



X-ray Flares from Postmerger Millisecond Pulsars

Z. G. Dai, *et al.*

Science **311**, 1127 (2006);

DOI: 10.1126/science.1123606

The following resources related to this article are available online at www.sciencemag.org (this information is current as of March 10, 2008):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:

<http://www.sciencemag.org/cgi/content/full/311/5764/1127>

This article **cites 27 articles**, 1 of which can be accessed for free:

<http://www.sciencemag.org/cgi/content/full/311/5764/1127#otherarticles>

This article has been **cited by** 26 article(s) on the ISI Web of Science.

This article appears in the following **subject collections**:

Astronomy

<http://www.sciencemag.org/cgi/collection/astronomy>

Information about obtaining **reprints** of this article or about obtaining **permission to reproduce this article** in whole or in part can be found at:

<http://www.sciencemag.org/about/permissions.dtl>

Supporting Online Material

www.sciencemag.org/cgi/content/full/311/5764/1123/DC1
SOM Text

28 November 2005; accepted 23 January 2006
10.1126/science.1123026

REPORTS

X-ray Flares from Postmerger Millisecond Pulsars

Z. G. Dai,^{1*} X. Y. Wang,¹ X. F. Wu,² B. Zhang³

Recent observations support the suggestion that short-duration gamma-ray bursts are produced by compact star mergers. The x-ray flares discovered in two short gamma-ray bursts last much longer than the previously proposed postmerger energy-release time scales. Here, we show that they can be produced by differentially rotating, millisecond pulsars after the mergers of binary neutron stars. The differential rotation leads to windup of interior poloidal magnetic fields and the resulting toroidal fields are strong enough to float up and break through the stellar surface. Magnetic reconnection–driven explosive events then occur, leading to multiple x-ray flares minutes after the original gamma-ray burst.

Gamma-ray bursts (GRBs) are flashes of gamma rays occurring at the cosmological distances. They fall into two classes (1): short-duration (<2 s) hard-spectrum bursts and long-duration soft-spectrum bursts. Long GRBs result from core collapses of massive stars (2), and short GRBs appear to be produced in mergers of neutron star binaries or black hole–neutron star binaries (3–9). Recently, thanks to accurate localizations of several short GRBs (3, 6, 8) by satellites Swift and High Energy Transient Explorer 2 (HETE-2), the multiwavelength afterglows from these events have been detected and the associated host galaxies have been identified. The observations provide a few pieces of evidence in favor of the binary compact object merger origin of short GRBs (10–12). Because it takes ~0.1 to 1 billion years of gravitational wave radiation before the binary coalesces, at least some short GRB host galaxies should contain a relatively old stellar population. Because neutron stars in the binary system usually receive a very high natal velocity, the merger site is preferably at the outskirts of the host galaxy, and the circumburst medium density is likely low. These characteristics have been revealed by recent observations: First, the

identified elliptical galaxies associated with GRB 050509B (3, 4) and GRB 050724 (8, 9) suggest that these hosts are early-type galaxies with a low star-formation rate, ruling out progenitor models invoking active star formation. Second, the nondetection of any supernova signal from GRB 050709 indicates that short bursts are not associated with collapses of massive stars (5, 7). Third, afterglow modeling of GRB 050709 suggests a low-density environment (13), which is consistent with that of the outskirts of the host galaxy or that of an intergalactic medium.

However, the above merger origin was recently challenged by the discovery of x-ray flares occurring after two short bursts. X-ray flares were discovered to occur at least ~100 s after the triggers of the short GRB 050709 (5) and GRB 050724 (8). These flares require that the central engine is in long-lasting activity. This requirement conflicts with the current models involving neutron star–neutron star mergers (14, 15) or neutron star–black hole mergers (16), because all of these models are attached to a common postmerger picture that invokes a black hole surrounded by a torus. The predicted typical time scales for energy release are much shorter than ≥100 s, as observed in GRBs 050709 and 050724. Therefore, understanding the origin of x-ray flares from short bursts is currently of great interest. Here, we show that such flares can be produced by differentially rotating, millisecond pulsars with typical surface magnetic fields that occur after the mergers of binary neutron stars.

