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NEUTRON STARS IN THE GALACTIC CENTER[†]

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Abstract: The Galactic Center is one of the most dense stellar environments in the Galaxy and is considered to be a plausible place to harbor many neutron stars. In this brief review, we summarize observational efforts in search of neutron stars within a few degrees about the Galactic Center. Up to 10% of Galactic neutron stars may reside in this central region and it is possible that more than a thousand neutron stars are located within only $\sim 25''$ (≤ 1 pc) about the Galactic Center. Based on observations, we discuss prospects of detecting neutron stars in the Galactic Center via gravitational waves as well as electromagnetic waves.

Key words: stars: neutron — pulsars: general — Galaxy: center

1. INTRODUCTION

Neutron stars (NSs) are remnants of massive stars formed during core-collapse (Baade & Zwicky 1934) or accretion-induced supernovae explosions (Miyaji et al. 1980). There are different NS populations that can be interesting for gravitational-wave (GW) observations. NS–NS binaries are expected to be strong GW sources. On August 17, 2017, a ∼100-second duration GW *chirp* signals emitted from two inspiralling NSs in a binary was observed during the second observation run (O2) with the advanced LIGO (Laser Interferometer Gravitational-wave Observatory) – advanced Virgo network. This *transient* GW signal was named GW170817 (Abbott et al. 2017a).

Theoretical models predict NSs can develop instabilities or asymmetry and emit *periodic* (or *continuous*) GWs. Rapidly spinning or highly magnetised NSs are most favored candidates to establish such instabilities (Andersson et al. 2011; Lasky 2015). Sources for periodic GWs are (a) the *isolated* NS population and (b) a population of *mass-accreting* NSs in low-mass X-ray binaries (LMXBs). Watts et al. (2008) provides a good summary on mass-accreting NSs as GW sources. Considering the theoretical predictions of source signal strength, design sensitivities of GW detectors, and observational GW frequency range between 10 – 2000 Hz, *some of the Galactic NSs emitting periodic GWs are expected to be observable.*

The GW community developed two observational strategies optimized for periodic signals: (i) all-sky blind searches and (ii) directed searches for known targets. Both approaches have been used for many years with ground-based interferometers. For example, the latest results from the full-sky, broad-band search for periodic GWs during the advanced LIGO's first observation run (O1) are presented in Abbott et al. (2018). There was no detection of GWs but this is by far the most sensitive full-sky search for periodic signals. The observation duration spans about two months. Sixty-six days of data taken between September 12, 2015 and January 19, 2016 were analyzed to look for periodic signals in the GW frequency band between 475 Hz and 2000 Hz. The search was sensitive to periodic GW signals emitted by isolated NSs with equatorial ellipticities as small as 1.8×10^{-7} at a distance up to 1 kpc (at highest GW frequencies). The distance scale corresponds to favorable binary orientations, taking into account the LIGO detector's beam response function. Directed GW search efforts for the central object associated with Cassiopeia A (a young supernova remnant at 3.4 kpc), Scorpius X-1 (an LMXB at 2.8 kpc), or a selected group of known pulsars including PSR J1813-1749 (a young pulsar, which is the counterpart of a TeV source at 4.8 kpc) were also carried out Abadie et al. (2010); Abbott et al. (2017b,c). With null detections, GW observations have only been able to put upper limits on the GW signal strengths originated from isolated or mass-accreting NSs.

In our Galaxy, most NSs were found as radio pulsars. There are almost 2700 NSs known in the Galaxy and most of them reside in the Galactic disk within a few kpc from the Earth (Manchester et al. 2005). Considering the beamed radio emission and sensitivity of surveys, it is expected that there are a lot more radio-quiet and off-beam NSs existing than the known sample of radio pulsars. NSs are also observable in X-rays or γ-rays. These high energy emission can be attributed to young, normal pulsars as pulsar wind nebulae (PWNe), old millisecond pulsars (MSPs), or NSs in LMXBs (e.g., Ritter & Kolb 2003), consisting of a NS as mass accretor.

