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Evolution of Primordial Dark Matter Planets in the Early Universe

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Abstract: In a recent paper we had discussed 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). In this paper we discuss the evolution of these DM objects as the universe expands. As universe expands there will be accretion of DM, Helium and Hydrogen layers (discussed in detail) on these objects. As they accumulate more and more mass, the layers get heated up leading to nuclear reactions which burn H and He when a critical thickness is reached. In the case of heavier masses of these DM objects, matter can be ejected explosively. It is found that the time scale of ejection is smaller than those from other compact objects like neutron stars (that lead to x-ray bursts). These flashes of energy could be a possible observational signature for these dense DM objects.

Keywords: dark matter; DM planets; early universe

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1. Introduction

Dark matter is theorized as one of the basic constituents of the universe, almost five times more abundant than ordinary matter. Many astronomical measurements have confirmed the existence of dark matter, leading to experiments worldwide like XENON1T experiment (Aprile et al., 2012; Undagoitia and Raunch, 2016) to directly observe dark matter particles. Till now the interaction of these particles with ordinary matter has proven to be so feeble that they have escaped direct detection. (Arun et al., 2018)

In the recent paper (Sivaram et al., 2019) we had discussed 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. Such DM objects could have formed in the earlier epoch of the universe (when local DM density was much higher) and be in existence now. Existence of primordial planets have been considered earlier (Shchekinov et al., 2013; Wickramasinghe et al., 2012).

In the above paper we had tabulated a wide range of masses and corresponding radii of such DM planets with an upper limit of Neptune mass all the way down to asteroid mass. Moreover in Sivaram et al. (2016), we had conjectured that the much talked about Planet 9, in our solar system (Batygin and Brown, 2016; Trujillo and Sheppard, 2014), 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. In this paper we discuss the evolution of these DM planets, formed in the early universe.

2. Evolution of DM planets by mass accretion

The DM planets over a period of time after their formation would have accreted mass according to:

$$\dot{M} = 4\pi R^2 \rho_{DM} v \qquad (1)$$

where R is the radius of planet, ρ_{DM} is the ambient DM density and v is the velocity of the accreted DM particles, given by, $v = v_{amb} + v_{esc}$

$$\text{where, } v_{esc} = \left(\frac{2GM}{R}\right)^{\frac{1}{2}} \qquad (2)$$

(here G is gravitational constant and M is the mass of planet) and v_{amb} being the ambient velocity (of DM particles). v_{esc} is important for higher mass DM objects and v_{amb} is assumed to be same for all objects.

The DM particles are heavier compared to the ambient hydrogen and helium atoms, and are accreted much earlier since they are not coupled to the background radiation. The hydrogen and helium atoms are accreted after decoupling from the background radiation, with helium getting accreted before hydrogen since it decoupled earlier (ionization temperature of He being higher) (Switzer et al., 2008). After the recombination epoch, hydrogen was formed at redshifts of $Z = 1000$. Since the ionization energy of helium is greater than that of hydrogen it recombines earlier and this takes place around redshifts of $Z = 3000$. Hence these DM planets are expected to have a layer of DM particles, followed by successive layers of helium and hydrogen.

From the equation for mass accreted per unit time (equation (1)) we have,

$$dM = 4\pi R(t)^2 \rho_{DM}(t) v \, dt \qquad (3)$$

As the Universe expands the ambient density changes with time, and the sizes of these planets changes with increase in mass. The density of these planets scales as the square of their mass. Their radius is given by (Sivaram and Arun, 2011):

$$R = \frac{92\hbar^2}{G m_D^{8/3} M^{1/3}} \qquad (4)$$

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where m_D is the DM particle mass. m_D is assumed to be $\sim 60GeV$. (Gelmini et al., 2006; Huang et al., 2016)

The ambient density of DM, H and He atoms varies with time as the Universe expands. At $Z = 10$ to present epoch the galactic density becomes more dominant than the ambient density. The time-dependent background density can be of the form (Rebecca et al., 2019):

$$\rho(t) = \rho_0(t_0)\left(\frac{t_0}{t}\right)^2 \tag{5}$$

where ρ_0 is the density at early epoch t_0.

