DARK MATTER POWERED STARS: CONSTRAINTS FROM THE EXTRAGALACTIC BACKGROUND LIGHT

A. MAURER\textsuperscript{1}, M. RAUE\textsuperscript{1}, T. KNEISKE\textsuperscript{1}, D. HORNS\textsuperscript{1}, D. ELSÄSSER\textsuperscript{2}, AND P. H. HAUSCHILDT\textsuperscript{3}

\textsuperscript{1}Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany; andreas.maurer@physik.uni-hamburg.de
\textsuperscript{2}Institut für Theoretische Physik und Astrophysik, Am Hubland, D-97074 Würzburg, Germany
\textsuperscript{3}Hamburger Sternwarte, Gojenbergsweg 112, D-21029 Hamburg, Germany

Received 2011 June 7; accepted 2011 December 17; published 2012 January 16

ABSTRACT

The existence of predominantly cold non-baryonic dark matter is unambiguously demonstrated by several observations (e.g., structure formation, big bang nucleosynthesis, gravitational lensing, and rotational curves of spiral galaxies). A candidate well motivated by particle physics is a weakly interacting massive particle (WIMP). Self-annihilating WIMPs would affect the stellar evolution especially in the early universe. Stars powered by self-annihilating WIMP dark matter should possess different properties compared with standard stars. While a direct detection of such dark matter powered stars seems very challenging, their cumulative emission might leave an imprint in the diffuse metagalactic radiation fields, in particular in the mid-infrared part of the electromagnetic spectrum. In this work, the possible contributions of dark matter powered stars (dark stars, DSs) to the extragalactic background light (EBL) are calculated. It is shown that existing data and limits of the EBL intensity can already be used to rule out some DS parameter sets.

Key words: dark ages, reionization, first stars – dark matter – infrared: diffuse background – stars: atmospheres

Online-only material: color figures

1. INTRODUCTION

Several independent observations provide compelling evidence for an accelerated expanding universe with a matter content dominated by a non-luminous (“dark”) component (\textit{ΛCDM} cosmology). Relevant parameters for this so-called \textit{ΛCDM} cosmology have been measured with high accuracy with \textit{Wilkinson Microwave Anisotropy Probe} \textparentheses{WMAP; Komatsu et al. 2011\textparentheses{}} and baryonic acoustic oscillations surveys and will be further refined with upcoming \textit{Planck} data. Large sky surveys \textparentheses{e.g., Sloan Digital Sky Survey, SDSS, Abazajian et al. 2009; Two-Degree Field, 2dF; Colless et al. 2003\textparentheses{}} and numerical simulations like, \textparentheses{e.g., the Millennium Run \textparentheses{Springel et al. 2005\textparentheses{}} point toward a convincing picture of large-scale structure formation within the cosmological concordance model. A promising particle candidate for the dark matter (DM) content of the universe is the weakly interacting massive particle \textparentheses{WIMP; see, e.g., Jungman et al. 1996; Bertone et al. 2005 for a review article}. Such particles can naturally have annihilation or decay channels leading to standard model particles.

The epoch where the first stars form \parentheses{\textit{z} \sim 30\textparentheses{}} is not yet observable with today’s astronomical instruments. The circumstances and mechanisms of stellar genesis are still topics of ongoing analysis and rely on sophisticated numerical simulations \parentheses{for a review see, e.g., Bromm & Larson 2004\textparentheses{}}. Recently, studies discussed the impact of WIMP DM on the formation of the first stars \parentheses{Spolyar et al. 2008; Iocco et al. 2008; Iocco 2008; Freese et al. 2008a\textparentheses{}}. During the epoch of reionization of the universe, DM may have affected the formation and evolution of stars. Assuming that self-annihilating particles provide the DM content of the universe, this new source of energy injection into the first stars may alter their properties. The energy injection from self-annihilating WIMPs can delay or even prevent the nuclear hydrogen burning.

