A HIGH RATE OF WHITE DWARF – NEUTRON STAR MERGERS & THEIR TRANSIENTS

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ABSTRACT

We argue that the recent groundbreaking discovery by Badenes et al. (2009) of a nearby ($D \approx 50$ pc) white dwarf-neutron star (or black hole) binary (SDSS 1257+5428) with a merger timescale $\lesssim 500$ Myr implies that such systems are common; we estimate that there are of order $10^6$ in the Galaxy. Although subject to large uncertainties, the nominal derived merger rate is $\Gamma_{\text{MW}} \sim 5 \times 10^{-4}$ yr$^{-1}$ in the Milky Way, just $\sim 3 - 6$ and $\sim 20 - 40$ times less than the Type Ia and core-collapse supernova (SN) rates, respectively. This implies that the merger rate is $\sim 0.5 - 1 \times 10^4$ Gpc$^{-3}$ yr$^{-1}$ in the local universe, $\sim 5000 - 10000$ times more than the observed (beaming-uncorrected) long-duration gamma-ray burst (GRB) rate. We estimate the lower limit on the rate in the Galaxy to be $\Gamma_{\text{MW}} \gtrsim 2.5 \times 10^{-5}$ yr$^{-1}$ at 95% confidence. We briefly discuss the implications of this finding for the census of long- and short-duration GRBs and their progenitors, the frequency of tight binary companions to Type-Ib/c SN progenitors, the origin of ultra-high energy cosmic rays (UHECRs), the formation of rapidly rotating neutron stars and $\sim 2 - 3 M_\odot$ black holes, the census of faint Ia-like SNe, as well as for upcoming and current transient surveys (e.g., LOSS, PTF, LSST), and for high- (LIGO) and low-frequency (LISA) gravitational wave searches.

Subject headings: binaries: close — white dwarfs — supernovae: general — gamma-rays: bursts — cosmic rays

1. INTRODUCTION: THE ARGUMENT

The recent paper by Badenes et al. (2009) describes their discovery as part of the SWARMS survey of a probable white dwarf-neutron star/black hole (WD-NS/BH)$^5$ binary (SDSS 1257+5428) at a distance of $D \approx 48^{+10}_{-9}$ pc, with orbital period of $\approx 4.6$ hr, and radial velocity semi-amplitude of $\approx 320$ km s$^{-1}$. The WD is of spectral type DA, has a g-band magnitude of 16.8, and has a cooling age of $t_{\text{cool}} \approx 2.0 \pm 1.0$ Gyr. The system masses are $M_{\text{WD}} \approx 0.92^{+0.23}_{-0.35} M_\odot$ and $M_{\text{NS/BH}} \sin(i) \approx 1.62^{+0.20}_{-0.25} M_\odot$. The transverse velocity of the system is $\approx 11$ km s$^{-1}$ and the total spatial velocity is plausibly $\sim 120$ km s$^{-1}$. For $i = 60^\circ$, the semi-major axis is $\approx 0.01$ AU. The orbital period and masses imply a merger timescale for the system of $t_{\text{merge}} \lesssim 511^{+342}_{-142}$ Myr and for an assumed inclination angle of $i = 60^\circ$, $t_{\text{merge}} \sim 267^{+165}_{-106}$ Myr.

Taken at face value, the detection of this remarkable binary implies that the number of such systems in the Galaxy is very large. The WD has an apparent g-band magnitude $\approx 2$ magnitudes brighter than the limiting magnitude of the survey, 18.9 (Badenes et al. 2009; Mullally et al. 2009). Thus, the volume probed by the survey for systems analogous to SDSS 1257+5428 is $V_{\text{SWARMS}} \approx f_{\text{SDSS}} (4\pi/3)(125\text{pc})^3 \approx 2 \times 10^6$ pc$^3$, where $f_{\text{SDSS}} \approx 1/4$ is the fraction of the sky probed by SDSS to $g \approx 18.9$ in SWARMS, and where we have taken $f_{\text{SDSS}} (4\pi/3) \sim 1$. The total volume of the Galaxy is $V_{\text{MW}} \sim 2\pi r^2 h$, where $r \approx 8.5 r_{8.5\text{kpc}}$ kpc is the galacto-centric radius and $h \sim 4h_{4\text{kpc}}$ kpc is the scale height accessible to objects with total space motion of $\sim 100$ km s$^{-1}$. Thus,

$$\frac{V_{\text{SWARMS}}}{V_{\text{MW}}} \sim 1 \times 10^{-6} r_{8.5\text{kpc}}^2 h_{4\text{kpc}}^{-1}. \quad (1)$$