Using equations (4) and (5) in equation (3), the accreted mass over the complete epoch (from t_0 to present) is given by:

$$\int_{M_0}^{M} M^{2/3}\, dM = 4\pi v {t_0}^2 \left(\frac{92\hbar^2}{G {m_D}^{8/3}}\right)^2 \rho_0 \int_{t_0}^{t} \frac{1}{t^2} dt \tag{6}$$

where M_0 is the initial mass.

Equation (6) integrates to:

$$M^{5/3} = {M_0}^{5/3} + 4\pi v \rho_0 \left(\frac{92\hbar^2}{G {m_D}^{8/3}}\right)^2 t_0 \tag{7}$$

The accreted mass of H and He is given by a similar relation to equation (3) with ρ now being the corresponding ambient density. The total mass accreted on the dark matter planet (whose mass varies from Neptune mass to asteroid mass) is tabulated for accretion of DM, He, and H separately in table 1.

(ρ_0 is the density at $t_0 = 10^{17}s$. At $Z = 3000$, $\rho_{0(DM)} = 5.4 \times 10^{-20} g/cc$, $\rho_{0(He)} = 2 \times 10^{-21} g/cc$. At $Z = 1000$, $\rho_{0(H)} = 3 \times 10^{-22} g/cc$)

Table 1. Velocity of the accreted particles and total mass of the ambient DM particles and H and He atoms accreted by the DM planets of various masses.

Mass of Planet (g)	velocity (cm/s)	Mass of DM accumulated (g)	Mass of H accumulated (g)	Mass of He accumulated (g)
10^{29}	9.53×10^8	1×10^{29}	1×10^{29}	1×10^{29}
10^{28}	2.14×10^8	1×10^{28}	1×10^{28}	1×10^{28}
10^{27}	5.37×10^7	1×10^{27}	1×10^{27}	1×10^{27}
10^{26}	1.94×10^7	1×10^{26}	1×10^{26}	1×10^{26}
10^{25}	1.20×10^7	1×10^{25}	1×10^{25}	1×10^{25}
10^{24}	1.04×10^7	1×10^{24}	1×10^{24}	1×10^{24}
10^{23}	1.01×10^7	1×10^{23}	1×10^{23}	1×10^{23}
10^{22}	1×10^7	1×10^{22}	1×10^{22}	1×10^{22}
10^{21}	1×10^7	1×10^{21}	1×10^{21}	1×10^{21}
10^{20}	1×10^7	1×10^{20}	1×10^{20}	1×10^{20}
10^{19}	1×10^7	1×10^{19}	1×10^{19}	1×10^{19}

10^{18}	1x10^{7}	1x10^{18}	1x10^{18}	1x10^{18}
10^{17}	1x10^{7}	1x10^{17}	1x10^{17}	1x10^{17}
10^{16}	1x10^{7}	1.01x10^{16}	1x10^{16}	1x10^{16}
10^{15}	1x10^{7}	2x10^{15}	1.07x10^{15}	1.01x10^{15}
10^{14}	1x10^{7}	2x10^{14}	3.19x10^{14}	1.46x10^{14}

3. Formation of accreted layers on the DM planets and their dynamics

As more and more mass gets accreted the temperatures of hydrogen and helium layers start increasing, whereas, DM will not be heated up. The temperatures of the accreted layers of hydrogen and helium on the DM planet is given by:

$$T = \frac{GMm}{Rk_B} \tag{8}$$

where M is mass of planet, m is mass of H or He atom, R is radius of planet and k_B is Boltzmann constant.

We have tabulated the temperatures (table 2) of these Hydrogen and Helium layers on the DM planet and found that the temperature is high enough for heavier DM planets to have nuclear reactions. But these nuclear reactions can happen only if these high temperatures are retained for sufficient time for the reactions to occur. The time scale of cooling is given as:

$$t = \frac{M_{acc}R_gT}{\sigma T^4 A} \tag{9}$$

where M_{acc} is mass accreted, R_g is gas constant, T is temperature of gas layer, σ is Stefan Boltzmann constant and A is the surface area of accreting planet, ($A = 4\pi R^2$, R as given in equation(4)).

