About detection of precessing circumpulsar discs

Catia Grimani

DiSBeF, Istituto Nazionale di Fisica Nucleare, Università degli Studi di Urbino ‘Carlo Bo’, Urbino (PU), I-61029 Florence, Italy

Accepted 2016 April 29. Received 2016 April 29; in original form 2015 October 12

ABSTRACT

Detections of circumpulsar discs and planetary systems through electromagnetic observations appear quite rare. In the case of PSR 1931+24 and B0656+14, the hypothesis of a precessing disc penetrating the pulsar light cylinder is found consistent with radio and gamma observations from these stars. Disc self-occultation and precession may affect electromagnetic measurements. We investigate here under which conditions gravitational waves generated by circumpulsar disc precession may be detected by the proposed second-generation space interferometers DECI-hertz Interferometer Gravitational Wave Observatory and Big Bang Observer. The characteristics of circumpulsar detectable precessing discs are estimated as a function of distance from the Solar system. Speculations on detection rates are presented.

Key words: gravitational waves – protoplanetary discs – pulsars: general.

1 INTRODUCTION

The observations of coplanar planets surrounding the millisecond pulsar PSR 1257+12 (Wolszczan & Frail 1992) and, possibly, of a disc around the anomalous X-ray pulsar (AXP) 4U0142+61 (Wang, Chakrabarty & Kaplan 2006) seem to suggest that circumpulsar disc formation occurs and that the role of these discs in pulsar spin-down (Menou, Perna & Hernquist 2001; Grimani 2009) and particle acceleration quenching in the pulsar magnetosphere (Grimani 2013) should be properly taken into account.

Jiang & Li (2005) carried out a Monte Carlo simulation of the pulsar evolution by assuming that all young pulsars are surrounded by discs. The comparison of the simulation results with observations allowed the authors to estimate the average effects of the propeller torque by constraining the parameters of the new-born pulsars in intervals of reasonable values.

The presence of circumpulsar discs was also invoked in the literature to explain observations from soft gamma repeaters (Tong, Song & Xu 2001), AXPs (Chatterjee, Hernquist & Narayan 2000), rotating radio transients (Li 2006), and central compact objects (Erdve, Kalenc & Alpar 2009). Grimani (2009) has also shown that the presence of discs near the light cylinder of a large sample of pulsars appears compatible with both observed braking indices and $e^+$ production in the Galactic pulsar magnetosphere contributing to near-Earth positron observations (Adriani et al. 2010; Aguilar et al. 2013, 2014).

In case of disc formation from supernova fallback material, it was found [Currie & Hansen (2007) and references therein] that after the supernova explosion $\leq0.1 \, M_\odot$ of material may remain with typical angular momentum of $10^{35}$ erg s. Material with this momentum value would naturally form Keplerian discs near the light cylinder of young pulsars and sets to $10^{23}$ kg the upper limit to the disc mass. However, Perna et al. (2014) have recently demonstrated that disc formation around neutron stars occurs only in case of minor magnetic coupling among star layers during the evolution and if the explosion geometry leaving the neutron star behind presents peculiar characteristics. Doubts were raised also for the case of 4U 0142+61 (Durant & van Kerkwijk 2006). Extensive campaigns of planet search around pulsars did not lead to any positive result [see Kerr et al. (2016) for instance]. In addition, small pulsar initial periods would prevent the formation of discs near the pulsar light cylinder. In Eksi, Hernquist & Narayan (2005), it is shown that fallback disc build up would not be allowed near the light cylinder of pulsars with periods smaller than approximately 40 ms. From the experimental point of view, it is difficult to prove unequivocally through electromagnetic observations that a large fraction of pulsars is surrounded by discs (Wolszczan 2008). Moreover, disc self-occultation may occur in case the outer part of the discs blocks the electromagnetic emission from the inner part. Disc precession may further reduce the detection probability. As an example, radio and gamma observations from the Rotating Radio Transients PSR 1931+24 (Li 2006) and B0656+14 (Grimani 2013), respectively, appear consistent with the presence of a precessing disc periodically entering the light cylinder of these pulsars and quenching electromagnetic emission (see Section 5 for details). The mentioned conflicting clues arising from models and electromagnetic observations do not allow us to say any final word about the presence and characteristics of discs around pulsars in the Galaxy. In Grimani (2013) we found that, in principle, the gravitational wave (GW) emission from a precessing disc around the nearby pulsar B0656+14 would have been observed by the proposed DECI-hertz Interferometer Gravitational Wave Observatory (DECIGO; Kawamura et al. 2011) and Big Bang Observer (BBO; Cutler & Harms 2006) devoted to GW detection in space.

