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Primordial Planets with an Admixture of Dark Matter Particles and Baryonic Matter †

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Abstract: It has been suggested that primordial planets could have formed in the early universe and the missing baryons in the universe could be explained by primordial free-floating planets of solid hydrogen. Many such planets were recently discovered around the old and metal-poor stars, and such planets could have formed in early epochs. Another possibility for missing baryons in the universe could be that these baryons are admixed with DM particles inside the primordial planets. Here, we discuss the possibility of the admixture of baryons in the DM primordial planets discussed earlier. We consider gravitationally bound DM objects with the DM particles constituting them varying in mass from 20 to100 GeV. Different fractions of DM particles mixed with baryonic matter in forming the primordial planets are discussed. For the different mass range of DM particles forming DM planets, we have estimated the radius and density of these planets with different fractions of DM and baryonic particles. It is found that for heavier-mass DM particles with the admixture of certain fractions of baryonic particles, the mass of the planet increases and can reach or even substantially exceed Jupiter mass. The energy released during the process of merger of such primordial planets is discussed. The energy required for the tidal breakup of such an object in the vicinity of a black hole is also discussed.

Keywords: primordial planets; dark matter; DM; baryonic admixture; early universe

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1. Introduction

Dark matter (DM), almost five times more abundant than ordinary matter, is theorized as one of the basic constituents of the universe. Many experiments are running worldwide to detect these DM particles [1,2], but to date, the interaction of these particles with ordinary matter has proven to be so feeble that they have escaped direct detection [3,4]. In the cosmic structure formation, the lightest objects would have formed first, i.e., the structure formation is a bottom-up scenario. It is of interest to note that the earliest objects to form could perhaps have been primordial planets dominantly composed of DM. Here, we consider gravitationally bound objects made of DM particles [5]. These particles are assumed to be CDM particles and are also assumed to be fermions. These objects will have low non-thermal energies and hence the degeneracy pressure will be dominant [6,7]. The formation of such objects and their presence in large numbers in our galaxy could significantly reduce the number of free DM particles moving around in the universe. The typical mass of such objects, made up mostly of DM particles of mass m_D, is given by [8].

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

where M_{Pl} is the Planck mass given by $M_{Pl} = \left(\frac{\hbar c}{G}\right)^{1/2} \approx 2 \times 10^{-5}$ g. If we consider the mass of DM particles to be 60 GeV, favored from the detection of excess of gamma rays from the galactic center, attributed to the decay of 60 GeV DM particles [9], the mass of the DM object works out to be 10^{29} g, which is the mass of Neptune.

The interior solution of the object is obtained in the same way as white dwarfs (WDs) [10]. The equation of state is the degeneracy pressure $P = k\rho^{\frac{5}{3}}$, where ρ is the density of DM. The degeneracy pressure is given by $P_d = \frac{\hbar^2 n_D^{\frac{5}{3}}}{m_D}$, where m_D is the DM particle mass and n_D is the number density given by $\frac{M}{m_D \frac{4}{3}\pi R^3}$, where M is the mass of the object and R is the radius of the object. Thus, the degeneracy pressure becomes $P_d = \frac{92\hbar^2 M^{\frac{5}{3}}}{m_D^{\frac{8}{3}} R^5}$. This degeneracy pressure is balanced by the gravitational pressure $\sim \frac{GM^2}{R^4}$, which gives the equation of the radius of the DM object [11]:

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

where G is the gravitational constant and $m_D \sim 60$ GeV is the DM particle mass [12].

As the density of these objects falls with M^2, the objects formed in later epochs would have a lower mass. If we consider the object density at a value 100 times the ambient density, say at $z = 10$, we obtain a lower mass limit of the object as $\approx 10^{14}$ g (typical asteroid mass). Therefore, the mass range of these DM objects will be from 10^{14} g (asteroid mass) extending to the mass of Neptune. These objects could have formed in the early epochs of the universe (when local DM density was much higher) and be in existence even now.

The existence of (baryonic) primordial planets has been considered previously by many authors [13–15]. In our recent paper [16], we discussed the possibility of DM at high redshifts forming primordial planets composed entirely of DM to be one of the reasons for not detecting DM as the flux of ambient DM particles would be consequently reduced. The evolution of these DM primordial planets is discussed in detail in [17]. In [18], we proposed that the hypothesized Planet 9, in our solar system ([19–21]), could indeed be such a DM planet, with a mass about that of Neptune. This might explain why it has not been visibly detected so far.

Here, we discuss the possibility of baryons being mixed with the DM particles in forming these primordial objects. During the phase of formation of these primordial objects, as the primeval ambient cloud collapses, we consider the presence of baryonic matter in addition to the DM particles.

