PROCEEDINGS OF SCIENCE

Constraints on dark matter powered stars from the extragalactic background light

Andreas Maurer[*,a], **Martin Raue**[a], **Tanja Kneiske**[a], **Dominik Elsässer**[b], **Peter H. Hauschildt**[c], **and Dieter Horns**[a]
[a]*Institut für Experimentalphysik, Universität Hamburg*
Luruper Chaussee 149, D-22761 Hamburg, Germany
[b]*Institut für Theoretische Physik und Astrophysik*
Am Hubland, D-97074 Würzburg, Germany
[c]*Hamburger Sternwarte*
Gojenbergsweg 112, D-21029 Hamburg, Germany
E-mail: andreas.maurer@physik.uni-hamburg.de,
martin.raue@physik.uni-hamburg.de,
tanja.kneiske@physik.uni-hamburg.de,
elsaesser@astro.uni-wuerzburg.de, yeti@hs.uni-hamburg.de,
dieter.horns@physik.uni-hamburg.de

Recently, it has been proposed that self-annihilating dark matter could have a significant effect on the formation and development of the first stars in the universe. In such a model, the energy released by the self-annihilating dark matter may be the main power source for this class of young stellar objects called Dark Stars. Their features (e.g. luminosity, temperature, lifetime) could differ from normal Population III stars and therefore makes them distinguishable. The contribution from Dark Stars to the extragalactic background light considering multiple initial parameters is calculated. By comparing our results with existing data and limits of the diffuse infrared background we can derive observational constraints on Dark Stars in the early universe. Future observations (e.g. with the forthcoming James Webb Space Telescope) will improve these results.

Cosmic Radiation Fields: Sources in the early Universe
November 9-12, 2010
Desy, Germany

[*]Speaker.

PoS(CRF 2010)019

1. Introduction

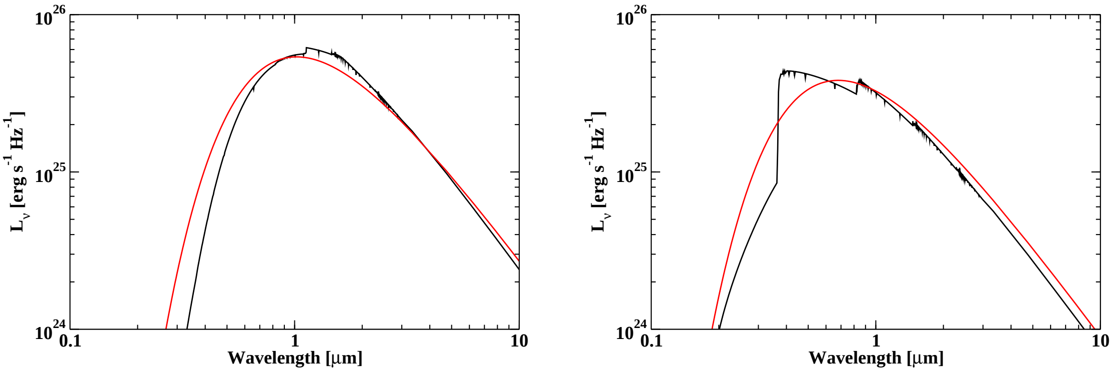
Astrophysical observations from the last decades hint towards a large mass contribution in the universe that is of an unknown, dark nature. Large sky surveys (e.g. SDSS [1] , 2dF [2]) and numerical simulations like the Millennium run [3] point towards a convincing scenario of large scale structure formation within a cold dark matter (DM) model in an accelerated expanding universe (ΛCDM). A good particle candidate for the DM content is a self-annihilating WIMP (Weakly Interacting Massive Particle, see e.g. [4, 5] for a review article). These WIMPs could affect the physics of the first stars in a significant way.

The epoch of the first star formation in the universe is not yet observable with today's astronomical instruments. The circumstances and mechanisms of these processes are still topics of ongoing analysis and rely on sophisticated numerical simulations (for a review, see e.g. [6]). In the last two years several studies discussed the role of WIMP dark matter on the formation of the first stars [7, 8]. Assuming that self-annihilating particles provide the dark matter content of the universe, it is obtained that this new source of energy injection into the first stars may alter their features remarkably. The additional energy injection of these self-annihilating WIMPs delay or even prevent the nuclear hydrogen burning which is normally the main energy source of stars. Two mechanisms are available to supply the star with high DM densities: adiabatic contracted DM due to the gravitational pull from the baryons that form the star (as investigated by [7]) and elastic scattering between WIMPs and baryons (see e.g. [8]). There can also be the possibility for a combination of these two mechanisms with different relative efficiencies. The exact physical process that provides the dark matter powered stars (Dark Star; DS) with "fuel" has no great impact on the results presented here as long as there is a high enough dark matter density in the center of the DS guaranteed. In both cases the resulting features of these stellar objects can be quite generic: low surface temperatures, high luminosities and possible enhanced lifetimes compared with Population III stars [8, 9]. After the "dark phase" the star is thought to evolve as a normal zero age main sequence star.