The primary point of this Letter is that this ratio is exceedingly small. Since equation (1) is equivalent to the probability of detecting such a system if it was the only such system in the Galaxy, we conclude that it is not the only such system. More probable is that each of the $V_{\text{SWARMS}}$-sized volumes that constitute the Galaxy is populated by $N \gtrsim 1$ such binaries. The total number of WD-NS/BH binaries in the Galaxy is then$^6$

$$N_{\text{MW}} \sim N \left( \frac{V_{\text{MW}}}{V_{\text{SWARMS}}} \right) \sim 10^5 N r_{8.5\text{kpc}}^2 h_{4\text{kpc}}^{-1} \quad (2)$$

and the current merger rate is

$$\Gamma_{\text{MW}} \sim \frac{N_{\text{MW}}}{t_{\text{life}}} \sim 5 \times 10^{-4} N \text{yr}^{-1} r_{8.5\text{kpc}}^2 h_{4\text{kpc}}^{-1} r_{2\text{Gyr}}^{-1}. \quad (3)$$

where $t_{2\text{Gyr}} = t_{\text{life}}/2$ Gyr and $t_{\text{life}} = t_{\text{cool}} + t_{\text{merge}}$ (e.g., Phinney 1991).

We caution that the estimate of the number of such systems in the Galaxy in equation (2) and the merger rate in equation (3) is highly uncertain. Ignoring the uncertainties in the ratio of volumes and in $t_{\text{life}}$, the Poisson error on $N$, given the single detection, yields a lower limit of $N \gtrsim 0.05$ ($N_{\text{MW}} \gtrsim 5 \times 10^4$; $\Gamma_{\text{MW}} \gtrsim 2.5 \times 10^{-5}$ yr$^{-1}$) and $\gtrsim 0.01$ ($N_{\text{MW}} \gtrsim 1 \times 10^4$; $\Gamma_{\text{MW}} \gtrsim 5 \times 10^{-6}$ yr$^{-1}$) at 95% and 99% confidence, respectively (e.g., Gehrels 1986). A single additional such binary detected in the

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$^5$ We adopt this terminology since it is not known if the unseen companion is a NS or BH. Badenes et al. (2009) discuss a third option — that the companion is another unseen WD — but they do not favor this option. We return to this issue in §3.
$^6$ We note that the density of stars in the Solar neighborhood can be estimated similarly, and with at least order-of-magnitude fidelity, from the first measured parallax of 61 Cygni by Bessel (1838).
local $\sim 10^6$ pc$^3$ would provide strong evidence for $N \sim 1$. Unfortunately, the lack of such a future detection in SWARMS does not strongly constrain $\dot{\Gamma}_{\text{MW}}$. In addition to the uncertainty in $N$, there is uncertainty at the factor of $\sim 2$–4 level in $V_{\text{MW}}$; however, our fiducial values for $r$ and $h$ are reasonable, given the age and space velocity of the binary considered. Note also that SWARMS selects for edge-on binaries due to the low resolution of the SDSS spectra used to target interesting WDs via radial velocity variations (Badenes et al. 2009; Mullally et al. 2009). This effect may increase the inferred rate by a factor of order $\sim 2$–4. The ambiguity in the cooling age of SDSS 1257$+$5428 adds an additional factor of $\sim 2$–4 uncertainty. Finally, our estimate tacitly assumes that the binary is equally detectable by SWARMS over its few Gyr lifetime from birth to death; the fact that the WD was brighter in the past implies a lower overall rate than given in equation (3), but the magnitude of this correction depends on the luminosity function of WDs in such binaries.