2. Mass and Radius of DM Planet Admixed with Baryonic Matter

If M_D is the total mass of DM particles and M_B is the total mass of baryonic particles in forming the primordial planet, then the total mass (M_T) of the planet is given by

$$M_T = M_D + M_B \tag{3}$$

The gravitational binding energy density (P_{planet}) of such a planet of radius R admixed with both baryons and DM is given by

$$P_{planet} = \frac{GM_T^2}{R^4} \tag{4}$$

As the DM particles are admixed with baryonic particles in forming these structures, the DM particles will exert pressure, and the DM degeneracy pressure [22] is given by [23]

$$P_{DM\ deg} = \frac{\hbar^2 M_D^{\frac{5}{3}}}{R^5 m_D^{\frac{8}{3}}} \tag{5}$$

where R is the radius of the planet and m_D is the mass of DM particles forming the planet. On the other hand, when they are admixed, baryonic particles will also exert thermal and radiation pressure in addition to degeneracy pressure like DM particles. The degeneracy pressure exerted by the baryons is given by [24,25]

$$P_{B\ deg} = \frac{\hbar^2 M_B^{\frac{5}{3}}}{R^5 m_p^{\frac{8}{3}}} \tag{6}$$

where m_p is proton mass. It is assumed that the gravitational self energy $\sim \frac{GM_T^2}{R}$ goes into heating only the baryonic particles of mass M_B as it is assumed that the DM does not interact with radiation. Thus, $M_B R_g T = \frac{GM_T^2}{R}$. This leads to Equations (7) and (8). The thermal pressure and the radiation pressure exerted by the baryonic particles is given by

$$P_{B\ Thermal} = \frac{M_B R_g T}{\frac{4}{3}\pi R^3} \tag{7}$$

where R_g is the gas constant and T is the temperature of baryonic matter given by

$$T = \frac{GM_T m_p}{k_B R} \tag{8}$$

where k_B is Boltzmann's constant. The radiation pressure is given by

$$P_{B\ rad} = aT^4 \tag{9}$$

where a is Stefan's constant.

For forming the planet admixed with DM and baryonic particles, the gravitational binding energy density of the planet must be in balance with the radiation pressure, thermal pressure and degeneracy pressure of the baryonic and DM particles. Thus,

$$\frac{GM_T^2}{R^4} = \frac{\hbar^2 M_D^{\frac{5}{3}}}{R^5 m_D^{\frac{8}{3}}} + \frac{\hbar^2 M_B^{\frac{5}{3}}}{R^5 m_p^{\frac{8}{3}}} + \frac{GM_T M_B}{R^4} + a\left(\frac{GM_T m_p}{k_B R}\right)^4 \tag{10}$$

where M_T is the total mass of the planet, M_B is the total mass of baryonic particles, M_D is the total mass of DM particles, R is the radius of the planet, m_d is the mass of a DM particle, m_p is the mass of a proton, a is Stefan's constant and k_B is Boltzmann's constant.

If we assume a fraction f of baryonic particles being mixed with a $(1-f)$ fraction of DM particles, then M_B and M_D in Equation (1) can be replaced by fM_T and $(1-f)M_T$, respectively. Thus, Equation (10) becomes

$$\frac{GM_T^2}{R^4} = \frac{\hbar^2 (1-f)^{\frac{5}{3}} M_T^{\frac{5}{3}}}{R^5 m_D^{\frac{8}{3}}} + \frac{\hbar^2 f^{\frac{5}{3}} M_T^{\frac{5}{3}}}{R^5 m_p^{\frac{8}{3}}} + \frac{GfM_T^2}{R^4} + a\left(\frac{GM_T m_p}{k_B R}\right)^4 \tag{11}$$

The mass of the planet formed with these particles will be given by

$$\mathrm{M} = \frac{M_{Pl}^3}{m_{eff}^2} \tag{12}$$

where m_{eff} is the effective mass of the constituent particles forming the planet given by

$$m_{eff} = (1-f)m_D + fm_B \tag{13}$$

When the effective mass is considered for the planetary formation, the mass of the object will increase (can be more than Jupiter mass) beyond the maximum limit (10^{29} g) proposed for DM planets [18]. This happens because the effective mass m_{eff} is reduced, since $m_D \gg m_B$.