It is expected that the Galactic Center is likely to have a good number of NSs. Results from directed GW search for periodic signals toward the Galactic Center during the initial LIGO's science run, covering the area

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within ~ 3 pc and ~ 8 pc around Sgr A*, are presented in Aasi et al. (2013). In order to improve the search strategies for NSs emitting periodic GW signals in the Galactic Center, it is important to estimate the expected NS contents in this region and to understand the confirmed NSs and/or nature of NS candidates implied by different observations.

Here, we present a concise summary on the NS populations inferred from various observations. We focus on the *Galactic Center region* (GCR), which corresponds to the region located a few square degrees or a few hundred parsecs about the Galactic Center ($-2.^\circ5 < l < 2.^\circ5$ and $|b| < 0.^\circ5$).[1]

The organization of this work is as follows. In Section 2, we calculate the number of NS candidates in the GCR based on different observations. In Section 3 we summarize our results and discuss prospects for GW detection and multimessenger astronomy.

2. Different Observations and NS Candidates in the GCR

2.1. Central Molecular Zone

The GCR is embedded in the central molecular zone (CMZ), which is a dense molecular gas layer within a few hundred pc of the central, super-massive black hole (BH). Working in Galactic coordinates, the CMZ has an extent of roughly $-1^\circ < l < 1.^\circ5$ and $-0.^\circ5 < b < 0.^\circ25$. Radio observations show that 10% of the molecular gas in the entire Galaxy is contained in this region(Güsten 1989; Serabyn & Morris 1996). The estimated stellar mass is 5×10^7 $\mathrm{M}_\odot$ within the central ~ 500 pc about the Galactic Center, corresponding to a star formation rate (SFR) of $\sim 0.3-0.6$ $\mathrm{M}_\odot \mathrm{yr}^{-1}$. As stars form directly from cooling molecular gas, the amount of gas in molecular form can be taken as a fair indication of the local SFR. Therefore, it is expected that roughly 10% of stars forming in our Galaxy today do so within the Galactic Center. Support for this hypothesis is provided by observations which reveal that $(5-10)$% of the infrared and Lyman continuum luminosity, which is measuring the presence of young, massive stars, comes from the Galactic Center (e.g., Law et al. 2008). Therefore, the GCR is likely to contain a good number of NSs, which are of interest to this work.

2.2. Supernova Remnants

More than a half of the known Galactic supernova remnants (SNRs) are considered to be core-collapsed (e.g., Tammann et al. 1994). Among the 295 known SNR (Green 2017), about 6% are located within the GCR, which is consistent with the expectations based on the CMZ observation discussed earlier. Supernovae (SNe) Type II+Ib/c are considered to be NS progenitors. Recalling the Galactic SN Type II+Ib/c rate, $\sim 1-3$ supernovae per century, then the Type II+Ib/c supernova rate in the GCR is $\sim 0.06-0.2$ per century. This implies roughly 10^7 NSs could have been formed over the past 10^{10} yr in the GCR. It is difficult to estimate age and distance of a SNR without a central object or strong absorption lines. Therefore, the NS number estimate based on the SN rate should be read as a upper limit, as the nature of the SNe as well as the association with the Galactic Center of the SNRs are not confirmed.

2.3. Radio Pulsars

Pulsars are strongly magnetised, fast-spinning NSs. Observed pulsars have surface magnetic fields $B \sim 10^8 - 10^{15}$ G and spin periods $P_\mathrm{s} \sim 1$ ms $-$ 10 s. Most pulsars are typically brightest in radio frequencies although some of them could be detected in X-/γ-rays. In this subsection, we summarize the progress made by Galactic Center pulsar surveys and empirical estimates for NS numbers in the GCR. Although distance measurements are required to confirm the association between the known pulsars and the GCR, we assume all radio pulsars found within the defined area of GCR are actually the Galactic Center population.