Instead of considering the very challenging direct detection of DS (see e.g. [10]), the approach here is to search for signatures of DS in the diffuse metagalactic radiation field (MRF). The local optical to infrared part of the MRF is also known as extragalactic background light (EBL, for a review see e.g. [11]). Its main contribution originates from integrated starlight and thermal dust emissions of all cosmic epochs. This fact makes the EBL an ideal probe for the star formation history of the universe and therefore offers a unique possibility to search for emission in the early universe, e.g. investigated in [12]. There are different types of observational strategies for the EBL. Lower limits to the EBL are derived from galaxy number counts which are available up to a redshift ≈ 2 from the Hubble Space Telescope [13] and the Spitzer instrument [14]. Upper limits can be derived from direct observations (COBE [15]), but these are presumably polluted by prominent foreground emission. A different method for obtaining upper limits on the EBL density makes use of the spectra from very high energy (VHE) γ-ray sources, in particular blazars (see e.g. [16]). These limits deliver the possibility to constrain DS scenarios.

For all calculations here a flat Friedmann cosmology is adopted with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and a Hubble constant of $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

PoS(CRF 2010)019



(a) Specific luminosity for a modelled DS atmosphere (black) and a blackbody (red) with same temperature and radius. DS parameters are $R_{\mathrm{DS}} = 2.4 \times 10^{12}\,\mathrm{m}$, $M_{\mathrm{DS}} = 106\,\mathrm{M}_{\odot}$, $T_{\mathrm{DS}} = 5000\,\mathrm{K}$

(b) Same as in (a). DS parameters are $R_{\mathrm{DS}} = 1.1 \times 10^{12}\,\mathrm{m}$, $M_{\mathrm{DS}} = 690\,\mathrm{M}_{\odot}$, $T_{\mathrm{DS}} = 7500\,\mathrm{K}$

Figure 1: Model spectra used as input parameters. DS properties taken from [9].

2. Method

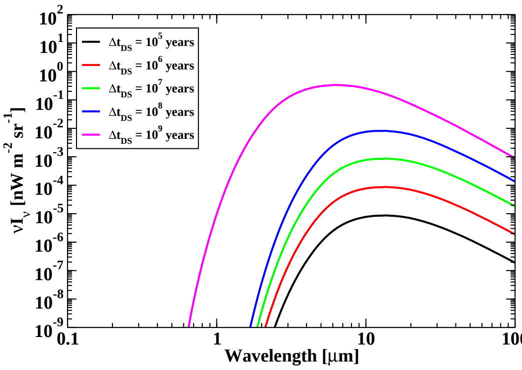
To calculate the contribution of dark matter powered stars to the extragalactic background light a forward evolution model is used, similar to [17]. In the following the individual input parameters of the model are described.

The spectra of DS are calculated with the model atmosphere package PHOENIX, version 16 [18]. For the model atmospheres used here 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. DS spectra with effective temperatures 5000 K and 7500 K and with parameters adopted from [9] have been computed (see Fig. 1).

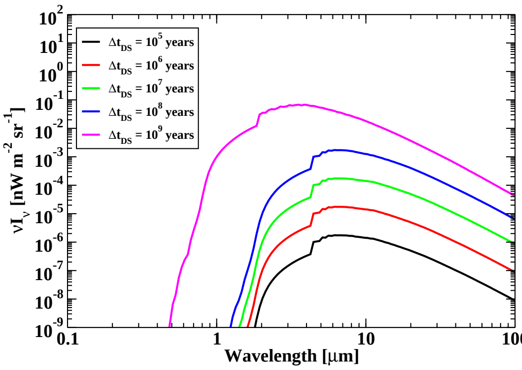
Independent of the exact mechanism powering the DM burning, models predict a stable phase which dominates the total radiative output of the DS [7, 8]. During this phase the luminosity is nearly constant (see e.g. Figure 2 in [9], Figure 4 in [8] and Figure 1 in [19]). The exact length of the DS lifetime (Δt_{DS}) is highly uncertain and depends on various factors, e.g. DM type, DS model, DM halo profile, etc (for an extensive discussion see [10]). In this work a wide band of possible DS lifetimes is explored ranging from $10^5 - 10^9$ years.