Consider such a planet with 50% of DM (assuming m_D of 60 GeV) and 50% of baryonic matter. The mass of the planet is $\sim 2M_J$, where M_J is the mass of Jupiter. For the planet of this mass, the baryonic radiation pressure will be very small compared to the degeneracy and thermal pressures. Hence the radiation pressure can be neglected from Equation (11). Thus,

$$\frac{GM_T^2}{R^4} = \frac{\hbar^2 (1-f)^{\frac{5}{3}} M_T^{\frac{5}{3}}}{R^5 m_D^{\frac{8}{3}}} + \frac{\hbar^2 f^{\frac{5}{3}} M_T^{\frac{5}{3}}}{R^5 m_p^{\frac{8}{3}}} + \frac{GfM_T^2}{R^4} \tag{14}$$

Thus, the radius of the object from the above equation becomes

$$R = \frac{\hbar^2 M_T^{-\frac{1}{3}}}{G} \left(\frac{(1-f)^{\frac{2}{3}}}{m_D^{\frac{8}{3}}} + \frac{f^{\frac{5}{3}}}{(1-f) m_p^{\frac{8}{3}}} \right) \tag{15}$$

For the planet with mass $\sim 2M_J$, as discussed in the above case, the radius works out to be 9.8×10^5 cm.

Table 1 shows the mass and radius of the primordial planets with an admixture of DM and baryonic particles of different fractions and for 60 GeV DM particles. Figure 1 shows that the mass of DM planets with an admixture of baryonic particles increases their mass limit beyond the Neptune mass. For planets made entirely of DM, the maximum mass limit was Neptune mass and it can go down to asteroid mass. But with an admixture of DM and baryonic particles, the mass of the planet increases with the increase in the fraction of baryonic matter. When the baryonic fraction increases with respect to that of DM particles, the planetary mass can increase and go beyond the Jupiter mass (up to about fifty Jupiter mass). It is also found that some objects can have substellar masses (above 50 Jupiter mass), like that of brown dwarfs. The radius of these planets (admixed with DM and baryonic matter) also increases with an increase in the fraction of baryonic matter. It is found from Figure 2 that if the DM particles involved in the formation of these planets are heavier, the size of the planets increases compared to the planets being formed by lighter DM particles.

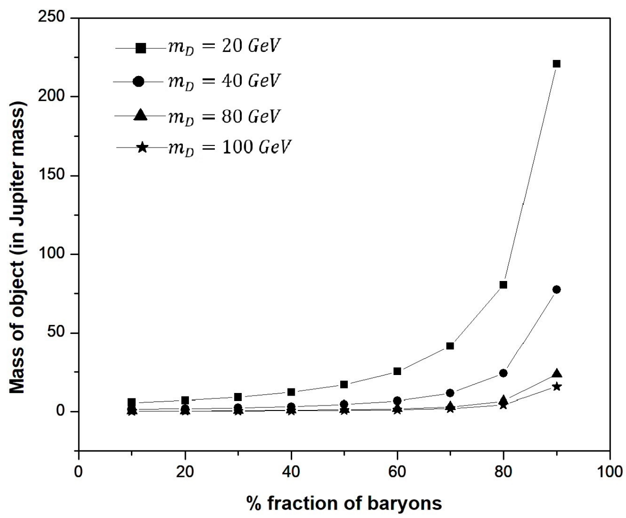

Figure 1. Mass of the primordial planet versus fraction of baryons.

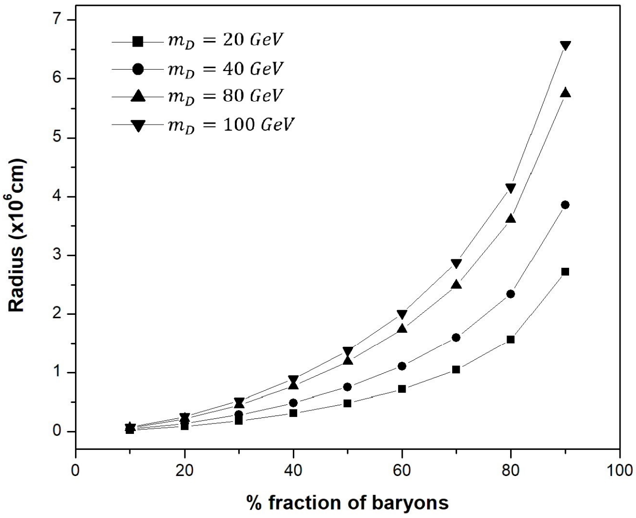

Figure 2. Radius of the primordial planet versus fraction of baryons.

Table 1. Mass and radius of primordial planet made of DM particle mass m_D = 60 GeV. Here, $M_J = 1.9 \times 10^{30}$ g is the Jupiter mass.

f (%)	$(1-f)$ (%)	m_{eff} (GeV)	Mass of Object (g)	Radius of Object (cm)
10	90	54.1	1.21×10^{30}	5.47×10^{4}
20	80	48.2	1.52×10^{30}	1.81×10^{5}
30	70	42.3	1.97×10^{30}	3.72×10^{5}
40	60	36.4	2.66×10^{30}	6.34×10^{5}
50	50	30.5	3.79×10^{30}	9.81×10^{5}
60	40	24.6	5.83×10^{30}	1.44×10^{6}
70	30	18.7	1.01×10^{31}	2.07×10^{6}
80	20	12.8	2.15×10^{31}	3.01×10^{6}
90	10	6.9	7.41×10^{31}	4.85×10^{6}

3. Rotating DM Object Admixed with Baryonic Matter

In the previous section, we discussed the possibility of the formation of DM planets with an admixture of baryonic and DM particles. There could be one such object within half a light year for the density of DM ≈ 0.1 GeV/cc around the solar neighborhood. These objects can rotate about their axis, thus emitting gravitational waves.

