BIGGER BURSTS FROM MERGING NEUTRON STARS

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ABSTRACT

GRB 990123 may have produced $4 \times 10^{54}$ ergs in gamma rays unless, as seems to be the case, it was significantly beamed. Even with beaming, it may be beyond the limiting binding energy available for neutron star mergers in the Schwarzschild metric. Neutron stars of $\sim 10 M_\odot$ are permitted in the Yilmaz metric. A merger of two neutron stars of about $10 M_\odot$ could release approximately $3 \times 10^{55}$ ergs. The spectral state switches of the galactic black hole candidates may be the signatures of the magnetic fields of such massive neutron stars.

Subject headings: black hole physics — gamma rays: bursts — stars: neutron

1. INTRODUCTION

The gamma-ray burst GRB 990123 was remarkable in several respects: a detailed light curve from early times has been observed (Akerloff et al. 1999); it has been associated with a galaxy at a redshift of $z = 1.6$ (Bloom et al. 1999); and a prompt optical flash, predicted by generic relativistic fireball models (Mészáros & Rees 1996; Sari & Piran 1999; but see Liang et al. 1999), was observed along with it (Odewahn, Bloom, & Kulkarni 1999). If gamma emissions from GRB 990123 were isotropic, then $\sim 4 \times 10^{54}$ ergs was emitted just in gamma rays (Kouveliotou et al. 1999). This would make it one of the most energetic bursts observed to date, but GRB 990123 shows evidence of beaming. Prior to GRB 990123, little evidence for the beaming of bursts had been published (Tavani 1999). The reduction of energy requirements by a factor of 100 due to beaming has been inferred (Sari, Piran, & Halpern 1999) from a sharp break in the light curve 2 days into the afterglow. For gamma-ray production efficiencies of $\sim 1\%$, however, the total radiated energy requirement may remain about $4 \times 10^{54}$ ergs.

Although there are several candidate GRB sources capable of providing the energy of GRB 990123 (e.g., hypernovae; Paczyński 1997), the popular neutron star (NS) models involving NS-NS mergers (or NS—black hole mergers) may still be adequate if the radiation is substantially beamed. However, the required population of sources must increase to the same extent that beaming reduces the energy requirements. This is an important constraint. Nevertheless, the NS merger models have several strong points in their favor (see, e.g., Paczyński 1986 and Narayan, Paczyński, & Piran 1992): (i) there is probably an adequate source population, (ii) orbital decay via a known mechanism of gravitational radiation should produce mergers at approximately the observed rate of bursts in star-forming epochs ($z \sim 1–3$), (iii) the timescale and source compactness for the release of energy are adequate, (iv) at least moderate beaming would be expected normal to the orbital plane, and (v) energy requirements may be satisfied if there is some beaming. If conversion efficiencies for gamma-ray production are only near $1\%$, however (see, e.g., Janka, Ruffert, & Eberl 1998), then there may be an energy crisis for the NS merger models.

The theoretical energy limit from NS mergers is imposed by black hole formation. According to the theory of general relativity, an object of nuclear density that is more than $2.8 M_\odot$ would be a black hole (Kalorgera & Baym 1996; Friedman & Ipser 1987). The energy limit for NS mergers can be raised by removing the event horizon obstacle of general relativity. It should be noted that a similar relaxation of limits would be expected for hypernovae or other GRB candidates limited by black hole formation. For the NS mergers in the Yilmaz metric considered here, the energy limit can be raised by a factor of $\sim 10$.

2. YILMAZ NEUTRON STARS

The Yilmaz theory passes the four classic weak-field tests. It permits local energy-momentum conservation, has no adjustable parameters, no singularities, no event horizons, and can be reconciled with quantum theory (Alley 1995; Yilmaz 1994, 1995). Gravitationally compact objects can exist in the Yilmaz metric (YM), but they are not black holes. Radially directed photons can always escape. Event horizons in the Schwarzschild metric (SM) of general relativity are indicated by the vanishing of the metric coefficient:

$$g_{uu} = 1 - 2u(r),$$

where

$$u(r) = \frac{GM}{c^2r},$$

is the gravitational potential at distance $r$ from mass $M$. In addition to an isotropic static limit metric, the YM (Yilmaz 1958, 1971, 1975, 1992, 1994, 1995) has a corresponding metric coefficient of

$$g_{rr} = \exp \left[-2u(r)\right].$$

This coefficient can be derived from the principle of equivalence and special relativity applied to frames comoving with an accelerated particle (Einstein 1989, from a paper of 1907; Rindler 1969, p. 146; Yilmaz 1975). With $g_{uu}(r)$ and $g_{rr}(r)$ ($= g_{uu}^{-1}$) metric coefficients differing only in second-order and higher order terms, SM and YM differ by only a few percent to radii as small as the innermost marginally stable orbit (Robertson 1999). Therefore, decisive tests of disk accretion theories with and without event horizons at the core should be possible.