A crucial parameter, to which the EBL flux is sensitive, is the formation density of DS. This quantity is directly linked to the cosmic star formation rate (SFR) $\dot{\rho}_*(z)$ for the first stars (Pop III) which can be expressed as a comoving mass formation rate in units of $\mathrm{M}_{\odot}\,\mathrm{year}^{-1}\,\mathrm{Mpc}^{-3}$. For the model calculations here, a constant SFR for Dark Stars is assumed, ranging from the maximum (z_{max}) to the minimum (z_{min}) redshift of the formation epoch. The linear scaling factor $\mathrm{SFR}_{\mathrm{Norm}}$ ranges from 10^{-7} to 10^{-3} comparable to typical values obtained for the first stars [20].

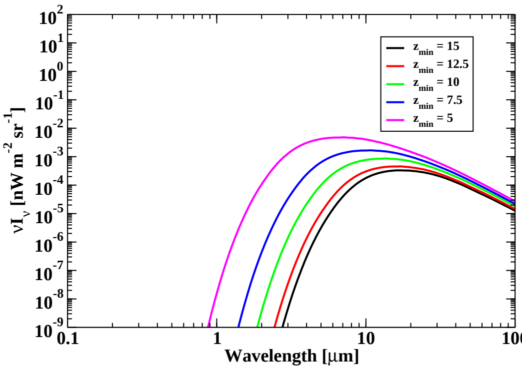
The influence of z_{max} on the resulting EBL is - due to the redshift dilution - negligible and so in the following its value is set to 30. The investigated range of z_{min} reaches from 5 to 15 which is in good agreement to simulated Population III star formation periods [21, 22].



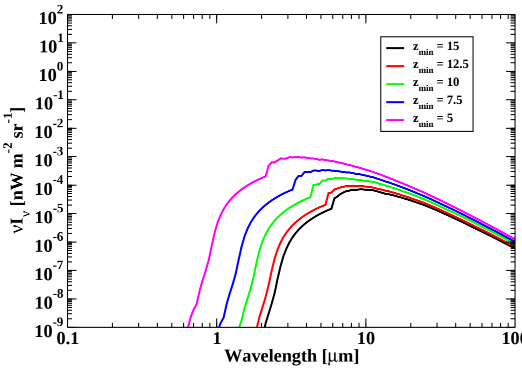
(a) EBL contribution for different DS lifetimes. DS parameters are $R_{DS} = 2.4 \times 10^{12}$ m, $M_{DS} = 106\,M_\odot$, $T_{DS} = 5\,000$ K



(b) Same as in (a). DS parameters are $R_{DS} = 1.1 \times 10^{12}$ m, $M_{DS} = 690\,M_\odot$, $T_{DS} = 7\,500$ K



(c) EBL contribution for different values of z_{min}. DS parameters are $R_{DS} = 2.4 \times 10^{12}$ m, $M_{DS} = 106\,M_\odot$, $T_{DS} = 5\,000$ K



(d) Same as in (c). DS parameters are $R_{DS} = 1.1 \times 10^{12}$ m, $M_{DS} = 690\,M_\odot$, $T_{DS} = 7\,500$ K

Figure 2: EBL signatures for two DS models. The resulting EBL fluxes for different DS lifetimes (Δt_{DS}) and minimum redshifts of the DS formation epoch (z_{min}) are shown.

	Δt_{DS}	z_{min}	SFR_{Norm}
min	10^5	15	10^{-7}
fiducial	10^7	10	10^{-5}
max	10^9	5	10^{-3}

Table 1: Dark Star parameter range

3. Results & Conclusion

The resulting contribution to the extragalactic background light is calculated for different sets of parameters. Both spectra of Dark Stars presented in Fig. 1 are taken as model input and a wide range of possible signatures in the infrared background are calculated. This is shown in Fig. 2; while varying one parameter in its assumed range, the others are set to a fiducial value. The details of the parameters are presented in table 1.

As SFR_{Norm} merely acts as a linear scaling factor, no plots for different values of it are shown. By varying the end of the Dark Star formation period two effects on the background flux can be observed (Fig. 2(c) and Fig. 2(d)). Decreasing z_{min} leads to less dilution in the background photon density, which goes as $(1+z)^{-3}$, and therefore the total yield to the extragalactic background light is increased. The second consequence is a wavelength dependency for the peak value of the resulting signature. This is caused by a non-zero value of the comoving luminosity density (emissivity) at lower redshift that leads to less redshifted peak wavelengths.