Consider such an object with 50% DM and 50% baryonic matter made up of DM particles of mass $m_D = 60$ GeV. The mass and radius of the object from Table 1 is $M_{obj} = 2M_J$ and $R_{obj} = 9.8 \times 10^5$ cm, where M_J is Jupiter mass. The gravitational wave energy emitted per unittime by the rotating individual object is given by

$$\dot{E} = \frac{32}{5}\frac{G}{c^5} I^2 {\omega_{obj}}^6 \epsilon^2 \tag{16}$$

where I is the moment of inertia of the object given by $I = \frac{2}{5} M_{obj} R_{obj}^2$, ω_{obj} is the frequency of the rotating object and ϵ is the ellipticity of the object. Then, Equation (16) becomes

$$\dot{E} = \frac{128}{125}\frac{G}{c^5} {M_{obj}}^2 {R_{obj}}^4 {\omega_{obj}}^6 \epsilon^2 \tag{17}$$

The rotational frequency of the DM object spinning close to breakup is given by

$$\omega_{obj}^2 R_{obj}^3 = G M_{obj} \tag{18}$$

where G is the gravitational constant. Thus, the maximum rotational frequency of the DM object is given by

$$\omega_{obj} = \sqrt{\frac{GM_{obj}}{R_{obj}^3}} \tag{19}$$

Considering $\epsilon = 0.1$ for the object of mass $2M_J$ and $R_{obj} = 9.8 \times 10^5$ cm, the energy emitted per second works out to be 7.2×10^{39} erg/s with the frequency of 518 Hz, which is well within the frequency of LIGO [26]. The typical period of rotation of the object is $\frac{2\pi}{\omega} = 0.012$ s. As the object rotates, it can break up emitting gravitational waves [27]. The binding energy of the object will be emitted as gravitational waves. The binding energy of the object is given by

$$E = \frac{GM_{obj}^2}{R_{obj}} \tag{20}$$

For the above object, the binding energy works out to be 9.82×10^{47} erg. The strain h (in the gravitational wave detector) is calculated using the formula

$$h = \frac{2GE}{rc^4} \tag{21}$$

where E is the binding energy of the object, c is the speed of light and r is the distance of the object from Earth. If we consider this object at a distance of 10 A.U. from Earth, then the corresponding strain is 10^{-14}.

4. Binary Systems of DM Objects Admixed with Baryonic Matter

These primordial planetary objects can form binary systems. Considering a binary system with each component of mass $2M_J$, size of 9.8×10^5 cm. and separation about ten times their size, the orbital period P is given by

$$GM_T P^2 = 4\pi^2 R^3 \tag{22}$$

where R is the orbital radius and M_T is the total mass of the system. The orbital period works out to be $P = 0.27$ s and the corresponding frequency is $\omega = 23$ Hz. The binary system will be emitting gravitational wave energy [28] as it revolves, and the energy emitted per unit of time is given by

$$\dot{E} = \frac{32}{5}\frac{G}{c^5}\mu^2 R^4 \omega^6 \epsilon^2 \tag{23}$$

where ϵ is the eccentricity of the orbit and μ is the reduced mass of the system given by

$$\mu = \frac{M_1 M_2}{M_1 + M_2} \tag{24}$$

M_1 and M_2 are the masses of individual objects in the binary system. During their orbit around one another, they lose energy and the orbital radius keeps decreasing until it becomes $2R_{obj}$. The final merger period and merger frequency of the binary system will be $P = 0.0243$ s and $\omega = 260$ Hz. This frequency is also within the existing range of LIGO. The binding energy of the binary system will be emitted as gravitational waves and is given by

$$E = \frac{GM_T^2}{R} \tag{25}$$

where $R = 2R_{obj}$.

Figure 3 shows the orbital frequency of a binary system of primordial objects admixed with baryonic matter versus fraction of baryonic matter. From the figure, we can conclude that most of the frequency emitted by these binary systems falls in the LIGO range of frequency. Table 2 shows the gravitational wave energy emitted by the binary system for different fractions of baryons admixed with DM particles of mass ranging from 20 to 100 GeV in forming the planet. It is found that for greater-mass DM particles, the energy emitted as gravitational waves decreases. As the fraction of baryons increases, the energy emitted by the binary system will increase. If we consider these binary systems to be situated at distance r from Earth, then the strain, h, on Earth due to the gravitational radiation emission from them is given by Equation (21). If this binary system is assumed to be at distances 1 kpc and 10 kpc from Earth, then the strain due to the gravitational wave is 2×10^{-23} and 2×10^{-24}. The corresponding flux on Earth at these distances will be 8×10^{-9} ergs/m^{2}s and 8×10^{-11} ergs/m^{2}s.