We extend here this approach to other pulsar-disc systems to study their detectability and characteristics in the Sun environment.

* E-mail: catia.grimani@uniurb.it

© 2016 The Author

Published by Oxford University Press on behalf of the Royal Astronomical Society
This manuscript is organized as follows: Section 2 describes briefly the processes leading to the formation of circumpulsar discs. In Section 3, we find consistent, independent results indicating that pulsar birth period average values are of hundreds of milliseconds suggesting that disc formation up to distances of the order of the pulsar light cylinder cannot be excluded. In Sections 4 and 5, the characteristics of precessing discs around pulsars detectable through GW emission with the second generation space interferometer are presented. In Section 6, the advantages of the detection of GWs generated by precessing discs with respect to direct electromagnetic observations from the same discs are illustrated. Finally, in Section 7 upper limits to detection rates are discussed.

2 ORIGIN AND EFFECTS OF CIRCUMPULSAR DISCS

Two possible origins were proposed for circumpulsar disc formation: supernova fallback matter and tidal disruption (Currie & Hansen 2007). In the first case, part of the outer shell of the supernova fails to escape the gravitational potential of the neutron star. A disc can form if the fallback material has enough angular momentum (Keplerian discs) or when the total pulsar energy output equals the gravitational potential energy gained by the infalling material forced into rotation by the electromagnetic interaction with the pulsar magnetosphere (Michel 1988).

Metal-rich circumpulsar discs are expected to form from supernova fallback material. Conversely, discs should consist of light elements in case the circumpulsar material originates from a companion star tidally disrupted by the pulsar. The first scenario is conceivable with isolated pulsars, while the second may likely occur in old, millisecond pulsars.

In the paper by Menou, Perna and Hernquist (Menou et al. 2001), it is found that the characteristics of some young radio pulsars, including Crab, are consistent with the hypothesis that they are surrounded by fallback discs. We have also shown (Grimani 2013) that in the case of PSR B0656+14, a precessing disc (see also Perna, Hernquist & Narayan 2000) penetrating the magnetosphere and quenching the particle production could explain the weak pulsed gamma-ray observations from this pulsar (Abdo et al. 2010). If this is the case, the role of nearby pulsars in contributing to near-Earth positron observations at energies larger than a few tens of GeV (Grimani 2007; Bühning et al. 2008; Hooper, Blasi & Serpico 2009; Di Mauro et al. 2013) should be reconsidered accordingly.

3 NEW-BORN PULSAR INITIAL PARAMETERS

It is commonly assumed that $10^9$ neutron stars belong to our Galaxy. Isolated neutron stars are generally associated with supernova events. The distribution of massive, short-lived stars in the Galaxy spiral arms constrains the pulsar spatial distribution [see for example Faucher-Giguère & Kaspi (2006)] and the supernova explosion rate in the Milky Way of one every 50 yr (Diehl 2006) sets an upper limit to the pulsar birthrate (PB). The Fermi/Large Area Telescope collaboration has found a PB of one pulsar born every 59 yr on the basis of a Monte Carlo simulation normalized to young gamma-ray pulsar observations (Watters & Romani 2011).

Star break-up sets the lower limit to the pulsar rotation periods to about 0.6 ms, however sub-millisecond pulsars have never been observed (Du, Xu & Qiao 2009). Maciesiak, Gil & Ribeiro (2011) report that approximately 1830 pulsars are known with periods ranging from 1.4 ms to 8.5 s. The pulsar period distribution is reported in Grimani (2007), for instance.

The simulation of the active pulsar sample in the Milky Way by Faucher-Giguère & Kaspi (2006) indicates pulsar initial periods of 300±150 ms. Observational clues on initial periods are obtained for those pulsars with known ages and braking indices. For the pulsars associated with supernovae G263.9-3.3, SNR 0540-69.3, G11.2-0.3, G320.4-1.2 birth periods of 52, 63, 63, and 39 ms were found, respectively [van der Svaluw & Wu (2001) and references therein]. By using the same method, for Crab it was found 19 ms while 16 and 62 ms were estimated for the pulsars PSR J0537−6910 and PSR J1811−1925 (Faucher-Giguère & Kaspi 2006). The accuracy of this approach may be limited by the assumption that braking indices are constant over the pulsar age. This is most probably untrue since all known braking indices are smaller than 3, indicating that pulsars lose energy via processes different from the electromagnetic ones (Shapiro & Teukolski 1983). Gravitational wave energy losses (Shapiro & Teukolski 1983) and interaction with surrounding discs (Alpar et al. 2001; Menou et al. 2001; Grimani 2009) may play some role in pulsar spin-down. To this purpose, van der Svaluw & Wu (2001) considered pulsars residing in composite supernova remnants consisting of plerionic and shell-type components to estimate the pulsar birth periods. A sample of 13 composite supernova remnants was studied. These authors found that pulsar initial periods vary between 37 and 484 ms. Their findings for the pulsars associated with the supernovae G263.9-3.3, SNR 0540-69.3, G11.2-0.3, G320.4-1.2 appear consistent with those inferred from braking indices and consistent with the other results reported above. We conclude that the uncertainty on the assumption of constant braking indices over the pulsar lifetime is negligible.

