AR Sco as a possible seed of highly magnetised white dwarf

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17 July 2018

ABSTRACT

We explore the possibility that the recently discovered white dwarf pulsar AR Sco acquired its high spin and magnetic field due to repeated episodes of accretion and spin-down. An accreting white dwarf can lead to a larger mass and consequently a smaller radius thus causing an enhanced rotation period and magnetic field. This spinning magnetic white dwarf temporarily can inhibit accretion, spin down, and, eventually, the accretion can start again due to the shrinking of the binary period by gravitational radiation. A repeat of the above cycle can eventually lead to a high magnetic field white dwarf, recently postulated to be the reason for over-luminous type Ia supernovae. We also point out that these high magnetic field spinning white dwarfs are attractive sites for gravitational radiation.

1 INTRODUCTION

Recently, we had shown that the mass-radius ($M-R$) relation of Chandrasekhar has to be suitably modified in the case of highly magnetised white dwarfs, namely B-WDs, leading to significantly higher mass limit for white dwarfs. By means of both analytical calculations and numerical modelling, we carried out a systematic study of how a strong magnetic field affects the structure and properties of the underlying white dwarf in a variety of ways. We progressed from constructing simplistic to more rigorous and self-consistent models (see, e.g., Das & Mukhopadhyay 2013; Das, Mukhopadhyay & Rao 2013; Subramanian & Mukhopadhyay 2015; Mukhopadhyay & Rao 2016). After our initiation, other independent groups also examined the implications of high magnetic fields for the mass-radius relation of white dwarfs (e.g. Liu, Zhang & Wen 2014; Bera & Bhattacharya 2016; Belyaev et al. 2015; Franzon & Schramm 2015).

The prime motivation of the B-WD model was to explain the peculiar over-luminous type Ia supernovae (Das & Mukhopadhyay 2015). The question, however, remained about the mechanism by which white dwarfs can attain high magnetic fields. The related question is to explore the observational consequences of the existence of a large number of B-WDs and proto-B-WDs. Since an increase in the mass of white dwarf leads to a decrease in its radius, the mechanism of accretion leading to an increase in its magnetic field by flux freezing, and hence leading to B-WDs, was also qualitatively explored to explain some other observed phenomena. They are soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs), particularly the ones exhibiting high X-ray luminosities (Mukhopadhyay & Rao 2016) which posit problem on the neutron star based model (see, e.g., Mereghetti 2012), and some white dwarf pulsars e.g. GCRT J1745-3009 (Zhang & Harding 2000; Mukhopadhyay & Rao 2016).

The recent discovery of a rotating magnetised white dwarf (Marsh et al. 2016) in AR Scorpii (AR Sco) demonstrates that some white dwarfs do acquire high magnetic field and high spin period. The evolutionary scenario of AR Sco, though not fully explored (see, however, Beskrovnaya & Ikhsanov 2016) in the literature, could involve the scenario envisaged for the generation of high magnetic field in B-WDs (accretion resulting in smaller radius). In this paper, we explore this possibility and point out that AR Sco appears to be a very suitable candidate to be a seed B-WD.

In the next section, we discuss the $M-R$ relations of moderately magnetised B-WDs, with surface (and central) magnetic fields similar to those inferred for AR Sco. Subsequently, in §3 we will discuss the possible time evolution of AR Sco and how being in a $M-R$ trajectory of moderately magnetised white dwarfs, it is expected to switch to a $M-R$ trajectory of B-WDs. We will also comment on the possible emission and detection of gravitational waves from it and in general B-WDs in §4, apart from the fact that the glitches and outbursts seen in SGRs/AXPs can be explained in the B-WD premises. Finally we end with a conclusion in §5.