Table 2. Temperature and the time scale of cooling for the H and He layers.

M (g)	T_H (K)	T_{He} (K)	t_H (s)	t_{He} (s)
10^{29}	5.38 $\times 10^{9}$	2.14 x 10^{10}	8.02 x 10^{2}	1.27 x 10^{1}
10^{28}	2,52 x 10^{8}	1.01 x 10^{9}	1.71 x 10^{5}	2.66 x 10^{3}
10^{27}	1.15 x 10^{7}	4.60 x 10^{7}	3.77 x 10^{7}	5.89 x 10^{5}
10^{26}	1.20 x 10^{6}	4.80 x 10^{6}	7.22 x 10^{8}	1.13 x 10^{7}
10^{25}	1.20 x 10^{6}	4.80 x 10^{6}	1.59 x 10^{7}	2.48 x 10^{5}
10^{24}	1.20 x 10^{6}	4.80 x 10^{6}	3.32 x 10^{5}	5.18 x 10^{3}
10^{23}	1.20 x 10^{6}	4.80 x 10^{6}	7.22 x 10^{3}	1.13 x 10^{2}
10^{22}	1.20 x 10^{6}	4.80 x 10^{6}	1.59 x 10^{2}	2.48
10^{21}	1.20 x 10^{6}	4.80 x 10^{6}	3.32	5.18 x 10^{-2}
10^{20}	1.20 x 10^{6}	4.80 x 10^{6}	7.22 x 10^{-2}	1.13 x 10^{-3}
10^{19}	1.20 x 10^{6}	4.80 x 10^{6}	1.59 x 10^{-3}	2.48 x 10^{-5}

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10^{18}	1.20 x 10^{6}	4.80 x 10^{6}	3.32 x 10^{-5}	5.18 x 10^{-7}
10^{17}	1.20 x 10^{6}	4.80 x 10^{6}	7.22 x 10^{-7}	1.13 x 10^{-8}
10^{16}	1.20 x 10^{6}	4.80 x 10^{6}	1.59 x 10^{-8}	2.53 x 10^{-10}
10^{15}	1.20 x 10^{6}	4.80 x 10^{6}	3.97 x 10^{-10}	8.51 x 10^{-12}
10^{14}	1.20 x 10^{6}	4.80 x 10^{6}	3.45 x 10^{-11}	1.16 x 10^{-12}

4. Nuclear reactions and ejection of mass from H and He layers

Helium burning requires a temperature of 200 million kelvin ($2 \times 10^{8} K$), and H burning requires few million degrees ($\sim 10 - 30 \times 10^{6} K$) (Burbidge et al., 1957; Caughlan and Fowler., 1988). So only the objects having masses $10^{29}\ g$ and $10^{28}\ g$ can fuse He, objects with $10^{27}\ g$ can fuse H (to He) and objects with masses $10^{26}\ g$ and below cannot undergo nuclear reactions. However for masses from $10^{25}\ g$ to $10^{22}\ g$, since the temperatures are not high enough and moreover the cooling times are smaller, the conditions are not sufficient for nuclear reactions to happen. These objects emit energy from the heat accumulated by the accreting layers. The energy radiated by these masses is tabulated in Table 6.