PBs can be also estimated on the basis of the off-centre dipole emission in which pulsar proper motion is correlated to initial periods. It has to be pointed out that since the orbital velocity of the progenitor and asymmetric kick in the supernova explosion may affect the observed pulsar velocity, the pulsar birth periods thus obtained must be considered lower limits. By following this approach, Huang & Wu (2003) estimate normal pulsar initial periods of a few milliseconds. Vranesic et al. (2004) find that up to 40 per cent of pulsars are born with periods ranging between 0.1 and 0.5 s. Similar results were obtained by Lorimer et al. (2006) and Vivekahand & Narayan (1981). More recently, Popov & Turolla (2012) studied a sample of 30 supernova remnants to infer the associated radio initial pulsar periods by assuming a standard magnetic dipole spin-down. These authors find results compatible with a Gaussian distribution with mean and deviation of about 100 ms.

Theoretical models of cosmic ray positron production in nearby pulsar magnetospheres (Bühning et al. 2008; Hooper et al. 2009) lead to a good agreement with PAMELA (Adriani et al. 2010) data by assuming for these pulsars initial periods of 40 or 60 ms. A pulsar origin for the $e^+$ excess in cosmic rays was also considered in Grimani (2011) with analogous findings.

Bednarek & Bartosik (2004, 2005) have shown that their model for high-energy cosmic rays accelerated by pulsars appears consistent with composition and spectra observations between a few $10^{15}$ eV and a few $10^{18}$ eV by assuming for pulsar birth periods an average value of 400 ms. Giller & Lipski (2002) and Feng, Kotera & Olinto (2013) found consistent results.

In conclusion, the majority of observations and models indicate that pulsar initial periods are larger than tens of milliseconds. Therefore, in principle, circumpulsar disc formation may occur down to distances from the pulsars of the order of the light cylinder (Ekşi et al. 2005).
4 CHARACTERISTICS OF CIRCUMPULSAR DISCS

4.1 Supernova fallback matter and circumpulsar disc masses

In Section 2, we have recalled that circumpulsar discs form if the in-falling matter has an angular momentum or in the case the total pulsar energy output, \( L \), matches the gravitational potential energy gained by the in-falling matter:

\[
M \frac{GM_o}{r_c} = L,
\]

where \( G \) is the gravitational constant, \( M \) is the in-falling matter rate, \( r_c = c/\Omega \) represents the radius of the pulsar light cylinder, \( c \) is the speed of light, \( \Omega = (2\pi/P) \), \( P \) is the pulsar period and \( M_o = 1.4 \, M_\odot \) is the pulsar mass.

The characteristics of circumpulsar discs are expected to change with time. In particular, discs surrounding pulsars with ages larger than \( 10^3 \) yr are supposed to be neutral (Cannizzo, Lee & Goodman 2001; Cordes & Shannon 2008).

In case of disc formation due to the interaction of the pulsar magnetosphere with the fallback matter, the fallback matter rate can be estimated from equation (1) as a function of the pulsar period (Michel 1988). Large mass fallback rates would be needed for disc formation around young pulsars with small initial periods, while fallback matter rates of \( 10^{-9} \) \( g \, s^{-1} \) \( \cdot 10^{-13} \) \( g \, s^{-1} \) would be sufficient for disc building-up around young pulsars with periods of hundreds of milliseconds. Menou, Perna and Hernquist (Menou et al. 2001) found \( 10^{-9} \) \( g \, s^{-1} \) \( \cdot 10^{-13} \) \( g \, s^{-1} \) for the disc mass inflow that could explain observations from the Crab pulsar in the case its magnetosphere torques the disc at the edge of the light cylinder. Disc masses are expected to range in the interval between \( 10^{-7} \) and \( 10^{-2} \, M_\odot \) as an upper limit (\( 10^{-5} \)–\( 10^{-8} \) kg; see Jiang & Li 2005).