In the conventional scenarios of short bursts (10–12), after the merger of a neutron

star binary, a stellar-mass black hole is formed with a transient torus of mass ~1 to 10% of the total. These scenarios are valid if the total mass (~2.5 to 2.8 M_{\odot} , where M_{\odot} is the solar mass) of the postmerger object is larger than the maximum mass of a nonrotating Tolman–Oppenheimer–Volkoff neutron star, $M_{\max,0}$. This is valid if the nuclear equation of state (EOS) is soft to moderately stiff (17). However, the total mass of the postmerger object is smaller than $M_{\max,0}$ for very stiff EOSs on the basis of mean field theory (17). Timing observations of the millisecond pulsar J0751+1807 in a circular binary system with a helium white-dwarf companion (18) reveal the existence of a neutron star with mass of $2.1 \pm 0.2 M_{\odot}$ (at the 1 σ confidence level). This measurement implies that the maximum mass of nonrotating neutron stars must be larger than $2.1 M_{\odot}$ so that stiff EOSs are favored. Furthermore, recent general relativistic numerical simulations (17, 19) have shown that for stiff to very stiff nuclear EOSs, the postmerger object is indeed a differentially rotating massive neutron star with period of ~1 ms, because uniform rotation and differential rotation can support a maximum mass ~20 and ~50% higher than $M_{\max,0}$, respectively. It is therefore reasonable to assume the existence of a differentially rotating millisecond pulsar after a double neutron star merger. Such a pulsar should also be surrounded by a hot torus with mass ~0.01 to 0.1 M_{\odot} . Similar to the previous scenarios, a short burst may be produced by the Parker instability in the torus (11) or the annihilation of neutrinos emitted from the torus (12).

After the GRB trigger, differential rotation starts to wind the interior magnetic field into a toroidal field (20, 21). To represent physical processes of windup and floating of the magnetic field, we considered a simple two-component model in which the star is divided into two zones with a boundary at the radius $R_c \cong 0.5 R_*$ (where R_* is the stellar radius): the core and the shell components. Their moments of inertia are I_c and I_s and their angular (rotation) velocities are Ω_c and Ω_s , respectively. The differential angular velocity is then $\Delta\Omega = \Omega_c - \Omega_s$ and its initial value (marked by a subscript zero) is taken as $(\Delta\Omega)_0 = A_0\Omega_{s,0}$ (where A_0 is the ratio of the initial differential angular velocity to the shell's initial angular velocity). If the radial magnetic field compo-

¹Department of Astronomy, Nanjing University, Nanjing 210093, China. ²Purple Mountain Observatory and Joint Center for Particle Nuclear Physics and Cosmology of Purple Mountain Observatory–Nanjing University, Chinese Academy of Sciences, Nanjing 210008, China. ³Department of Physics, University of Nevada, Las Vegas, NV 89154, USA.

*To whom correspondence should be addressed. E-mail: dzg@nju.edu.cn

ment is B_r , then the toroidal field component B_ϕ increases as

$$\frac{dB_\phi}{dt} = (\Delta\Omega)B_r \quad (1)$$

There is a magnetic torque, $T_m = (2/3)R_c^3 B_r B_\phi$, acting between the core and shell (22). This torque opposes the differential rotation. Another torque results from magnetic dipole radiation, $T_d = 2B_s^6 R_*^6 \Omega_s^3 / (3c^3)$, where c is the speed of light and $B_s = \varepsilon B_r$ (here, ε is defined by the ratio of the effective surface dipole field strength to the radial field strength). Under action of these two torques, the angular velocities of the shell and the core components evolve according to

$$I_s \frac{d\Omega_s}{dt} = T_m - T_d \quad (2)$$

and

$$I_c \frac{d\Omega_c}{dt} = -T_m \quad (3)$$

respectively. The torque from magnetic dipole radiation can be neglected if $B_\phi \gg B_r \varepsilon^2 (R_*/R_c)^3 (R_* \Omega_s / c)^3$. This condition is easily satisfied at the time $t \gg t_0 \equiv \varepsilon^2 A_0^{-1} \Omega_{s,0}^{-1} (R_*/R_c)^3$ (where $t_0 \approx 0.2$ ms for typical parameters). Thus, from Eqs. 1 to 3, we obtained