Johnston et al. (2006) discovered two pulsars separated from the Galactic Center less than ~ 40 pc ($\sim 0.3^\circ$), PSRs J1745−2912 and J1746−2856, from the 3.1-GHz Galactic center survey with the Parkes radio telescope. Deneva et al. (2009) reported three normal radio pulsars close to Sgr A* by 2-GHz observations with the Green Bank Telescope (GBT). Macquart et al. (2010) observed the central parsec about the Galactic Center at 15 GHz. With 10 hours of integration time, this is one of the most sensitive pulsar surveys toward the Galactic Center but they did not find any convincing pulsar candidate. The authors estimated an upper limit of 30–460 normal pulsars (with typical pulse width and radio spectrum) in the inner parsec about the Galactic Center based on the null detection and survey characteristics at the 99% confidence level. Assuming a beaming fraction of 20% for normal pulsars, this implies that there are at most a couple of thousand NSs (as observable radio pulsars) in the inner parsec about the Galactic Center.

Cordes & Lazio (1997) suggested that $10^7 - 10^8$ NSs could have formed in the central 100 pc (less than a degree) from the Galactic Center, taking into account the stellar mass of $\sim 7\times10^8$ $\mathrm{M}_\odot$that is confined in the region (Genzel et al. 1994), different initial mass functions, and a constant mass-to-light ratio for NS progenitors. Considering a typical radio pulsar with a lifetime of radio emission ($\sim 10^7$ yrs) and the mean space velocities of ~ 100 km/sec, they concluded that only 0.1% of NSs in this region would be still seen as radio active pulsars. That is, most NSs formed in central 100 pc about the Galactic Center are likely to be radio-quiet. If some NSs emit strong GWs that can be observable from the Earth, they can be accessible via GWs. If we assume a constant star formation rate over the age of our Galaxy ($\sim 10^{10}$ yrs), we can calculate the NS birth rate in this central region, i.e. $(10^7 - 10^8$ NSs$)/10^{10}$ yrs $= 10^{-3} - 10^{-2}$ NSs yr^{-1}. By multiplying the typical timescale for a radio pulsar (10^7 yrs) to this birth rate, we expect about $10^4 - 10^5$ pulsars to be located within 100 pc

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[1] $1^\circ \equiv 140$ pc for a distance from the Sun to the Galactic Center of 8 kpc.