Robertson (1999) has calculated maximum NS masses for the two metrics using a simple model of a nonrotating star of
constant proper density. For nuclear saturation density, \(2.8 \times 10^{14} \text{ g cm}^{-3}\), a maximum NS mass of \(2.4 M_{\odot}\) is obtained for the SM. The maximum mass found for a nonrotating Yilmaz star is about \(9 M_{\odot}\). Maximally rotating stars could be about 25% more massive (Friedman & Ipser 1987).

If one of a pair of merging Yilmaz NSs were near maximum mass, the binding energy released while reaching a stable state would be close to the mass equivalent of the smaller star. Without exploring the endless possibilities for mergers, consider the merger of two stars of equal mass. For such pairs, Figure 1 shows the results for the two metrics. The merger of two \(9 M_{\odot}\) Yilmaz stars would yield \(11 M_{\odot}\) or \(2 \times 10^{53}\) ergs, perhaps enough to relieve both the energy and efficiency crises of the merged NS models. Although binding energies of the innermost marginally stable orbit differ by only 3.5%, low-mass NSs are clearly more tightly bound in the SM.

3. DISCUSSION

The Yilmaz star model is consistent with the known properties of the galactic black hole candidates (GBHCs). Although there are some spectral differences between GBHCs and low-mass NSs, particularly in high states, none have been convincingly attributed to the presence of an event horizon. Indeed, event horizon atmospheres and magnetic fields external to the accreting plasma have been invoked (Chou & Tajima 1999) for explanations of GBHC high-state phenomena. Robertson (1999) has argued that GBHCs may simply be massive NSs and has estimated spins and magnetic fields for them using spectral data. Those in low-mass X-ray binary (LMXB) systems would typically spin at a few tens of hertz and have magnetic fields of \(~10^{9}–10^{11}\)G, which are sufficient to suppress surface bursts. The distribution of dynamically determined GBHC masses seems to be limited to something less than \(~12 M_{\odot}\), with a peak near \(7 M_{\odot}\) (Chen, Shrader, & Livio 1997), in accord with the Yilmaz NS model. GBHCs of \(~7 M_{\odot}\) appear to constitute a large fraction of the compact objects in LMXBs (see, e.g., Barret, McClintock, & Grindlay 1996). This suggests that a sufficient population of such objects exists to provide blasts such as GRB 990123.

There may be a straightforward test of the hypothesis that GBHCs are merely massive NSs. In addition to possessing surfaces rather than event horizons, they should have substantial magnetic fields. Such an attribute is forbidden for a black hole. A spinning magnetic field and accompanying propeller effect (Illarionov & Sunyaev 1975) would cut off the accretion disk flow to NS surfaces until a boundary layer of sufficient pressure forces the magnetosphere inside the corotation radius (where the Keplerian orbit frequency matches the star spin). The magnetosphere radius is often estimated as the radius at which the impact pressure of the accreting plasma matches the magnetic pressure (Lamb, Pethick, & Pines 1973). At the corotation radius of typical atolls, the magnetic pressure is on the order of 10 Mbar. One would expect that black holes lacking such impediments to plasma flow would have very different disk structures and spectra, but apparently that is not the case. From quiescence to the low-high switch, there are strong similarities in the spectral and timing characteristics between low-state atolls and GBHCs (Tanaka & Shibazaki 1996; van der Klis 1994).

Recent observations appear to confirm the propeller effect. With the surface flow cut off, X-ray luminosities dropped, X-ray pulses ceased, and spectral changes occurred for GX 1+4, GRO J1744−28 (Cui 1997), SAX J1808.4−3658 (Gilfanov et al. 1998), and a spectral state change was observed for Aql X-1 (Campana et al. 1998; Zhang, Yu, & Zhang 1998). In addition, spectral modeling of GBHC low states has revealed a disruption of the inner disk by some robust physical mechanism (Done & Zycki 1999). The X-ray spectrum is essentially a power law in the low state for both GBHCs and atoll class NSs. After the spectral state switch, a softer thermal component may be observed, which is softest for the most massive objects. For NSs, it is clearly of surface origin. If GBHCs are actually massive NSs, their surface emissions should appear softer because of greater redshifts. If it can be shown that propeller effects mediate the spectral state switches for NSs of known spin, then there would be strong reason for believing that the similar behaviors of GBHCs are produced in the same way. Careful studies of spectral state switches and accompanying QPOs, using the current generation of satellites and archival data, should be capable of deciding this issue.

