors called black-hole candidates whose compact components have masses of order 7 $M_\odot$. In my understanding, they fill the gap between the low-mass and high-mass systems. They can form during the second stage of mass transfer, when the donator transfers some 10^3 times the Edington rate of a neutron star, which mass has no other way to go than to stay in orbit around the neutron star, evolving towards a rigidly rotating, flat McLaurin spheroid. During the heavy disk's formation, it will shine as a 'supersoft' X-ray source, between 20 and 60 eV (Greiner 1996). Heavy disks are likely present in the super-Eddington sources, with powers $\lesssim 10^{41}$ *erg/s*, feeding the neutron star with heavy blades in the orbit plane at super-Eddington rates. Such disks are thought to contain some 5 $M_\odot$.

3. Ejectors : Not all binary neutron stars are accretors. Important counter examples are jet sources, like SS 433, whose rapidly rotating magnetosphere plus hot companion are thought to re-eject the matter falling in from the inner edge of the accretion disk. Magnetic reconnections provide the pair plasma necessary to drive the jets (Kundt 1996).

The class of ejectors is likely to contain the sources of the cosmic rays : rapidly rotating, strong magnetospheres which can be strained by infalling clumps of matter. Most of the straining matter would cut its way through resisting field lines, in the form of diamagnetic blades, and land on the star's surface whilst the remainder gets radially catapulted out by the recovering magnetosphere, which acts as a relativistic slingshot. Only in this way can protons be boosted to $10^{20.5}$ eV in single-step manoeuvers, and only in this way can we find a non-exotic explanation for the 20% 'repeaters' above 10^{20} eV among the otherwise isotropic arrival directions. At the same time, we may understand why hydrogen and helium are depleted in the cosmic rays.

4. Gamma-ray Bursters : Among the now over 3000 detected gamma-ray bursts – some 3 per day – there are at least 5 repeaters, SGRs, whose occasional high-intensity, hard signals are indistinguishable from all the others. Their spin periods, between 5s and 8s, and their surrounding synchrotron nebulae (Kundt & Chang 1992) suggest that they are the extinct pulsar population, at distances between 50 pc and 0.3 Kpc, emitting sparks in the orbit plane during spasmodic accretion. Their more distant cousins would leave us out of the beam when radiating preferentially at right angles to the Galactic plane (Kundt & Chang 1993). Recent identifications with 'host galaxies' may well be spurious, and afterglows resemble the light echo of SN 1987A. Their absorption redshifts are reminiscent of SS 433; they can form as transverse Doppler shifts in transient hadronic winds from the accreting neutron star's surface.

2. Outstanding problems with neutron stars

Neutron-star physics has faced slow progress over the decades, due to the difficulty of the involved problems. Some of them have already been mentioned, a few others will be touched now.

1. Pulsar Winds : These winds, thought to be leptonic because formed in vacuum, must be quite strong, some 10^4 times the shunting Goldreich-Julian density escaping at the speed of light, as follows in particular from the observed standoff radii against the ISM, some $10^{17\pm1}$cm for at least 9 pulsars (Kundt 1998a). They are probably formed by oscillating electric fields above the polar caps (Chang 1995).

2. Clock accuracy : Pulsar-clock accuracies vary between 10^{-9} and 10^{-15}, increasing with decreasing $\dot{P}$ and thereby beating our best terrestrial clocks. Even so, none of them is without noise: there are occasional discrete 'glitches', and there is quasi-continuous noise which can be expressed by the fact that the braking index $n := \Omega\ddot{\Omega}/\dot{\Omega}^2$ can take values of either sign with magnitudes as high as 10^6. In (1998a) I have shown that both phenomena can be understood as due to mild superrotation, $\delta\Omega/\Omega \lesssim 10^{-3}$, of some neutral superfluid component of net moment of inertia $\lesssim 10\%$.

3. Radio Pulses : Pulsar pulses, whose brightnesses can reach 10^{32} K in extreme cases (giant pulses, microstructure), are thought to be emitted coherently, somewhere between the surface and the speed-of-light distance. By what mechanism ? The literature contains various suggestions, most of which have been refuted by Don Melrose. In (1998a, 1999) I propose that they can be obtained by integration of the Lorentz-Dirac equation of motion, as small-pitch-angle synchro-curvature radiation: once the guiding field strength has dropped towards 10^7G, transverse perturbations can lead to coherent, strongly damped gyrations for which the tiny radiation term in the L-D equation gets significant when multiplied by the large number Z ($\approx 10^{14}$) of electrons gyrating in phase. Even though these gyrations are small, they can yield huge excesses over curvature radiation.

4. Beaming Pattern : Pulse intensities have been found to have a large dynamic range, exceeding 10^3, often even distinctly outside the pulse window. Such observations sample the antenna lobe's latitude structure; its longitude structure can only be guessed, or derived statistically from many pulsars. In any case, we see so many pulsars, and have no single hint at a 'beamed-away' pulsar, that it is my impression that pulsar beams are spiky fan beams, i.e. spiky beams which do not leave out large fractions on the sphere of seeing. Quite likely, a lot of scattering is involved (Sincell & Krolik 1992).

5. Birth Rates : The interval Δt between two successive pulsar births can be estimated from the equation $\Delta t = tf / N$ in which t is the average lifetime, f (≤ 1) is the beaming fraction, and N the number of pulsars. As mentioned above, pulsar statistics yield $t = 10^{6.4}$ yr, and accounting for incomplete sampling yields $N \gtrsim 10^{5.1}$ in the Galaxy. We thus find $\Delta t \lesssim 20f$ yr, i.e. a birth interval of pulsars in the Galaxy of less than 20 yr (for a beaming fraction of unity !). If pulsars are the younger brothers in binaries, the birth interval of neutron stars is at most half as long, 10yr, shorter than generally stated. But we know nine SN explosions within the Galaxy within the past millennium, all of them within some 2.7 Kpc (!) from the Sun, so that the inferred SN rate is certainly of this same order, one event in ten years.

6. Supernovae : The literature treats SNe as thin-walled bombs, after Shklovskii, even though they are extremely thick-walled. Spectra show a broad range of radial velocities, implying a splinter structure. Splinters also follow from the Rayleigh-Taylor instability during the acceleration of the progenitor star's envelope, as the piston must be relativistic. Consequently, SN remnants are not SN shock waves but collision sites of the SN ejecta with the circumstellar medium, often mainly the spherical swept-up edge of the progenitor's windzone.

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