The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
Proceedings IAU Symposium No. 303, 2013
L. O. Sjouwerman, C. C. Lang & J. Ott

doi:10.1017/S1743921314001045

Detecting gravitational waves from the Galactic center with pulsar timing

Alak Ray[1], **Bence Kocsis**[2] **and Simon Portegies Zwart**[3]

[1]Tata Institute of Fundamental Research, Mumbai 400005, India
[2]Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA
[3]Sterrewacht Leiden, Leiden University, P. O. Box 9513, 2300 RA Leiden, The Netherlands

Abstract. Black holes orbiting the supermassive black hole (SMBH) Sgr A* in the Galactic center (GC) of the Milky Way generate gravitational waves (GW). The resulting spectrum, due to stars and black holes (BHs), is continuous below 40 nHz while individual BHs within about 200 AU of the central SMBH stick out in the spectrum at higher frequencies. The GWs can be detected by timing radio pulsars within a few parsecs of this region. Future observations with the Square Kilometer Array of such pulsars with sufficient timing accuracy may be sensitive to signals from intermediate mass BHs (IMBH) in a 3 year observation baseline. The recent detection of radio pulsations from the magnetar SGR J1745−29 very near the GC opens up the possibilities of detecting millisecond pulsars (which can be used as probes of the GWs) through lines of sight with only moderate pulse and angular broadening due to scattering.

Keywords. galaxies: nuclei – gravitational waves – pulsars

1. Introduction

The central region of the Galaxy has a dense population of visible stars and most likely, also of compact objects, such as black holes, neutron stars and intermediate mass black holes (IMBH). In combination with the supermassive black hole (SMBH), Sgr A*, these BHs or IMBH can make their presence felt e.g., by gravitational waves (GW). The Laser Interferometric Gravitational Observatory (LIGO) will attempt to detect GW by a change of baselines (the “strains” or the fractional changes) between two arms of an interferometer. The alternate idea of detecting GWs by monitoring the arrival times of radio pulses from neutron stars (pulsar timing) was proposed by Sazhin (1978) and Detweiler (1979). The formulation in terms of an array of pulsars and their correlations of pulse arrival time residuals was given by Hellings and Downs (1983). While LIGO and Advanced LIGO are sensitive to a frequency range 10Hz −100 kHz, the Pulsar Timing Arrays (PTAs) probe GWs typically in the 300 picoHz to 100 nanoHz. In this frequency band, the strongest gravitational waves are likely to be from binary systems in which two massive black holes orbit one another resulting from galaxies merging with one another. For the GW source in the central part of our own galaxy, the prospects of resolving individual objects through GW measurements improve closer to Sgr A* even if the number density of objects steeply increases inward, quite unlike the case of imaging by electromagnetic techniques. In this paper we discuss future prospects of detecting gravitational waves from the Galactic center by accurate timing of pulsars which may be discovered in the GC with sensitive telescope arrays in the future (we refer to Kocsis *et al.* (2012) for more details).

2. Sources of gravitational waves in the Galactic center

The central region of the Galaxy, very likely, has a dense population of compact objects, including about 20,000 stellar mass black holes (BHs; Morris 1993; Freitag *et al.* 2006a) and perhaps a few IMBH of mass $10^3\mathrm{M}_\odot$ IMBHs (Portegies Zwart *et al.* 2006) may be created by the collapse of Pop III stars in the early universe (Madau & Rees 2001), runaway collisions of stars in the cores of globular clusters (Portegies Zwart & McMillan 2002, Freitag *et al.* 2006b), or the merger of stellar mass black holes (O'Leary *et al.* 2006, Gültekin *et al.* 2004). The globular clusters can be tidally stripped when they sink to the Galactic nucleus as a result of dynamical friction, leaving their IMBHs behind in the Galactic nucleus. Portegies Zwart *et al.* (2006) predict that the inner 10 pc of the GC hosts 50 IMBHs of mass $M \sim 10^3\mathrm{M}_\odot$. These objects as also the stellar mass BHs are much more massive than regular stars populating the GC and they segregate and settle to the core of the central star cluster. For a circular binary of an object ($m_\star$) e.g. an IMBH or a BH, orbiting around a SMBH of mass $M_\bullet$ the orientation averaged RMS strain generated at distance D from the source in one GW cycle is

