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Dark Matter Objects: Possible New Source of Gravitational Waves

C. Sivaram[1] · Kenath Arun[2]

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Abstract
Gravitational waves from mergers of black holes and neutron stars are now being detected by LIGO. Here we look at a new source of gravitational waves, i.e., a class of dark matter objects whose properties were earlier elaborated. We show that the frequency of gravitational waves and strains on the detectors from such objects (including their mergers) could be within the sensitivity range of LIGO. The gravitational waves from the possible mergers of these dark matter objects will be different from those produced by neutron star mergers in the sense that they will not be accompanied by electromagnetic radiation since dark matter does not couple with radiation.

Keywords Dark matter · Dark matter objects · Gravitational waves · LIGO

Gravitational waves as predicted by Einstein 100 years earlier, were first detected by LIGO in 2016 (Abbott et al. 2016). The waves came from two black holes circling closer and closer to each other till they finally collide and coalesced. Most of the radiation was released in the final orbit, which had a period of about a millisecond, with the wave frequency from 0.6 to 1.2 kHz, typical of such stellar events. About three solar masses were converted to energy of gravitational waves, i.e. around 5×10^{54} erg. LIGO has detected five more such events of black hole mergers since. Apart from black hole mergers, in 2017, LIGO detected gravitational waves from the collision of two neutron stars. Unlike the black hole mergers which are only detectable gravitationally, this event (GW170817) was also detected electromagnetically (Abbott et al. 2017). In this note, we look at a new source of gravitational waves, i.e., dark matter (DM) objects.

Dark matter particles, of several GeV rest mass, could gravitationally condense, and form degenerate objects of planetary mass as discussed in recent papers (Narain et al. 2006; Sivaram and Arun 2011; Sivaram et al. 2016). These objects, made up mostly of DM particles of mass m_D, will have a typical mass given as (Sivaram and Arun 2009, 2011):

✉ Kenath Arun
kenath.arun@cjc.christcollege.edu

C. Sivaram
sivaram@iiap.res.in

1 Indian Institute of Astrophysics, Bangalore 560 034, India

2 Christ Junior College, Bangalore 560 029, India

$$M = \frac{M_{Pl}^3}{m_D^2} \tag{1}$$

where $M_{Pl} = \left(\frac{\hbar c}{G}\right)^{1/2} \approx 2 \times 10^{-5}$ g is the Planck mass.

There is some interest in the detection of excess gamma-rays from the galactic centre, which is attributed to the decay of 60 GeV DM particles (Huang et al. 2016). This mass for the DM particle is also favoured from other results (like DAMA experiment, among others) (Gelmini 2006). Thus we put $m_D = 60\,\mathrm{GeV}$ in Eq. (1), which gives the mass of these objects of the order of,

$$M \approx 10^{29}\ \mathrm{g} \tag{2}$$

which is about the Neptune mass. The size of these objects (for the usual degenerate gas configuration) is given by Sivaram et al. (2016):

$$M^{1/3} R = \frac{92\hbar^2}{G m_D^{8/3}} \tag{3}$$

For a Neptune mass object the size is of the order of,

$$R \approx 10^4\ \mathrm{cm} \tag{4}$$

For the density of DM of $\sim 0.1\,\mathrm{GeV/cc}$ around the solar neighbourhood, there could be one such object within about half a light year (Sivaram et al. 2016).

These DM objects could rotate about their axis. The limiting speed is given by:

$$v = \left(\frac{GM}{R}\right)^{1/2} \tag{5}$$

For M and R as given by Eqs. (2) and (4), the corresponding frequency and period of rotation are,

$$\omega \approx 1\,\mathrm{kHz}, \quad P \approx 10^{-3}\ \mathrm{s} \tag{6}$$

If these objects are not spherically symmetric and have an ellipticity, $\epsilon \approx 0.1$, they would emit gravitational waves, and the energy lost through gravitational waves is given by:

$$\dot{E} = \frac{32}{5}\frac{G}{c^5} M^2 R^4 \omega^6 \epsilon^2 \tag{7}$$

where M and R are the mass and radius of these objects, as given by Eqs. (2) and (4). For a typical DM object as discussed above, of mass 10^{29} g and size of 10^4 cm, the power lose due to gravitational waves [from Eq. (7)] is,

$$\dot{E} \approx 10^{31}\ \mathrm{ergs/s} \tag{8}$$

at a frequency of $\approx 1\,\mathrm{kHz}$. This just corresponds to the LIGO frequency. The corresponding flux from a distance of about 100 AU, will be, $f \approx 1\,\mathrm{erg/cm^2/s}$.

The flux of gravitational waves is related to the strain as:

$$f = \frac{c^3}{32\pi G}\omega^2 h^2 \tag{9}$$

For a flux of ~ 1 erg/cm^2/s, the strain is,

$$h \sim 10^{-22} \tag{10}$$

This strain and the frequency (~1 kHz) are both within the sensitivity of LIGO (Abadie et al. 2011).