In principle, two mechanisms could lead to DM accretion into a star. The first one, investigated by Spolyar et al. \textparentheses{2008\textparentheses{}}\textparentheses{,} is adiabatic contraction \parentheses{AC} where additional DM from outside the forming first star is gravitationally pulled along with accreting baryonic gas onto the proto-star. Due to the very low surface temperature of the dark star \parentheses{DS} compared to its enormous mass there should be no or very little radiative feedback mechanisms preventing further accretion. The other possibility to replenish the DM inside a star is capture of WIMPs via scattering. The efficiency of this mechanism depends on the product of the elastic scattering cross section between baryonic and DM and the surrounding DM density \parentheses{Iocco et al. 2008; Iocco 2008; Freese et al. 2008a\textparentheses{}}. Both mechanisms can lead to generic properties of the DS; low surface temperatures \parentheses{\textsim 5000–10,000 K\textparentheses{,}} high luminosities \parentheses{\textsim 10^{5} L_{\odot}\textparentheses{,}} and presumably longer lifetimes than conventional Population III \parentheses{Pop III\textparentheses{}} stars. After a “dark phase,” the star evolves as a normal zero-age main-sequence star.

Direct detection, even of a DS cluster, is a challenging task which may only be possible with future instruments like the upcoming \textit{James Webb Space Telescope} \textparentheses{JWST; Gardner et al. 2006\textparentheses{}} and under the assumption of an optimistic model \parentheses{Zackrisson et al. 2010\textparentheses{}}. A different approach for the search of emission in the early universe is to probe the diffuse metagalactic radiation field \parentheses{MRF; see, e.g., Hauser & Dwek 2001\textparentheses{}}. Its main contribution comes from integrated starlight and thermal dust emissions of all cosmic epochs \parentheses{Kneiske et al. 2002, 2004; Stecker et al. 2006; Franceschini et al. 2008; Primack et al. 2008; Gilmore et al. 2009; Finke et al. 2010; Kneiske & Dole 2010\textparentheses{}}. This fact makes the EBL a unique probe for the integrated star formation history of the universe. There are different types of observational approaches to measure the EBL. Direct observations—e.g., with the DIRBE instrument on board the \textit{COBE} satellite—suffer from prominent foreground emission, like zodiacal light, that is caused by scattered sunlight by dust in the zodiacal cloud, and diffuse galactic radiation \parentheses{Hauser et al. 1998\textparentheses{}}. Lower limits to the EBL are derived from integrated galaxy number counts which are available up to a
redshift ≈ 2 from Hubble Space Telescope (Madau & Pozzetti 2000) and the Spitzer instrument (Fazio et al. 2004). A powerful method for obtaining upper limits on the EBL density makes use of the spectra from very high energy (VHE) γ-ray sources, especially blazars (see, e.g., Mazin & Raue 2007). Galaxy number counts and upper limits from VHE γ-ray observations can be used to constrain possible DS scenarios.

In this paper, the so far unknown contribution of DSs to the EBL is calculated. Constraints for some DS scenarios are derived as well as a convenient parameterization to calculate the maximum EBL density produced by a set of DS parameter values. The paper is organized as follows. In Section 2 the model calculations for the EBL from DSs are described. In Section 3 the resulting EBL for different sets of DS parameters is calculated and compared with recent data and EBL models. The multidimensional DS parameter space is constrained and a parameterization for the peak EBL contribution of DSs is derived. Section 4 summarizes the results obtained and compares them with existing direct and indirect approaches to detect/constrain DSs. Throughout this paper a flat Friedmann cosmology is adopted with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \) and a Hubble constant of \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. THE DS CONTRIBUTION TO THE EXTRAGALACTIC BACKGROUND LIGHT (EBL)

