Baryon-dark matter scattering and first star formation

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ABSTRACT
The recent detection of the sky-averaged 21-cm cosmological signal indicates a stronger absorption than the maximum allowed value based on the standard model. One explanation for the required colder primordial gas is the energy transfer between the baryon and dark matter fluids due to non-gravitational scattering. Here, we explore the thermal evolution of primordial gas, collapsing to form Population III (Pop III) stars, when this energy transfer is included. Performing a series of one-zone calculations, we find that the evolution results in stars more massive than in the standard model, provided that the dark matter is described by the best-fit parameters inferred from the 21-cm observation. On the other hand, a significant part of the dark matter parameter space can be excluded by the requirement to form massive Pop III stars sufficiently early in cosmic history. Otherwise, the radiation background needed to bring about the strong Wouthuysen-Field coupling at $z \gtrsim 17$, inferred to explain the 21-cm absorption feature, could not be built up. Intriguingly, the independent constraint from the physics of first star formation at high densities points to a similarly narrow range in dark matter properties. This exploratory study has to be followed-up with self-consistent three-dimensional simulations for a more rigorous derivation.

Key words: methods: numerical – stars: formation – stars: Population III – dark ages, reionization, first stars – dark matter – cosmology: theory

1 INTRODUCTION
One of the fundamental open questions in modern science is to elucidate the nature of dark matter (DM). Due to the lack of any direct detections in the laboratory yet, astrophysical probes have gained increasing prominence. Specifically, the detailed properties of the DM particle(s) are reflected in cosmological structure formation, with a particular sensitivity on small-scales. This regime is accessible either locally by probing dwarf galaxies in the Local Group (e.g. Bullock & Boylan-Kolchin 2017), or at high redshifts, when the first stars form in low-mass DM haloes (e.g. Fialkov et al. 2012; Bromm 2013; Dayal et al. 2017b). This latter probe will be rendered even more powerful when the James Webb Space Telescope (JWST) and other frontier facilities will become available in the near future (e.g. Dayal et al. 2017a).

An alternative pathway to first star formation is given by 21-cm cosmology, which probes the redshifted radiation emitted in the spin-flip transition of neutral hydrogen (reviewed in Furlanetto 2006). The Experiment to Detect the Global Epoch of Reionization Signature (EDGES) has recently reported the spectral absorption feature when the spin temperature is coupled to that of the cold intergalactic medium (IGM) gas (Bowman et al. 2018). This coupling is mediated through the Lyman-$\alpha$ radiation produced by the first stars, the so-called Wouthuysen-Field effect (Wouthuysen 1952; Field 1958). The best-fit absorption profile is centred at a frequency of $78 \pm 1$ MHz, corresponding to $z = 17.2$, with a brightness temperature of $T_{21} = -500^{+200}_{-500}$ mK. This represents an unexpectedly deep absorption, compared to the expectation within the standard model (Pritchard & Loeb 2012). To explain the strength of the absorption signal, the primordial gas must have been colder than expected. Any astrophysical phenomena could only have acted to raise the IGM gas temperature, such as the heating from early sources of X-ray radiation (e.g. Jeon et al. 2012), and thus cannot explain it.

One of the theoretical explanations for the additional cooling is non-standard DM particle physics in the form of baryon-dark matter (b-DM) scattering (Barkana 2018). Such non-gravitational interaction may act to solve a number of discrepancies between the standard cold dark matter (CDM) cosmological model and observational constraints (e.g. de Blok 2010; Boylan-Kolchin et al. 2012; Bullock 2013). Because the DM fluid decouples from the cosmic microwave background (CMB) earlier than the baryons, the latter can be cooled by the colder DM component via b-DM scattering. The baryons, thus cooled, can imprint their signature on the redshifted 21-cm line from the neutral hydrogen during cosmic dawn when the Wouthuysen-Field ef-
fect re-established the spin coupling to the gas temperature (Tashiro et al. 2014). Additionally, the baryons could also thermalize with a kinematically hotter DM component (Muñoz et al. 2015), such as the supersonic streaming velocity left over after cosmic recombination (Tseliakhovich & Hirata 2010).