With about one such object within a solar system volume ($\sim 10^{50}$ cc), and total galactic DM mass of $\sim 10^{45}$ g, there could be as much as $\sim 10^{17}$ such DM objects (of course not all DM particles will coalesce to form these objects). The most massive of these objects ($\sim 10^{-4} M_\odot$), i.e. Neptune mass could indeed be candidates for gravitational microlensing observations (Alcock et al. 2000; Tisserand et al. 2007). We are not saying that the DM objects in the halo are of Neptune mass. We conjectured (Sivaram et al. 2016) that there could be one such DM object in a solar system volume. This could be testable. No other such object in our system is expected. As we have noted, the Neptune mass is the upper limit. There could still be 10^{12} Neptune mass DM objects, either tied to other stellar systems or mostly floating as free planets. The gravitational radiation of around a kilohertz frequency (i.e. within range of LIGO) could arise from such objects, both in individual cases (when the objects are not spherically symmetrical) or in binaries (of such objects) where they have a usual quadrupole moment. Our estimates are for such objects, as they could provide an interesting alternate source for gravitational waves.

There could be a whole host of such objects starting with asteroid mass (primordial DM planet hypothesis). The halo could consist mainly of such objects with masses $< 10^{-6} M_\odot$. Objects of lower mass with similar features or in binaries would also emit gravitational radiation but with reduced frequency, frequency scaling as $\propto M$. These could be detectable in future (tuneable) detectors now planned. A mass function for the DM objects could be suggested like $N(M, dM) = \frac{dM}{M^2}\beta$, where $N(M, dM)$ is the number of such objects between M and dM, β is a constant. The lowest mass as estimated above is $\sim 10^{-18} M_\odot$ (for stellar objects, even the Salpeter mass function involving $M^{-2.3}$ is empirical). This power law distribution would put only a small fraction ($\sim 0.1\%$) in the upper mass range of $10^{-4} M_\odot$.

We also note that 10^{17} objects is an upper limit, assuming all DM is in the form of these objects. Only a fraction of the DM particles may be in the form of these objects, so we have a real upper limit. This will give a total gravitational power from all the DM objects of,

$$\dot{E} \approx 10^{48}\ \text{ergs/s} \tag{11}$$

The energy density of gravitational waves in the galaxy will be given by the background flux, given by:

$$f = \frac{\dot{E}}{4\pi d^2} \approx 10\,\text{erg/cm}^2/\text{s} \tag{12}$$

where $d \approx 10^{23}$ cm is the distance to the galactic centre.

These DM objects as binaries could also be a source of gravitational waves. If a binary system containing such objects of mass and size given by Eqs. (2) and (4) are separated by distance, $r = 10R$, then the period is given as:

$$GMP^2 = 4\pi^2 r^3 \tag{13}$$

This gives a period of $P \approx 10^{-3}$ s, and frequency $\omega \approx 1$ kHz.The power radiated through gravitational waves is,

$$\dot{E} = \frac{32}{5}\frac{G}{c^5} M^2 r^4 \omega^6 \approx 10^{33}\ \text{erg/s} \tag{14}$$

The energy released during the final stages of the merger is their binding energy given by:

$$E = \frac{GM^2}{R} \approx 10^{47}\,\mathrm{erg} \tag{15}$$

We note that all the binding energy need not be emitted as gravitational radiation, this is again the upper limit. But in the case of these DM objects, unlike neutron stars, energy is not carried away in the form of neutrinos or electromagnetic waves, hence most of the binding energy would be converted to gravitational radiation.

These binaries merging at around the galactic centre with a millisecond burst of gravitational waves will produce a strain given by,

$$h = \frac{GE}{c^4 r} \sim 10^{-24} \tag{16}$$

which is just outside the sensitivity of LIGO. If such a binary merger occurs over a kiloparsec distance it would give a strain within LIGO sensitivity ($\sim 10^{-22}$), at 1 kHz frequency.

For individual objects and binaries, separated by a distance comparable to their radius, the angular frequencies are ~ kHz (similar to merging neutron stars). The frequency scales with mass M, so even a mass ten times smaller than the upper limiting mass would have angular frequency ~ 100 Hz. These will be in the range of LIGO. When they merge and collapse, if a black hole is formed, the radius of the black hole is ~ 1 cm. So the ring down time in this case would be about a nanosecond. However if the merging objects are well below the 'Neptune' limiting mass, they would result in formation of a compact DM object close to limiting mass, so the ring down frequency is now ~ kHz, similar to merging neutron stars (or stellar mass black holes).

In short, we have a possible new source of gravitational waves at kilohertz frequency, within the sensitivity of LIGO. Here we have considered the mass of the DM particles $m_D = 60\,\mathrm{GeV}$. We could have DM particles of mass ranging from 10 to 100 GeV (Sivaram and Arun 2011; Arun et al. 2017), but the current preferred mass of 60 GeV gives the frequency of gravitational waves that are within the sensitivity of LIGO.

Like in the case of black hole mergers, gravitational waves from these DM objects will not be accompanied by electromagnetic radiation since DM does not couple with radiation. This is unlike the case of merger of neutron stars. Neutron star merger will produce millisecond bursts of 10^{52} erg of gravitational waves accompanied by electromagnetic radiation, while merger of DM objects will produce millisecond bursts of 10^{47} erg, without corresponding electromagnetic radiation being emitted.

Finally we point out that gravitational wave astronomy could in principle be used to distinguish between Einstein's GR and some alternative gravitational theories. For instance even in the framework of the linearized versions of these theories different gravitational wave polarisations are allowed. These correspond to different response functions of the interferometers and may enable distinction to be made between some of these theories. These aspects have for instance been elaborated in Corda (2009) and Sivaram (2015).

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