In order to calculate the EBL produced by DM burning stars a forward evolution model is used based on the calculations of Kneiske et al. (2002) and Raue et al. (2009, see also Dwek et al. 1998; Salamon & Stecker 1998). In the model, the specific intensity of the EBL \( I_{\nu}(z) \) is obtained by integrating the specific comoving luminosity density \( \varepsilon_{\nu}(z) \) over redshift \( z \):

\[
I_{\nu}(z) = \frac{c}{4\pi} \int_{z}^{z_{\max}} \frac{d\nu}{dz'} \varepsilon_{\nu}(z') \frac{dt}{dz'} , \tag{1}
\]

where \( \varepsilon_{\nu}(z) \) is given by

\[
\varepsilon_{\nu}(z) = \int_{z}^{z_{\max}} \frac{d\nu}{dz'} L_{\nu}(t) (t' - t(z')) \rho_{\nu}(z') \frac{dt}{dz'} . \tag{2}
\]

\( L_{\nu}(t) \) is the time-dependent specific luminosity, \( \rho_{\nu}(z') \) is the comoving formation rate of DSs at a given redshift \( z' \), and \( v' = v(1+z)/(1+z') \) is the redshifted frequency. The integration limit \( z_{\max} \) determines the maximum redshift where DM burning stars begin to form. Cosmological parameters enter through

\[
\frac{dt}{dz} = \frac{1}{H_0(1+z)E(z)} \tag{3}
\]

\[
E(z) = \Omega_m (1+z)^4 + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda , \tag{4}
\]

as described in, e.g., Peebles (1993). Further details on the method and formulas used here can, for example, be found in Kneiske et al. (2002).

DS spectrum with PHOENIX. The atmospheres and spectra of DSs are modeled with the model atmosphere program PHOENIX, version 16. A basic description of the code can be found in Hauschildt & Baron (1999) and recent applications to stellar objects can be found in Srt & Hauschildt (2009) and in Fuhrmeister et al. (2010). The current version 16 of the PHOENIX package (Hauschildt & Baron 2010) uses the ACES equation of state (Barman et al. 2011) to allow for a temperature range from 100 K to above 10^6 K and includes a multitude of molecular and dust species. The models presented here use the one-dimensional (1D) mode PHOENIX/1D of PHOENIX with spherical symmetry. The model atmospheres are computed for radiative and convective equilibrium with a mixing length to pressure scale height ratio of 2, with the assumption that no energy is generated in the atmosphere. The abundance of H was set to 0.92 by number (mass fraction: 0.75) and that of He was set to 0.08 by number (mass fraction: 0.25) for all models; all other elements (including Li) have an abundance of zero in these models. Models with effective temperatures from 5000 K to 7500 K with parameters (gravities, masses) taken from Spolyar et al. (2009) have been computed. For all the models a number of different variants by, for example, varying the line profiles or the equation of state setup to investigate the effects on the models and the synthetic spectra have been computed. For each setup discussed below, the individual models are relaxed to equilibrium before computing high-resolution synthetic spectra.

For a given effective temperature, the choice of line profiles produces the largest variations in the emitted spectra (see Figure 1). The two sets of models were computed by (1) using Stark profiles for the H lines and (2) using van der Waals (vdW) broadening for the H lines. At \( T_{\text{eff}} = 5000 \text{ K} \) the vdw broadening is the dominant line broadening process whereas at \( T_{\text{eff}} = 7500 \text{ K} \) Stark broadening is more important, despite the absence of free electrons from the light metals: see the comparison to a spectrum with solar abundances in Figure 2. The hottest model in Figure 1 clearly shows the electronic lines of H\(_2\) in their UV spectra; these are also present in the DS spectra with lower effective temperatures but are much weaker due to their high excitation energies. In solar abundance models these are overwhelmed by the metal lines in the UV and would not be detectable. For the model parameters considered, the non-local thermal equilibrium (NLTE) effects are small and appear to be insignificant. At higher effective temperatures this will likely be different; however, this parameter range is not considered here.

As can be seen from Figure 1 no significant hydrogen ionizing radiation is emitted to the stellar temperature range considered here.

DS formation rate. The formation density of DSs \( \dot{n}_s(z) \) can be linked to the star formation rate (SFR) \( \dot{\rho}_s(z) \) for the first stars (Pop III). Spolyar et al. (2008, 2009) propose that every Pop III star that forms inside the center of an undisturbed DM halo could establish a DS phase \( \Delta_{\text{DS}} \). This implies that the mass formation rate of DSs can be written as \( \dot{\rho}_s(z) = \dot{n}_s(z) \times M_{\text{DS}} \).

