Gamma-ray Bursts from rapidly spinning neutron stars

H.C. Spruit

Max-Planck-Institut für Astrophysik
Box 1523, D-85740 Garching, Germany

INTRODUCTION

A neutron star in an X-ray binary (XRB) is spun up by mass transfer from its companion to rotation periods of the order of a millisecond. Evidence for this are the existence of ms pulsars, believed to descend from X-ray binaries. Direct evidence of such rotation rates in XRB is the of 2.5ms rotation in SAX 1808. The rotation energy in a neutron star spinning at 1ms is 10^{52} erg, in the range of that required for GRB. The environment also satisfies the baryon loading constraint, since the accretion disk contains only of the order $10^{-9}\mathrm{M}_\odot$, and the companion star blocks only of the order 1% of the sky as seen from the neutron star.

Extraction of the rotation energy from a spinning neutron star to power a GRB looks very implausible at first sight. The energy must be extracted in 0.3–30 seconds (e.g. Fishman and Meegan 1995). This requires an extremely efficient 'brake' which does not exist in an ordinary XRB.

In the following I show, however, that such a brake can very elegantly be produced by the neutron star itself, through a sequence of straightforward events involving only known neutron star physics (Spruit 1999a):

- 1. The neutron star's spin slowly increases by accretion of angular momentum from the companion.
- 2. At a period of the order of a ms, the star becomes unstable to an r-mode oscillation, coupled to the emission of a gravitational wave.
- 3. The negative temperature dependence of the visosity of neutron star matter makes this instability run away in a finite time of the order of 100 years. The last few e-foldings of the oscillation amplitude take place on a time scale of minutes.
- 4. The star loses angular momentum from its outer parts by the emitted gravitational wave, and starts rotating differentially by ~10-30%.
- 5. A weak initial magnetic field in the star (10^6–10^8G) gets wound up by the differential rotation into a field of $\sim 10^{17}$G on a time scale of days to months.

- 6. This field becomes buoyantly unstable at a threshold of $10^{16}-10^{17}$G, rises through the surface on a time scale of ms to seconds, creating a nonaxisymmetric field of the order 10^{13}G at the light cylinder. (From this point on, the model is like that of Kluźniak and Ruderman 1998).
- 7. The star spins down on the pulsar spindown time scale, which for these conditions is of the order of seconds. The angular momentum is carried by a relativistic MHD wind. This powers a GRB, and extracts essentially all the rotation energy of the star (as in Usov's 1992 model).

RUNAWAY GRAVITATIONAL WAVE INSTABILITY

Rotating neutron stars are naturally unstable to excitation of their oscillation modes by the emission of gravitational waves (e.g. Shapiro and Teukolsky 1983). A mode is excited like a squeaking brake. The deformation of the oscillation star provides surface roughness, and the gravitational wave provides the torque coupling the star to the vacuum outside, analogous to the frictional coupling of a brake lining.

Rotational modes (Rossby waves) turn out to be much more effectively excited than the pulsation modes of the star (Andersson 1997, Andersson et al. 1998). Modes with angular quantum numbers $l=m=2$ grow fastest. The unstable displacements in these modes are mainly along horizontal surfaces. Their frequency in an inertial frame is $2/3\,\Omega$, and in the corotating frame $-4/3\,\Omega$ (retrograde). In the absence of viscous damping, the growth rate of the most unstable mode is (Andersson et al. 1998) $\sigma_{\rm GW}=5\times10^{-2}P_{-3}^{-6}\quad {\rm s}^{-1}$. Including viscous damping, the growth rate is $\sigma=\sigma_{\rm GW}-1/\tau_{\rm v}$, where $\tau_{\rm v}$ is the viscous damping time $\tau_{\rm v}=(\Delta R)^2/\nu$, and $\Delta R\approx 0.5R$ is the width of the unstable eigenfunction. For the kinematic viscosity ν the standard value quoted (van Riper 1991) for a neutron superfluid is $\nu\approx 2\times10^{7}T_7^{-2}$ cm^{2}s^{-1} at an average density of 3×10^{14} g cm^{-3}, where $T=10^7T_7$ is the temperature. This expression holds at low temperatures; at temperatures above $\sim 3\times10^{9}$K the viscosity starts increasing strongly with T. During the spinup by accretion, the temperature of the star is determined by the accretion rate, $T_7\approx\dot M_{-9}^{1/4}$, where $\dot M=10^{-9}\dot M_{-9}$ M$_\odot$/yr is the mass accretion rate [taking into account heating by nuclear reactions in the accreted atmosphere (Miralda-Escudé et al. 1990, Brown 1999), yields somehat higher temperatures]. With the typical value $\dot M_{-9}=1$, the critical rotation period for instability to set in is 3 msec.

