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THE MASSIVE PULSAR PSR J1614−2230: LINKING QUANTUM CHROMODYNAMICS, GAMMA-RAY BURSTS, AND GRAVITATIONAL WAVE ASTRONOMY

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ABSTRACT

The recent measurement of the Shapiro delay in the radio pulsar PSR J1614−2230 yielded a mass of 1.97±0.04 $M_{\odot}$, making it the most massive pulsar known to date. Its mass is high enough that, even without an accompanying measurement of the stellar radius, it has a strong impact on our understanding of nuclear matter, gamma-ray bursts, and the generation of gravitational waves from coalescing neutron stars. This single high mass value indicates that a transition to quark matter in neutron-star cores can occur at densities comparable to the nuclear saturation density only if the quarks are strongly interacting and are color superconducting. We further show that a high maximum neutron-star mass is required if short duration gamma-ray bursts are powered by coalescing neutron stars and, therefore, this mechanism becomes viable in the light of the recent measurement. Finally, we argue that the low-frequency ($\leq$ 500 Hz) gravitational waves emitted during the final stages of neutron-star coalescence encode the properties of the equation of state because neutron stars consistent with this measurement cannot be centrally condensed. This will facilitate the measurement of the neutron star equation of state with Advanced LIGO/Virgo.

Subject headings: pulsars — neutron star physics

1. INTRODUCTION

Neutron stars are associated with the most diverse and energetic phenomena in the Universe, from gamma-ray bursts to the emission of gravitational waves and from periodic millisecond radio signals to month-long X-ray outbursts. The strength and even the occurrence of some of these phenomena depend on the neutron star mass. For decades, precise dynamical measurements of the masses of neutron stars resulted in highly clustered values around 1.25–1.4 solar masses (Thorsett & Chakrabarty 1999). This paradigm has recently changed with the measurement of the neutron star mass for PSR J1614−2230.

PSR J1614−2230 is a 3.1 ms radio pulsar in a 8.7 day orbit around a massive white dwarf (Hessels et al. 2005). Its very high inclination, at 89.17°, allowed the detection of a strong Shapiro delay signature in highly accurate timing observations with the Green Bank Telescope and a precise measurement of the neutron star mass. The inferred value of 1.97±0.04 $M_{\odot}$ is by far the highest observed from any neutron star to date (Demorest et al. 2010).

The high mass of PSR J1614−2230 provides a lower limit on the maximum mass of neutron stars and sets the dividing line between neutron stars and black holes to at least this value. This has significant implications for the fraction of neutron stars that will collapse into black holes as a result of mass accretion in X-ray binaries. For a maximum neutron star mass that is $> 2\ M_{\odot}$, the relative frequency of black hole binaries that are formed through this evolutionary channel is at most 25% (Pfahl, Rappaport, & Podsiadlowski 2003). Such a small fraction would help explain the lack of low-mass black holes in binary systems with dynamical mass measurements (Özel et al. 2010b).

The highest neutron star mass that can be supported against collapse depends very sensitively on the underlying equation of state. In particular, if quark, hyperon, or boson degrees of freedom are excited at high densities, the equation of state softens and cannot support massive neutron stars (see, e.g., Lattimer & Prakash 2001). The discovery of even a single very high mass neutron star can, therefore, provide strong constraints on the fundamental properties of ultradense matter. In this *Letter*, we explore in detail the constraints imposed by the recent mass measurement on the radii of neutron stars and on the properties of quark matter in their interiors.

The maximum neutron star mass also plays a crucial role in determining the outcome of the coalescence of two neutron stars. These astrophysical events are thought to be the central engines of short-duration gamma-ray bursts (see reviews by Nakar 2007 and Lee & Ramirez-Ruiz 2007). Furthermore, they are expected to be the primary sources of gravitational waves that will be detected by ground-based observatories such as LIGO, Virgo, and GEO600. In §3, we investigate the viability of the coalescing neutron-star scenario for short-duration gamma-ray bursts in view of the above lower limit on the maximum mass of neutron stars. Finally, in §4, we discuss the prospect of measuring the equation of state of neutron-star matter using ground-based gravitational wave observatories.

2. THE STRUCTURE AND COMPOSITION OF NEUTRON STARS

The high mass of the PSR J1614−2230, in conjuction with the requirement of causality for the neutron star matter equation of state, places a strong lower limit on its radius, independent of the composition of its interior.