4.2 Circumpulsar disc size

Discs plausibly form at very different distances from the pulsars. The evidence of circumpulsar planet formation indicates a typical disc size of \( 10^{10} \, m \). The disc observed around the AXP 4U 0142+61 presents an internal radius of \( 2.02 \times 10^9 \, m \) and an external radius of \( 6.75 \times 10^8 \, m \). Finally, if discs form near the pulsar light cylinder, the size of the disc inner radius for young-aged (typical periods \( 40 \) ms) and middle-aged pulsars (typical periods \( 500 \) ms) would range between \( 2 \times 10^9 \, m \) and \( 2.4 \times 10^8 \, m \), respectively. On the basis of the observational clues reported above, in the following, we will consider discs with an inner radius ranging between \( 10^8 \) and \( 10^{10} \, m \) and an outer radius twice the size of the inner radius.

5 DO CIRCUMPULSAR DISC PRECESS?

The dispersed radio emission from the 1.6 million year old pulsar PSR 1931+24 is compatible with the presence of a precessing disc, formed from supernova fallback matter or interstellar matter, entering the light cylinder periodically (Li 2006). Disc precession around magnetized neutron stars was also suggested by Pfeiffer & Lai (2004). The age of PSR 1931+24 seems to indicate that pulsar-disc systems may be stable over a period of at least one million years. In Grimani (2013), it was considered that a precessing disc quenching radio and pair production in the B0656+14 magnetosphere could have explained observations from this pulsar. The presence of precessing discs was also observed in X-ray binaries and active galactic nuclei (e.g. Ogilvie & Dubus 2001) and references therein]. In the following, the Keplerian frequency associated with circumpulsar precessing discs is estimated on the basis of the size of the disc inner radius (Grimani 2009; Erkut 2011). To investigate on the possible presence of circumpulsar precessing discs, we study the detection of GWs resulting from disc precession with the second-generation space interferometers. The advantages that this technique presents with respect to electromagnetic observations are also illustrated in the next section.

6 DETECTABILITY OF CIRCUMPULSAR DISCS

6.1 Infrared/optical/X-ray surveys for circumpulsar disc detection

After the discovery of the planetary system around the millisecond pulsar PSR 1257+12, searches for circumstellar matter around neutron stars were conducted around objects of different characteristics and ages with near-, mid-, far-infrared and optical observations. The X-ray emission is found to provide precious clues about the origin of the infrared emission from the disc. In 1993, Van Buren & Tereby (1993) searched the IRAS data base for far-infrared emission from the locations of 478 known pulsars. The flux density sensitivity was larger than 500 mJy and the result was that none of the stars showed the presence of discs. A following more sensitive search for \( 10 \) \( \mu \)m emission from PSR 1257+12 indicated a flux upper limit of \( 7 \pm 11 \) mJy. Kock-Miramond et al. (2002) searched for evidence of emission at \( 15 \) \( \mu \)m from six nearby pulsars, both isolated and in binary systems, up to a distance of \( 1 \) kpc. No emission was detected. For the nearest pulsar J0108–1431, the 3\( \sigma \) upper limits on the flux density was about 66 mJy at \( 15 \) \( \mu \)m and 22.5 mJy at \( 90 \) \( \mu \)m. The authors of this work set upper limits to the mass of circumpulsar dust in a range between less than \( 10^{-23} \) kg and less than \( 10^{-21} \) kg for pulsar distances up to \( 1 \) kpc. However, these observations were mainly sensitive to dust with \( T \approx 300 \) K. In case the temperature around old neutron stars is smaller or the disc heating efficiency is quite low, sub-millimetre emission detection would be privileged.

Phillips & Chandler (1994) reported a disc search at millimetre and sub-millimetre wavelengths from five neutron stars: two middle aged, isolated pulsars with characteristic ages of \( 10^5 \text{–} 10^6 \) yr and three millisecond pulsars with ages of \( 10^8 \text{–} 10^9 \) yr. The distance of these pulsars range between \( 100 \) pc and \( 3.6 \) kpc. No emission was found down to very low noise limits. Upper limits to disc masses of \( 10^{-5} \, M_\odot \text{–} 10^{-7} \, M_\odot \) for nearby pulsars and between \( 10^{-6} \, M_\odot \) and a few \( M_\odot \) for the most distant pulsars were consequently set.

More recently, Posselt et al. (2010) presented the results of sub-millimetre measurements from RX J1856.5–3754, a neutron star located at 167 pc. Observations could have been explained by a passively irradiated disc surrounding the star. Under these conditions, a mass accretion of \( 10^{14} \, g \, s^{-1} \), a disc inner radius of \( 10^{13} \) cm and an upper limit to the disc mass of a few Earth masses were estimated.