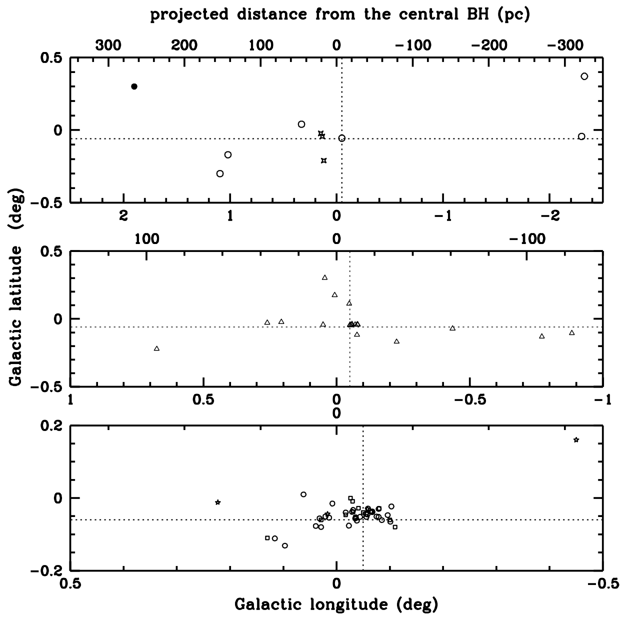

Figure 1. Projected locations of objects likely to be associated NSs in the GCR. The location of Sgr A*, $(l, b) = (359^\circ\!.95, -0^\circ\!.06)$, is indicated by the dotted guide lines. Top panel: SNRs and SNR candidates (open circles, Law et al. 2008) located in $-2^\circ\!.5 < l < 2^\circ\!.5$ and $|b| < 0^\circ\!.5$ about $(l, b) = (0, 0)$. The black dot is G1.9+0.3 (Reynolds et al. 2008), the youngest known SNR of 100 yrs of age. Crosses are radio pulsars that fall in the region (see text, also Figure 3 in Schnitzeler et al. (2016) for known radio pulsars within $\simeq \pm 0.5^\circ$ from the Galactic Center). Middle panel: 19 LMXB candidates found in $l < |1|^\circ$ and $|b| < 0^\circ\!.5$ about Sgr A*. Bottom panel: 50 X-ray filaments within the area of $l < |1|^\circ$ and $|b| < 0^\circ\!.5$ are presented. Open circles, open squares, stars are dataset from different observations.

distance about Sgr A*. This is roughly consistent with the expected number of radio pulsars obtained from radio the observations described above.

In 2013, *NuSTAR* and *Swift* discovered a SGR J1745–29 (Mori et al. 2013; Kennea et al. 2013), which has the projected distance of only 3″ (or 0.097 pc) from Sgr A* (Bower et al. 2015). This source is also confirmed to be a radio-emitting magnetar (Eatough et al. 2013) and is likely to be associated with the GCR. Magnetars form a subset of NSs with enormous surface magnetic fields larger than 10^{13} G. There are only 23 confirmed magnetars known in the Galaxy (Olausen & Kaspi 2014).[2] Since the discovery, extensive radio follow-ups for PSR J1745–2900 have been carried out with observational frequencies from ~ 1 GHz up to 291 GHz (Torne et al. 2017). Dodson et al. (2014) tried to observe PSR J1745–2900 with the Korean VLBI network (KVN). Several hours of integration time was not enough to detect the pulsed signal from this magnetar, but PSR J1745–2900 is still the most plausible pulsar target for KVN and the KVN and VERA Array (KaVA).

2.4. LMXBs

As mentioned earlier, some unidentified X-ray sources in the GCR can be associated with NSs. For example, *Chandra* found about 9000 X-ray point sources in the GCR (Muno et al. 2009) and some are speculated as LMXB/PWNe candidates. Out of 14 *Swift* transient point X-ray sources within $25' \times 25'$ region about the Galactic Center, three sources including AX1745.6-2901 are identified as NS LMXBs (Table 3 in Degenaar et al. 2015). SNRs and PSR J1745–2900 found in the Galactic Center implies young, normal pulsars and/or MSPs could be formed and exist in the Galactic Center, either in solitary or in binaries. Due to the high stellar density similar to globular clusters, LMXBs and/or even compact binaries (e.g., NS–NS binaries) can be formed in the GCR through stellar interaction. In this work, we consider NS LMXBs and Pulsar Wind Nebulae (PWNe) as candidates for the unidentified X-ray sources found in the GCR.

X-ray binaries (XRBs) consist of a compact object accretor and main sequence or late-type star as a donor. About 300 XRBs consisting of NSs as accretors are known where most of them are LMXBs in the Galactic disk and about half of them are persistent XRBs (Reig 2011; Liu, van Paradijs & van den Heuvel 2007; Liu et al. 2006). As mentioned earlier, LMXBs with NS accretors (or NS LMXBs) are considered to be detectable GW sources with laser interferometers between $10 - 2000$ Hz (e.g., Watts et al. 2008).