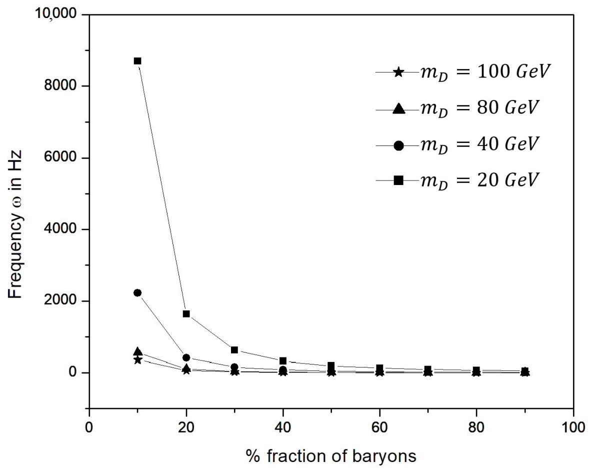

Figure 3. Orbital frequency of binary system of primordial planets admixed.

Table 2. Total energy emitted as gravitational waves by the binary system for different masses of DM particles and with different fractions of baryons for forming the planet.

f (%)	E (in ergs) for m_D = 20 GeV	E (in ergs) for m_D = 40 GeV	E (in ergs) for m_D = 80 GeV	E (in ergs) for m_D = 100 GeV
10	1.16×10^{50}	4.68×10^{48}	1.86×10^{47}	6.57×10^{46}
20	5.51×10^{49}	2.24×10^{48}	8.94×10^{46}	3.17×10^{46}
30	4.40×10^{49}	1.82×10^{48}	7.35×10^{46}	2.61×10^{46}
40	4.54×10^{49}	1.93×10^{48}	7.90×10^{46}	2.81×10^{46}
50	5.67×10^{49}	2.50×10^{48}	1.04×10^{47}	3.72×10^{46}
60	8.50×10^{49}	3.95×10^{48}	1.69×10^{47}	6.08×10^{46}
70	1.58×10^{50}	8.00×10^{48}	3.59×10^{47}	1.30×10^{47}
80	4.00×10^{50}	2.36×10^{49}	1.16×10^{48}	4.27×10^{47}
90	1.73×10^{51}	1.49×10^{50}	9.21×10^{48}	3.58×10^{48}

5. Tidal Breakup of DM Object Admixed with Baryonic Matter near a Black Hole

If a primordial degenerate object (as discussed in the above sections) of mass M_T and radius R approaches a BH of mass M_{BH}, the tidal force is given by

$$F_{tidal} = \frac{4GM_{BH}M_TR}{d^3} \tag{26}$$

where d is the separation between the BH and the primordial object. The self-gravitational force of the object is given by

$$F_{self} = \frac{GM_T^2}{R^2} \tag{27}$$

For the object to break up, the tidal force must be greater than the self-gravitational force of the object [29], i.e.,

$$\frac{4GM_{BH}M_T R}{d^3} \geq \frac{GM_T^2}{R^2} \tag{28}$$

Considering the distance between the BH and object to be around 10 times the Schwarzschild radius ($d \approx 10\left(\frac{2GM_{BH}}{c^2}\right)$), the minimum mass of BH required for tidal break-up of the object is given by

$$M_{BH} = \frac{c^3 R^{\frac{3}{2}}}{45 G^{\frac{3}{2}} M_T^{\frac{1}{2}}} \tag{29}$$

Figure 4 shows the mass of BH required for the tidal break-up of the primordial planet when it comes near the BH. The mass of the BH required for tidal break-up increases with the increase in the mass of DM particles as well as with the fraction of baryons in the primordial planet. As these objects orbit the BH, they lose energy according to Equation (23). Table 3 shows the gravitational wave energy emitted per second by the DM object consisting of different-mass DM particles with different fractions of baryons in forming the primordial object. It is found that energy decreases with the increase in the mass of the DM particles.