A star slowly spun up by accretion (on a time scale of 10^9yr) would become weakly unstable to the gravitational wave mechanism as its period decreases below the critical value. The unstable mode dissipates energy by viscous friction. This causes heating of the star, and a decrease of the viscosity. This upsets the delicate balance between the instrinsic growth and the viscous damping that exists at the time the marginal stability line is crossed, and the *growth rate* increases with the wave amplitude. This results in a runaway of the mode amplitude in a finite time.

A few hundred years after the rotation rate has crossed the instability threshold, the mode amplitude diverges. During the final runaway phase the temperature is so high (a few 10^9 K) that viscous damping is weak and the mode grows on a time scale of the order of hours to minutes (depending on the initial rotation rate).

DIFFERENTIAL ROTATION AND WINDING-UP OF THE MAGNETIC FIELD

The angular momentum loss by gravitational wave emission is largest in the outer parts of the star, where the unstable eigenfunction typically have their largest amplitudes, and where the coupling to the gravitational wave emitted is strongest. Depending on the saturation amplitude assumed for the r-mode oscillation, this creates differential rotation on a time scale of hours to days. The differential rotation, absent before the final runaway of the instability, winds the initial magnetic field into a toroidal (azimuthal) field. Because the rotation period is so short, the nonaxisymmetric components of the initial field are quickly eliminated by magnetic diffusion (Rädler 1980, 1986, for a recent discussion see Spruit 1999b). The remaining axisymmetric and nearly azimuthal field is as sketched in Kluźniak and Ruderman (1998). To represent these processes in a simple model, I divide the star into two zones with boundary at $r \approx 0.5R$, such that the outer shell has approximately the same moment of inertia as the core, and rotating at rates $\Omega_{\rm s}$ and $\Omega_{\rm c}$ respectively. The angular momentum loss by gravitational waves is taken to be restricted to the outer shell for simplicity. The azimuthal field increases at a rate given by the difference in rotation between the two zones. The magnetic torque between the two zones is taken into account as it modifies the differential rotation during the winding process.

The growth of the unstable mode is limited at large amplitude by nonlinear mode couplings. Since these have not been computed yet, they are parametrized by adding a damping term which becomes effective at an assumed saturation level $\xi/R = 0.03$.

BUOYANT INSTABILITY OF THE TOROIDAL FIELD

The increasing azimuthal magnetic field inside the star does not manifest itself at the surface until it becomes unstable to buoyancy instability. For this to happen the field has to become strong enough (Kluźniak and Ruderman 1998), of the order $B_{\rm c} = 10^{17}$G, to overcome the stable stratification associated with the increasing neutron/proton ratio with depth. The growth time $\tau_{\rm B}$ of the instability is of the order of the Alfvén travel time: $\tau_{\rm B} \sim R/(V_{\rm A} - V_{\rm Ac})$, where $V_{\rm Ac}$ is the Alfvén speed at the critical field strength $B_{\rm c}$. Buoyancy instability is generally nonaxisymmetric, forming loops of field lines which erupt through the surface (e.g. Matsumoto and Shibata, 1992). The action of the radial velocities in the eruption process on the azimuthal field produces a strong small scale radial field component, which couples to the differential rotation and links the different parts of the star together on an

Alfvén crossing time scale. The whole process is likely to yield a complex time dependent field configuration, but important aspects can be illustrated with a simple model (Spruit 1999a). It takes into account the gradual crossing of the buoyancy stability limit, the time scale (of the order of a millisecond) of this instability, the magnetic torques coupling the star, and the external torque exerted by the spinning magnetic field.