2. DISCUSSION: THE RATE

The nominal estimate of the merger rate for WD-NS/BH binaries in equation (3) is very high. Taking the core-collapse supernova (SN) rate to be $\sim 1$–$2 \times 10^2$ yr$^{-1}$ in the Galaxy, we see that the WD-NS/BH merger rate is $\sim 20$–$40$ times smaller. Comparison with the observed rate of core-collapse SNe in the local 100 Mpc volume (see, e.g., the compilation of data by Horiuchi et al. 2009), $\sim 1$–$2 \times 10^5$ Gpc$^{-3}$ yr$^{-1}$, implies that the average rate of WD-NS/BH mergers in the local universe is $\sim 0.5$–$1 \times 10^3$ Gpc$^{-3}$ yr$^{-1}$. This is a factor of just $\sim 3$–$6$ lower than the local Type Ia rate, $\sim 3 \times 10^4$ Gpc$^{-3}$ yr$^{-1}$ (Dilday et al. 2008). See Table 1.

Although the rates of short- and long-duration gamma-ray bursts (GRBs) are uncertain because of the overall beaming correction for the two populations, $\Gamma_{\text{MW}}$ in equation (3) is at least $\sim 10^5$ times larger than the rates inferred for either population; the long-duration GRB rate is observed to be $\sim 1$ Gpc$^{-3}$ yr$^{-1}$, and the beaming-corrected rate is $\sim 30$ Gpc$^{-3}$ yr$^{-1}$ (e.g., Guetta et al. 2005). The rate of short-duration GRBs is also small ($\sim 10$ Gpc$^{-3}$ yr$^{-1}$; Nakar 2007). This disparity between $\Gamma_{\text{MW}}$ and the GRB rate is particularly interesting because these mergers have been suggested as a mechanism for some long- and short-duration GRBs (§3). Interestingly, our rate for $\Gamma_{\text{MW}}$ is only $\sim 5$ times higher than the current estimate for the rate of NS-NS mergers in the Galaxy (Kalogera et al. 2004ab), often thought to be associated with short-duration GRBs (see Table 1).

Our estimate of $\Gamma_{\text{MW}}$ is also significantly larger than the rate derived from statistical methods based on the 3 previously known WD-NS (pulsar) binaries that will merge within a Hubble time, $\sim 0.2$–$10 \times 10^{-6}$ yr$^{-1}$, obtained without making an overall correction for pulsar beaming (Kim et al. 2004). This result is statistically dominated by the single WD-NS binary system PSR J1141-6545, whose merger timescale is similar to the system described here. The rate derived in Kim et al. (2004) is about an order of magnitude smaller than that obtained from population synthesis studies (e.g., Kalogera et al. 2005), and it is about $\sim 10^2$ times smaller than $\Gamma_{\text{MW}}$ in equation (3). The estimate by Fryer et al. (1999a) is similarly small, but with large uncertainties.

Our estimate of $\Gamma_{\text{MW}}$ is $\sim 1$–$10$ times higher than the rate advocated by Davies et al. (2002) in their binary evolution scenario developed to explain the WD-pulsar systems J1141-6545 and B2303+46. In their model, the initial primary transfers enough of its mass to the secondary that the latter becomes the more massive star. The core of the original primary makes the WD, which enters a common envelope with the more massive secondary when it evolves off the main sequence. In the case of their PSR J1141-6545-like binaries, the secondary helium star evolves to contact with the primary and the majority of its envelope is ejected from the system. The secondary then undergoes core collapse, producing a NS.

Our 95% confidence lower limit on the rate — $\Gamma_{\text{MW}} \gtrsim 2.5 \times 10^{-5}$ yr$^{-1}$ — is still larger than either of the observed or beaming-corrected short- or long-duration GRB rates, but overlaps with the probable distribution of NS-NS merger rates for the Galaxy (Kalogera et al. 2004ab), the upper end of the pulsar beaming-corrected rates derived from PSR J1141-6545 (Kim et al. 2004), the rates inferred from population synthesis studies (Davies et al. 2002; Kalogera et al. 2005), the rate derived by Nelemans et al. (2001), and the estimate of Edwards & Bailes (2001) of $\sim 10^{-5}$ yr$^{-1}$ based on PSR J1141-6545.