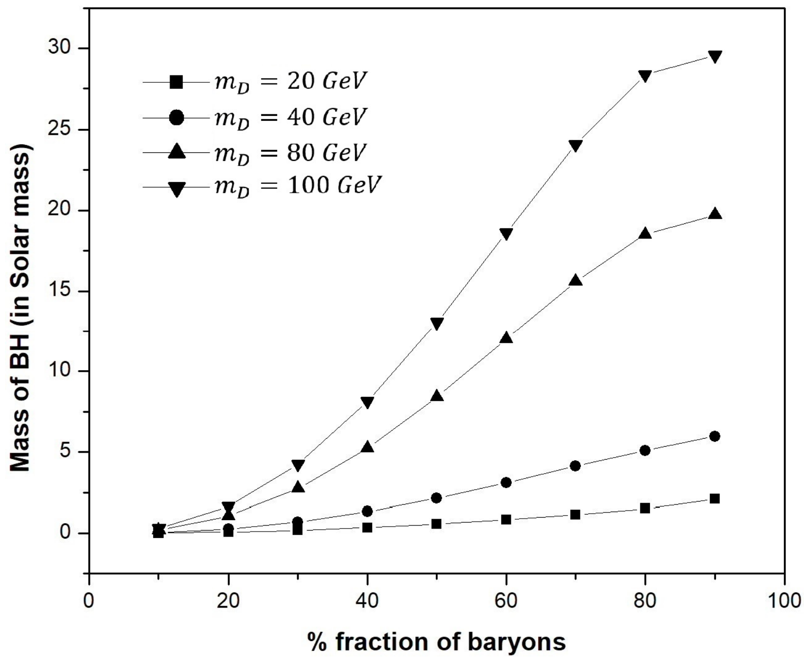

Figure 4. Mass of BH for tidal break-up versus fraction of baryonic particles admixed to form the primordial planet.

Table 3. Gravitational radiation energy emitted per second by the DM planet admixed with baryons for different-mass DM particles.

f (%)	$\dot{E}$ (erg/s) for m_D = 20 GeV	$\dot{E}$ (erg/s) for m_D = 40 GeV	$\dot{E}$ (erg/s) for m_D = 60 GeV	$\dot{E}$ (erg/s) for m_D = 80 GeV	$\dot{E}$ (erg/s) for m_D = 100 GeV
10	9.39×10^{51}	2.79×10^{49}	1.08×10^{48}	1.08×10^{47}	1.82×10^{46}
20	3.97×10^{50}	1.51×10^{48}	5.95×10^{46}	6×10^{45}	1.01×10^{45}
30	9.13×10^{49}	3.72×10^{47}	1.49×10^{46}	1.51×10^{45}	2.56×10^{44}
40	4.21×10^{49}	1.82×10^{47}	7.41×10^{45}	7.58×10^{44}	1.29×10^{44}
50	3.01×10^{49}	1.39×10^{47}	5.79×10^{45}	5.98×10^{44}	1.02×10^{44}

Table 3. *Cont.*

f (%)	$\dot{E}$ (erg/s) for m_D = 20 GeV	$\dot{E}$ (erg/s) for m_D = 40 GeV	$\dot{E}$ (erg/s) for m_D = 60 GeV	$\dot{E}$ (erg/s) for m_D = 80 GeV	$\dot{E}$ (erg/s) for m_D = 100 GeV
60	3.06×10^{49}	1.55×10^{47}	6.65×10^{45}	6.99×10^{44}	1.21×10^{44}
70	4.43×10^{49}	2.58×10^{47}	1.16×10^{46}	1.26×10^{45}	2.2×10^{44}
80	9.85×10^{49}	7.38×10^{47}	3.67×10^{46}	4.17×10^{45}	7.55×10^{44}
90	4.03×10^{50}	5.59×10^{48}	3.58×10^{47}	4.66×10^{46}	9.21×10^{45}

When they lose energy, the orbital radius keeps decreasing until the radius becomes equal to the Schwarzschild radius (R_{sch}). At the Schwarzschild radius, the frequency is given by

$$\omega = \sqrt{\frac{GM_T}{R^3}} \tag{30}$$

where M_T is the total mass of the system and the orbital radius $R = R_{sch}$. The orbital binding energy will be emitted as gravitational waves at this frequency. The time of merger of the primordial object with the BH is given by [30,31]

$$t = \frac{5c^5 r_i^4}{256 M^2 \mu G^3} \tag{31}$$

where c is speed of light, r_i is the initial orbital radius, M is the total mass of the system involving the BH and object, μ is the reduced mass of the system and G is the gravitational constant. For an object with 50% DM and 50% baryonic matter and made of 60 GeV DM particles, the merger time is 10^7 s.

Figure 5 shows the relation between the merger time and fraction of baryons in forming the primordial planet. It is found that the merger time increases with the increase in DM particle mass. Also, the merger time increases with the fraction of baryons, reaching a maximum for planets made of 60% baryonic matter.