SPINDOWN AND POWERING OF THE GRB

If the field emerging at the surface were a vacuum field, the energy output would be in the form of the Poynting flux of an electromagnetic wave, and would simply be given by the usual pulsar spindown formula. At the a surface field strength of 10^{16}G and a spin period of 1 ms this yields a spin down time of seconds. In reality, the presence of some matter lifted into the atmosphere by the eruption of the magnetic field, and a pair plasma produced by the dissipation of some of this magnetic energy will enforce nearly ideal MHD conditions. The energy is then emitted in the form of a relativistic MHD wind instead of a pure EM wave. The energy output is still given approximately by the pulsar spindown formula, however (Usov, 1992).

DISCUSSION

The model presented is related to that of Kluźniak and Ruderman (1998), but provides a plausible scenario for the development of the strong differential rotation assumed by these authors. It has a number of properties that make it attractive as a possible GRB engine. The baryon loading is intrinsically low. The natural time scale for variations in the energy output is the Alfvén travel time through the star, of the order of ms as observed. Burst durations as short as a second or as long as a minute can be accomodated by variation of the initial rotation rate. It invokes only properties of neutron stars and X-ray binaries believed to be known from current theory and observations.

The model also produces a reasonable energy output. For the largest observed energies, however, (such as the 23 January event), it is necessary to assume a significant beaming factor (as in other GRB engine models). Whether such a beaming is natural in the model depends on properties of the relativistic wind produced by a rotating neutron star which are not fully understood at present.

The model makes some predictions that differ from engine models based on collapsing neutron stars or black holes. In these models, the bulk of the gravitational wave energy is emitted at the time of the GRB itself. In the present model, the gravitational waves are emitted at the peak of the gravitational wave instability, which precedes the GRB by days to months. This is because it the differential rotation is generated only at this peak, and the winding up of the magnetic field that finally powers the GBR takes some time (depending on the initial field strength

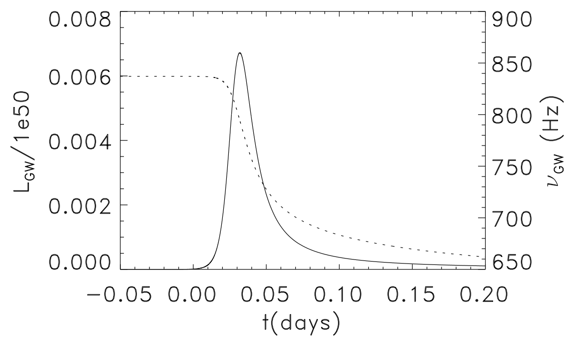

FIGURE 1. Typical variation of gravitational wave luminosity and frequency during the peak of the r-mode instability (which precedes the electromagnetic GRB emission). Assumed parameters are initial spin period of 1.5msec, and saturation amplitude of the r-modes $\xi_{\mathrm{max}}/R = 0.03$.

on the star). This difference should be obvious in gravitational wave observations whenever these become sensitive enough to detect GRB. The estimated amplitude and frequency of a gravitational wave produced near the peak of the r-mode instability are shown in figure 1.

REFERENCES

1. Andersson, N., 1997, ApJ 502, 708
2. Andersson, N., Kokkotas, K., Schutz, B., 1999, ApJ 510, 846
3. Brown E., 1999, astro-ph/9910215
4. Fishman G.J., Meegan, C.A., 1995 ARAA 33, 415
5. Kluźniak, W., Ruderman, M., 1998, ApJ 505, L113
6. MacFadyen, A., Woosley, S.E., 1998, ApJ 524, 262
7. Matsumoto, R., Shibata, K., 1992, PASJ 44, 167
8. Miralda-Escudé J., Paczyński B., Haensel P., 1990, ApJ 362, 572
9. Paczyński, B., 1998, ApJ 494, L45
10. Rädler, K.-H., 1980, Astron. Nachr. 301, 101
    Rädler, K.-H., 1986, in Plasma Astrophysics (Proceedings Joint Varenna-Abastumani Workshop), ESA SP-251, p.569
11. Shapiro, S.L., Teukolsky, S.A., 1983, Black Holes, White Dwarfs and Neutron Stars, Wiley, N.Y.
12. Spruit H.C., 1999a, A&A , 341, L1 (astro-ph/9811007)
13. Spruit H.C., 1999b, A&A , 349, 189 (astro-ph/9907138)
14. Usov, V.V., 1992 Nature 357, 472
15. van Riper, K.A., 1991 ApJS 75, 449