GRAVITATIONAL RADIATION FROM ACCRETING MILLISECOND PULSARS

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It is widely assumed that the observed reduction of the magnetic field of millisecond pulsars can be connected to the accretion phase during which the pulsar is spun up by mass accretion from a companion. A wide variety of reduction mechanisms have been proposed including the burial of the field by a magnetic mountain, formed when the accreted matter is confined to the poles by the tension of the stellar magnetic field. A magnetic mountain effectively screens the magnetic dipole moment. On the other hand, observational data suggests that accreting neutron stars are sources of gravitational waves, and magnetic mountains are a natural source of a time-dependent quadrupole moment. We show that the emission is sufficiently strong to be detectable by current and next generation long-baseline interferometers. Preliminary results from fully three-dimensional magnetohydrodynamic (MHD) simulations are presented. We find that the initial axisymmetric state relaxes into a nearly axisymmetric configuration via toroidal magnetic modes. A substantial quadrupole moment is still present in the final state, which is stable (to ideal MHD modes) yet highly distorted.

1. Introduction

Despite considerable effort, an unequivocal direct detection of gravitational waves (GW) is yet to be achieved. The expected wave strain is several orders of magnitude weaker than the sensitivity of current interferometric detectors.[1] One possibility is to coherently integrate the signal of a continuous source. In this case, the signal-to-noise ratio increases with the square root of the observation time.[2]

A variety of physical mechanisms for the generation of continuous gravitational waves have been proposed,[3,4] among them nonaxisymmetric distortions of the neutron star crust, either due to temperature variations[5,6] or strong magnetic fields,[7] r-mode instabilities,[8–11] or free precession.[12,13]

A promising GW source was recently suggested by two of us.[14] Matter accreting onto a neutron star in a low-mass X-ray binary (LMXB) accumulates at the magnetic poles until the latitudinal pressure gradient overcomes the magnetic tension and the plasma spreads equatorwards. The frozen-in magnetic field is carried along with the spreading matter, and is therefore compressed, until the magnetic tension is again able to counterbalance the thermal pressure. This configuration is termed a magnetic mountain.[15]

It is motivated by two independent facts: (i) the magnetic moments of neutron stars decrease with accreted mass;[15,16] (ii) the observed cutoff at ~ 700 Hz in the spin frequency distribution of LMXBs — much slower than the breakup frequency.[5]

We examine the prospect of detection of GW from magnetic mountains in section 2. In section 3, we present preliminary results from fully three-dimensional magneto-hydrodynamic (MHD) simulations.

2. Gravitational radiation

A typical mountain with $M_a \approx 10^{-4} M_\odot$ and a pre-accretion dipolar magnetic field of $B = 10^8$ can provide[14] a gravitational ellipticity $\epsilon = |I_1 - I_3|/I_1 \approx 10^{-5}$, where I_1, I_3 are the principal moments of inerta, considerably higher than the deformation a conventional neutron star could sustain ($\epsilon \approx 10^{-7}$) as a response to shear-strain and only surpassed ($\epsilon \approx 10^{-4}$) by exotic solid strange stars.[17]

The characteristic GW strain[18] is defined as $h_c = (128\pi^4/15)^{1/2} G I_{zz} f^2 \epsilon/(dc^4)$, where $I_{zz} \approx 10^{45}$g cm^2 is the principal moment of inertia, f the frequency and d the distance of the object. Fig. 1 (left) shows h_c as a function of f at a distance of $d = 1$kpc and a mountain mass of $10^{-8} M_\odot \leq M_a \leq 10^{-2} M_\odot$ together with the design sensitivities of LIGO and advanced LIGO for a coherent integration time[a] of 10^7 s. Even a mountain with a comparably low total mass of $M_a \approx 10^{-6} M_\odot$ should be clearly visible for a spin frequency $f > 200$ Hz. We therefore expect a direct detection of GW from magnetic mountains with LIGO.

3. Three-dimensional hydromagnetic stability

Surprisingly, the distorted magnetic configuration is stable to axisymmetric modes.[19] However, the full three-dimensional hydromagnetic stability is yet to be examined. We perform three-dimensional simulations by loading the axisymmetric configuration into the ideal MHD-code ZEUS-MP. A preliminary result is displayed in Fig. 1 (right). Shown is the time evolution of the three cartesian quadrupole moments Q_{22}, Q_{33}, and Q_{12}, defined as $Q_{ij} = \int d^3x' \, (3x'_i x'_j - r'^2 \delta_{ij}) \rho(x')$, where ρ denotes the density. After a violent transition phase, the system settles down into state that still has a considerable quadrupole moment. Furthermore, the small magnitude of the off-diagonal element Q_{12} (which vanishes for an axisymmetric configuration) suggests, that the mountain is still nearly axisymmetric (deviating by ≈ 1 per cent).