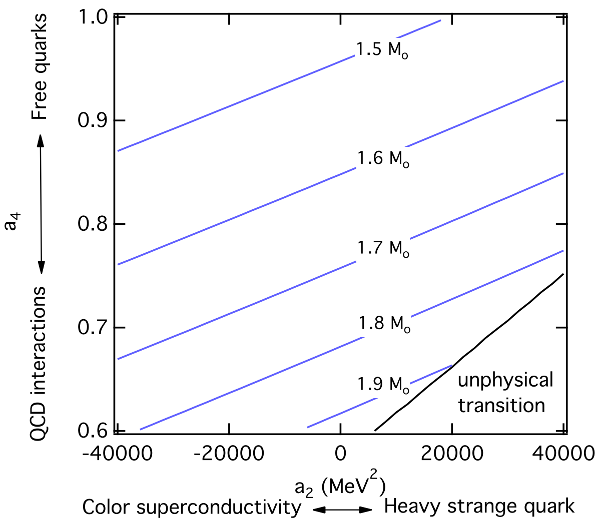

FIG. 1.— The maximum neutron star mass as a function of two parameters of quark matter when the density at which the transition from nucleonic to quark matter occurs is equal to 1.5 times the nuclear saturation density. The measurement of a pulsar mass of $\geq 1.93\ M_\odot$ from Shapiro delay observations indicates that, if the transition to quark matter occurs at densities that are relevant to neutron star interiors, such a massive star can be supported against collapse only if the quarks are strongly interacting ($a_4 \leq 0.63$).

Assuming an equation of state that arises from normal interactions in the outermost neutron star layers (where the density ρ is less than a characteristic value ρ_0) and requiring that the sound speed c_s everywhere in the neutron star core is less than the speed of light c, such that $dP/d\rho < c^2$, leads to a firm lower limit on the radius R of a neutron star as a function of its mass M (Lindblom 1984; Glendenning 2000; Koranda et al. 1997). This is, of course, true only for neutron stars, which are gravitationally bound and have densities that drop smoothly to zero in their atmospheres; the causality limit does not apply to strange stars.

The BPS equation of state (Baym, Pethick, & Sutherland 1971) is a standard choice for low-density matter. Assuming it is accurate up to a density $\rho_0 = 3\times10^{14}$ g cm^{-3}, which is comparable to the nuclear saturation density of atomic nuclei $\rho_{\rm sat} = 2.7\times10^{14}$ g cm^{-3}, the bound imposed by causality is

$$R \geq 2.83\,\frac{GM}{c^2} = 8.3\left(\frac{M}{1.97M_\odot}\right)\ \text{km}. \quad (1)$$

All realistic equations of state for gravitationally bound stars predict radii that are either very weakly dependent on or decreasing with increasing neutron-star mass (Lattimer & Prakash 2001). The causality bound, in conjunction with the recent spectroscopic measurements of neutron-star radii in X-ray binaries that place them at values $\lesssim 12$ km (Özel, Baym, & Güver 2010, Steiner, Lattimer, & Brown 2010), lead to the very narrow range 8.3 km $\leq R \leq$ 12 km for all neutron stars.

Stronger constraints on the composition of the neutron star interior can be placed by requiring that the equation of state support a maximum neutron star mass that is at least as high as the measured value. In general, the appearance of new degrees of freedom at and above the nuclear saturation density, such as quarks, hyperons, or bosons, softens the equation of state and lowers the maximum mass that can be supported against collapse.

In Figure 1, we show how the mass measurement for PSR J1614$-$2230 constrains the quark matter equation of state. We use a specific model of quark matter, the phenomenological equation of state proposed by Alford et al. (2005), which has three parameters: a_4, a_2, and the bag coefficient. The quartic coefficient a_4 measures the degree of interaction between quarks, with $a_4 = 1$ corresponding to free quark plasma. The quadratic coefficient a_2 depends on the mass of the strange quark and the color superconducting energy gap; it is large in unpaired quark matter with a heavy strange quark, and small in color superconducting (for example color-flavor locked) quark matter with a light strange quark. We calculate the maximum neutron star mass $M_{\rm max}$ for a range of values of a_4 and a_2, while fixing the bag coefficient so that the transition from nuclear matter to quark matter occurs when the baryon density n of the nuclear matter is $1.5\,n_{\rm sat}$, where nuclear density is $n_{\rm sat} = 0.16\,{\rm fm}^{-3}$. For the nuclear matter equation of state, we use BPS (Baym, Pethick, & Sutherland 1971) at low densities and APR (Akmal, Pandharipande, & Ravenhall 1998), which we assume is valid up to a density $2\,n_{\rm sat}$. We chose the APR equation of state because it describes well the nucleon-nucleon scattering data and is believed to be accurate up to the nuclear saturation density. The excluded region in the lower right part of the figure is the region where, after the transition from nuclear to quark matter at $n = 1.5n_{\rm sat}$, there is another transition back to nuclear matter at $1.5n_{\rm sat} < n < 2n_{\rm sat}$. Such a transition seems unlikely to be physical, so we do not calculate masses in this region.