$$\frac{d^2 \Delta\Omega}{dt^2} = -\frac{2I}{3I_c I_s} R_c^3 B_r^2 (\Delta\Omega) \quad (4)$$

where $I = I_c + I_s$ is the total moment of inertia of the star. Letting

$$\tau = \left(\frac{2I}{3I_c I_s} R_c^3 B_r^2 \right)^{-1/2} \approx 2.3 \times 10^5 (\varepsilon/0.3) B_{s,8}^{-1} \text{ s} \quad (5)$$

where $I_c \approx I_s = 10^{45} \text{ g} \cdot \text{cm}^2$ and $R_* = 10^6 \text{ cm}$ are taken and $B_{s,8}$ is in units of 10^8 G , we found a solution of Eq. 4:

$$\Delta\Omega = A_0 \Omega_{s,0} \cos(t/\tau) \quad (6)$$

This indicates that differential rotation would behave as a resonator if there were no energy dissipation.

The increasing toroidal field becomes unstable because of the buoyancy effect when $B_\phi = B_b \approx 10^{17} \text{ G}$ (20). This corresponds to the time

$$t_b = \frac{B_b}{B_r A_0 \Omega_{s,0}} \approx 4.8 \times 10^4 (\varepsilon/0.3) \times B_{s,8}^{-1} A_0^{-1} P_{s,0,\text{ms}} \text{ s} \quad (7)$$

where $P_{s,0,\text{ms}}$ is the initial spin period of the shell component in units of milliseconds.

Comparing Eqs. 5 and 7, we see that t_b is substantially less than τ for $A_0^{-1} P_{s,0,\text{ms}} \leq 1$ and that the differential angular velocity $\Delta\Omega$ is approximately constant until the time t_b . At this time, the buoyant force is just equal to the force from antibuoyant stratification existing in the star. As the time increases, the buoyant force acting on the toroid would begin to exceed the antibuoyant force, and the toroid will float up toward the stellar surface. The net force density acting on this toroid is given by

$$f_b = \frac{B_r B_b A_0 \Omega_{s,0} (t - t_b)}{4\pi c_s^2} g \quad (8)$$

where c_s is the speed of sound of the embedding medium and g is the surface gravity. In terms of Eq. 8 and Newton's second law, we obtained the buoyancy time scale for the toroid to float up and penetrate through the stellar surface:

$$\Delta t_b = \left[\frac{12\pi\rho R_* c_s^2}{B_r B_b g A_0 \Omega_{s,0}} \right]^{1/3} \approx 0.26 (\varepsilon/0.3)^{1/3} \times B_{s,8}^{-1/3} A_0^{-1/3} P_{s,0,\text{ms}}^{1/3} \text{ s} \quad (9)$$

where $\rho \approx 10^{14} \text{ g cm}^{-3}$ is the mass density of the embedding medium, and the typical values of the speed of sound and the surface gravity are $10^{10} \text{ cm s}^{-1}$ and $10^{14} \text{ cm s}^{-2}$, respectively. This time scale is much shorter than t_b , suggesting that the toroid, after its field strength reaches B_b , would rapidly float up to the stellar surface.

Once penetrating through the surface, the toroidal fields with different polarity may reconnect (20), giving rise to an explosive event. Its energy is

$$E_b = \frac{B_b^2}{8\pi} V_b \approx 1.6 \times 10^{51} \text{ ergs} \left(\frac{V_b}{V_*} \right) \quad (10)$$

where V_b and V_* are the toroid's volume and the stellar volume, respectively. This energy depends on the toroid's volume rather than on the initial magnetic field and the stellar spin period. An upper limit to the outflow mass ejected is estimated by

$$M_{b,\text{max}} = f_b V_b / g \approx 0.9 \times 10^{-7} M_\odot (\varepsilon/0.3)^{-2/3} \times B_{s,8}^{2/3} A_0^{2/3} P_{s,0,\text{ms}}^{-2/3} \left(\frac{V_b}{V_*} \right) \quad (11)$$