Since massive NSs in the YM and black holes in the SM would essentially differ only by the presence or absence of surfaces and magnetic fields, the YM provides a tool that is capable of confirming or rejecting the existence of event horizons. If the YM survives the tests and resolves the GRB energy problem, we may also need to reexamine the luminosity-redshift relation for accelerations of the cosmic expansion rate.

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REFERENCES

Alley, C. O. 1995, in Ann. NY Acad. Sci., 755, Fundamental Problems in Quantum Theory, ed. J. A. Wheeler, D. M. Greenberger, & A. Zeilinger, 464
Akerloff, C., et al. 1999, IAU Circ. 7100
Barret, D., McClintock, J. E., & Grindlay, J. E. 1996, ApJ, 473, 963
Bloom, J., et al. 1999, preprint (astro-ph/9902182)
Campana, S., et al. 1998, ApJ, 499, L65
Chen, W., Schrader, C., & Livio, M. 1997, ApJ, 491, 312
Chou, W., & Tajima, T. 1999, ApJ, 513, 401
Cui, W. 1997, ApJ, 482, L163
Done, C., & Zyci, P. T. 1999, in Disk Instabilities in Close Binary Systems—25 Years of the Disk Instability Model, ed. S. Minishige & J. C. Wheeler (Tokyo: Universal Academy Press), 251
Einstein, A. 1989, in The Collected Papers of Albert Einstein, Vol. 2, The Swiss Years: Writings 1900–1909, ed. J. J. Stachel (Princeton: Princeton Univ. Press), 457
Friedman, J., & Ipser, J. 1987, ApJ, 314, 594
Gilfanov, M., Revnivtsev, M., Sunyaev, R., & Churazov, E. 1998, A&A, 338, L83
Illarianov, A., & Sunyaev, R. 1975, A&A, 39, 185
Janka, H.-Th., Ruffert, M., & Eberl, T. 1998, preprint (astro-ph/9810057)
Kalogera, V., & Baym, G. 1996, ApJ, 470, L61
Kouveliotou, C., et al. 1999, Nature, submitted
Lamb, F., Pethick, C., & Pines, D. 1973, ApJ, 184, 271
Liang, E. P., Crider, A., Boettcher, M., & Smith, I. A. 1999, ApJL, submitted (astro-ph/9903438)
Mészáros, P., & Rees, M. 1997, ApJ, 476, 232
Narayan, R., Paczyński, B., & Piran, T. 1992, ApJ, 395, L83
Odewahn, S., Bloom, J., & Kulkarni, S. 1999, GCN Circ. 201 (http://gcn.gsfc.nasa.gov/gcn/gcn3/201.gcn3)
Paczyński, B. 1986, ApJ, 308, L43
———. 1997, ApJ, 494, L45
Rindler, W. 1969, Essential Relativity (New York: Van Nostrand Reinhold Co.)
Robertson, S. L. 1999, ApJ, 515, 365
Sari, R., & Piran, T. 1999, preprint (astro-ph/9901338)
Sari, R., Piran, T., & Halpern, J. 1999, preprint (astro-ph/9903339)
Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
Tavani, M. 1999, Astrophys. Lett. Commun., in press (astro-ph/9812422)
van der Klis, M. 1994, ApJS, 92, 511
Yilmaz, H. 1958, Phys. Rev., 111, 1417
———. 1971, Phys. Rev. Lett., 27, 1399
———. 1975, Am. J. Phys., 43, 319
———. 1992, Nuovo Cimento, 107B, 941
———. 1994, in Frontiers of Fundamental Physics, ed. M. Barone & F. Selleri (New York: Plenum), 115
———. 1995, in Ann. NY Acad. Sci., 755, Fundamental Problems in Quantum Theory, ed. J. A. Wheeler, D. M. Greenberger, & A. Zeilinger, 477
Zhang, W., Yu, W., & Zhang, S. 1998, ApJ, 494, L71