We see from Figure 1 that values of $M_{\rm max}$ compatible with the measurement for PSR J1614$-$2230 can only be achieved if $a_4 \lesssim 0.63$ and $a_2 \lesssim 10^4\,{\rm MeV}^2$. In Alford et al. (2005), such values were associated with strong interactions between the quarks (pushing a_4 well below unity) and color superconductivity (which allows a_2 to remain small by cancelling the contribution to a_2 from the strange quark mass).

3. THE MAXIMUM MASS OF NEUTRON STARS AND SHORT-DURATION GAMMA-RAY BURSTS

Short gamma-ray bursts have characteristic timescales $\leq$ 2 s, which are much longer than the dynamical timescale for the coalescence of two neutron stars. In the coalescing neutron star scenario, the required longer timescales can be achieved in two ways (Nakar 2007; Lee & Ramirez-Ruiz 2007; Duez 2010; Rezzolla et al. 2010). The initial remnant may be a differentially rotating massive neutron star that is temporarily supported by centrifugal forces. The dissipation of the differential rotation on timescales $\sim$ 1 s leads to the delayed collapse of the remnant into a black hole and produces the gamma-ray burst. In order for this channel to occur, the sum of the masses in the initial system has to be larger than the maximum neutron star mass for solid body rotation but less than the maximum mass that can be supported by differential rotation. Numerical simulations of spinning neutron stars place these limits at $\sim 1.2\ M_{\rm max}$ and $\sim 1.4\ M_{\rm max}$, respectively, where $M_{\rm max}$ is the maximum mass of a non-spinning neutron star (Duez 2010;

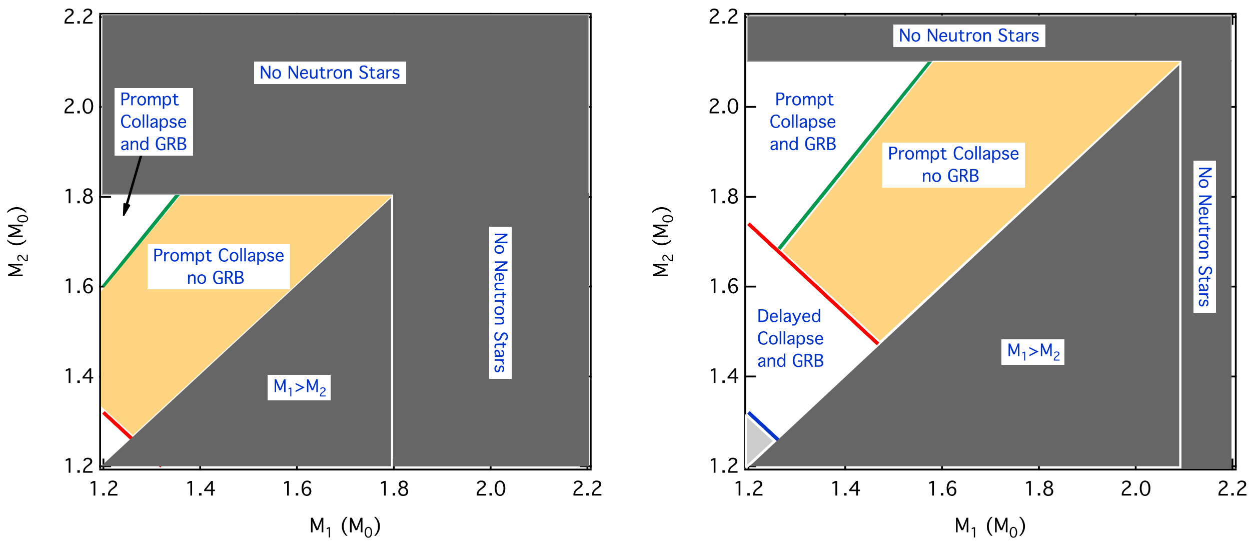

FIG. 2.— Allowed regions of the parameter space of the masses of two coalescing neutron stars that leads to a short-duration gamma-ray burst. For simplicity, the second neutron star is assumed to be larger than the first neutron star. The left panel shows the result when the maximum mass of a non-spinning neutron star is equal to $M_{\rm max} = 1.8\ M_\odot$ and the right panel shows the result for a maximum mass of 2.1 $M_\odot$. In the right panel, the blue line corresponds to a total mass of $M_1 + M_2 = 1.2\ M_{\rm max}$, below which a neutron star rotating as a solid body can be supported against collapse by centrifugal forces. In both panels, the red line corresponds to a total mass of $M_1 + M_2 = 1.4\ M_{\rm max}$, above which a neutron star cannot be supported against collapse, even if it is rotating differentially. The green line corresponds to a mass ratio of $M_2/M_1 = 4/3$, above which the initial outcome of the collision is a black hole surrounded by a massive torus. Short duration gamma ray bursts can be generated when the outcome of the collision is either the delayed collapse of a supermassive neutron star into a black hole, or the prompt collapse of the two stars into a black hole surrounded by a massive torus. The allowed region of the parameter space for $M_{\rm max} = 1.8\ M_\odot$ is marginal but increases rapidly as $M_{\rm max}$ exceeds 2 $M_\odot$.