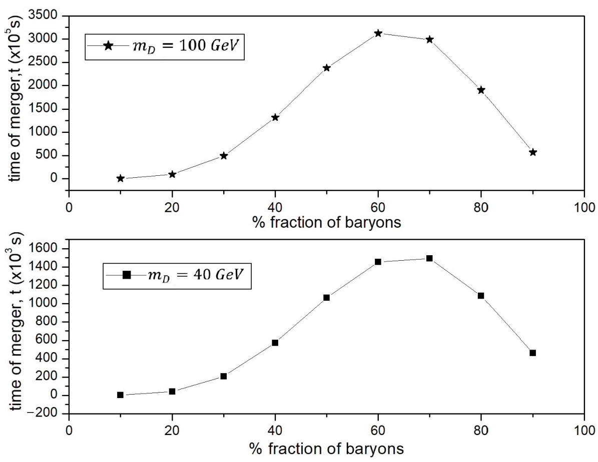

Figure 5. Merger time versus fraction of baryons in forming the primordial planet for DM particles of mass 40 GeV and 100 GeV.

6. Primordial Planetary Object at Galactic Center

At the center of our galaxy is a BH of mass 4 million solar masses (M_{BH}). It appears reasonable to assume that stars near the Galactic center (several stellar clusters are known to exist near galactic center [32,33] have planets and other small orbiting bodies, such as asteroids and comets. When the parent star approaches the central black hole, tidal interaction may either strip these bodies off their parent stars [34,35] or cause them to become more tightly bound. If we consider the primordial object orbiting around this BH, at $R = 10R_{sch}$, where R is the orbital radius, then according to Kepler's law, the orbital frequency is given by

$$\omega_{orb} = \sqrt{\frac{GM_{BH}}{R^3}} \tag{32}$$

The system will lose energy as the object orbits around the central BH and the orbital radius keeps decreasing. The energy emitted per second is given by Equation (23). For the primordial planet of mass $2M_J$ and $R_{\rm obj} = 9.8 \times 10^5$ cm, the energy emitted per unit of time works out to be 1.6×10^{33} erg/s. At an orbital radius equal to the Schwarzschild radius of the central BH, the binding energy will be emitted as gravitational waves. The final orbital frequency and energy emitted as gravitational waves for the above object works out to be 0.0178 Hz and 1.7×10^{51} erg. The flux per unit of time falling on Earth from the gravitational waves is given by

$$F = \frac{\dot{E}}{4\pi r^2} \tag{33}$$

where $\dot{E}$ is the energy emitted per unit of time from the system and r is the distance of Earth from the center of the galaxy, equal to 8kpc. The merger time of the object with the BH is given by Equation (31), and for the above object, $t \approx 10^{19}$ s.

Tables 4–6 show the variation in merger time with different fractions of baryons mixed with DM and with different masses of DM particles ranging from 20 GeV to 100 GeV for various separations of these objects from the BH. It is found that the merger time of the planet with the BH decreases as the fraction of baryons increases in the primordial planet and also increases with the increase in mass of the DM particles forming the planet. Considering the primordial planet at the center of the galaxy (≈8 kpc from Earth), the flux per unit of time on Earth is very low, of the order of 10^{-12} ergs/m^{2}s.

Table 4. Merger time of DM planet admixed with baryons for different-mass DM particles separated by a distance of $2R_{sch}$ from BH.

f (%)	t (s) for m_D = 20 GeV	t (s) for m_D = 40 GeV	t (s) for m_D = 80 GeV	t (s) for m_D = 100 GeV
10	4.65×10^{15}	1.85×10^{16}	7.38×10^{16}	1.15×10^{17}
20	3.73×10^{15}	1.47×10^{16}	5.85×10^{16}	9.14×10^{16}
30	2.90×10^{15}	1.14×10^{16}	4.50×10^{16}	7.02×10^{16}
40	2.18×10^{15}	8.46×10^{15}	3.33×10^{16}	5.18×10^{16}
50	1.57×10^{15}	5.97×10^{15}	2.33×10^{16}	3.62×10^{16}
60	1.05×10^{15}	3.91×10^{15}	1.51×10^{16}	2.34×10^{16}
70	6.38×10^{14}	2.29×10^{15}	8.67×10^{15}	1.34×10^{16}
80	3.27×10^{14}	1.10×10^{15}	4.01×10^{15}	6.15×10^{15}
90	1.19×10^{14}	3.41×10^{15}	1.13×10^{15}	1.69×10^{15}

Table 5. Merger time of DM planet admixed with baryons for different-mass DM particles separated by a distance of $10R_{sch}$ from BH.