2 MODERATELY MAGNETIZED WHITE DWARFS: PULSAR AR SCO

AR Sco has been shown to be a rotating magnetised white dwarf (Marsh et al. 2016). This is argued based on various properties of it, e.g. increasing optical flux detected in radio,
higher spin-down power compared to electromagnetic radiation, no obvious sign of accretion, broadband spectrum characteristic of synchrotron radiation requiring relativistic electrons etc. The underlying white dwarf/cold star binary system emits radiation from X-ray to radio, which is pulsating in brightness on a period $P = 1.97$ min and period derivative $\dot{P} \approx 4 \times 10^{-13}$ sec$^{-1}$. The maximum and mean luminosities of AR Sco are $\sim 6.3 \times 10^{32}$ erg s$^{-1}$ and $\sim 1.7 \times 10^{32}$ erg s$^{-1}$ respectively. The mass $M$ of the white dwarf inferred to be in the range $0.8 - 1.29M_\odot$, where $M_\odot$ is the mass of the Sun. For the corresponding radius $R = 7000 - 3200$ km, the spin-down power turns out to be $L_\nu \sim 1.5 \times 10^{32-33}$ erg s$^{-1}$, which is adequate to explain its luminosity mentioned above. However, a neutron star based model with its typical mass and radius, $L_\nu$ turns out to be much smaller $\sim 10^{28}$ erg s$^{-1}$, which rules it out to be a spinning down neutron star. In the framework of an accreting compact object (which indeed does not have any sign in it), a neutron star requires the accretion rate $\dot{M} \sim 10^{-14}M_\odot$ yr$^{-1}$, while a white dwarf needs to have a much higher rate $\dot{M} \sim 1.3 \times 10^{-11}$ M$_\odot$ yr$^{-1}$ which is very high to see the Doppler-broaden emission lines from accretion, but AR Sco shows features from M-star.

Keeping all the features in mind, AR Sco is confirmed to be a white dwarf rather than a neutron star, which qualifies it to be the first ever detected white dwarf radio pulsar. Its surface magnetic field can be estimated by assuming the standard dipole radiation from rotating magnetised compact objects (e.g. Mukhopadhyay & Rao 2016, see §3 for details) as $B_0 \sim \sqrt{5c^3 MPP}/4\pi^2 R^4 \sin^2 \alpha \sim 6 \times 10^{8-9}$ G with the angle between the spin and magnetic axes $\alpha = 90$ degree, where $c$ is the speed of light. However, for smaller $\alpha$, which cannot be ruled out (see, e.g., Tong & Xu 2012), $B_0$ could exceed $10^{11}$ G. As a range of mass is inferred for AR Sco from observation which corresponds to a range of radius, a range of $B_0$ is inferred. Hence, central field $B_0$ could even be $10^{14}$ G. Such $B_0$ and $B_c$ could influence stellar structure due to the effect of magnetic pressure, however, are small enough to practically affect electron-degenerate matter. Hence, Chandrasekhar’s equation of state (Chandrasekhar 1935) would suffice.

In the presence of stronger magnetic fields, even for $B_0 \sim 10^{14}$ G as is expected in AR Sco, white dwarfs’ structure and $M - R$ relation may deviate from that of Chandrasekhar’s theory. In fact, such white dwarfs (and B-WDs) need not necessarily be spherical, depending on the field values. Such B-WDs were explored in past by us and other groups (Das & Mukhopadhyay 2015; Franzon & Schramm 2015; Bera & Bhattacharya 2016), when the focus was mainly to investigate how massive B-WDs could be in the presence of various kinds of fields. For the present purpose, when field magnitudes are rather restricted from observational inference, we construct $M - R$ relations of B-WDs based on publicly available LORENE code\footnote{\url{http://www.lorene.obspm.fr}} (Bocquet et al. 1995; Bonazzola et al. 1993). By construction, LORENE describes compact stars, in the general relativistic framework, having purely poloidal fields. Such B-WDs could be oblate, depending on field strength, with a smaller equatorial radius ($R_e$) compared to their weakly magnetic counterparts (see, e.g., Subramanian & Mukhopadhyay 2015), unlike toroidally dominated B-WDs which are prolate spheroids. Their mass is also restricted to $\sim 2M_\odot$, unlike their toroidally dominated counterparts (Das & Mukhopadhyay 2015; Subramanian & Mukhopadhyay 2015). However, such massive B-WDs are possible for $B_c \gtrsim 3 \times 10^{14}$ G. As mentioned above, fields in AR Sco are smaller.