In the case with b-DM scattering, other astrophysical phenomena can be affected, in addition to the impact on the 21-cm signal, such as the properties of the Lyman-α forest (Dvorkin et al. 2014) and the abundance of high-z galaxies (e.g. Mirocha & Furlanetto 2018). All of these effects, however, probe the low-density diffuse regime, and it is an open question how such potential b-DM scattering would influence the collapse of primordial gas to the high densities where star formation occurs. It is well known that the formation physics of the first, so-called Population III (Pop III), stars can depend on the particle-physics nature of DM (e.g. Stacy et al. 2014; Hirano et al. 2018). We here specifically ask: Does a model with b-DM scattering, calibrated at low densities, result in Pop III star formation? To achieve the early Wouthuysen-Field coupling implied by the EDGES measurement, Pop III stars would need to produce a critical background Lyman-α intensity of $1.8 \times 10^{-21} (1+z)/20 \, \text{erg s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$ (Madau et al. 1997; Ciardi & Madau 2003). The ionizing stellar UV radiation is reprocessed into Lyman-α photons in the surrounding emission nebula, and the ionizing rate per stellar mass is higher for more massive stars (Bromm et al. 2001; Schaerer 2002). We estimate that Pop III stars characterized by a top-heavy initial mass function (IMF) are required to provide the critical intensity for effective Wouthuysen-Field coupling. How then do the first stars form in a model with b-DM scattering?

We specifically wish to assess how important this effect is for primordial stars in minihaloes, the standard formation site in ΛCDM cosmology. Ultimately, self-consistent cosmological simulations including the b-DM scattering throughout are necessary to reach definitive conclusions. Here, we carry out a first survey of the effect, and evaluate the energy transfer rate between the baryon and DM components with a series of one-zone calculations, thus assessing the dependence on model parameters.

2 MODIFIED THERMAL EVOLUTION

As the most important impact of b-DM scattering on the star-formation process, we consider the energy transfer between the baryon and DM components. We assume a scattering cross section, $\sigma_{\text{DM}}(n_{\text{DM}}) = \sigma_1 (n_{\text{DM}}/1 \, \text{km s}^{-1})^{-4}$, as a function of the b-DM relative velocity $v_{\text{DM}}$. This general dependence is often considered, and would formally correspond to a Coulomb-like b-DM scattering (e.g. Tashiro et al. 2014). The energy transfer rate, $\dot{Q}_{\text{DM}}$, is calculated with equation (16) in Muñoz et al. (2015),

$$\dot{Q}_{\text{DM}} = \frac{m_p m_{\text{DM}} c^2}{(m_p + m_{\text{DM}})^2} \left( \frac{T_{\text{DM}} - T_\text{b}}{u_{\text{th}}} \right) \left\{ \frac{2}{\sqrt{\pi}} e^{-z^2} \right\}$$

$$+ \frac{m_{\text{DM}}}{v_{\text{DM}}} \left[ \text{erf} \left( \frac{r}{\sqrt{2}} \right) - \frac{2}{\sqrt{\pi}} e^{-z^2} \right] r, \quad (1)$$

where $m_p$ and $m_{\text{DM}}$ are proton and DM particle mass, $\rho_{\text{DM}}$ is the density of the DM fluid, $T_b$ and $T_{\text{DM}}$ (where $(1/2)m_{\text{DM}}v^2 = (3/2)k_B T_{\text{DM}}$) are (effective) temperatures of the two fluids, $u_{\text{th}} = \sqrt{T_b/m_p} + T_{\text{DM}}/m_{\text{DM}}$ is the variance of the thermal relative motion of the two components, and $r = \sqrt{n_{\text{DM}}/n_{\text{b}}}$ indicates which term is more important. The first term, giving the temperature-dependent heating (cooling), dominates when $r \ll 1$ ($n_{\text{DM}} \ll n_{\text{b}}$). The second term, on the other hand, describing heating due to the relative velocity, becomes important when $r \gg 1$ ($n_{\text{DM}} \gg n_{\text{b}}$), where the expression in the curly bracket increases from zero to one for $r = 0 \to \infty$. Based on the DM properties, the two key parameters are: $m_{\text{DM}}$ governs which term is dominant, and $\sigma_1$ determines the strength of the total contribution. Here, we adopt the best-fit parameter set from the recent 21-cm observation, $(m_{\text{DM}}/\text{GeV}, \sigma_1/\text{cm}^2) = (0.3, 8 \times 10^{-20})$, as fiducial values for these parameters (Barkana 2018).
To compute $Q_{\text{bDM}}$ in the primordial star-forming gas cloud, we derive the typical properties in a host minihalo from three-dimensional cosmological hydrodynamic simulations (Hirano et al. 2014). The simulations were carried out in the standard ΛCDM cosmology without b-DM scattering. We thus make the idealizing assumption that the early stages of structure formation, occurring at low densities, is not significantly different across models that include the b-DM scattering effect. Evidently, this needs to be tested in future, self-consistent cosmological simulations, but we present justification for this approximation below, at least for an important part of parameter space (see Section 3). Based on the cosmological simulations, we analyse averaged properties of $\rho_b$, $\rho_{bDM}$, $T_b$, $T_{DM}$, and $n_{bDM}$. Fig. 1 presents averaged profiles based on 110 primordial star-forming gas clouds.

