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Primordial Planets Predominantly of Dark Matter

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Abstract

Cosmic structure formation is thought to occur as a bottom-up scenario, i.e. the lightest objects would have formed first. It has been suggested that the earliest structures to form could have been primordial planets. Here we propose the possibility of formation of primordial planets at high redshifts composed predominantly of dark matter (DM) particles, with planetary masses ranging from Neptune mass to asteroid mass. Most of these primordial DM planets could be free floating without being attached to a host star and a substantial fraction could be present in the halo contributing to the DM. Here we suggest that the flux of DM particles could be significantly reduced as substantial number of DM particles are now trapped in such objects, perhaps accounting for the negative results seen so far in the ongoing DM detection experiments.

Keywords Dark matter · Primordial planets · DM planets

It is now generally believed that complex structures formed in the early universe less than a billion years after the initial big bang. The earliest stellar objects could have formed even perhaps two hundred million years after the expansion began. To form such objects, the dominant atoms present, i.e. of hydrogen and helium, had to form by recombination, so that the matter could gravitate. However, dark matter (DM), in the form of massive particles could have gravitated much earlier as they do not have this constraint of decoupling from radiation.

In recent papers we had considered how presence of DM could have affected the earliest stars and also helped in the formation of supermassive black holes, less than a billion years after the beginning (Sivaram et al. 2018; Arun et al. 2019). As the scenario of structure

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formation is visualised to occur as a bottom-up scenario, the lightest objects would have formed first (White and Rees 1978).

Indeed it has been suggested that primordial planets could have formed early (Wickramasinghe et al. 2012) and arguments have been presented that primordial free-floating planets of solid hydrogen may account for the whole of the 'missing baryons' in the universe. When recalculated for the Milky Way, the number of such primordial planets could be as numerous as $\sim 10^{14}$. Also in a recent paper (Shchekinov et al. 2013) the formation of planets around old and metal poor stars were discussed as several planets around such stars (which would have formed very early) were recently discovered (Sumi et al. 2011; Strigari et al. 2012). Such planets could have formed at early epochs.

More interesting from our point of view is the possibility of DM at high redshifts forming primordial planets composed entirely of this matter. In a recent paper (Sivaram et al. 2016) we had pointed out the possibility of Planet Nine in our solar system (which has so far been found invisible at all wavelengths despite its dynamic dominance) to be indeed one such DM planet. The motivation for considering Planet Nine to be such an object was that DM particles of around 60 GeV mass, favoured by some experimental results (Gelmini 2006; Huang et al. 2016) could form (especially at earlier cosmic epochs) degenerate objects (i.e. gravity supported by the degeneracy pressure exerted by these particles) of an upper mass given by (Sivaram and Arun 2009, 2011):

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

where, $M_{Pl} = \left(\frac{\hbar c}{G}\right)^{1/2} \approx 2 \times 10^{-5}$ g is the Planck mass, m_D is the DM particle mass. For $m_D = 60$ GeV, this works out to:

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

This is of Neptune mass, i.e. about the mass of Planet Nine. If made up of mostly DM particles, such objects would not emit any radiation (at any wavelength) and therefore not be seen in the usual observational searches. We also estimated (Sivaram et al. 2016) that there could be one such object in a volume covering the Oort cloud in our solar system. So in our galaxy there could be 10^{15} such objects. This would be testable as discussed in the above paper.

The above mass [given by Eqs. (1) and (2)] is an upper limit. There could be in principle DM planets having a wide range of masses with Eq. (1) giving the upper limit.

The density of these degenerate objects scales as the square of their mass. Their radius is given by:

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

Table 1 gives the mass and size of such DM planets. The usual homologous law, $M^{1/3}R = const.$, implies that ρ scales as M^2.