3. IMPLICATIONS

The estimate of the merger rate in equation (3) has a number of implications:

1. GRBs & Transients: The merger of WD-NS/BH binaries has been discussed as a mechanism for producing long-duration GRBs (e.g., Fryer et al. 1999b) and the new class of

| Event Type | Rate ($10^4$ Gpc$^{-3}$ yr$^{-1}$) | Reference |
|------------|---------------------------------|-----------|
| WD-NS/BH Merger | 0.5–1 | this work |
| Type II SN | $10^{-2}$ | Horiuchi et al. (2009) |
| Type Ia SN | 3 | Dilday et al. (2008) |
| NS-NS Merger | 0.1$^a$ | Kalogera et al. (2004ab) |
| Short GRB | 0.001$^{bc}$ | Nakar (2007) |
| Long GRB | 0.0001$^b$ | Guetta et al. (2005) |

$^a$Calculated using the rate $\approx 10^{-4}$ yr$^{-1}$ derived in Kalogera et al. (2004ab) and the conversion factor of $10^{-2}$ Mpc$^{-3}$ based on the $B$-band luminosity of the local universe from Kalogera et al. (2001), their Section 4.

$^b$Uncorrected for beaming.

$^c$Short-duration GRBs with extended emission (e.g., 060614) amount to $\sim 25\%$ of the total short-duration GRB population (Norris et al. 2009).
of short-duration GRBs with extended emission (e.g., GRB 060614; King et al. 2007; see Gehrels et al. 2006 & Gal-Yam et al. 2006). A recent study by Norris et al. (2009) finds that only \( \sim 25\% \) of short duration GRBs have extended emission. Thus, if King et al. (2007) are correct and WD-NS mergers are the central engine for 060614-like bursts, then either equation (3) overestimates the rate by a factor of \( \sim 10^{-2} \sim 10^{-1} \), only a very small percentage of WD-NS/BH mergers produce GRBs, or these events are very highly beamed — with jet opening angles many times smaller than most estimates (e.g., Nakar 2007; Guetta et al. 2005). Similar statements can be made for short-duration GRBs without extended emission, or for long-duration GRBs unaccompanied by SNe (see Table 1). The natural timescale for such transients is long (\( \gtrsim 100\) s) since the WD will be tidally disrupted at a radial distance from the NS comparable to its own radius. Equation (3) implies that transients generated by WD-NS/BH mergers should be relatively common in Milky Way-like galaxies (\( \sim 10 \sim 30\% \) of the Ia rate), contrary to what is observed for long-duration GRBs (Stanek et al. 2006). Whatever transients these mergers produce (see [4] below), they should be associated with relatively old (\( \sim 1\) Gyr) stellar populations, may occur many kpc from their host galaxies, and should not correlate with recent star formation.

2. Potential Neutrino Signature: Whether the unseen companion in SDSS 1257+5428 is a NS or BH, the merger may generate an interesting neutrino signature, with a maximum possible total energy radiated of \( \sim 3 \times 10^{53} \) ergs (similar to a NS-producing core-collapse SN). However, because the accretion rate is likely to be modest, \( \lesssim 10^{-2} M_{\odot} \text{s}^{-1} \), the merger disk is unlikely to be radiatively efficient in neutrinos (e.g., Popham et al. 1998; Chen & Beloborodov 2007). Since BH formation is a likely outcome of the merger (see [6] below), a distinct signature of this NS-to-BH transformation may be seen in the neutrino (or potentially high-energy photon) lightcurve.