$$h_0(f) = \sqrt{\frac{32}{5}}\,\frac{M_\bullet m_\star}{D\,r(f)} = 8.8\times10^{-15} m_3 D_{\mathrm{pc}}^{-1} f_8^{2/3}\,,$$

where $D_{\mathrm{pc}} = D/\mathrm{pc}$, $m_3 = m_\star/(10^3\mathrm{M}_\odot)$, $f_8 = f/(10^{-8}\ \mathrm{Hz})$ with the GW frequency $f = 2f_{orb}$, $r(f)$ is the orbital radius around SMBH and the index 0 on h stands for zero eccentricity. The total GW signal with frequency f (the "characteristic spectral amplitude" h_c^2) from a population of sources (with a number in a shell $dN = 4\pi r^2 n_\star(r)dr$ where $n_\star(r)$ is the number density of objects) is:

$$h_c^2(f) = \frac{8\pi}{3} r^3 n_\star(r)\, h_0^2 = \frac{256\pi}{15}\frac{M_\bullet m_\star^2}{D^2}\,(\pi M_\bullet f)^{-2/3}\, n_\star[r(f)]\,.$$

The GW signal generated by a population of objects (the "foreground") is smooth if the average number per Δf frequency bin satisfies $\langle \Delta N\rangle \gg 1$. The GW spectrum becomes spiky (with $\langle \Delta N\rangle \leqslant 1$) above a critical frequency f_{res} that depends on the number of objects within 1pc of the GC and on the timing observation span. Sources within r_{res} generate distinct spectral peaks above frequency f_{res}. These sources are *resolvable.* The GW spectrum transitions from continuous to discrete at higher frequencies inside the PTA band and there may be a number of resolvable sources (Kocsis *et al.* 2012).

3. Using Pulsar Timing to detect GWs

If pulsars are observed repeatedly in time for an observation span $T = 10$ yr and with $\Delta t = 1$ week, the range of GW frequencies is: 3×10^{-9} Hz (3 nHz) $<$ f $<$ 3×10^{-6} Hz (3000 nHz). The cosmological GW background from the whole population of MBHBs is actually an astrophysical"noise" for the purpose of measuring the GWs of objects orbiting Sgr A*. The characteristic GW amplitudes (either of a stochastic background or of a resolvable source) can be translated into into a "characteristic timing residual" $\delta t_c(f)$ corresponding to a delay in the time of arrivals of pulses due to GWs, after averaging over the sky position and polarization. The timing signal to noise ratio (S/N) is proportional to $h_c/(2\pi f)$ which incorporates the $(fT)^{1/2}$ factor that accounts for the residual built-up over the number of GW cycles, h_c^2 being the characteristic spectral amplitude. The distance within which a PTA could measure the GWs of an individual source with a fixed timing precision $\delta t = 10\,\delta t_{10}$ is $D_{\delta t} = 14\, m_3 \delta t_{10}^{-1} T_{10}^{1/2} f_8^{1/6}$pc. The expressions for the strain amplitudes (see Eq. (13) and (16) of Kocsis *et al.* (2012))