The comoving SFRs of the first stars that form in such environments are calculated by Trenti & Stiavelli (2009) with a variety of radiative and chemical (metal enrichment) feedback parameters and for different numbers of stars forming. They obtain values for the Pop III mass formation rate of 10^−5−10^−3 M\(_\odot\) yr\(^−1\) Mpc\(^−3\) up to \( z = 10 \) depending on the exact model parameters considered. Pop III SFRs in a similar range are also found for lower redshifts (Schneider et al. 2006; Tornatore et al. 2007; Maio et al. 2010). There exist two negative feedback mechanisms for Pop III star formation: radiative feedback from H\(_2\) ionizing photons and metal enrichment. For DSs, due to their cooler temperatures and longer lifetimes than Pop III stars, both feedback mechanisms mentioned can be

---

4 This assumption holds true if one specific DS model with mass \( M_{\text{DS}} \) is considered.

5 For a detailed description of these processes please refer to Trenti & Stiavelli (2009) and references therein.
Figure 1. Synthetic spectra for DS models derived with the PHOENIX code. The model parameters are from top to bottom: $T_{\text{eff}} = 7500$ K, $\log(g) = 1.0$, $M = 690 M_\odot$, $T_{\text{eff}} = 6000$ K, $\log(g) = 0.0$, $M = 371 M_\odot$, $T_{\text{eff}} = 5500$ K, $\log(g) = -0.5$, $M = 106 M_\odot$, and $T_{\text{eff}} = 5000$ K, $\log(g) = -0.5$, $M = 106 M_\odot$. The gravitational acceleration $g$ is given in CGS units. (A color version of this figure is available in the online journal.)

Figure 2. Comparison of the DS synthetic spectra for $T_{\text{eff}} = 7500$ K, $\log(g) = 1.0$, $M = 690 M_\odot$ with a solar abundances model with the parameters $T_{\text{eff}} = 7400$ K, $\log(g) = 1.0$, $M = 1 M_\odot$. (A color version of this figure is available in the online journal.)

suppressed and thus DS formation can, in principle, be enhanced and prolonged. It is also possible that DSs can grow to larger masses than the usual first stars ($M_\text{DS} > M_\text{PopIII}$) which results in a higher SFR $\dot{\rho}_s(\tau)$. In summary it can be concluded that the SFR of DSs suffers from large uncertainties. Therefore a reasonable fiducial value is derived from the Pop III SFR ($10^{-5} M_\odot$ yr$^{-1}$ Mpc$^{-3}$) and a wide range limited by extreme models ($10^{-7}$–$10^{-3} M_\odot$ yr$^{-1}$ Mpc$^{-3}$) is explored.
Hence, as a simplification, a constant SFR over a certain redshift period is assumed which can be expressed as a mass formation rate in units of $M_{\odot}/\text{yr}^{-1}/\text{Mpc}^{-3}$:

$$\dot{\rho}_s(z) = \begin{cases} \text{SFR}_\text{Norm} & \text{for } z_{\text{min}} \leq z \leq z_{\text{max}} \\ 0 & \text{elsewhere,} \end{cases}$$

(5)

where SFR$_\text{Norm}$ is a normalization factor, varied in the range mentioned above, $z_{\text{min}}$ indicates the minimal value of redshift $z$ where DS formation can still occur, and $z_{\text{max}}$ denotes the beginning of the DS formation epoch. The ansatz for the SFR used in this paper is strongly simplified and more elaborate elaborations of the SFR are available (see, e.g., Greif & Bromm 2006; Sandick et al. 2011). Raue et al. (2009) have investigated the impact of a wide range of SFRs on the resulting EBL density and found the position and overall height of the peak to be the dominant factors, while the choice of the shape only resulted in a weak change in the resulting peak EBL density (factor $\sim 2$). Given the range of parameters investigated in this work (e.g., the overall normalization of the SFR ranges over several orders of magnitude), this simplified approach for the SFR is sufficient.