In the case of the disc around the AXP 4U 0142+61, Wang et al. (2006) inferred from the comparison of X-ray, optical and mid-infrared observations that the disc was passively illuminated by the X-ray emission from the star. In addition, they found that accretion was not the origin of the X-ray emission since accretion would have generated an optical flux well above observations. It is assumed that the X-ray emission is due to magnetar activity. In conclusion, at present time electromagnetic surveys allow for the detection of discs with masses larger than \( 10^{-22} \) kg within a few kpc distance, at most.
6.2 Gravitational wave detection from circumpulsar precessing discs

A preliminary discussion on the possibility to detect circumpulsar planetary systems and precessing discs through GW observations near Earth was presented in Grimani (2009). The frequencies of GWs generated by circumpulsar disc precession are \( \omega \) and \( 2\omega \), where \( \omega \) is defined as it follows (Grimani 2009; Lee, Lee & Hongsu 2004):

\[
\omega = \frac{I_3}{I_1 \cos \theta} \Omega_3.
\]

(2)

We call \( I_1 \), \( I_2 \), and \( I_3 \) the principal moments of inertia with respect to the principal axes, \( x_1 \), \( x_2 \), and \( x_3 \), fixed in the disc. \( \Omega_3 \) is the angular velocity along the symmetry axis \( x_3 \) and \( \theta \) is the wobble angle defined as the angle between the angular momentum and the symmetry axis of the disc.

In the literature, \( \Omega_3 \) is commonly assumed equal to the Keplerian frequency \( \Omega_K \) (Lee et al. 2004) at the inner disc radius (see for example, Grimani 2009; Erkut 2011). We recall that the Keplerian frequency for the disc is determined from the equation \( V = \Omega_K R \), where \( V \) is the disc velocity at the inner radius, \( R \), and \( V = \sqrt{GM_*/R} \) where \( G \) and \( M_* \) were defined in Section 4.

Under the small wobble angle approximation, the GW frequencies associated with Keplerian frequencies of discs with inner radius ranging from \( 2 \times 10^6 \) m to \( 10^{11} \) m, vary between \( 10.4(20.7) \) Hz for young pulsars and \( 10^{-6} \) Hz for planetary discs.

The GW amplitudes \( (h) \) depend on the inclination angle \( (i) \) of the disc angular momentum with respect to the line of sight (see Lee et al. (2004) and references therein) for details. For instance, in the case \( i \approx 0 \) and \( \theta \) small:

\[
h \simeq \frac{G \omega^2}{c^3 r} \Delta I \dot{\theta}^2,
\]

(3)

where \( r \) is the distance between the precessing disc and the observer and \( \Delta I \) is defined as follows:

\[
I_1 = I_2 = \frac{1}{2} I_3 = \Delta I.
\]

(4)

If we take into account the component of the radiation reaction force perpendicular to the angular momentum, under the small angle approximation only, the wobble angle change can be expressed as a function of \( \theta \):

\[
\dot{\theta} = -\frac{1}{\tau_0} \theta,
\]

(5)

where

\[
\frac{1}{\tau_0} \equiv \frac{2G}{5c^3} \frac{\Delta I}{I_1} \omega^4.
\]

(6)

For the detection of GWs generated by precessing circumpulsar discs we consider the DECIGO (Kawamura et al. 2011) and BBO (Cutler & Harms 2006) missions, proposed as second-generation space interferometers. The DECIGO/BBO interferometers consist of a constellation of four triangular LISA (Laser Interferometer Space Antenna)-like apparatus (Bender et al. 1998) orbiting the Sun at 1 au. In Fig. 1, we have reported the BBO sensitivity curve (Cutler & Harms 2006; Harms, private communication). An analogous performance was predicted for DECIGO.

The BBO sensitivity curve was estimated from the experiment spectral noise densities \( S'(A); S'(E); S'(T) \) reported in equations (7) and (8) as a function of frequency, \( f \), for the experiment uncorrelated channels \( A, E, \) and \( T \) (Harms et al. 2008; Harms, private communication):

\[
S'(A) = S'(E) = 16 \sin^2(2\pi f L/c) (3 + 2 \cos(2\pi f L/c))
\]

\[
+ \cos(4\pi f L/c) S'^m + 8 \sin^2(2\pi f L/c)
\]

\[
\times (2 + \cos(2\pi f L/c)) S'^{shot},
\]

(7)

\[
S'(T) = 128 \sin^2(2\pi f L/c) \sin^2(\pi f L/c) S'^m + 16
\]

\[
\times (1 - \cos(2\pi f L/c)) \sin^2(2\pi f L/c) S'^{shot}.
\]