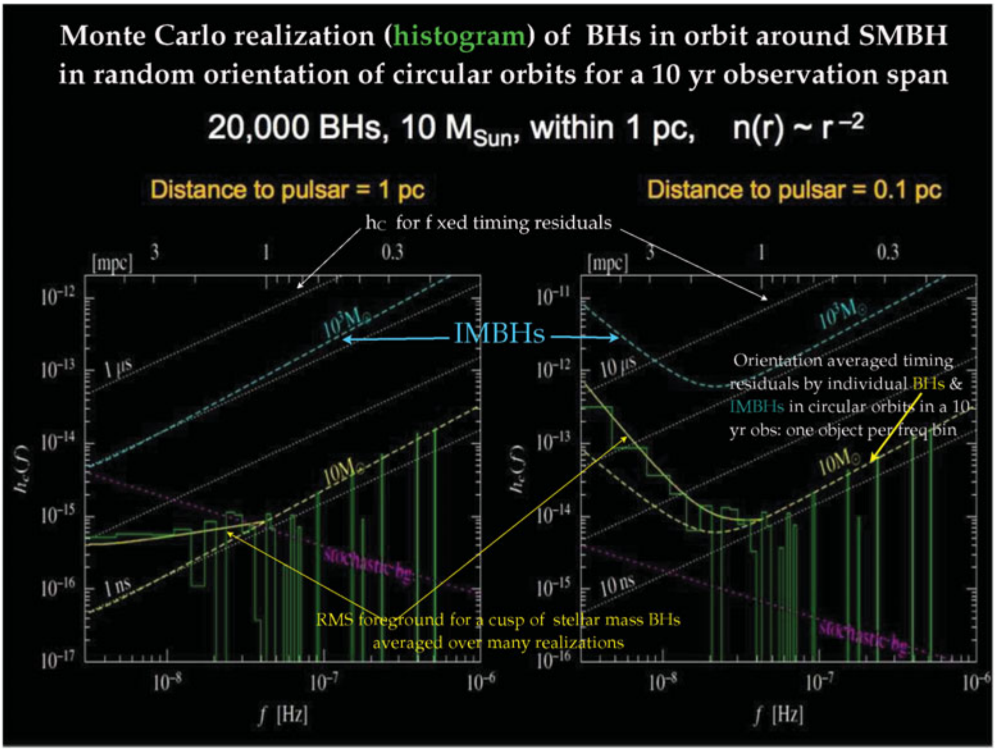

Figure 1. Phase space of characteristic strain amplitude h_c vs. GW frequency f for detection by a pulsar at 1 pc (**left**) and 0.1 pc (**right**) from the GC. Dotted white lines show the orientation-averaged h_c for fixed timing residuals. Yellow and cyan dashed lines show respectively the orientation-averaged timing residuals caused by individual stellar BHs and IMBHs on circular orbits in a 10 yr observation, assuming 1 object per frequency bin. Green lines (histogram) show the timing residuals for a random realization of $10 M_\odot$ stellar BHs in the cluster (20,000 BHs within 1 pc with number density $\propto r^{-2}$). At high f, only few bins are occupied, generating a spiky signal. Magenta dashed lines show the cosmological RMS stochastic GW background. [A color version is available online.]

for a resolved binary source and that for the stochastic GW background (dominated by SMBHB in spirals) show that the GWs from an individual BH in the GCs rises above the stochastic GW background within a distance $D_{\rm bg} = 8.7\, m_3 T_{10}^{1/2} f_8^{11/6}$pc. Thus a pulsar within $D_{\delta t}$ and $D_{\rm bg}$ to the GC could be used to detect GWs from individual objects in the GC. Prospects of GW detection from the GC depends upon future discoveries of pulsars near the GC and timing them with sufficient accuracy. Active radio pulsars/ms PSRs may segregate to the outer parts of the GC as heavier objects sink inward (Chanamé & Gould 2002). Liu *et al.* (2012) examined the expected timing accuracy of pulsars in the GC and found that the 1hr timing accuracy of SKA is expected to be between 10–100 μs for regular pulsars. Our results summarized in Figure 1 indicate that the necessary accuracy to detect timing variations associated to individual $10\,M_\odot$ BHs within 1 mpc requires much higher timing accuracy, which might be prohibitively difficult even with MSPs with a factor of 100–1000 better timing accuracy. However, the net variations caused by a population of these objects is detectable between 2–5 mpc at these accuracy levels. As seen from Figure 1, a 10–100 μs timing accuracy is sufficient to individually resolve or rule out the existence of $10^3\,M_\odot$ IMBHs within 5 mpc from

Sgr A*. As a point of reference, the Parkes Pulsar Timing Array (PPTA) project aims to time 20 pulsars, with an RMS of 100 ns over five years Wen *et al.* (2011).