As the duration of the DS-forming period in the universe is directly linked to the amount of photons that are emitted by DSs the influence of $z_{\text{min}}$ and $z_{\text{max}}$ on the EBL is also explored. The contribution of $\dot{\rho}_s(z)$ for large $z$ is suppressed because of the redshift dilution of the photon field which goes as $(1+z)^{-3}$ and so the value of $z_{\text{max}}$ is, in the following, set to 30. For $z_{\text{min}}$ (the end of the DS formation epoch) values between 5 and 15 are considered. These values are in good agreement with assumed Pop III formation periods (Schneider et al. 2006; Tornatore et al. 2007; Trenti & Stiavelli 2009; Trenti et al. 2009; Maio et al. 2010).

**DS luminosity.** Independent of the exact mechanism powering the DM burning, models predict a stable phase which dominates the total radiative output during the DS phase (Spolyar et al. 2008; Iocco et al. 2008). During this phase the luminosity is nearly constant (see, e.g., Figure 2 in Spolyar et al. 2009; Figure 4 in Iocco et al. 2008; Figure 1 in Yoon et al. 2008). Therefore the following ansatz is adopted for $L_\nu$:

$$L_\nu(t(z) - t(z')) = \begin{cases} L_\nu^0 & \text{for } t(z) - t(z') \leq \Delta_{\text{DS}} \\ 0 & \text{elsewhere,} \end{cases}$$

(6)

with $\Delta_{\text{DS}}$ the duration of this stable phase (also referred to as DS lifetime) and $L_\nu^0$ the specific DS luminosity according to its synthetic spectrum (cf. Figure 1). For $\Delta_{\text{DS}} \ll t(z_{\text{min}}) - t(z_{\text{max}})$ the emissivity calculation reduces to

$$\varepsilon_\nu(z) \approx L_\nu^0 \Delta_{\text{DS}} \int_{z_{\text{min}}}^{z_{\text{max}}} dz' \dot{\rho}_s(z')$$

(7)

leading to a linear scaling of the resulting EBL with $\Delta_{\text{DS}}$. The exact length of the DS lifetime is not constrained and depends on various factors, e.g., DM type, DS model, DM halo profile, etc. (for an extensive discussion see Zackrisson et al. 2010). In this work a wide band of possible DS lifetimes is explored, ranging from $10^5$ to $10^9$ years.

The total bolometric luminosity of a single DS is connected to DM particle properties via

$$L = \int dv L_\nu' \propto \frac{\langle \sigma v \rangle_{\text{ann}}}{m_x}$$

(8)

(Spolyar et al. 2008).

Given a certain stellar mass formation rate the DS luminosity produced per mass has to be specified in the model. The mass range of Pop III stars, and, for this reason, also the mass range of DSs is not very well constrained but is expected to be within roughly 10 up to a few hundred solar masses (Abel et al. 2002; Schaerer 2002). The model assumptions for the DM burning and the star formation lead to a wide spread in the DS luminosity per stellar mass. This luminosity-to-(stellar) mass ratio (LMR) of published DS models (Iocco et al. 2008; Spolyar et al. 2009; Freese et al. 2010) can be computed and used as input for the EBL calculation presented here and ranges from $\sim 10^2$ to $10^5 L_\odot/M_{\odot}$.

The influence of DM particle properties on the LMR will be further discussed in Section 3.2.