(8)

with test-mass noise \( S'^m = S'^m/(2\pi f c)^2 \) and shot noise \( S'^{shot} = (h_{0,0}/P_{rec} \omega_0) (2\pi f / \omega_0)^2 \) in terms of double-sided spectral densities. We recall that the channels \( A, E, \) and \( T \) are defined in terms of basic vectors \( X_1, X_2, \) and \( X_3 \). Each time-delay interferometer \( X_i \) mimic an unequal arm Michelson interferometer centred at the interferometer \( i \). The standard design of BBO provide a spectral density of test-mass acceleration \( S'^{acc} = 9 \times 10^{-34} \text{ m}^2 \text{s}^{-4} \text{ Hz}^{-1} \) assumed equal for all test masses and a light power, \( P_{rec} \), equal to 9 W as received by a spacecraft from one of its neighbours. The carrier frequency of the laser is \( \omega_0 = 5.31 \times 10^{15} \text{ s}^{-1} \) and \( L = 50 \text{ 000 km} \) is the nominal arm length of the interferometer.

The signal-to-noise (S/N) ratio for a quasi-periodic signal, can be estimated on the basis of the well-approximated expression (see for example Vetrano 2013):

\[
S/N \approx \frac{h_0}{S_0} \sqrt{\Delta f},
\]

(9)

where \( h_0 \) is the amplitude of the GW signal, \( S_0 \) is the mean value of the amplitude spectral density, and \( \Delta f \) is the observation time.

It is worthwhile to recall that discs formed near the light cylinder of young-aged (hereafter pulsars with an age <10^7 yr) and middle-aged (hereafter pulsars with an age of 10^5 yr–5 \times 10^5 yr) pulsars are expected to generate GWs that lie in the range of frequencies of maximum sensitivity of DECIGO and BBO (10^{-1}–10 Hz; see Figs 1 and 2). Gravitational waves of frequencies near 1 Hz are privileged for detection in terms of disc precession period as well. Precession...
periods of discs around middle-aged pulsars inferred from GW energy losses are larger than one million yr, while precessing periods for discs surrounding young pulsars range between a few years and thousands years. On the basis of clues reported in the literature (Patterson, Halpern & Shambrook 1993; Shepherd 2003; Montgomery 2012), we reasonably assume wobble angles ranging from 0.1 to 10 deg and disc masses up to \(10^{27}\) kg as an upper limit. This range of masses is adopted on the basis of the simulation of the Galactic pulsar sample possibly surrounded by discs (Jiang & Li 2005) and of limits on pulsar infrared observations reported in Section 6.1. DECIGO/BBO mission possible durations of 1 and 10 yr are considered.

Precessing discs with dimensions larger than \(10^{9}\) m generate GWs of frequencies \(<10^{-2}\) Hz. The amplitudes of these GWs lie below the sensitivity curves of the future space interferometers even within the assumption of 10-yr mission duration. The frequency range between \(10^{-2}\) and \(10^{-1}\) Hz corresponds to GWs generated by discs around pulsars of periods larger than 1 s. These pulsars have characteristic ages larger than one million years. There is no evidence that pulsar-disc systems survive well beyond this limit. Gravitational wave frequencies above 20 Hz would be associated with young pulsars with periods smaller than 40 ms for which disc formation is not allowed. Therefore, we draw our attention essentially to precessing discs around young- and middle-aged pulsars. Maximum distances from the Solar system of detectable circumpulsar precessing discs are reported in Figs 3–5 for frequencies ranging from 0.2 to 20 Hz as a function of the wobble angle. An S/N ratio > 5 was required.

Discs around middle-aged pulsars with masses \(>10^{25}\) kg would be detected for the whole disc precession period for wobble angles of a few degrees at distances larger than 10 kpc for 10-yr mission duration. Precessing discs with small wobble angles would be detected up to 1 kpc distance from the Solar system for disc masses larger than \(10^{26}\) kg. For discs of \(10^{25}\) kg mass detection distances would overcome 1 kpc only in case of wobble angles larger than 5 deg.

We point out that GW signals generated by precessing discs below 1 Hz lie above those expected from primordial GWs as it can be observed in Fig. 1 (Cutler & Harms 2006). Coalescing intermediate-mass black hole binaries could be also feasible sources of GWs in the same frequency range of circumpulsar precessing discs (Kawamura et al. 2011). However, doubts remain about the very existence of intermediate-mass black holes (Mapelli, Ferrara & Rea 2006).