The influence of different Dark Star lifetimes is displayed in Fig. 2(a) and Fig. 2(b). For lifetimes smaller than the formation period $t(z_{\text{min}}) - t(z_{\text{max}})$ the resulting background light scales linearly with increasing Δt_{DS}. At higher lifetimes than $\sim 10^8$years the yield to the diffuse photon field is increased to a greater amount as well as the peak value of the Dark Star signature is shifted towards lower wavelengths. This is caused by a non-vanishing emissivity at redshifts $z < z_{\text{min}}$. If Δt_{DS} is short enough, the end of the Dark Stars formation epoch will be roughly equal to the time when the Dark Stars cease to emit photons as the amount of Dark Stars drops off almost instantly. When considering lifetimes higher than $\sim 10^8$years the declining population of dark matter powered stars causes a residual emissivity at $z < z_{\text{min}}$ and explains the shifted peak of the cumulative signature as well as the higher contribution to the total background light flux (see in Fig. 2(a) and in Fig. 2(b) the results for $\Delta t_{\text{DS}} = 10^9$years).

Considering the chosen parameter ranges (cf. table 1), peak contributions to the extragalactic background light from 10^{-9} to roughly 70 nW m^{-2} sr^{-1} can be obtained. As Fig. 2 shows, the wavelength of the maximum contribution to the diffuse radiation field is located roughly between $1-10\mu$m. In this wavelength regime the extragalactic background light is measured between ~ 10 (lower limits) and ~ 100 nW m^{-2} sr^{-1} (upper limits)[1]. This shows that the contributions from Dark Stars can reach into the detectable range of the infrared background and thus can deliver constraints for Dark Star parameters. Further work on the constraints delivered by contributions from dark matter powered stars to the diffuse infrared background will be published in [23]. Future efforts to measure the extragalactic background light via deep galaxy counts (e.g. with the James Webb Space Telescope) and to derive refined upper limits (e.g. measurements of VHE γ-ray sources with forthcoming Cherenkov telescopes like CTA) will improve the possibility to put constraints on Dark Stars enormously.

Acknowledgments

The participation in the International Workshop: Cosmic Radiation Fields - Sources in the early universe was made possible with the support of the Cluster of Excellence: Connecting Particles with the Cosmos of the Landesexzellenzinitiative Hamburg. This work has made use of NASA's Astrophysics Data System Service.

References

[1] K. N. Abazajian, J. K. Adelman-McCarthy, M. A. Agüeros, S. S. Allam, C. Allende Prieto, D. An, K. S. J. Anderson, S. F. Anderson, J. Annis, N. A. Bahcall, and et al., *The Seventh Data Release of the Sloan Digital Sky Survey*, *Astrophys. J., Suppl. Ser.* **182** (June, 2009) 543–558, [0812.0649].

[1] see e.g. [11] and references therein

[2] M. Colless, B. A. Peterson, C. Jackson, J. A. Peacock, S. Cole, P. Norberg, I. K. Baldry, C. M. Baugh, J. Bland-Hawthorn, T. Bridges, R. Cannon, C. Collins, W. Couch, N. Cross, G. Dalton, R. De Propris, S. P. Driver, G. Efstathiou, R. S. Ellis, C. S. Frenk, K. Glazebrook, O. Lahav, I. Lewis, S. Lumsden, S. Maddox, D. Madgwick, W. Sutherland, and K. Taylor, *The 2dF Galaxy Redshift Survey: Final Data Release*, *ArXiv Astrophysics e-prints* (June, 2003) [astro-ph/0306581].

[3] V. Springel, S. D. M. White, A. Jenkins, C. S. Frenk, N. Yoshida, L. Gao, J. Navarro, R. Thacker, D. Croton, J. Helly, J. A. Peacock, S. Cole, P. Thomas, H. Couchman, A. Evrard, J. Colberg, and F. Pearce, *Simulations of the formation, evolution and clustering of galaxies and quasars*, *Nature* **435** (June, 2005) 629–636, [astro-ph/0504097].

[4] G. Jungman, M. Kamionkowski, and K. Griest, *Supersymmetric dark matter*, *Phys. Rep.* **267** (Mar., 1996) 195–373, [hep-ph/9506380].

[5] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: evidence, candidates and constraints*, *Phys. Rep.* **405** (Jan., 2005) 279–390, [hep-ph/0404175].

[6] V. Bromm and R. B. Larson, *The First Stars*, *Ann. Rev. Astron. Astrophys.* **42** (Sept., 2004) 79–118, [astro-ph/0311019].

[7] D. Spolyar, K. Freese, and P. Gondolo, *Dark Matter and the First Stars: A New Phase of Stellar Evolution*, *Physical Review Letters* **100** (Feb., 2008) 051101–+, [astro-ph/0705.0521].