### 3. RESULTS

#### 3.1. Constraining the DS Parameter Space

The EBL contribution of DSs is calculated using the methods and parameters discussed in the previous section. The range of the specific parameter values is shown in Table 1. A fiducial set of “intermediate” parameter values is also displayed which acts as the default when a single parameter is varied. As can be seen from Equation (5) in combination with Equations (1) and (2) the resulting EBL density scales linearly with the SFR and the LMR. In Figure 3 the EBL contribution for two different DS models is displayed in comparison with a strict lower limit for the guaranteed astrophysical EBL from stars and dust
in galaxies (Kneiske & Dole 2010). Comparing the resulting DS EBL signatures (red dashed and blue dashed curves) with their respective input spectra (see Figure 1) it can be seen that the spectral features are smoothed by the redshift integration. The peak of the EBL for both models is located at wavelengths $>2\mu$m which differs from the value ($\sim 1\mu$m) for Pop III stars (Santos et al. 2002) as expected due to lower effective temperatures. The peak of both EBL signatures clearly reaches into the detectable region of the infrared background. This shows that the EBL offers the potential to constrain DS parameter space. A DS contribution from these models would result in a total EBL which is the sum of the lower limit and the DS signature (red and blue lines). These EBL shapes are already disfavored by upper limits from TeV observations (gray line).

In Figure 4 the peak EBL contribution for three values of $z_{\text{min}}$ with respect to varying DS lifetimes is displayed. As a consequence of Equation (7), for DS lifetimes smaller than the formation period $t(z_{\text{min}}) - t(z_{\text{max}})$ the resulting EBL scales linearly with increasing $\Delta t_{\text{DS}}$. At higher lifetimes than $\sim 10^8$ years the intensity of the EBL is increased to a greater amount and the peak value of the DS signature is also shifted toward lower wavelengths (Figure 5). This is caused by a residual emissivity at lower redshifts $z < z_{\text{min}}$ as the end of DS formation is not the end of DS photon emission. Due to the strong dilution of the photon number density with redshift $(1+z)^{-3}$ the most recent emission dominates the EBL contribution. If $\Delta t_{\text{DS}}$ is short enough the end of DS formation is roughly equal to the end of DS emitting photons as the number of DSs drops of almost instantly. The dashed lines display a linear relationship between $\Delta t_{\text{DS}}$ and the maximum EBL flux. Please note that DSs with lifetimes $\Delta t_{\text{DS}} \approx 10^{10}$ years, as displayed in Figures 4 and 5, would be still present in today’s universe and therefore most likely to be detected.

The model results can be summarized in a formula giving the peak EBL contribution at $z = 0$ from a DS population normalized to the fiducial DS parameters:

$$(vI_v)_{\text{max}} = 2 \times 10^{-5} \text{ nW m}^{-2} \text{ sr}^{-1} \times \left(\frac{\Delta t_{\text{DS}}}{10^7 \text{ years}}\right) \times \left(\frac{\text{SFR}_{\text{Norm}}}{10^{-5}}\right) \times \left(\frac{\text{LMR}}{10^5 \text{ L}_\odot / \text{M}_\odot}\right) \times \left(\frac{\mu}{10}\right)^{-2.5} \times \left(\frac{z_{\text{min}}}{10}\right).$$

(9)

In Figure 5 the wavelength of the peak in the EBL SED as a function of DS lifetime for the 7500 K DS model. For $\Delta t_{\text{DS}} > 10^9$ years the values converge toward the intrinsic emission maximum indicating that DSs still emit light at $z = 0$.

(A color version of this figure is available in the online journal.)

The calculation of the resulting EBL contribution via this formula offers a conservative estimate as the DS lifetime only enters linearly which is true for $\Delta t_{\text{DS}}$ up to values as large as $\sim 10^8$ years. The possible enhancement of the EBL contribution due to longer DS lifetimes is not taken into account here, but one can estimate it from Figure 4 or it has to be calculated as described in this work. Comparing lower with upper limits on the EBL one finds an allowed EBL contribution from DSs in the range of $5-25 \text{ nW m}^{-2} \text{ sr}^{-1}$ for wavelengths between 2 and 10 $\mu$m (see, e.g., Mazin & Raue 2007, Figure 15). Adopting this range limits on DS parameters can be derived. For example, a DS with $M_{\text{DS}} = 106 \text{ M}_\odot$, $L_{\text{DS}} = 9 \times 10^6 \text{ L}_\odot$, a DS lifetime $\Delta t_{\text{DS}} = 10^8$ years, and minimum formation redshift $z_{\text{min}} = 5$ results in a constraint on the DS formation rate between $5 \times 10^{-4}$ and $3 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$. In this way several DS parameter sets can be used to constrain specific DS scenarios.