The realization of future space interferometers appears more feasible after the first detection of GWs from a binary black hole merger (Abbott et al. 2016) and the European Space Agency in 2013 November selected the Gravitational Universe as one of its cornerstone science themes. In particular, the eLISA mission should be the first interferometer devoted to GW detection in space operating
in the interval $10^{-4}$–$10^{-1}$ Hz. The maximum sensitivity expected for eLISA is $3 \times 10^{-21}$ at $10^{-2}$ Hz (Amaro Seoane et al. 2013), while at 1 Hz is six orders of magnitude smaller than that expected for DECIGO/BBO. eLISA would be able to detect precessing circumpulsar discs within 100 pc between $10^{-2}$ and 1 Hz with an S/N ratio of 1 with 10-yr mission by assuming wobble angles of at least a few degrees. Unfortunately, as we will show in the next section, no more than one middle-aged pulsar-disc system should be found within this distance. Therefore, eLISA is not expected to be able to detect circumpulsar precessing discs.

7 UPPER LIMIT TO THE DETECTION RATE OF CIRCUMPULSAR DISCS WITH DECIGO/BBO

In order to estimate the possible number of detectable pulsar-disc systems in the Sun environment, we use the results of the work reported by Jiang & Li (2005). These authors investigate the fallback disc involved spin-down of young pulsars. In the first part of their work, they use the measured values of braking indices, second braking indices and characteristic ages of specific pulsars in addition to their surface magnetic field, matter accretion and initial periods to constrain the role of the propeller torque exerted by the discs on neutron stars. With proper assumptions on the propeller mechanisms all parameters of the studied pulsars appear in agreement with observations. In the second part of their paper, Jiang & Li (2005) simulated the evolution of $2 \times 10^6$ neutron stars up to an age of $10^8$ yr. They assumed that, in principle, disc formation could have been allowed in the whole sample of the studied stars. Plausible values following from observational evidences and theoretical models for neutron star surface magnetic fields, initial periods and disc masses were used in the simulations. For the star surface magnetic fields, a lognormal distribution of mean 12.5 and standard deviation 0.3 was considered. The neutron star initial periods were assumed uniformly distributed between 10 and 100 ms and for the initial mass of the discs the log($M_\text{disc}/M_\odot$) was uniformly distributed between $-6$ and $-2$. It was found that depending on the propeller mechanism actually applying, a fraction ranging between 25 per cent and 50 per cent of pulsars is compatible with surrounding discs in the age range $10^3$–$10^7$ yr. We conclude that, on the basis of the results reported in Section 3, the upper limit of 50 per cent of pulsars surrounded by discs follows from considering initial periods smaller than 50 ms for almost half of the simulated pulsar sample. In conclusion, this simulation work indicates that, in principle, the whole sample of isolated pulsars could be surrounded by discs if pulsar initial periods are of the order of hundreds of milliseconds. The spatial distribution of pulsars in the Galaxy can be set by Faucher-Giguère & Kaspi (2006) and Guseinov & Kosumov (1978). In these works the authors show that pulsars are concentrated in the Milky Way spiral arms and present a radial distribution with a maximum at 3.5 kpc from the Galactic Center (GC). On the basis of fig. 2 in both above papers, we find that approximately 13 per cent of pulsars can be found in the region of the Galaxy between 7.5 and 9.5 kpc from the GC. This fraction increases to 36 per cent between 6 and 11 kpc from the GC. We recall that the Solar system lies at 8.5 kpc from the GC.

By assuming a PB of one pulsar born every 60 yr (see Section 3) and an upper limit to the active pulsar lifetime of $2 \times 10^7$ yr (Michelson & Wood 1989), the maximum number of active pulsars in our Galactic disc is $3.3 \times 10^8$. This simple estimate is consistent with the results obtained with radio surveys as it can be observed in Table 1. A uniform distribution of active pulsars versus age indicates that a fraction of 2.5 per cent of the Galactic sample is constituted by pulsars younger than $5 \times 10^5$ yr: this amounts to 8250 pulsars.

The average number density of young- and middle-aged pulsars within 1 kpc from the Solar system is, for instance, 33 pulsars kpc$^{-3}$. This result follows from the aforementioned fig. 2 of the works by Faucher-Giguère & Kaspi (2006) and Guseinov & Kosumov (1978) by considering an effective Milky Way disc volume of 32.8 kpc$^3$ for the region between 7.5 and 9.5 kpc from the GC. Up to 32 pulsar-disc systems could be found within 1 kpc from the Solar system. Out of them, about 1 per cent of discs surrounding young pulsars and the whole sample of precessing discs around middle-aged pulsars could be detected. This amounts to a maximum of 26 possible detections with one-year DECIGO/BBO mission duration for disc masses above $10^{25}$ kg since middle-aged pulsars constitute 80 per cent of the total young and middle-aged pulsar sample. This number would increase up to hundreds or thousands for 10-yr mission duration in the whole considered disc mass and wobble angle range. It is worthwhile to point out that the actual number of detections would depend on the inclination angle of the disc angular momentum with respect to the line of sight.