Cook et al. 1994; Baumgarte et al. 2000); the exact value of this limit depends on the radial profile of the differential rotation. As a result, the delayed collapse channel requires that

$$1.2\ M_{\rm max} \le M_1 + M_2 \le 1.4\ M_{\rm max}. \qquad (2)$$

The second channel involves the prompt collapse of the remnant of the coalescence into a black hole and the formation of a $\gtrsim 0.1\ M_\odot$ torus around it that is accreted onto the black hole in the required timescale. All numerical simulations of coalescing neutron stars show that equal mass mergers hamper the formation of these massive thick accretion disks. If, on the other hand, the ratio of the merging neutron star masses is larger than 4 : 3, the lower mass neutron star fills its Roche lobe before contact and loses the required amount of mass into a torus before the remnant collapses into a black hole (Shibata & Taniguchi 2006; Duez 2010). (The value of this ratio depends on the mass of the torus required to achieve the timescale of the GRBs by the subsequent accretion of this torus; see Rezzolla et al. 2010). This prompt collapse channel, therefore, requires that the total mass of the coalescing neutron stars is $\gtrsim 1.4\ M_{\rm max}$ and their mass ratio is $\gtrsim 4/3$.

In Figure 2, we calculate the outcome of mergers in the parameter space defined by the masses of the two coalescing neutron stars and delineate the areas in which short duration gamma-ray bursts can be generated via either channel. The two panels demonstrate the very strong sensitivity of these outcomes on the maximum mass that can be supported against collapse in a non-rotating neutron star. For a maximum neutron star mass of 1.8 $M_\odot$, the allowed area in this parameter space is marginal (left panel) but increases rapidly as $M_{\rm max}$ grows to values larger than 2 $M_\odot$ (right panel). Therefore, the unequivocal detection of a 1.97 $M_\odot$ neutron star makes the idea of coalescing neutron stars as the central engines of short duration gamma-ray bursts viable.

Figure 2 shows that the largest part of the parameter space that leads to short duration gamma-ray bursts is populated by double neutron star systems in which one of the neutron stars is significantly more massive than the other. This is in contrast to the double neutron star systems observed in the Galactic disk, where both neutron stars have surprisingly similar masses (Thorsett & Chakrabarty 1999). Indeed, a significant amount of mass transfer onto one of the two neutron stars is likely to take place only in a low-mass X-ray binary system, which does not lead to the formation of a double neutron star. Double neutron stars with high mass ratios are perhaps most easily formed in globular clusters via exchange interactions. Globular clusters have large populations of low-mass X-ray binaries and, therefore, may harbor the systems responsible for the short duration gamma-ray bursts (see also Grindlay et al. 2007). This would explain the recent observations of optical counterparts of short duration gamma-ray bursts, which appear to lie outside the host galaxies (e.g., Berger 2010).

4. MEASURING THE EQUATION OF STATE OF NEUTRON STARS WITH GRAVITATIONAL WAVES

The coalescence of two neutron stars is also expected to be the primary source of gravitational waves detected with current and future ground-based detectors such as LIGO, VIRGO, and GEO 600 (Anderson et al. 2009). Detailed modeling of the waveforms during the final stages of the coalescence can place strong constraints on the equation of state of neutron-star matter (Read et al. 2009). This will be possible with a generation of detectors beyond Advanced LIGO, as it requires following the gravitational wave signal to frequencies ≥ 1 kHz. However, even the low-frequency waveforms may encode the characteristics of the equation of state as they are affected by the tidal deformation experienced by the two neutron stars at larger separations (Flanagan & Hinderer 2008).

The degree of tidal deformation, as measured by the Love number, is relatively insensitive to the compactness of the neutron star but depends strongly on how centrally condensed the density profile inside the stars is (Hinderer 2008; Damour & Nagar 2009; Binnington & Poisson 2009), because stars that are centrally condensed are weakly deformed in the presence of an external tidal gravitational field.

Equations of state that allow pulsar masses $\geq 2M_\odot$ typically yield neutron stars that are not centrally condensed (as can be inferred from the polytropic models of Hinderer 2008). Therefore, the discovery of the 1.97 $M_\odot$ pulsar indicates that coalescing neutron stars will undergo significant tidal deformation, and information about the equation of state of the stellar interior will be encoded in low-frequency ($\leq$ 600 Hz) gravitational waves emitted during coalescence. Detection of these waves will allow accurate measurements of the equation of state of neutron-star matter in the near future.

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