3.2. Implications for Dark Matter Properties

The dominant factor for the DS luminosity due to DM burning is the square of the DM density distribution $\rho_\chi$ which is determined by the original DM density profile inside primordial virialized halos, the change of the profile under the influence of contracting baryonic material (AC), and repopulation of the inner cusp of the DM halo due to scattering processes (Freese et al. 2008b, 2009). The characteristics (temperature, radius, luminosity) of a DS rely on the efficiency of the DM luminosity compared to other energy generation mechanisms like nuclear fusion. In general the more DM contributes to the total stellar luminosity of the star, the cooler and bigger it grows regardless of the mechanism that produces the high DM density inside the star.

As explained above the DS luminosity scales with $\rho_\chi^2$. The replenishment of the DM density inside a DS is possible either by the gravitational pull of the collapsing gas onto the DS or by multiple elastic scattering processes between DM and the stellar baryons or a combination of both. The LMR of the specific DM powered stars presented in Spolyar et al. (2009) tend to be slightly dependent on $(\sigma v)_{\text{ann}}/m_\chi$; higher values result in higher DS masses and at the same time also in higher DS luminosities. For the early stages of DS formation the LMR is nearly proportional to $(\sigma v)_{\text{ann}}/m_\chi$. In the case of DM capture,
as investigated by Iocco et al. (2008), the DS luminosity scales linearly with the elastic scattering cross section $\sigma_0$. It is also shown that DM burning due to WIMP capture is more efficient in low-mass stars, but under the assumption that the product $\sigma_0 \times \langle v \rangle_{\text{ann}}$ is of the order $10^{-26} \text{ GeV cm}^{-1}$ Yoon et al. (2008) have shown that a great mass range of stars can undergo a stable DM burning phase.

It is further worthwhile to note that, while conservative models of the DS contribution to the EBL do not strongly constrain WIMP properties such as mass or annihilation cross section, this picture can change when our prior assumptions are relaxed. As outlined in Spolyar et al. (2009), the DS LMR—and therefore the peak EBL contribution (see Equation (9))—will roughly scale with the square root of the annihilation cross section and WIMP mass as $\text{LMR} \propto \sqrt{(\sigma v)_{\text{ann}}/m_\chi}$, where $m_\chi$ is the mass of the WIMP. Assuming cross sections of the order $10^{-23} \text{ cm}^3 \text{ s}^{-1}$ for TeV scale WIMPs, as have recently been invoked to explain PAMELA measurements of the cosmic-ray positron fraction (Cirelli & Strumia 2008), at least the “max” model presented in Table 1 would already be strongly constrained by existing EBL data. In comparison to other indirect DM detection channels, the DS-induced EBL component is unique in that it is not sensitive to the exact branching ratios of the annihilation yields into photons or charged particles and their resulting spectra, as all annihilation products (with the exception of neutrinos, of course) are trapped and thermalized within the DS. In this regard, the calculations presented here can also serve as an independent and complementary template for indirect DM searches in other wave bands.

Implications also exist regarding the elastic scattering cross section of the DM particles. As capture via elastic scattering is a dominant channel for replenishing the fuel of the DS (see, e.g., Iocco et al. 2008), once equilibrium has been reached the luminosity of such a star scales linearly with the WIMP–proton scattering cross section $6$ (hydrogen of course being the dominant target for an assumed primordial mixture). There is considerable discussion ongoing with regard to experimental searches for elastic WIMP–nucleon scattering in underground experiments.