Because of an initial huge optical depth, the outflow will expand relativistically and its minimum average Lorentz factor is

$$\Gamma_{b,\text{min}} \approx 1.0 \times 10^4 (\varepsilon/0.3)^{2/3} B_{s,8}^{-2/3} A_0^{-2/3} P_{s,0,\text{ms}}^{2/3} \quad (12)$$

The x-ray flares observed at $t_{\text{flare}} \sim t_b \approx 100 \text{ s}$ after GRBs 050709 and 050724 require that the

surface magnetic field of a central pulsar $B_s \sim 4.8 \times 10^{10} (\varepsilon/0.3) A_0^{-1} P_{s,0,\text{ms}} (t_{\text{flare}}/100 \text{ s})^{-1} \text{ G}$. For typical values (19, 22) of the model parameters (i.e., $A_0 \sim 1$, $P_{s,0} \sim 1 \text{ ms}$, and $\varepsilon \sim 0.3$), this field strength is in the range of the surface magnetic fields of isolated pulsars. Furthermore, it is characteristic of the stellar magnetic field that has decayed in ~ 0.1 to 1 billion years before the merger of a neutron star binary (23). Inserting this field into Eq. 12, we found the minimum average Lorentz factor of the outflow from a magnetic reconnection-driven explosion, $\Gamma_{b,\text{min}} \sim 160 (t_{\text{flare}}/100 \text{ s})^{2/3}$, showing that the outflow is ultrarelativistic. After the end of this event, a similar windup of the interior magnetic field with B_r would start again following the same processes described above, leading to another explosion.

Collisions among the outflows with different Lorentz factors would produce late internal shocks and x-ray flares (24, 25). These shocks must produce lower energy photons than did the earlier internal shocks during the prompt GRB phase. For the internal shock model, the characteristic synchrotron frequency is $\nu_m \propto L^{1/2} R_{\text{sh}}^{-1} \propto L^{1/2} \Gamma_b^{-2} \delta t^{-1}$ (where L is the luminosity, R_{sh} is the shock radius, Γ_b is the bulk Lorentz factor, and δt is the time interval between two adjacent energy shells that the central engine ejects). The late, soft flare is the result of the combination of a lower luminosity and a longer time interval (than that of the prompt emission, where $\delta t \sim t_b$ in our flare model). In addition, as the stellar differential rotation weakens (i.e., A_0 decreases), the time interval δt and the outflow's Lorentz factor Γ_b increase (see Eqs. 7 and 12). Because the maximum flux density of the synchrotron radiation scales as $F_{\nu,\text{max}} \propto \Gamma_b^{-3}$ (24), the flux density at frequency ν is $F_\nu = F_{\nu,\text{max}} (\nu/\nu_m)^{-(p-1)/2} \propto \Gamma_b^{-(2+p)} \delta t^{-(p-1)/2}$ for $\nu > \nu_m$ in the slow-cooling case (where p is the spectral index of the shock-accelerated electrons) (26). Thus, the flare occurring at later times has a smaller flux density because of the larger Lorentz factor and longer time interval. This result is consistent with the observed reduced flaring activity of GRB 050724. Therefore, our model can provide a self-consistent explanation for all the observations including the energetics (see Eq. 10) and the temporal and spectral properties of the x-ray flares.

Generally speaking, the surface magnetic field of the postmerger pulsar could have a wider range than the preferred value invoked here to interpret the ~ 100 -s flares in GRBs 050709 and 050724. For stronger fields, this would give rise to multi-peaks in the prompt phase (as observed in some short GRBs) or, if the flares are not bright enough, they may be masked by the steep decay component of the prompt emission tail (25). For weaker fields, the putative flares occur much later and are energetically insignificant. This would give rise to smoother x-ray afterglow lightcurves as in several GRBs observed by Swift (e.g., GRB 050509B) (3).