For lower masses ($10^{21}\ g$ and below), the temperature of these gases cools down very fast leaving no time for nuclear reaction to occur. But however for heavier masses there are reactions possible where H and He could get converted into heavier elements. (Sivaram et al., 2014)

For the reactions to happen a certain thickness of Hydrogen and Helium layers should be accumulated above these DM planets' surfaces. The potential energy of the accreted mass is given by:

$$\Delta U = \frac{GMM_{acc}}{R} \tag{10}$$

where M_{acc} is the mass accreted on the planet. This potential energy keeps on increasing with the mass accumulation leading to an increase in the pressure energy (thermal energy density) given by:

$$P = \rho R_g T \tag{11}$$

where R_g is the gas constant, T is the temperature of the layer. This thermal energy density must be equal to the potential energy density, (i.e. $\rho R_g T = \rho g h$) and thus we obtain the thickness of the layer accreted on the planet as,

$$h = \frac{R_g T}{g} \tag{12}$$

Here g is acceleration due to gravity of the planet given by, $g = GM/R^2$. To estimate required thickness of layer i.e. h, T is taken as $200 \times 10^{6} K$ for He and $30 \times 10^{6} K$ for H to undergo fusion. By using equations (10) and (11) and differentiating with time we get:

$$\dot{\rho} = \frac{GM\dot{M}_{acc}}{4\pi R^3 h R_g T} \tag{13}$$

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where $\dot{\rho}$ is the rate of change of density of the mass accumulated and $\dot{M}_{acc}$ is rate of mass accreted. The density of the accreted layers keeps increasing over time which increases the gravitational pressure. The gravitational pressure is given by:

$$P = \frac{GM_{DM}M_{acc}}{R^4} \tag{14}$$

The radiation pressure exerted by the heated up accreted gas also increases and when gravitational pressure and corresponding radiation pressure reaches a maximum, the layer is ejected out into space. The maximum value of gravitational pressure is obtained by equating it with the radiation pressure, i.e.:

$$\frac{GM_{DM}M_{acc}}{R^4} \leq \frac{\sigma T^4}{c} \tag{15}$$

where σ is Stefan-Boltzmann constant, c is the speed of light.

Equation (15) implies that if M_{acc} exceeds some value, radiation pressure will dominate and could lead to ejection of mass. The mass accreted for a thickness of layer h is given by:

$$M_{acc} = 4\pi R^2 h\rho \tag{16}$$

By using equations (15) and (16) we can obtain the maximum density of the accreted layers as given by:

$$\rho = \frac{\sigma T^4 R^2}{GM_{DM}4\pi hc} \tag{17}$$

Thus the mass of the Hydrogen and Helium layers for the estimated thickness on the heavier DM objects is tabulated (using the above equations) in table 3.

Table 3. Height (thickness), density, and mass of the accreted layers on the heavier DM objects.

$M_{DM}(g)$	Helium layer			Hydrogen layer		
	$h\ (cm)$	$\rho\ (g/cc)$	$M_{acc}\ (g)$	$h\ (cm)$	$\rho\ (g/cc)$	$M_{acc}\ (g)$
10^{29}	4.5×10^{2}	2.37×10^{9}	3.01×10^{21}	3.15×10^{1}	1.35×10^{8}	1.2×10^{19}
10^{28}	2.05×10^{4}	1.17×10^{4}	3.09×10^{18}	1.43×10^{3}	6.50×10^{2}	1.2×10^{16}
10^{27}	9.8×10^{5}	5.05×10^{-2}	3.05×10^{15}	6.86×10^{4}	2.82×10^{-3}	1.19×10^{13}
10^{26}	4.5×10^{7}	5.99×10^{-6}	7.61×10^{13}	3.15×10^{6}	3.34×10^{-7}	2.97×10^{11}

The Eddington Luminosity of a body of mass M is given by:

$$L = \frac{4\pi GMm_p c}{\sigma_T} \tag{18}$$

where σ_T is Thompson scattering cross section for electron and m_p is the mass of proton.

For a mass of $10^{29}\ g$, the Eddington Luminosity is $10^{34}\ erg/s$. The energy released when 1 g of H fuses to He is $3\times10^{18}\ erg$. So for a Luminosity of $10^{34}\ erg/s$, the corresponding mass required is $10^{16}\ g$. So any accumulated mass more than $10^{16}\ g$ will be ejected out with Eddington luminosity.