Figure 1 describes the $M - R$ relation obtained by LORENE keeping the field restriction in AR Sco in mind. We also choose the star to be rotating with period 1.95 min, as is for the white dwarf in AR Sco. In order to obtain a solution, hence $M$ and $R$, by LORENE, first we assign a central density ($\rho_c$) and a certain parameterisation of the magnetic fields (and hence current), namely “charge function”. Each $M - R$ curve’s the sequence of top-most to bottom-most points follow the sequence of increasing $\rho_c$, for a given charge function. Now with the change of charge function, we obtain the family of $M - R$ relation, shown in Fig. 1. For a given charge function, increasing $\rho_c$ corresponds to increasing $B_c$ and $B_e$ for self-consistency\footnote{2 However, the trend of increasing fields with the increase of $\rho_c$ would change for the very high field stars.}, as given in Fig. 1 caption. The readers interested to understand more details are referred to the LORENE manual. As seen in Fig. 1, generally $M$ decreases as $\rho_c$ decreases along with increasing $R$ for low (or non) magnetic white dwarfs, which bring them in the very similar trend, except for the top two curves. The maximum $\rho_c$, for completeness, is chosen to be $2 \times 10^{11}$ g cm$^{-3}$ which leads to an unstable zone in the $M - R$ curve where $M$ further decreases with increasing $\rho_c$. Upto $\rho_c \sim 2 \times 10^{10}$ g cm$^{-3}$, however, the $M - R$ curve remains stable. The chosen minimum $\rho_c$ is $6.3 \times 10^6$ g cm$^{-3}$, except for top two curves where they are $2 \times 10^7$ g cm$^{-3}$ (top but one) and $1.3 \times 10^8$ g cm$^{-3}$ (top-most). For $B_c > 2 \times 10^{12}$, i.e. for top two curves, the trend changes. This is because at lower densities, gravitational power decreases rendering a bigger size of white dwarfs which however would be massive due to the additional effects of stronger magnetic pressure unlike the nonmagnetic (low magnetic) cases. For $B_c < 10^{11}$ G and $B_e < 10^{12}$ G, $M - R$ relations are practically same as of non-magnetic white dwarfs.

However, Fig. 1 shows that in the mass range $0.8 - 1.29M_\odot$, the increase in radius due to such stronger fields could be at most a factor of 1.6 only which would render about a factor of 2.6 increase only in $L_\nu$. Hence, apparently the fields in AR Sco seem not to be playing any practical role in determining its mass and radius currently, which eventually controls its observed luminosity. Nevertheless, note importantly that all the inferences are based on LORENE with purely poloidal field geometry, which need not be the general configuration.
where $G$ is Newton’s gravitation constant. Therefore, for $M_1 = 4 \times 10^{33}$ gm, $M_2 = 2 \times 10^{33}$ gm, $r_1 = 5 \times 10^5$ km and $r_2 = 10^5$ km, $\Delta t$ turns out to be below $10^8$ Yr and hence significant binary shrinkage is justified during the repeated episodes of mass accretion and spin-powered phases. However, such a white dwarf (might turn out to be a B-WD candidate) would also radiate gravitational wave due to its non-spherical shape as a consequence of magnetic effects and spinning nature (as will be discussed more quantitatively in §4).

Hence, after restarting accretion, the whole cycle described above would repeat again and again rendering much of mass in a CV and in the following we sketch a tentative scheme of repeated episodes of mass accretion as a reason for the high magnetic field and spin rate in AR Sco. This mechanism can quite possibly lead to a B-WD. An accretion driven scenario for the spin-up of AR Sco has been considered by Beskrovnaya & Ikhsanov (2016) and here we present a comprehensive picture of the increase of mass, spin, and magnetic filed in white dwarfs, which might eventually lead to a B-WD. It is important to note the observational evidence for transitions between rotation/spin-powered and accretion-powered phases in a binary millisecond pulsar (Papitto et al. 2013) — further strongly motivating us to explore similar possibility in the case of a white dwarf pulsar.

We assume that AR Sco actually was a binary which accretes mass from its companion. As a result of mass gain, its gravitational power might have increased rendering decreasing radius and from the flux freezing increasing of its any initial magnetic fields. On the other hand, due to the conservation of angular momentum, its angular velocity and hence spin frequency varies with the change of mass and radius, whether decreasing or increasing, that depends on the trend of moment of inertia (i.e. $MR^2$), as depicted in Fig. 2 (will be discussed below). In addition, at some point, accretion might also have been inhibited temporarily due to appreciable increase in fields creating significant outward force to oppose infall (this also could be due to its entering in the propeller phase, see, e.g., Ghosh 1995). As a result, it would behave as a spin-powered pulsar (we interchangeably use the phrase rotation-powered and spin-powered) with increasing spin period $P_s$ and with time $P_s$ turns out to be what we see today.