X-ray flares were observed in nearly half of long Swift bursts (27, 28). Even though the two classes of bursts have different progenitors (namely collapsars for long bursts and binary neutron star mergers for short bursts), similar temporal properties (e.g., peak times and temporal indices before and after the peaks) suggest that the x-ray flares may have a common origin. Therefore, we suggest that some long bursts may originate from moderately magnetized millisecond pulsars with hyperaccreting accretion disks after the collapses of massive stars, and their x-ray flares are the result of strong interior differential rotation of these pulsars. The differences in duration, energetics, and spectrum for the two classes of bursts would be due to different accretion disks [e.g., a transient torus for short bursts (10–12) and a fall-back accretion disk for long bursts (29, 30)]. When the surface magnetic fields are strong enough, the spin down of this central engine pulsar would provide energy injection to the postburst relativistic outflow (31), which could interpret the late x-ray humps detected in many GRBs (25, 28).

References and Notes

1. C. Kouveliotou *et al.*, *Astrophys. J.* **413**, L101 (1993).
2. For a review, see B. Zhang, P. Mészáros, *Int. J. Mod. Phys. A* **19**, 2385 (2004).
3. N. Gehrels *et al.*, *Nature* **437**, 851 (2005).
4. J. S. Bloom *et al.*, *Astrophys. J.* **638**, 354 (2006).
5. D. B. Fox *et al.*, *Nature* **437**, 845 (2005).
6. J. S. Villaseñor *et al.*, *Nature* **437**, 855 (2005).
7. J. Hjorth *et al.*, *Nature* **437**, 859 (2005).
8. S. D. Barthelmy *et al.*, *Nature* **438**, 994 (2005).
9. E. Berger *et al.*, *Nature* **438**, 988 (2005).
10. D. Eichler, M. Livio, T. Piran, D. N. Schramm, *Nature* **340**, 126 (1989).
11. R. Narayan, B. Paczyński, T. Piran, *Astrophys. J.* **395**, L83 (1992).
12. R. Mochkovitch, M. Hernanz, J. Isern, X. Martin, *Nature* **361**, 236 (1993).
13. A. Panaitescu, in preparation (preprint available at <http://arXiv.org/astro-ph/0511588>).
14. S. Rosswog, E. Ramirez-Ruiz, M. B. Davies, *Mon. Not. R. Astron. Soc.* **345**, 1077 (2003).
15. M. A. Aloy, H.-T. Janka, E. Müller, *Astron. Astrophys.* **436**, 273 (2005).
16. M. B. Davies, A. Levan, A. King, *Mon. Not. R. Astron. Soc.* **356**, 54 (2005).
17. The soft EOS at high densities models the interaction of nucleons with a Reid soft-core potential, the moderately stiff EOS uses the two-body and three-body interactions, and the very stiff EOS models the nucleon interaction in terms of a mean scalar field. The effects of these EOSs, uniform rotation, and differential rotation on the maximum mass of neutron stars have been explored in (32).
18. D. J. Nice *et al.*, *Astrophys. J.* **634**, 1242 (2005).
19. M. Shibata, K. Taniguchi, K. Uryū, *Phys. Rev. D* **71**, 084021 (2005).
20. W. Kluzniak, M. Ruderman, *Astrophys. J.* **505**, L113 (1998).
21. Z. G. Dai, T. Lu, *Phys. Rev. Lett.* **81**, 4301 (1998).
22. H. C. Spruit, *Astron. Astrophys.* **341**, L1 (1999).
23. P. Goldreich, A. Reisenegger, *Astrophys. J.* **395**, 250 (1992).
24. Y. Z. Fan, D. M. Wei, *Mon. Not. R. Astron. Soc.* **364**, L42 (2005).
25. B. Zhang *et al.*, *Astrophys. J.*, in press (preprint available at <http://arXiv.org/astro-ph/0508321>).
26. To calculate the x-ray flux, two spectral break frequencies should be considered (2): the characteristic frequency ν_m and the cooling frequency ν_c . For typical parameters in our model, $\nu_m < \nu_c$, implying the slow-cooling case.
27. D. N. Burrows *et al.*, *Science* **309**, 1833 (2005).
28. P. T. O'Brien *et al.*, in preparation (preprint available at <http://arXiv.org/astro-ph/0601125>).
29. R. Popham, S. E. Woosley, C. Fryer, *Astrophys. J.* **518**, 356 (1999).
30. A. I. MacFadyen, S. E. Woosley, *Astrophys. J.* **524**, 262 (1999).
31. Z. G. Dai, T. Lu, *Astron. Astrophys.* **333**, L87 (1998).
32. I. A. Morrison, T. W. Baumgarte, S. L. Shapiro, *Astrophys. J.* **610**, 941 (2004).
33. We thank P. F. Chen and M. D. Ding for helpful discussions about solar flare models that have motivated us to consider x-ray flare mechanisms and Y. F. Huang for valuable suggestions. This work is supported by the National Natural Science Foundation of China (grant numbers 10221001, 10233010, 10403002, and 10503012). B.Z. is supported by NASA (grant numbers NNG05GB67G, NNG05GH92G, and NNG05GH91G).