3. Nucleosynthesis: The outflow produced from the NS/BH during the accretion phase of the WD — either in a jet or a wind — may produce thermodynamic conditions favorable for interesting nucleosynthesis. For very high accretion rates (\( \sim 1 M_{\odot} \text{s}^{-1} \); Chen & Beloborodov 2007; Metzger et al. 2009) the outflow may become neutron rich, producing conditions favorable for production of the r-process nuclei (e.g., Metzger et al. 2007). Even in the absence of a neutron excess (as is more likely for the low accretion rates one estimates for such a merger/disk) if the dynamical timescale for ejection is short enough, the r-process might still occur (Meyer 2002). Since the rate estimated in equation (3) is relatively high with respect to NS-NS mergers (a commonly discussed r-process production site; Freiburghaus et al. 1999), WD-NS/BH mergers may make an interesting contribution to the heavy-nucleus budget of the Galaxy.

4. Optical Signature: Similar to the case of WD-WD mergers, or accretion-induced collapse of a WD to a NS as a result of accretion from a companion, as considered in Metzger et al. (2009), there may be a low-luminosity optical transient generated by \( \lesssim 10^{-2} M_{\odot} \) of $^{56}$Ni associated with the merger of WD-NS binaries. This material may be ejected as an initially proton-rich outflow from the disk around the NS or BH. The total ejecta mass would be small on the scale of normal SNe. The rate in equation (3) is small enough that such transients may be so far unknown, but we speculate that they might be linked to classes of unusual SNe like SN 1991bg (Filipenko et al. 1992), 2002bj (Poznanski et al. 2009), 2008ha (Foley et al. 2009; Valenti et al. 2009), or 2005cz (Kawabata et al. 2009) and 2005E (Perets et al. 2009). Such events should be relatively common in the local universe (\( \sim 10 \sim 30\% \) of the Ia rate), trace relatively old stellar populations, have no optically-visible progenitors, be seen many kpc from their host galaxies (e.g., SN 2005E), and many should be seen by current transient survey efforts such as LOSS (Li et al. 2000), Palomar Transient Factory (PTF) and the Panoramic Survey Telescope and Rapid Response System (PanSTARRS); the future Large Synoptic Survey Telescope (LSST) should see many hundreds per year. The composition of the ejecta may vary, depending on the type of WD disrupted (e.g., He, C/O, O/Ne/Mg).

5. Gravitational Waves: Assuming \( M_{WD} = 0.9 M_{\odot}, M_{NS/BH} = 1.6 M_{\odot} \), and \( c \approx 0 \) for SDSS 1257+5428 results in a gravitational wave (GW) strain amplitude of \( h \approx 2.3 \times 10^{-21} \), which exceeds the nominal sensitivity of LISA of \( \sim 10^{-21} \) at \( f_{GW} \sim 1 \) mHz (Roelofs et al. 2007). The estimate of equation (3) suggests that WD-NS/BH binaries will also contribute significantly to the GW background in the LISA band (Badenes et al. 2009; Kim et al. 2004), which may affect the detectability of the SDSS 1257+5428 signal. Importantly, individual mergers in the local universe may also be important GW sources for LIGO if the merger results in BH formation or if the massive NS merger remnant is initially rapidly rotating (Garcia-Berro et al. 2007; Paschalidis et al. 2009).

6. The Lowest Mass Black Holes: Note that the total mass of SDSS 1257+5428 probably exceeds the maximum mass for a NS (e.g., Lattimer & Prakash 2007). Thus, if the WD was entirely accreted, this event would be accompanied by BH formation with \( \sim 2.5 M_{\odot} \) (see Brown et al. 2001). The rate of WD-NS/BH mergers estimated in equation (3) is large enough that the Galaxy should be littered with \( \sim 2 \sim 3 M_{\odot} \) BHs; there should be \( \sim 10^{6} \sim 10^{7} \) low-mass free-floating BHs throughout the Galaxy.

7. The Origin of Ultra-High Energy Cosmic Rays: If WD-NS/BH mergers produce a BH and accretion disk (see Popham et al. 1998; Fryer et al. 1999b), the magnetic luminosity via the Blandford-Znajek mechanism will likely be large enough for production of UHECRs (e.g., Waxman & Loeb 2009; see also Waxman 1995). Because the energy reservoir in WD-NS mergers is comparable to the energy budget of GRBs, but the overall rate of WD-NS/BH mergers within the local GZK volume (\( \sim 100 \) Mpc) is \( \gtrsim 100 \) times larger (eq. 3; §2), WD-NS/BH mergers may dominate the UHECR budget. The merger may also produce a rapidly rotating (ms spin period) NS with potentially short-lived magnetar strength (\( \sim 10^{15} \) G) magnetic fields. In this case, the mechanism advocated by Arons (2003) for UHECR production may obtain. The rate needed by Arons to account for the observed UHECR budget is close to the rate derived for WD-NS/BH mergers estimated here (Table 1). Additionally, note that the formation of NS magnetar-like conditions via WD-NS/BH mergers alleviates the problem of getting UHECRs out of the overlying dense massive star progenitor discussed by Arons.