After $\gtrsim 10^9$ Yr (as verified in §3, Fig. 4), due to continuous radio emission, its angular velocity as well as fields would decay significantly (as is the case for a rotating dipole, see, e.g., Jackson 1999) and eventually radiation would stop. However, at this stage it would start accreting again. Moreover, because of the shrinkage in the binary system resulting from gravitational wave emission, the white dwarf by this time would acquire stronger gravitational power to accrete matter from the companion more efficiently. A simple estimate (Bertschinger & Taylor 2015) argues that the time $\Delta t$ taken for the decrease of separation between white dwarf of mass $M_1$ and its companion of mass $M_2$ from $r_1$ to $r_2$ is given by

$$\Delta t = \frac{5}{256 G^3} \left( \frac{r_1^3 - r_2^3}{M_1 M_2 (M_1 + M_2)} \right),$$

where $G$ is Newton’s gravitation constant. Therefore, for $M_1 = 4 \times 10^{33}$ gm, $M_2 = 2 \times 10^{33}$ gm, $r_1 = 5 \times 10^5$ km and $r_2 = 10^5$ km, $\Delta t$ turns out to be below $10^8$ Yr and hence significant binary shrinkage is justified during the repeated episodes of mass accretion and spin-powered phases. However, such a white dwarf (might turn out to be a B-WD candidate) would also radiate gravitational wave due to its non-spherical shape as a consequence of magnetic effects and spinning nature (as will be discussed more quantitatively in §4).

Hence, after restarting accretion, the whole cycle described above would repeat again and again rendering much
stronger fields eventually. Note that once the binary shrinkage takes place significantly, the decay phase of angular velocity and magnetic fields gets abolished and frequency and fields both would start increasing uninterruptedly, until the companion is exhausted. As a consequence, the underlying white dwarf would not follow the theory of non-magnetic white dwarfs and would cross the Chandrasekhar’s limit. Eventually, it would deviate from Chandrasekhar’s $M - R$ trajectory to B-WD’s trajectory, as demonstrated earlier by Das, Mukhopadhyay & Rao (2013).

Based on a toy model, the above speculative proposition can be examined. There are two phases: accretion-powered and rotation-powered. There are three conservation laws controlling the accretion-powered phase: linear and angular momenta conservation and conservation of magnetic flux, around the stellar surface, which could be closer to the inner edge of accretion disc depending on the field strength, given by

$$l\Omega(t)^2 R(t) = \frac{GM(t)}{R(t)^2},$$

$$l(t)\Omega(t) = \text{constant},$$

$$B_s(t)R(t)^2 = \text{constant},$$

(2)

where $l$ takes care of inequality due to dominance of gravitational force over the centrifugal force in general (so that terms with pressure and magnetic fields are parameterized in $l$; larger the value of $l$, stronger the effects of pressure and fields over rotation assumed), $I$ is the moment of inertia of star and $\Omega$ is the angular velocity of the star which includes the additional contribution acquired due to accretion as well. Solving equations in (2) simultaneously, we obtain the time evolution of radius (or mass), magnetic field and angular velocity during accretion. Accretion stops when

$$-\frac{GM}{R^2} = \frac{1}{\rho} \frac{d}{dt} \left[ \frac{B^2}{8\pi} \right]_{r=R} \sim -\frac{B_s^2}{8\pi R \rho},$$

(3)

where $\rho$ is the density of inner edge of disc.

If the magnetic field is of dipole nature, $\dot{\Omega} \propto \Omega^2$ for a fixed magnetic field (see, e.g., Mukhopadhyay & Rao 2016), where over-dot implies time derivative. Generalizing it, for the present purpose we assume $\dot{\Omega} = k\Omega^m$ with $k$ being constant. Therefore, during the phase of spin-powered pulsar (when accretion inhibits, even temporarily), without having explicit knowledge of field geometry, time evolution of angular velocity and surface magnetic field are given by

$$\Omega = \left[ \Omega_0^{1-n} - k(1-n)(t-t_0) \right]^{1/n},$$

(4)

$$B_s = \sqrt{\frac{5c^3 I k \Omega_0^{n-m}}{R^6 \sin^2 \alpha}},$$

(5)

where $\Omega_0$ is the angular velocity at the beginning of spin-powered phase (when accretion just stops) at time $t = t_0$, $k$ is fixed in order to constrain $B_s$ at $t = t_0$, at the beginning of first spin-powered phase, which is known from the evolution of fields in the preceding accretion-powered phase. Note that $n = m = 3$ corresponds to dipole field, hence $m$ represents the deviation from dipolar field particularly for $n = 3$.