We tentatively interpret these (very preliminary) results as a first proof of three-dimensional stability. However, the influence of resistivity still needs to be examined.

[a] This is currently too optimistic due to computational limitations. The S2 run managed to reduce a five hour stream of data.[3] Improvements are expected using added computational resources and hierarchical search stragies.

Resistive ballooning and resistive Rayleigh-Taylor modes may allow plasma slippage on a short timescale. Non-ideal MHD simulations to investigate these effects are currently underway.

References

1. J. A. Lobo, *LNP Vol. 617: Current Trends in Relativistic Astrophysics* 617, 210 (2003).
2. P. Jaranowski, A. Królak and B. F. Schutz, *Phys. Rev. D* 58, 063001 (1998).
3. The LIGO Scientific Collaboration, *Preprint(gr-qc/0605028)* (2006).
4. B. J. Owen, *Classical and Quantum Gravity* 23, 1(April 2006).
5. L. Bildsten, *ApJ* 501, L89+ (1998).
6. G. Ushomirsky, C. Cutler and L. Bildsten, *MNRAS* 319, 902 (2000).
7. C. Cutler, *Phys. Rev. D* 66, 084025 (2002).
8. N. Stergioulas, *Living Reviews in Relativity* 6, 3 (2003).
9. B. J. Owen, L. Lindblom, C. Cutler, B. F. Schutz, A. Vecchio and N. Andersson, *Phys. Rev. D* 58, 084020 (1998).
10. N. Andersson, K. D. Kokkotas and N. Stergioulas, *ApJ* 516, 307 (1999).
11. M. Nayyar and B. J. Owen, *Phys. Rev. D* 73, 084001(April 2006).
12. D. I. Jones and N. Andersson, *MNRAS* 331, 203(March 2002).
13. C. Van Den Broeck, *Classical and Quantum Gravity* 22, 1825(May 2005).
14. A. Melatos and D. J. B. Payne, *ApJ* 623, 1044(April 2005).
15. D. J. B. Payne and A. Melatos, *MNRAS* 351, 569(June 2004).
16. A. Melatos and E. S. Phinney, *Publications of the Astronomical Society of Australia* 18, 421 (2001).
17. B. J. Owen, *Physical Review Letters* 95, 211101 (2005).
18. P. R. Brady, T. Creighton, C. Cutler and B. F. Schutz, *Phys. Rev. D* 57, 2101(February 1998).
19. D. J. B. Payne and A. Melatos, *paper in preparation* .

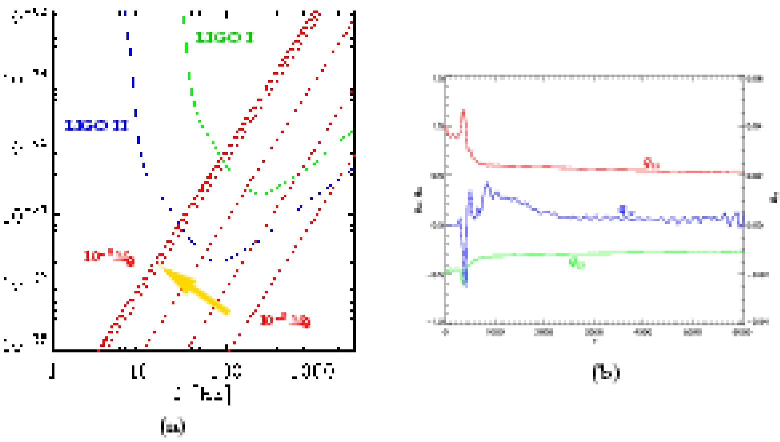

Fig. 1. (a) characteristic wave strain h_c for mountain masses $10^{-8} M_\odot \leq M_a \leq 10^{-2} M_\odot$ along with the design sensitivity of LIGO and advanced LIGO for a 99 per cent confidence and an integration time of 10^7 s. (b) Time evolution of the quadrupole tensor. The left axis gives the scale for the diagonal components, while the right axis scales the off-diagonal component. The time base is the Alfvén crossing time for a radial scale height $\tau_A = 5.4 \times 10^{-7}$ s.