[8] F. Iocco, A. Bressan, E. Ripamonti, R. Schneider, A. Ferrara, and P. Marigo, *Dark matter annihilation effects on the first stars*, *Mon. Not. R. Astron. Soc.* **390** (Nov., 2008) 1655–1669, [0805.4016].

[9] D. Spolyar, P. Bodenheimer, K. Freese, and P. Gondolo, *Dark Stars: A New Look at the First Stars in the Universe*, *Astrophys. J.* **705** (Nov., 2009) 1031–1042, [0903.3070].

[10] E. Zackrisson, P. Scott, C. Rydberg, F. Iocco, B. Edvardsson, G. Östlin, S. Sivertsson, A. Zitrin, T. Broadhurst, and P. Gondolo, *Finding High-redshift Dark Stars with the James Webb Space Telescope*, *Astrophys. J.* **717** (July, 2010) 257–267, [1002.3368].

[11] M. G. Hauser and E. Dwek, *The Cosmic Infrared Background: Measurements and Implications*, *Ann. Rev. Astron. Astrophys.* **39** (2001) 249–307, [astro-ph/0105539].

[12] M. Raue, T. Kneiske, and D. Mazin, *First stars and the extragalactic background light: how recent γ-ray observations constrain the early universe*, *Astron. Astrophys.* **498** (Apr., 2009) 25–35, [0806.2574].

[13] P. Madau and L. Pozzetti, *Deep galaxy counts, extragalactic background light and the stellar baryon budget*, *Mon. Not. R. Astron. Soc.* **312** (Feb., 2000) L9–L15, [astro-ph/9907315].

[14] G. G. Fazio, M. L. N. Ashby, P. Barmby, J. L. Hora, J.-S. Huang, M. A. Pahre, Z. Wang, S. P. Willner, R. G. Arendt, S. H. Moseley, M. Brodwin, P. Eisenhardt, D. Stern, E. V. Tollestrup, and E. L. Wright, *Number Counts at 3 μm $< \lambda <$ 10 μm from the Spitzer Space Telescope*, *Astrophys. J., Suppl. Ser.* **154** (Sept., 2004) 39–43, [astro-ph/0405595].

[15] M. G. Hauser, R. G. Arendt, T. Kelsall, E. Dwek, N. Odegard, J. L. Weiland, H. T. Freudenreich, W. T. Reach, R. F. Silverberg, S. H. Moseley, Y. C. Pei, P. Lubin, J. C. Mather, R. A. Shafer, G. F. Smoot, R. Weiss, D. T. Wilkinson, and E. L. Wright, *The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. I. Limits and Detections*, *Astrophys. J.* **508** (Nov., 1998) 25–43, [astro-ph/9806167].

[16] D. Mazin and M. Raue, *New limits on the density of the extragalactic background light in the optical to the far infrared from the spectra of all known TeV blazars*, *Astron. Astrophys.* **471** (Aug., 2007) 439–452, [astro-ph/0701694].

PoS(CRF 2010)019

[17] T. M. Kneiske, K. Mannheim, and D. H. Hartmann, *Implications of cosmological gamma-ray absorption. I. Evolution of the metagalactic radiation field*, *Astron. Astrophys.* **386** (Apr., 2002) 1–11, [astro-ph/0202104].

[18] P. H. Hauschildt and E. Baron, *A 3D radiative transfer framework. VI. PHOENIX/3D example applications*, *Astron. Astrophys.* **509** (Jan., 2010) A36+, [0911.3285].

[19] S. Yoon, F. Iocco, and S. Akiyama, *Evolution of the First Stars with Dark Matter Burning*, *Astrophys. J., Lett.* **688** (Nov., 2008) L1–L4, [0806.2662].

[20] M. Trenti and M. Stiavelli, *Formation Rates of Population III Stars and Chemical Enrichment of Halos during the Reionization Era*, *Astrophys. J.* **694** (Apr., 2009) 879–892, [0901.0711].

[21] M. Trenti, M. Stiavelli, and J. Michael Shull, *Metal-free Gas Supply at the Edge of Reionization: Late-epoch Population III Star Formation*, *Astrophys. J.* **700** (Aug., 2009) 1672–1679, [0905.4504].

[22] U. Maio, B. Ciardi, K. Dolag, L. Tornatore, and S. Khochfar, *The transition from population III to population II-I star formation*, *Mon. Not. R. Astron. Soc.* (June, 2010) 905–+, [1003.4992].

[23] A. Maurer, *et al. in preparation*, .