Figure 2 shows a couple of sample possible evolutions of angular velocity and magnetic field with mass. Note that the mass of star is varying with time (shown in Fig. 4 below) and hence considered in the horizontal axis to describe the evolution. $M$ in all the accretion-powered phases is chosen to be $10^{-8}M_\odot\text{yr}^{-1}$, which is slightly higher than that of a typical intermediate polar, but an order of magnitude lower $\dot{M}$ would also suffice our purpose. Other parameters, mentioned in the Fig. 2 caption, are some of their typical representative values. In both the cases, initial larger $\Omega$ with accretion is seen to be dropped significantly during spin-powered phase (when accretion stops and hence no change of mass), followed by a phase of its increasing trend. The case with solid line shows a few such phases/cycles with dip; they are determined by the choice of $n$ and $m$. Similar trend is seen in surface magnetic field profiles with a sharp increasing trend (with value $\sim 10^{11}$ G) at the last cycle. This corresponds to the increase of $B_c$ as well leading to a B-WD. At the end of evolution, it could be left out as a super-Chandrasekhar white dwarf and/or a SGR/AXP candidate with a higher spin frequency. Of course, they are just representative samples and they may depend on many other factors and hence they apparently do not match exactly with what is expected to happen in AR Sco itself.

Figure 3 shows how the $M - R$ trajectory with the increase of fields could deviate from Chandrasekhar’s to B-WD’s ending with an eventual larger limiting mass. This is similar to what was argued earlier (Das, Mukhopadhyay & Rao 2013) in the presence of even stronger fields. With the increase of mass due to accretion, radius decreases which leads to the increase of magnetic fields assuming conservation of magnetic flux. Increasing magnetic fields however creates increasing outward pressure which is able to oppose stronger gravitational field even at lower density. This eventually leads to massive super-Chandrasekhar white dwarfs even below $\rho_c = 2 \times 10^{10}$ g cm$^{-3}$. Figure 4 confirms that the above mentioned increase of mass $\Delta M$, with $\dot{M} \sim 10^{-8} M_\odot\text{yr}^{-1}$, would complete in $\sim 10^9$ yr, which is quite legitimate given the current age of Universe. It is clear by comparing Fig. 4 with Fig. 2 that the dip of $\Omega$ and $B_s$ in the latter corresponds to the sharp increase of $t$ in the former, as in the spin-powered phase there is no change of mass.

As indicated in Fig. 2 qualitatively, repeating the cycles described above will reveal lower and lower $P_s$ apart from higher and higher fields, ending up forming a fast spinning B-WD, which might behave as a SGR/AXP. For quantitative estimates, one should explore more rigorous model. Indeed, several SGRs/AXPs have been argued to be fast spinning B-WDs and those sources are successfully explained without invoking extraordinarily high unobserved yet magnetic fields (Mukhopadhyay & Rao 2016). As B-WDs are expected to be about 100 pc away, many AR Sco like objects are expected to be seen in future astronomical missions like Square Kilometer Array (SKA).
Figure 2. Time evolution of (a) angular velocity in sec$^{-1}$, (b) magnetic field in G, as functions of mass in units of solar mass. The solid curves correspond to the case with $n = 3$, $m = 2.7$, $\rho = 0.05$ gm cm$^{-3}$, $l = 1.5$ and dotted curves correspond to the case with $n = 3$, $m = 2$, $\rho = 0.1$ gm cm$^{-3}$, $l = 2.5$. Other parameters are $k = 10^{-14}$ CGS, $M = 10^{-8} M_\odot$ yr$^{-1}$, $\alpha = 10$ degree and $R = 10^4$ km at $t = 0$.

4 EMISSION OF GRAVITATIONAL WAVE AND STAR-QUAKE

Neutron stars are already proposed to be the candidates of continuous gravitational wave signal due to their quadrupolar nature. Such a signal is possible to emit by a tri-axial compact star rotating around a principle axis of inertia due to its quadrupole moment characterized by the amplitude \citep{Palomba2013}

$$h_+(t) = h_0 \left( \frac{1 + \cos^2 \alpha_0}{2} \right) \cos \Phi(t), \quad h_{\times}(t) = h_0 \cos \alpha_0 \sin \Phi(t),$$

where $\alpha_0$ is the inclination of the star’s rotation axis with respect to the line of sight and

$$h_0 = \frac{4\pi^2 G I_{zz} \epsilon}{c^4 P_s^2 d^2} \Phi(t)$$

$\Phi(t)$ is the signal phase function, $I_{zz}$ is the moment of inertial about z-axis, $\epsilon$ is the measure of ellipticity of the star and $d$ is the distance of the star from the detector.