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Same way the energy released in the nuclear fusion of He is $10^{18}\ erg/s$ and hence mass required for Eddington luminosity is again $10^{16}\ g$. We have tabulated the Eddington luminosities and the critical mass limit for ejection of these layers of H and He in table 4.

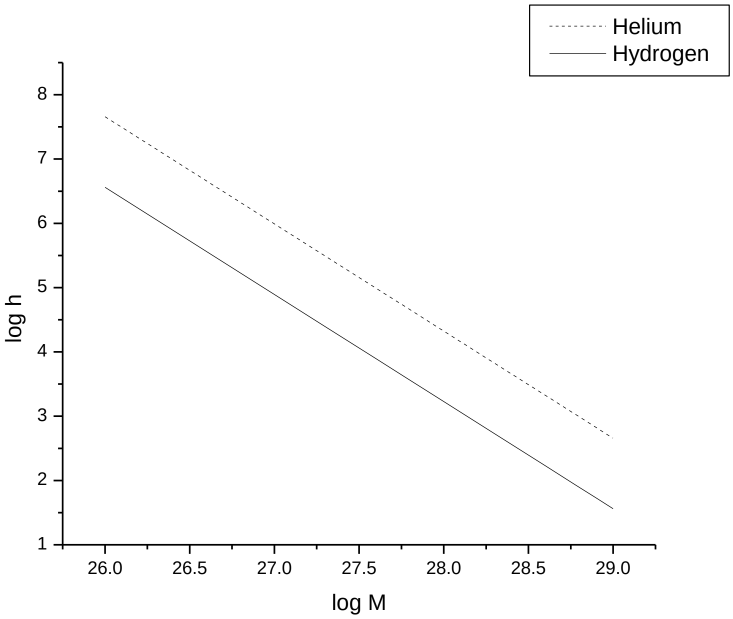

Figure 1. Variation of log of Mass of the object with log of thickness of layer accumulated for H and He.

For larger masses the mass accreted is more than the limiting mass rate. So these larger masses will eject this excess mass with Eddington luminosity in the timescale given by:

$$t_{eject} = \frac{Mass\ accreted}{limiting\ mass\ rate} \quad (19)$$

The lower mass DM objects which accrete masses lower than the limiting mass rate will continue to release energy with luminosity given by:

$$L = 4\pi R^2 \sigma T^4 \quad (20)$$

where R is radius of planet and T is the temperature of layer.

The total energy released by the mass accreted is given by:

$$\text{Energy released} = \text{Mass accreted} \times \text{Energy released per gram} \quad (21)$$

The luminosity of the ejected mass is given by:

$$\text{Luminosity} = \frac{\text{Energy released}}{\text{Time scale of ejection}} \quad (22)$$

These are tabulated in table 5.

Table 4. Critical Mass limit and Eddington luminosities of H and He layers accreted on DM objects of heavier mass

$M_{DM}(g)$	$L_{Edd}(erg$	**Helium layer**	**Hydrogen layer**

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	$/s)$	Limiting mass rate (g/s)	Mass accreted (g)	Limiting mass rate (g/s)	Mass accreted (g)
10^{29}	10^{34}	10^{16}	3.01×10^{21}	10^{16}	1.2×10^{19}
10^{28}	10^{33}	10^{15}	3.09×10^{18}	10^{15}	1.2×10^{16}
10^{27}	10^{32}	10^{14}	3.05×10^{15}	10^{14}	1.19×10^{13}
10^{26}	10^{31}	10^{13}	7.61×10^{13}	10^{13}	2.97×10^{11}

Table 5. Energy released by the layers and the time scale of these ejections

$M_{DM}(g)$	Helium layer			Hydrogen layer		
	Energy released (erg)	Time of ejection (s)	Luminosity (ergs/s)	Energy released (erg)	Time of ejection (s)	Luminosity (ergs/s)
10^{29}	3.01×10^{39}	3.01×10^{5}	10^{34}	3.6×10^{37}	1.2×10^{3}	3×10^{34}
10^{28}	3.09×10^{36}	3.09×10^{3}	10^{33}	3.6×10^{34}	1.2×10^{1}	3×10^{33}
10^{27}	3.05×10^{33}	3.05×10^{1}	10^{32}	3.57×10^{31}	1.19×10^{-1}	3×10^{32}
10^{26}	7.61×10^{31}	7.61	10^{31}	8.91×10^{29}	2.97×10^{-2}	3×10^{31}