We note that persistent LMXBs are likely to be progenitors of millisecond pulsars (MSPs) through the long ($\sim 10^8 - 10^9$ yrs), stable mass transfer from its donor star to the NS accretor (Irwin 2005). The LMXB-MSP connection is supported by the discovery of a 'new-born' MSP coincident with a known LMXB (Archibald et al. 2009). Considering the LMXB birth rate of 10^{-6} yr^{-1} (Kalogera & Webbink 1998) and the observed LMXB candidates in the GCR, we can calculate a fraction of LMXBs in the GCR. Among the ~ 30 Chandra LMXBs within the GCR (Muno et al. 2003; Revnivtsev et al. 2008; Muno et al. 2009; Jonker et al. 2011), 19 of them are within $|l| < 1^\circ\!.0$ and $|b| < 0^\circ\!.5$ (Muno et al. 2009). Assuming all are persistent NS LMXBs, the GCR may contain $\sim 10\%$ of accreting NSs comparing with the expected Galactic population of a few hundreds. Recently, Hailey et al. (2018) suggested that if some of the non-thermal X-ray point sources could be attributed to MSPs, the upper limit of ~ 200 MSPs can reside within the 3 pc ($\sim 75''$) about the Galactic Center.

2.5. PWNe

PWNe are diffused emission observed around pulsars, typically bright in X-rays. They are considered to be signatures of young, isolated pulsars like the Crab pulsar ($\sim 10^3 - 10^6$ yrs, $B \sim 10^{12-13}$ G) or MSPs with sufficiently large spin-down energy loss. Multiwavelength observations are crucial in order to identify a counterpart of a PWN. If the pulsar moves relatively fast (with transverse speed of a few hundred km/s), the interaction between the pulsar and ambient matter creates a

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[2] `http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

Table 1
NS content in the GCR implied by different observations.

	area (deg^2)	area (l,b)	$\mathrm{M_{CMZ}}$ ($\mathrm{M_\odot}$)	$\mathrm{M_{mw}}$ ($\mathrm{M_\odot}$)	
CMZ	$2\overset{\circ}{.}5 \times 0\overset{\circ}{.}75$	$-1\overset{\circ}{.} < l < 1\overset{\circ}{.}5$, $-0\overset{\circ}{.}5 < b < 0\overset{\circ}{.}25$	a few $\times 10^7$	10^{11}	
class	area (deg^2)	area (l,b)	birth rate (yr^{-1})	$\mathrm{NS_{gcr}}$	$\mathrm{NS_{mw}}$
radio pulsars	$< 1^\circ$	$-0\overset{\circ}{.}3 < l < 0\overset{\circ}{.}1$, $\lvert b\rvert < 0\overset{\circ}{.}2$	$10^{-3} - 10^{-2}$	$10^4 - 10^5$	10^8
SNRs	$5^\circ \times 1^\circ$	$\lvert l\rvert < 2\overset{\circ}{.}5$, $\lvert b\rvert < 0\overset{\circ}{.}5$	$(2-6) \times 10^{-4}$	8	295
LMXBs	$2^\circ \times 1^\circ$	$\lvert l\rvert < 2\overset{\circ}{.}0$, $\lvert b\rvert < 0\overset{\circ}{.}5$	$\sim 10^{-6}$	19	300
PWNe	$1^\circ \times 0\overset{\circ}{.}4$	$\lvert l\rvert < 0\overset{\circ}{.}5$, $\lvert b\rvert < 0\overset{\circ}{.}2$	$\sim 10^{-4}$	50	~ 56

The *area* is a *projected* angular area (in sq-degree) about the Galactic Center for each population. We also provide the area in Galactic coordinates. The CMZ mass ($\mathrm{M_{CMZ}}$) is compared with the mass of the Galaxy ($\mathrm{M_{mw}}$). $\mathrm{NS_{gcr}}$ is the inferred number of NSs within the *area*. The birth rate for each population is estimated from $\mathrm{NS_{gcr}}$ and a characteristic lifetime. $\mathrm{NS_{mw}}$ is the Galactic sample of each population from the literature or a catalog. See text for details.

bow-shock and the PWNe often show bright point-like 'heads' and long diffused filament-like 'tails' in their morphologies (Gaensler & Slane 2006). Without correcting biases and/or clear SNR associations, it is difficult to directly compare the number of Galactic PWNe and the filament-like features found in the GCR. However, it is encouraging that there are tens of PWNe candidates clustered within only a square arcminute about Sgr A* as shown in Figure 1. Assuming some PWNe could be associated with magnetars like PSR J1745-2900, we suggest these X-ray filaments as good candidates for targeted observation with KVN/KaVA.