8 CONCLUSIONS

Pulsar average initial parameters are compatible with the possibility that a large fraction of young- and middle-aged pulsars are

| Author | Number of active pulsar |
|--------|-------------------------|
| VN81   | $6 \times 10^3$         |
| LMT85  | $2 \times 10^5$         |
| N87    | $1.5 \times 10^5$       |
| LEA93  | $7 \times 10^4$         |
| VEA04  | $7 \times 10^4$–$1.2 \times 10^5$ |
surrounded by discs. Precessing Keplerian discs near the light cylinder of young- and middle-aged pulsars are expected to generate GWs in the frequency range 0.2–20 Hz. Detection of these GWs appears feasible with the proposed DECIGO/BBO space interferometers. Upper limits of the order of thousand disc-pulsar systems could conceivably be detected up to tens of kpc distance during 10 yr of space interferometer mission durations and disc mass of the order of $10^{27}$ kg for wobble angles < 1 deg. Gravitational waves generated by smaller mass precessing discs could be observed for wobble angles of a few degrees. The actual number of circumpulsar precessing disc detections will be set by individual values of the inclination angle between disc angular momentum and line of sight. The observations of GWs generated by circumpulsar precessing discs would allow us to estimate the disc geometrical characteristics and to study their role in quenching the particle production in the pulsar magnetosphere.

Cosmic ray positrons observed near Earth at energies larger than tens of GeV are produced within one kpc from the Solar system. In case they originate in the magnetosphere of middle-aged pulsars, the characteristics of circumpulsar discs inferred from GW measurements should be properly taken into account in $e^+$ production models.

ACKNOWLEDGEMENTS

This research work was funded by the Department of Pure and Applied Sciences of the University of Urbino ‘Carlo Bo’. The author is greatly indebted to Dr J. Harms of the University of Urbino ‘Carlo Bo’ for providing precious comments and suggestions in addition to the data used to reproduce Fig. 1. A special thank is due to K. J. Kieswetter for kindly proofreading the manuscript and to M. Fabi for technical support.

REFERENCES

Abbott B. P. et al., 2016, Phys. Rev. Lett., 116, 061102
Abdo A. A. et al., 2010, ApJS, 187, 460
Adriani O. et al., 2010, Astropart. Phys., 34, 1
Aguiar M. et al., 2013, Phys. Rev. Lett., 110, 141102
Aguiar M. et al., 2014, Phys. Rev. Lett., 113, 121102
Alpar M. A., Ankay A., Yazgan E., 2001, ApJ, 557, L61
Bednarek W., Bartosik K. M., 2005, Proc. of the 29th International Cosmic-Ray Conference (ICRC) (Pune), Vol. 6, p. 349
Bender P. et al., 1998, LISA Laser Interferometer Space Antenna: a corner stone mission for the observation of gravitational waves. European Space Agency Internal Report, ESA-SCI Report number 11
Büchner J., d’Erlanger C., Potgieter M. S., Venter C., 2008, ApJ, 678, L39
Cannizzo J. K., Lee H. M., Goodman J., 2001, ApJ, 351, 38
Carney J. M., Shannon R. M., 2008, ApJ, 682, 1152
Cordes J. M., Graff M., 2007, ApJ, 666, 1232
Currie T., Hansen B., 2007, ApJ, 666, 1232
Cutler C., Harms J., 2006, Phys. Rev. D, 73, 042001
D’Amico M., Donato F., Fornengo N., Lleres R., Vittino A., 2014, J. Cosmol. Astropart. Phys., 1404, 066
Diehl R. et al., 2006, Nature, 439, 45
Du Y. J., Xu R. X., Qiao G. J., 2009, MNRAS, 399, 1587
Durant M., van Kerkwijk M. H., 2006, ApJ, 652, 576
Eksi K. Y., Hernquist L., Narayan R., 2005, ApJ, 623, L41
Erdei L., Kalemci E., Alpar M. A., 2009, ApJ, 696, 1792
Erkut M. H., 2011, in Gögüüs E., Ünal Ertan, Belloni T., eds, AIP Conf. Proc. Vol. 1379, Astrophysics of Neutron Stars 2010. Am. Inst. Phys., New York, p. 103

This paper has been typeset from a $\tilde{t} \tilde{v} \tilde{X} / \tilde{B} \tilde{I} \tilde{X}$ file prepared by the author.