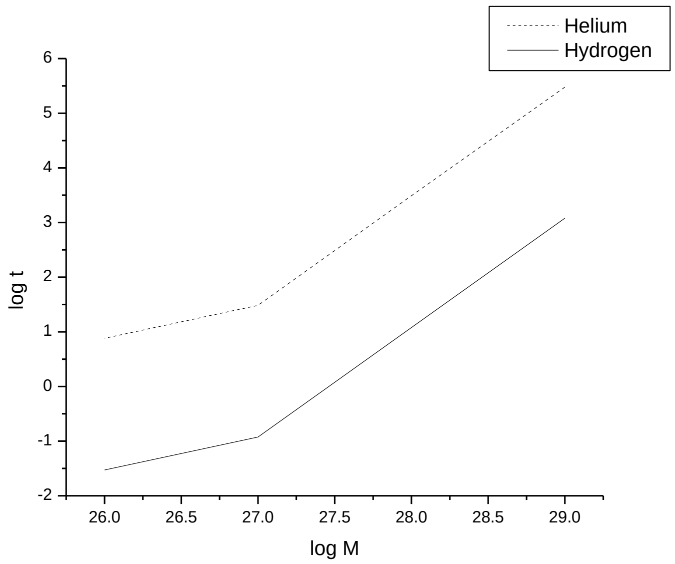

Figure 2. Variation of log of Mass of the DM object with log of the time scale of ejection of the accumulated layers of H and He.

The Luminosity (L) and Radius (R) of the objects is calculated by equation (20) and equation (4), respectively. Here T is the temperature of layer, t is the time scale of cooling, the values are taken from table 2. The Energy radiated is given by $E =$ Luminosity $\times$ time of cooling.

Table 6. Energy released by H and He layers accumulating on heavier masses

$M(g)$	$R(cm)$	Hydrogen layer				Helium layer			
		$T_H\ (K)$	$L(erg/s)$	$t_H\ (s)$	$E\ (erg)$	$T_{He}\ (K)$	$L(erg/s)$	$t_{He}\ (s)$	$E\ (erg)$
10^{25}	3.2×10^{5}	1.2×10^{6}	1.5×10^{32}	1.6×10^{7}	2.4×10^{39}	4.8×10^{6}	3.9×10^{34}	2.5×10^{5}	9.6×10^{39}
10^{24}	7×10^{5}	1.2×10^{6}	7.2×10^{32}	3.3×10^{5}	2.4×10^{38}	4.8×10^{6}	1.8×10^{35}	5.2×10^{3}	9.6×10^{38}
10^{23}	1.5×10^{6}	1.2×10^{6}	3.3×10^{33}	7.2×10^{3}	2.4×10^{37}	4.8×10^{6}	8.5×10^{35}	1.1×10^{2}	9.6×10^{37}
10^{22}	3.2×10^{6}	1.2×10^{6}	1.5×10^{34}	1.6×10^{2}	2.4×10^{36}	4.8×10^{6}	3.9×10^{36}	2.48	9.6×10^{36}

5. Conclusions

Following our earlier works on primordial planets composed of DM, we have considered their evolution as the universe expands. This involves accretion of ambient DM, hydrogen and helium on these objects forming successive layers (after H and He recombine in the early universe). The H and He layers get heated up and for the heavier DM objects, the layers after reaching a critical thickness could undergo nuclear reactions burning He and H. The luminosities are estimated. The time scales of ejection in case of Eddington luminosity reached by the layers is estimated.

The ejections leading to flashes would be less energetic than the bursts (X-ray bursts) from neutron stars, the corresponding time scales being shorter. The above estimates could be typical signatures for future observations. A more detailed study is under way.

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