8. Binaries in Type Ic SNe: If the scenario outlined by Davies et al. (2002), which predicts a formation rate of SDSS 1257+5428-like binaries within a factor of \( \sim 1 \sim 10 \) of the estimate in equation (3), is correct, then the star that produces the NS (originally the secondary) explodes after becoming a He star and transferring a significant fraction of its envelope to...
the WD, and potentially expelling it from the system. The fact that the overall rate of Type-Ib/c SNe is $\sim 10^{-20}$% of core-collapse SNe (Prieto et al. 2008) implies that if the Davies et al. mechanism is correct, and if $\Gamma_{\text{MW}}$ is correct, then many Type Ib/c SNe ($\sim 20-50\%$) explode with a very close WD companion.

9. Tight Companion Interaction: Regardless of the binary formation channel, the SN explosion that produces the NS may interact with the close secondary, be it a WD, main sequence star, or otherwise. In this case, there may be a signal of interaction in the very early-time lightcurve of many stripped envelope Type-Ib/c SNe as a result of the break-out flash and shockwave interacting with the nearby companion (see, e.g., Marietti & Burrows 2000; Kasen 2009).

10. Star & Binary Formation: The Galactic birth rate of massive stars is approximately equal to the core-collapse SN rate. Thus, equation (3) implies that $\sim 2-4\%$ of all massive stars are born with a close binary companion capable of producing a SDSS 1257+5428-like binary. If true, this has important implications for the physics of massive star formation and the demographics of young massive star binaries (e.g., Krumholz et al. 2009), as well as for pulsar binaries. The low eccentricity of the orbit of SDSS 1257+5428 suggests interaction with the companion subsequent to the NS birth. Additionally, if WD production precedes the NS, equation (3) implies a significant number of young pulsars with very tight WD companions. However, only one such system has been detected among the $> 1000$ non-millisecond pulsars (MSPs) — the highly-eccentric PSR J1141-6545 (see Edwards & Bailes 2001; Davies et al. 2002; Kim et al. 2004) — disfavoring this as an analog. If the NS preceded the WD and was recycled into a MSP, then MSPs should be embedded in the centers of a fraction of young planetary nebulae, potentially visible either in radio and/or X-rays and gamma-rays.

Indeed, the estimate of equation (3) is large enough that the simplest explanation for the discovery of SDSS 1257+5428 is either that SWARMS was very lucky, or that instead of a WD-NS/BH binary, this system is a tight WD-WD binary (Badenes et al. 2009). Although the high nominal space velocity of the system argues against this possibility, if SDSS 1257+5428 is in fact a WD-WD binary, then the similarity between the derived rate and the observed Type Ia SN rate is not a coincidence (see Table 1), particularly in light of the results of Mulally et al. (2009) (see also Kilic et al. 2009). The relatively high value for the rate in equation (3) is yet more perplexing if the companion to the observed WD is in fact a BH, and not a NS (see Brown et al. 2001). Nevertheless, the relative lack of pulsars with tight binary companions may argue for a BH companion, and it should be kept in mind that the SWARMS survey is perhaps the first where such tight WD-BH binaries could have been detected. Clearly, a more complete census and analysis — as will be provided by the SWARMS survey (Mulally et al. 2009) — and follow-up observations of SDSS 1257+5428, including a search for (potentially pulsed) radio and X-ray emission as well as a parallax measurement, are needed. These will be vital, since, if SDSS 1257+5428 is radio-quiet, this would imply a class of binaries distinct from any presently known.

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