f (%)	t (s) for m_D = 20 GeV	t (s) for m_D = 40 GeV	t (s) for m_D = 80 GeV	t (s) for m_D = 100 GeV
10	2.91×10^{18}	1.16×10^{19}	4.62×10^{19}	7.21×10^{19}
20	2.33×10^{18}	9.2×10^{18}	3.66×10^{19}	5.71×10^{19}
30	1.82×10^{18}	7.11×10^{18}	2.81×10^{19}	4.39×10^{19}
40	1.37×10^{18}	5.29×10^{18}	2.08×10^{19}	3.24×10^{19}
50	9.79×10^{17}	3.73×10^{18}	1.46×10^{19}	2.26×10^{19}
60	6.57×10^{17}	2.45×10^{18}	9.43×10^{18}	1.46×10^{19}
70	3.99×10^{17}	1.43×10^{18}	5.42×10^{18}	8.37×10^{18}
80	2.05×10^{17}	6.87×10^{17}	2.51×10^{18}	3.84×10^{18}
90	7.47×10^{16}	2.13×10^{17}	7.03×10^{17}	1.05×10^{18}

Table 6. Merger time of DM planet admixed with baryons for different-mass DM particles separated by a distance of $100R_{sch}$ from BH.

f (%)	t (s) for m_D = 20 GeV	t (s) for m_D = 40 GeV	t (s) for m_D = 80 GeV	t (s) for m_D = 100 GeV
10	2.91×10^{22}	1.16×10^{23}	4.62×10^{23}	7.21×10^{23}
20	2.33×10^{22}	9.2×10^{22}	3.66×10^{23}	5.71×10^{23}
30	1.82×10^{22}	7.11×10^{22}	2.81×10^{23}	4.39×10^{23}
40	1.37×10^{22}	5.29×10^{22}	2.08×10^{23}	3.24×10^{23}
50	9.79×10^{21}	3.73×10^{22}	1.46×10^{23}	2.26×10^{23}
60	6.57×10^{21}	2.45×10^{22}	9.43×10^{22}	1.46×10^{23}
70	3.99×10^{21}	1.43×10^{22}	5.42×10^{22}	8.37×10^{22}
80	2.05×10^{21}	6.87×10^{21}	2.51×10^{22}	3.84×10^{22}
90	7.47×10^{20}	2.13×10^{21}	7.03×10^{21}	1.05×10^{22}

7. Possible Electromagnetic Radiation from Baryonic Fraction of the Merging Objects

If the objects were made of pure DM, the binding energy of the merging objects would be released as gravitational waves [36,37]. In the case of a primordial planet admixed with DM and baryons, the binding energy due to baryons will be emitted as electromagnetic waves (like merging neutron stars). Thus, during the merger, there will be emission of gravitational waves and electromagnetic waves by the baryonic particles inside the object. For objects with an equal proportion of DM and baryonic matter, the energy released as EM waves will be of the order of 10^{47} erg and it will be emitted in the frequency range of gamma radiation. These gamma rays emitted would be in short-duration bursts with a period the same as the final orbital period before the merger (around 5 ms).

8. Conclusions

Here, we have discussed the possibility of admixture of baryons in the DM primordial planets with the DM particles varying in mass from 20 GeV to 100 GeV. We have considered different fractions of admixture to form the planets. The mass of the primordial planets made completely of DM ranges from asteroid mass to Neptune mass, whereas the mass of primordial planets (admixed with DM and baryonic matter) is found to increase with the fraction of baryonic matter in the planets, and the mass of these objects can go well beyond the mass of Jupiter (around 40 times Jupiter mass) and can also approach substellar mass (brown dwarf mass). So far, thousands of exoplanets have been discovered by the Kepler mission and more will be found by NASA's Transiting Exoplanet Survey Satellite (TESS) mission, which is observing the entire sky to locate planets orbiting the nearest and brightest stars. Many exoplanets (exo-Jupiters) discovered so far fall in this mass range and we are not very sure whether these exoplanets are entirely made of baryons. Some of the exoplanets with a mass several times Jupiter mass could be possible signatures of the presence of primordial planets with an admixture of baryonic and DM particles. It is also found that some of these planets could even reach substellar mass $\left(10^{32}\ \text{g}\right)$, like that of brown dwarfs [38,39]. Also, even if a small fraction of DM particles is trapped in these objects, the flux of ambient DM particles would be reduced significantly. This could be one of the many reasons for not detecting the DM particles in various experiments like the XENON1T experiment, etc., as suggested earlier. If two such primordial planets merge, they will release a lot of energy. The energy released and the time scale of merger of these objects is found to increase with the mass of primordial objects. The frequency of gravitational waves emitted during the merger is found to match with the frequency range of LIGO. The objects near the galactic center could consist of such primordial objects, planets, comets, etc. Here, we have also discussed the possibility of tidal break-up of these primordial objects in the presence of a BH. The mass of BH required for tidal break-up is calculated and it is found that the mass of BH required for tidal break-up increases with the DM particle mass and also with the increase in fraction of baryons in these objects. The energy released in the form of gravitational waves as well as the frequency of emission is tabulated and, again, it is found that the frequency falls in the sensitivity range of LIGO.

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