2.6. Gamma-Ray Sources

Recent γ-ray observations including the High Energy Stereoscopic System (HESS) Galactic Center observation, found some excess in the very high-energy (VHE) γ-ray emission (up to tens of TeV) that are extended to ~ 100 pc about Sgr A* (Abramowski et al. 2017). Although the origin of γ-ray emission in the Galactic Center is unclear, Hooper, Cholis & Linden (2018) argued that the VHE γ-ray excess could be interpreted as the emission from young pulsars (with a typical age of 10^7 yrs) in the region, assuming the two well-known γ-ray emitting pulsars in the Galactic disk, the Geminga pulsar ($\sim 3 \times 10^5$ yrs old) and PSR B0656+14 ($\sim \times 10^5$ yrs old), as representative examples for γ-ray emitting pulsars in the Galactic Center. The authors also calculated the number of γ-ray pulsars required to explain the observed γ-ray flux to be $\sim 250 - 1900$ within 70 pc about Sgr A*.

Many of the most energetic or rapidly spinning pulsars are γ-ray emitters, and hence, they are good candidates for GW sources. The *Fermi* γ-ray space telescope discovered about hundred pulsars in our Galaxy, and about 10% of them are millisecond pulsars (MSPs), with spin periods faster than 30 ms and spin derivatives less than 10^{-17} (Abdo et al. 2010). It is interesting that the fraction of MSPs in γ-ray pulsars is higher than the fraction of radio pulsars among the known sample. However, the radio versus γ-ray pulsar demography in the Galactic Center can be different from that of the disk. Further observations in γ-rays toward the Galactic Center are expected to provide independent constraints for one of the most energetic NS populations in this region.

3. DISCUSSION

Table 1 summarizes our results of confirmed NSs and NS candidates associated with the GCR. All observations considered in this work cover areas roughly consistent with the CMZ. Up to 10% of NSs in our Galaxy would reside within a few degrees from the Galactic Center, based on the estimated mass and light contents. We emphasize that the NS distribution within the GCR is likely to be *concentrated* within the central arcmin about Sgr A* as shown in Figure 1. The number of NSs in the GCR, based on the mass contents based on radio pulsar studies is roughly 10^3 (within the central arcsec) up to 10^4 (within a few degrees).[3] Considering the existence of LMXBs in the GCR, MSPs are also expected in the GCR. The future Square Kilometer Array (Dewdney et al. 2009)[4] will be a powerful tool to search and to observe MSPs in this region. Finding MSPs in the vicinity of the central black hole, as the most precise astrophysical 'clock', would be in particular useful to test the tehory of general relativity (Wharton et al. 2011; Liu et al. 2012). In principle, the current generation of laser interferometers are sensitive to detect GW signals from the GCR, provided by the strongest GW strain predicted by the theory on NS instabilities attributed to GW emission. As long as the location and pulse period and period derivatives are well constrained, directed GW observations put stronger constraints on the NS ellipticity and other GW emission mechanism.

With improved sensitivities, multimessenger astronomy can be particularly useful to confirm the nature of a unidentified X-ray source via GW observation or vice versa. Targeted imaging or astrometry with KVN will be possible for PSR J1745–2900 or other filament-like Chandra sources, if a cooled-down 6.7-GHz receiver is installed at all three KVN stations.

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[3] Although more than a half of isolated NSs formed in the Galactic disk are now distributed in the halo (Sartore et al. 2010; Ofek 2009), due to the far distance (> 20 kpc), halo NSs are difficult to observe via GWs.

[4] `https://www.skatelescope.org`

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