If they have a small admixture of baryonic matter, the mass M_{planet} could be slightly more than that given by Eq. (1). Arguments similar to the effect of DM on white dwarfs formed at early epochs (Arun et al. 2018) would also apply here. A twenty per cent admixture of baryons could change the mass for instance by a factor of 1.4. The lighter the DM

Table 1 Mass and size of DM planets

M_{planet} (g)	R (cm)
10^{29}	1.5×10^{4}
10^{28}	3.2×10^{4}
10^{27}	7×10^{4}
10^{26}	1.5×10^{5}
10^{25}	3.2×10^{5}
10^{24}	7×10^{5}
10^{23}	1.5×10^{6}
10^{22}	3.2×10^{6}
10^{21}	7×10^{6}
10^{20}	1.5×10^{7}
10^{19}	3.2×10^{7}
10^{18}	7×10^{7}
10^{17}	1.5×10^{8}
10^{16}	3×10^{8}
10^{15}	7×10^{8}
10^{14}	1.5×10^{9}

particles the larger the object mass. We had discussed in detail, the masses and radii of these objects constituted of DM particles of varying masses (10–100 GeV) (Sivaram and Arun 2009).

As the density of these objects fall of as M^2, the objects formed at later epochs would have a lower mass. So if we cut off the object density at a value 100 times the ambient density, say at $z \approx 10$, we get a lower mass limit of the object as $\sim 10^{14}$ g (typical asteroid mass). Thus this implies that there could be primordial DM 'asteroids'. Figure 1 gives the variation of size and density of these DM planets with their mass.

Most of these primordial DM planets could be free floating without being attached to a host star. A substantial fraction could be in the mass range below $10^{-6}M_\odot$ and be present in the halo contributing to the DM, but still not detectable by microlensing. The mass function (or spectrum) for these objects could be of the form:

$$N(M, dM) = \frac{dM}{M^2}\beta \tag{4}$$

$N(M, dM)$ 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.)

In short, it is of interest that the earliest objects to form could perhaps have been primordial planets dominantly composed of DM. It is not implied that all the DM particles go into forming such objects. What is of interest is 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 and this may provide an explanation as to why none of the several ongoing experiments have so far not detected any such particles. Our argument suggests the flux of such DM particles is significantly reduced as they are now trapped in such objects. Even if half (or a third) of the DM particles were in such objects, the free particle flux, which the detectors are trying to detect, would be significantly reduced, perhaps accounting for the negative results seen so far (Question

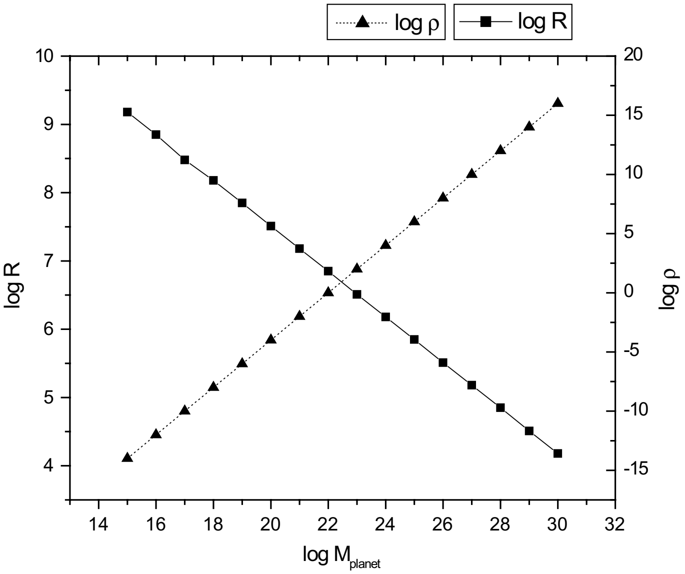

Fig. 1 Variation of size and densities of DM planets with their mass

of having the cake and eating it too!). So we can still have DM particles and not detect them. Here we would like to point out that DE problem could also be solved through extended gravity models as emphasised in Corda (2009).

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