As rotating B-WDs are ellipsoid and could rotate faster than their standard counter-parts, they also could be plausibly candidates for continuous gravitational wave signal \citep[see also][]{Heyl2000, Franzon2017}. A B-WD with mass $\sim 2M_\odot$, polar radius $\sim 700$ km, $P_s \sim 1$ sec \citep{Subramanian2015}, $\epsilon \sim 5 \times 10^{-4}$ and at $\sim 100$ pc away from us would produce $h_0 \sim 10^{-22}$, which is within the sensitivity of the Einstein@Home search for early Laser Interferometer Gravitational Wave Observatory (LIGO) S5 data \citep{Palomba2013}. However, a firm confirmation of gravitational wave emission can be provided by detectors more sensitive in their frequency range like Deci-hertz Interferometer Gravitational wave Observatory or Big Bang Observer \citep[DE-CIGO/BBO][]{Yagi2011}. In fact, if the B-WD’s polar radius is $\sim 2000$ km with $P_s \sim 10$ sec and other parameters intact, even DECIGO/BBO can detect it with $h_0 \sim 10^{-23}$. Nevertheless, high magnetic field rotating white dwarfs approaching B-WDs would be common and it is possible that such white dwarfs of radius $\sim 7000$ km, $P_s \sim 20$ sec and $d \sim 10$ pc will have a $h_0 \gtrsim 10^{-22}$ which is detectable by Laser Interferometer Space Antenna (LISA) \citep{Moore2015}. Note that the chosen value for $\epsilon$ needs to be realised based on rigorous theory.

Also if observed spin-down is totally due to gravitational wave emission, the absolute upper limit of signal is \citep{Palomba2013}

$$h_{0d}^s = 8.06 \times 10^{-19} I_{45} d_{kpc}^{-1} \sqrt{[\nu_s/\text{Hz} \text{sec}^{-1}]/\nu_s/\text{Hz}}, \quad \text{(8)}$$

where $\nu_s = 1/P_s$, $I_{45}$ is the moment of inertia in units of $10^{45}$
Figure 4. Time taken in Yr to evolve the mass and magnetic fields of white dwarfs shown in Fig. 2.

\[ \Delta E_G \sim \frac{GM^2}{R} \frac{\Delta R}{R} \]  

(10)

Here \( \Delta \) denotes the change of respective quantities. The corresponding gain of rotational energy is

\[ \Delta E_{\text{rot}} = -4\pi^2 I \frac{\Delta P_s}{P_s^3} \]  

(11)

For a \( 2M_\odot \) B-WD with \( R \sim 1000 \text{ km} \), \( \Delta E_G \sim 5 \times 10^{51} \Delta P_s/P_s \) and \( \Delta E_{\text{rot}} \sim -1.6 \times 10^{51} \Delta P_s/P_s^3 \), hence rotational energy could be explained by available gravitational energy, particularly for \( P_s \sim 1 \text{ sec} \), and observed flares/gaint-flares/outbursts in SGRs/AXPs of energy \( 10^{43} - 10^{46} \text{ ergs} \) could be explained as star quakes.

5 CONCLUSION

The idea of B-WD is in the literature for quite sometime (see also Ostriker & Hartwick 1968), however without any direct proof of their existence. The major motivation of introducing B-WD by us was to explain peculiar over-luminous type Ia supernovae. Later on, other sources like SGRs/AXPs, a white dwarf pulsar were also explained under the B-WD premise. Nevertheless, there is no direct observational evidence for them yet. Of course, due to the small size, they were speculated to be of low luminosity (Das & Mukhopadhyay 2014). Also, as total gravitational force of B-WDs does not appear to change significantly (for similar radius, there may be about 50\% increase of mass), in the presence of high magnetic field, thermal pressure and hence luminosity may be decreased (which however needs to be checked in a rigorous calculation).