We use the snapshots when the central baryon number density reaches $10^3$ cm$^{-3}$, so that we can resolve the collapse stage where the temperature assumes a minimum, and the cloud becomes gravitationally unstable, the so-called loitering point (Bromm et al. 2002). This scale, closely related to the pre-stellar core in present-day star formation (e.g. McKee & Ostriker 2007), describes the overall mass scale of Pop III stars (see below). During the cloud collapse, the baryon density exceeds the DM density at $n_H \gg 10^3$ cm$^{-3}$ (panel a). For our fiducial parameters, the DM effective temperature remains below the gas temperature until the loitering time, $n_H < 10^3$ cm$^{-3}$, and becomes comparable during the subsequent collapse (panel b). Thus, the first term of $Q_{bDM}$ is a cooling term in the early phase, but acts as a heating term later on. The relative velocity between the two fluids, calculated as the mean-square average inside the smoothed particle hydrodynamics (SPH) spline kernel, $v_{N_{\text{DM}}} = \sqrt{(1/N) \sum N_{\text{DM}} (v_b - v_{bDM})^2}$, is about $4 \pm 5$ km s$^{-1}$. This is larger than the typical velocities discussed in the literature to explain the 21-cm observation ($\sim 1$ km s$^{-1}$), but is of order the virial velocity in a typical Pop III host minihalo. The heating from the second term becomes more important in the star-forming cloud during the later collapse stage.

Fig. 2 shows the energy transfer rate $Q_{bDM}$ for the representative primordial star-forming cloud (Fig. 1) with the fiducial parameters. The energy transfer behaviour switches from cooling to heating when the gas cloud contracts inside the host DM minihalo beyond $n_H \sim 100$ cm$^{-3}$. During the initial collapse phase, the possible thermal impact from b-DM scattering is weaker than that from the standard primordial chemistry and cooling ($Q_{bDM} < |\Gamma + \Lambda_{\text{prim}}|$). Once the collapse has proceeded to higher densities, however, the heating due to b-DM scattering overtakes the standard contribution ($Q_{bDM} > |\Gamma + \Lambda_{\text{prim}}|$). This heating and cooling sequence will influence the thermodynamics of primordial star-forming gas, modifying the mass scale for gravitational instability. As a consequence, the typical mass of the first stars will also be affected, as we will discuss next.

3 COLLAPSE AND FRAGMENTATION

To assess the fragmentation properties of primordial gas, we introduce the energy transfer rate due to the b-DM scattering to an one-zone calculation to model the thermal evolution of a cloud collapsing into a minihalo. We employ the same chemical network as in the cosmological simulation used to derive the typical minihalo properties (Hirano et al. 2014). The thermal evolution of the collapsing cloud depends on the collapse rate (e.g. Chiaki et al. 2016), and we adjust the parameters of our one-zone model to reproduce the averaged data from the cosmological simulation. In Fig. 3, we show three different thermal pathways due to the additional energy transfer rate, depending on the nature of the DM.