8 December 2005; accepted 23 January 2006
10.1126/science.1123606

Explaining the Color Distributions of Globular Cluster Systems in Elliptical Galaxies

Suk-Jin Yoon,^{1,2*} Suhyoung Ken Yi,^{1,2} Young-Wook Lee¹

The colors of globular clusters in most large elliptical galaxies are bimodal. This is generally taken as evidence for the presence of two cluster subpopulations that have different geneses. However, here we find that, because of the nonlinear nature of the metallicity-to-color transformation, a coeval group of old clusters with a unimodal metallicity spread can exhibit color bimodality. The models of cluster colors indicate that horizontal-branch stars are the main drivers behind the empirical nonlinearity. We show that the scenario gives simple and cohesive explanations for all the key observations and could simplify theories of elliptical galaxy formation.

One of the most outstanding discoveries from observations of elliptical galaxies over the past decade is the bimodal color distribution of globular clusters, gravitationally bound collections of millions of stars (1–8). The phenomenon is widely interpreted as evidence of two cluster subsystems with distinct geneses within individual galaxies (9). However, given the many ways of forming

clusters in elliptical galaxies, it is surprising that the cluster color distributions behave in an orderly way. For instance, the numbers of blue and red clusters in large galaxies are roughly comparable (1–8); blue and red clusters are old (>10 billion years) and coeval (9) and differ systematically in spatial distribution and kinematics (5, 10–16); and their relative fractions and peak colors strongly correlate with host galaxy properties (2–8). Here, we propose a simpler solution that does not necessarily invoke distinct cluster subsystems and has a sound basis in both empirical and theoretical relations between metallicity and colors.

A recent observation (8) reveals that the $g - z$ color (17) of clusters correlates with their

[Fe/H] (18) (Fig. 1A). The observed relation is tight enough to show a notable departure from linearity with a slope rapidly changing at $[\text{Fe}/\text{H}] \approx -1.0$. A closer inspection suggests that it might follow an inverted S-shaped “wavy” curve with a quasi-inflection point at $[\text{Fe}/\text{H}] \approx -0.8$. To examine this indication, we overplotted predicted colors of 13-billion-years (Gy) clusters from two different models (19, 20). Although there is good agreement between the models, they predict systematically redder colors for the $[\text{Fe}/\text{H}] \approx -1.0$ clusters that serve as key part of the possible inverted-S shape of the observed relation. We present our equivalent 13-Gy models with the $[\text{Fe}/\text{H}]$ grid spacing of $\Delta[\text{Fe}/\text{H}] = 0.1$ (Fig. 1B), a resolution sufficient to sample the region of $[\text{Fe}/\text{H}] \approx -1.0$. The main asset of our model is the consideration of the systematic variation in the mean color of horizontal-branch (HB) stars as a function of $[\text{Fe}/\text{H}]$ (21–24). The version of our model that excludes the prescription for the systematic HB variation, although showing agreement with the other models, does not match the observations as well. However, by including the realistic HB variation we can reproduce the clusters with $[\text{Fe}/\text{H}] \approx -1.0$ and, in turn, the observed wavy feature. This suggests that the wavy feature along the sequence defined by the observed clusters is real.

The observed wavy feature in the metallicity-color relation is a result of two complementary effects (Fig. 1B): (i) The integrated color of the stars before the HB stage (i.e., the main se-

¹Department of Astronomy and Center for Space Astrophysics, Yonsei University, Seoul 120-749, Korea. ²Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, UK.

*To whom correspondence should be addressed. E-mail: sjyoon@galaxy.yonsei.ac.kr