With respect to DSs, it is interesting that, again assuming the basic setup from Iocco et al. (2008), a spin-dependent WIMP–proton cross section of the order 1 pb for a WIMP with a rest mass of tens of GeV would already result in DSs with LMRs very close to the “max” value of Table 1. While backing up the constraints down to the multiple-femtobarn level from the non-detection of annihilation neutrinos from the Sun (Hooper et al. 2009), the as yet definitive missing detection of a DS contribution to the EBL therefore reinforces the conclusion that spin-dependent scattering can reconcile the DAMA and CoGeNT measurements of an annual modulation of event rates (Bernabei et al. 2010; Aalseth et al. 2011) with null results from other experiments only for cases in which the WIMP–neutron cross section is several orders of magnitude greater than the WIMP–proton cross section, as, e.g., discussed in Ullio et al. (2001). It should however be noted that for the case of light DM particles, there exist windows where a surprisingly high spin-independent scattering cross section of the order $10^{-40} \text{ cm}^2$ is compatible with the DAMA/LIBRA and CoGeNT measurements (Hooper & Kelso 2011). This may again be a case where DM annihilation might significantly affect the life cycle of the first stars, and should be a focus of future work.

4. DISCUSSION AND CONCLUSION

WIMP DM can have an impact on the evolution of the first stars. In this work, the detectability of DS-generated signatures in the EBL is investigated. This approach opens a new window to search for DM effects: the near-infrared (NIR). The EBL contributions from different DS parameter sets have been calculated and, for certain sets of parameters, the resulting EBL flux can reach into the detectable range of the infrared background. A parameterization is presented to calculate the peak EBL contribution for a variety of model input values. The resulting EBL can be used to constrain certain DS scenarios by comparing the calculated peak EBL contribution of DSs with existing upper limits in the EBL density. The results of this work can be seen as a complementary approach to put constraints on DS formation scenarios as investigated by Schleicher et al. (2009) where the influence of DSs on reionization, the $\gamma$-ray, and neutrino background has been investigated.

Freese et al. (2010) recently proposed a scenario in which DSs can reach enormously high masses ($10^7 \text{ M}_\odot$) due to very efficient and long-lasting accretion processes of baryonic matter onto the DS, so-called super-massive dark stars (SMDSs). Under these conditions very long lived and luminous SMDSs can be produced. As suggested by the authors nearly all baryonic matter inside the DM halo the SMDS forms in is accreted onto the star. This fact translates in a very high SFR which can be used as input for Equation (9) to also put constraints on the SMDS scenarios.

As a final note, it should be stressed that the ability to constrain DS scenarios via EBL depends crucially on the improvement of EBL limits and measurements. The upcoming JWST will provide new data on deep field galaxy counts, as well as refined direct measurements of the infrared background. The next generation of Imaging Air Cherenkov Telescopes, like the Cherenkov Telescope Array (The CTA Consortium 2010), will radically improve upon existing TeV measurements, hopefully providing for a direct measurement of the EBL-induced cutoff in active galactic nucleus (AGN) spectra (see, e.g., Raue & Mazin 2010). Fully self-consistent models of DS formation, internal structure, and evolution are also demanding to finally tackle the question whether WIMP annihilation played a role in the first luminous objects in the universe.

This work was made possible with the support of the Cluster of Excellence: “Connecting Particles with the Cosmos,” part of the Landesexzellenzinitiative Hamburg, and the collaborative research center (SFB) 676 “Particles, Strings and the early Universe” at the University of Hamburg. The authors thank Alessandro Mirizzi and Götz Heinzelmann for reading of the manuscript and helpful comments. The authors also thank the anonymous referee for useful comments.

REFERENCES

Aalseth, C. E., Barbeau, P. S., Bowden, N. S., et al. 2011, Phys. Rev. Lett., 106, 131301
Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Barnet, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Barnet, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Barman, T. S., Macintosh, B., Konopacky, Q. M., & Marois, C. 2011, ApJ, 733, 65
Bernabei, R., Belli, P., Cappella, E., et al. 2010, Eur. Phys. J. C, 67, 39
Bertone, G., Hooper, D., & Silk, I. 2005, Phys. Rep., 405, 279
Bromm, V., & Larson, R. B. 2004, ARA&A, 42, 79

$6$ In the case of extended adiabatic contraction being the main mechanism of DM replenishment the DS luminosity scales only with the stellar mass (Freese et al. 2010).