$T_{\text{CMF}} < T < T_{\text{Vir}}$: The solid black line in Fig. 3 shows the thermal evolution under the influence of b-DM scattering, with the fiducial parameters which can well explain the deep absorption in the detected 21-cm spectrum. The resulting thermal history is almost the same as for the standard case without b-DM interaction until $n_H \sim 100$ cm$^{-3}$, because of the negligible contribution from the additional cooling and heating terms in this density regime (see Fig. 2). We note that this supports our idealizing assumption that the standard ΛCDM cosmological simulations provide a valid representation of the initial stages of structure formation, even if non-gravitational b-DM scattering were present. Towards higher densities, however, the collapsing cloud heats up strongly due to the energy exchange from the b-DM scattering. Assuming that the gas cloud becomes gravitationally unstable when the temperature reaches its minimum value during the collapse, the fragmentation scale can be estimated via the Bonnor-Ebert (BE) mass, $M_{\text{BE}} \approx 1000 M_\odot (T/200 \text{ K})^{3/2} (n_H/10^2 \text{ cm}^{-3})^{-1/2}$ (Abel et al. 2002; Bromm et al. 2002). The BE mass in the fiducial b-DM scattering case (the black line in Fig. 3) is then $\sim 2 \times 10^4 M_\odot$, about 40 times larger than the case without such scattering (the thick grey line), where $M_{\text{BE}} \approx 500 M_\odot$.

Because the mass accretion rate onto a protostar depends on the gas temperature, $M = M_{\text{BE}}/\dot{M}_\text{g} \sim T^{3/2}$, such hot cloud core could host more massive Pop III stars. The conclusion is that very massive first stars could form in a cosm-
Figure 3. Thermal evolution of the collapsing primordial gas cloud evaluated with idealized one-zone calculations. The red, black, and blue lines show results for select parameters, as follows: \((m_{DM}/\text{GeV}, \sigma_{\text{DM}}/\text{cm}^2)\) = (2, 3 \times 10^{15}), (0.3, 8 \times 10^{20}), and (0.01, 1 \times 10^{-18}), respectively. Thin lines show cases for additional parameter choices. The thick grey line represents the standard case without b-DM energy transfer, and well reproduces the averaged data for an ensemble of cosmological clouds (dashed line). The diagonal lines show the \(n_{\text{H}} - T\) relation for the given BE masses. The extreme cases, of either driving the gas temperature above the minihalo virial temperature (\(T > T_{\text{vir}}\); red line), or quickly cooling to the CMB floor (\(T = T_{\text{CMB}}\); blue), are not well captured by our simplified modelling. The long-term thermal evolution is therefore uncertain, as indicated by the dashed arrows.

4 CONSTRAINTS ON DM PHYSICS

In Fig. 4, we summarize the calculation results, in terms of the dependence on DM parameter space, \(m_{DM}\) and \(\sigma_{\text{DM}}\). The b-DM scattering acts as an additional cooling source for low \(m_{DM}\), whereas as heating for large \(m_{DM}\). The overall thermal impact increases with \(\sigma_{\text{DM}}\). The colour contour represents the mass scale for gravitational instability, \(M_{\text{KE}}\), whereas the two light-coloured zones indicate regions in parameter space that are excluded, because of constraints on Pop III star formation, as discussed in the previous section. Furthermore, any region is effectively excluded, where \(M_{\text{BE}}\) is too low to accommodate a top-heavy IMF, as is the case for low values of \(m_{DM}\). The hatched region reproduces the constraints from the EDGES measurement, assuming the 3.5\(\sigma\) observational results: \(T_{21} = -231\) mK at \(z = 17\) (Barkana 2018). Intriguingly, the allowed parameter range is highly confined by combining constraints derived from high- and low-density physics.

The case with the 21-cm observation best-fit DM parameter set is located in the region where the energy transfer due to b-DM scattering changes from cooling to heating during the cloud collapse (Fig. 2). Around \(m_{DM} \sim 0.35\) GeV, the b-DM cooling is negligible, or at most comparable to the cooling provided by the standard primordial chemistry, and cannot affect the collapse of the baryon fluid, gravitationally trapped inside a DM minihalo. Subsequently, however, the efficient b-DM heating can greatly change the thermal evolution of the collapsing gas cloud. As a result, the mass scale of a gravitationally unstable object significantly increases, to \(M_{\text{BE}} \sim 10^{8}\) M\(_{\odot}\) compared with the standard ΛCDM case \((-1000\) M\(_{\odot}\)).