4. Pulsar discovery near the Galactic center

A large population of pulsars may reside inside the GC (Pfahl & Loeb 2004, Lorimer & Kramer 2004). Wharton *et al.* (2012) predict as many as 100 canonical PSRs and a larger population of ms PSRs in the central parsec of the GC. The discovery of GC magnetar SGR J1745−29 with *NuSTAR* and subsequently in the $1.2 - 18.95$ GHz radio bands (Bower *et al.* 2014, Spitler *et al.* 2014) shows that the source angular sizes are consistent with scatter broadened size of Sgr A* at each radio frequency. This demonstrates that the two sources, separated by $3''$ (0.12 pc in projection) are both located behind the same hyperstrong scattering medium, e.g. a "thin" screen at $\sim$6 kpc from the GC. The pulse broadening timescale at 1 GHz (Spitler *et al.* 2014) is several orders of magnitude lower than the scattering predicted by NE2001 model. The scattering in the GC is lower than previously thought. The scattering material could be patchy at small angular (Spitler *et al.* 2014) and it may be possible to peer through such "keyholes" in the radio bands for a region around GC. Chennamangalam & Lorimer (2013) using Monte Carlo simulation estimate an upper limit of 950 potentially observable radio loud pulsars in the GC. However, Dexter & O'Leary (2013) point out that despite several deep radio surveys, no ordinary pulsars have been detected very close to the GC and suggest an intrinsic deficit in the ordinary pulsar population. This analysis does not constrain the millisecond pulsar population significantly as yet. Since it now appears that they can be observed at somewhat lower frequencies because of the nature of the scattering, deeper surveys at $\geqslant 8$ GHz may be able to discover them. Future discovery of such pulsars in the GC may facilitate the long term timing and search for gravitational waves due to IMBHs.

BHs in orbit around SMBH Sgr A* generate a continuous GW spectrum with $f <$ 40 nHz. Individual BHs within 1 milliparsec to Sgr A* stick out in the spectrum at higher frequency. GWs can be resolved by timing PSRs located within this region. A 100 ns - 10 μs timing accuracy with SKA will be sufficient to detect IMBHs ($10^3 M_\odot$) in a 3 yr observation if the PSR is $0.1 - 1$ pc away from Sgr A*. Unlike electromagnetic imaging, resolving individual binaries via GWs detected by pulsar timing will improve as one probes the region closer to Sgr A*.

References

Bower, G. *et al.* 2014, *ApJ* 780, L2
Chanamé, J. & Gould, A. 2002, *ApJ* 571, 320
Chennamangalam, J. & Lorimer, D. 2013, *arXiv* 1311.4846
Detweiler, S. 1979, *ApJ* 228, 939
Dexter, J. & O'Leary, R. 2013, *arXiv*:1310.7022
Freitag, M., Amaro-Seoane, P. & Kalogera, V. 2006, *ApJ* 649, 91
Freitag, M., Gürkan, M. A., & Rasio, F. A. 2006b, *MNRAS* 368, 141
Gillessen, S. *et al.* 2009, *ApJ* 692, 1075
Gültekin, K., Miller, M. C. & Hamilton, D. P. 2004, *ApJ* 616, 221
Hellings, R. W. & Downs, G. S. 1983, *ApJ* 265, L39
Kocsis, B., Ray, A. & Portegies Zwart, S. 2012, *ApJ* 752, 67
Liu, K., *et al.* 2012, *ApJ* 747, 1
Lorimer, D. & Kramer, M. 2004, *Handbook of Pulsar Astronomy*, Cambridge Univ Press
Madau, P. & Rees, M. 2012, *ApJ* 551, L27
Morris, M. 1993, *ApJ* 408, 496

O'Leary, R. M., Rasio, F., Fregeau, J. M., Ivanova, N. & O'Shaughnessy, R. 2006, *ApJ* 637, 937
Pfahl, E. & Loeb, A. 2004, *ApJ* 615, 253
Portegies Zwart, S. *et al.* 1993, *ApJ* 641, 319
Portegies Zwart, S. & McMillan, S. 2002, *ApJ* 576, 899
Sazhin, M. V. 1978, *Sov. Astron.* 22, 36
Spitler, L. *et al.* 2014, *ApJ* 780, L3
Wen, Z. L. *et al.* 1993, *ApJ* 730, 29
Wharton, R. S. *et al.* 1993, *ApJ* 753, 108