We have explored the possibility of AR Sco being the seed of B-WD. Although observed data of AR Sco currently at hand do not seem to violate Chandrasekhar’s theory, we have shown that weak magnetic fields in the underlying white dwarf may enhance during accretion, which may deviate it from Chandrasekhar’s \( M - R \) trajectory and leading to a spinning B-WD in the life-time of Universe. This is however an exploratory study based on a simple model, which should be re-investigated in detail in future.

We have also touched upon the issue of gravitational wave possibly emitted from B-WDs. While LISA appears to be very appropriate to detect them, even LIGO S5 may do so. All in all, the present work is the first attempt to unfold the issue of direct observational evidences of B-WDs. Although not evident yet, it indicates a plausible path and future prospect of their direct detection.

6 ACKNOWLEDGMENT

We thank Varun Bhalerao, A. Gopakumar and Nirupam Roy for discussion. The work was partly supported by the project with research Grant No. ISTC/PPH/BMP/0362.
REFERENCES

Belyaev V. B., Ricci P., Simkovic F., Adam J., Tater M., Truhlík E., 2015, Nucl. Phys. A, 937, 17
Beskrovnaya N. G., Ikhsanov N. R., 2016, Proceeding of the “Stars from collapse to collapse”, Nizhnij Arkhyz, Karachai-Cherkessian Republic, Special Astrophysical Observatory of the Russian Acad. of Sci., October 3-7, 2016; arXiv:1612.07831v1
Bera P., Bhattacharya D., 2016, MNRAS, 456, 3375
Bertschinger E., Taylor E. F., 2015, in AW Physics Macros, GravWaves150909v1, 1, 15
Bocquet M., Bonazzola S., Gourgoulhon E., Novak J., 1995, A&A, 301, 757
Bonazzola S., Gourgoulhon E., Salgado M., Marck J. A., 1993, A&A, 278, 421
Chandrasekhar S., 1935, MNRAS, 95, 207
Das U., Mukhopadhyay B., 2013, Phys. Rev. Lett., 110, 071102
Das U., Mukhopadhyay B., 2014, MPLA, 29, 1450035
Das U., Mukhopadhyay B., 2015, JCAP, 05, 016
Das U., Mukhopadhyay B., Rao A. R., 2013, ApJ, 767, L14
Franzon B., Schramm S., 2015, Phys. Rev. D, 92, 083006
Franzon B., Schramm S., 2017, MNRAS, 467, 4484
Ghosh P., 1995, ApJ, 453, 411
Liebert J., Ferrario L., Wickramasinghe D. T., Smith P. S., 2015, ApJ, 804, 93
Jackson J. D., 1999, in Classical Electrodynamics, 3rd Edn., John Wiley & Sons
Heyl J. S., 2000, MNRAS, 317, 310
Liu W.-M., Li, X.-D., 2016, ApJ, 832, 80
Liu H., Zhang X., Wen, D., 2014, Phys. Rev. D, 89, 104043
Marsh T. R., et al., 2016, Nature, 537, 374
Mereghetti S., 2012, in Proceedings of the 26th Texas Symposium on Relativistic Astrophysics, Sao Paulo, December 16-20, 2012; arXiv1304.4825
Moore C. J., Cole R. H., & Berry C. P. L., 2015, Class. Quant. Grav., 32, 015014
Mukhopadhyay B., Rao A. R., 2016, JCAP, 05, 007
Ostriker J. P., Gunn J. E., 1969, ApJ, 157, 1395
Ostriker J. P., Hartwick F. D. A., 1968, ApJ, 153, 797
Paczynski B., 1990, ApJ, 365, L9
Palomba C., 2012, the LIGO Scientific Collaboration and the Virgo Collaboration – Proceedings of the Recontres de Moriond, 2011; arXiv:1201.3176
Papitto A., et al., 2013, Nature, 501, 517
Subramanian S., Mukhopadhyay B., 2015, MNRAS, 454, 752
Tong H., Xu R. X., 2012, ApJ, 757, L10
Warner B., 1995, Cam. Astrophys. Ser., 28
Whelan J., Iben I. Jr., 1973, ApJ, 186, 1007
Yagi K., Seto N. 2011, Phys. Rev. D, 83(4), 044011
Zhang B., Harding A. K., 2000, 535, L51
Zorotovic M., Schreiber M. R., & Gänsicke B. T., 2011, A&A, 536, A42

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