Our series of one-zone models is capable of exploring the basic DM parameter dependence of first star formation. In so

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1 As parameters of the host minihalo, we adopt the average value obtained from a large cosmological sample (see fig. 3 of Hirano et al. 2015): \(z = 19\) and \(M_h = 3 \times 10^5\) M\(_{\odot}\).
First stars with baryon-DM scattering

Figure 4. Constraints on DM properties, $m_{DM}$ and $\sigma_1$, using first star formation. The physics of primordial star formation delineates regions where the formation of massive stars at early epochs is disfavoured: (1) the gas temperature reaches the CMB floor, thus leading to predominantly low-mass stars (light-blue region) and (2) the gas temperature exceeds the minihalo’s virial temperature, thus delaying the collapse and onset of star formation (light-red region). For the region where massive stars can form, on the other hand, we indicate the Bonner-Ebert mass with the coloured contours. The three dashed lines show the $m_{DM}$–$\sigma_1$ relation for the given BE masses, specifically $M_{BE} = 100$, $500$, and $1000M_\odot$, respectively. Finally, the hatched region shows the region excluded by EDGES, assuming absorption by at least $T_{21} = -231$ mK at $z = 17$ (see fig. 3 in Barkana 2018). The three crosses correspond to the three parameter sets used in Figs. 1 and 3. As can be seen, there is only a narrow parameter range where all available constraints are fulfilled.

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REFERENCES

Abel T., Bryan G. L., Norman M. L., 2002, Science, 295, 93
Barkana R., 2018, Nature, 555, 71
Barkana R., Loeb A., 2001, Phys. Rep., 349, 125
Bertone G., 2010, Nature, 468, 389
Bowman J. D., Rogers A. E. E., Monsalve R. A., Mozdzen T. J., Mahesh N., 2018, Nature, 555, 67
Boylan-Kolchin M., Bullock J. S., Kaplinghat M., 2012, MNRAS, 422, 1203
Bromm V., 2013, Reports on Progress in Physics, 76, 112901
Bromm V., Kudritzki R. P., Loeb A., 2001, ApJ, 552, 464
Bromm V., Coppi P. S., Larson R. B., 2002, ApJ, 564, 23
Bullock J., 2013, Notes on the missing satellites problem. Cambridge University Press, pp 95–122, doi:10.1017/CBO9781139152303.004
Bullock J. S., Boylan-Kolchin M., 2017, ARA&A, 55, 343
Chiaki G., Yoshida N., Hirano S., 2016, MNRAS, 463, 2781
Ciardi B., Madau P., 2003, ApJ, 596, 1
Dayal P., Choudhury T. R., Pacucci F., Bromm V., 2017a, MNRAS, 472, 4414
Dayal P., Choudhury T. R., Bromm V., Pacucci F., 2017b, ApJ, 836, 16
Dvorkin C., Blum K., Kamionkowski M., 2014, Phys. Rev. D, 89, 023519
Falkov A., Barkana R., Tseliakhovich D., Hirata C. M., 2012, MNRAS, 424, 1335
Field G. B., 1958, Proceedings of the IRE, 46, 240
Furlanetto S. R., 2006, MNRAS, 371, 867
Hirano S., Hosokawa T., Yoshida N., Umeda H., Omukai K., Chikai G., Yorke H. W., 2014, ApJ, 781, 60
Hirano S., Hosokawa T., Yoshida N., Omukai K., Yorke H. W., 2015, MNRAS, 448, 568
Hirano S., Sullivan J. M., Bromm V., 2018, MNRAS, 473, L6
Jeon M., Pawlik A. H., Greif T. H., Glover S. C. O., Bromm V., Milosavljević M., Klessen R. S., 2012, ApJ, 754, 1
Madau P., Meiksin A., Rees M. J., 1997, ApJ, 475, 429
McKee C. F., Ostriker E. C., 2007, ARA&A, 45, 565
Mirocha J., Furlanetto S. R., 2018, preprint, (arXiv:1803.03272)
Muñoz J. B., Kovetz E. D., Ali-Haimoud Y., 2015, Phys. Rev. D, 92, 083528
Pritchard J. R., Loeb A., 2012, Reports on Progress in Physics, 75, 086901
Schaerer D., 2002, A&A, 382, 28
Stacy A., Pawlik A. H., Bromm V., Loeb A., 2014, MNRAS, 441, 822
Tashiro H., Kadota K., Silk J., 2014, Phys. Rev. D, 90, 083522
Tseliakhovich D., Hirata C., 2010, Phys. Rev. D, 82, 083520
Wouthuysen S. A., 1952, AJ, 57, 31
de Blok W. J. G., 2010, Advances in Astronomy, 2010, 789293

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