PROCEEDINGS OF SCIENCE

Imprints of dark stars in the 21-cm signal

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A strongly self-interacting component of dark matter can lead to formation of compact objects. These objects (dark stars) can in principle be detected by emission of gravitational waves from coalescence with black holes or other neutron stars or via gravitational lensing. However, in the case where dark matter admits annihilations, these compact dark matter made objects can have significant impact on the cosmic reionization and the 21-cm signal. We demonstrate that even if dark matter very small annihilations, dark stars could inject a substantial amount of photons that would interact with the intergalactic medium. For dark matter parameters compatible with current observational constraints, dark stars could modify the observed reionization signal in a significant way.

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1. Introduction

Dark matter (DM) is a fundamental yet elusive component of the universe, making up approximately 27% of its energy content, known primarily through its gravitational effects on visible matter. While direct detection efforts have yielded no non-gravitational evidence, the possibility exists that DM particles interact strongly within their own sector, potentially forming compact dark stars (DS) [1, 2]. These DSs, which could emit detectable signals such as dark photons [3], could also accrete matter from the interstellar medium, producing radiation and possibly bright outbursts. If DM is asymmetric, it might also efficiently annihilate or decay into Standard Model particles, producing observable signatures in gamma-ray or neutrino telescopes [4].

In this proceedings we concentrate on this last possibility. DSs could have formed before ordinary stars, and the annihilation into photons at very early times could outshine the galaxy, potentially producing a dramatic effects on the reionization of the Universe and the 21 cm spectrum. This work is organized to review the structure and cosmological implications of fermionic DSs, including their potential to inject energy into the intergalactic medium, and presents a modified cosmological model to assess these effects.

2. Dark Stars

2.1 Structure

We model DM as an asymmetric fermionic particle with mass m that self-interacts via a dark photon γ_D with mass m_{γ_D}. The equation of state for such a scenario has been calculated in [1] and is given in the parametric form

$$\rho(x) = m^4 \left[\xi(x) + \frac{2\alpha_D}{9\pi^3} \left(\frac{m}{m_{\gamma_D}} \right)^2 x^6 \right], \; P(x) = m^4 \left[\psi(x) + \frac{2\alpha_D}{9\pi^3} \left(\frac{m}{m_{\gamma_D}} \right)^2 x^6 \right]. \qquad \text{(1a)}$$

Here α_D is the Yukawa coupling between the DM particle and the dark photon γ_D, which has positive sign for repulsive interactions, and the functions ξ and ψ are given in the reference [1].

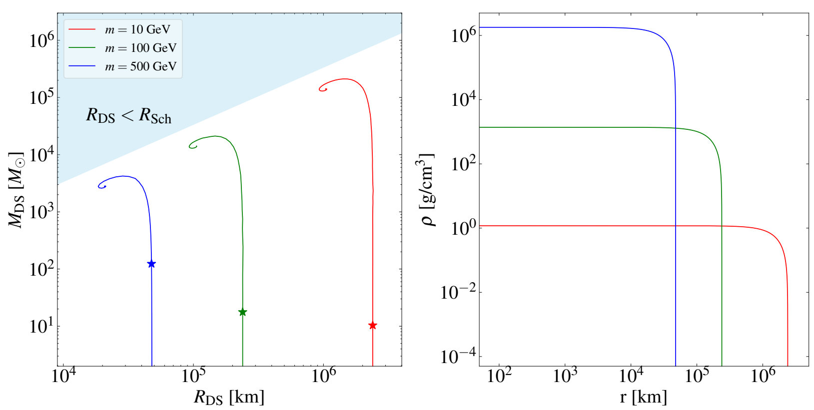

Figure 1: Left panel: Mass versus radius relation for the fermionic DS. The light-blue colored area denotes the region where the radius is smaller than the Schwarzschild radius. Right panel: Density profile for the points indicated in the left panel. In both panels we have have taken $\alpha_D = 10^{-1}$ and $m_{\gamma_D} = 100$ eV.

We solve the relativistic equations of stellar structure with this model and plot some examples in fig. 1. As in the case of neutron stars, within our model, it is the Fermi pressure that balances gravity. In the left panel of fig. 1, similarly to the case of white dwarfs or neutron stars, there are stable configurations up to a maximum mass shown with a dot on top of these mass-radius curves. The curly branch of the solution to the left of this maximum “Chandrasekhar mass" of the DSs is unstable.

2.2 Formation

Provided we know the structure of DS, we must estimate under what conditions they can form in the first place. On general grounds a virialized self-gravitating cloud can proceed to further collapse only if there is an efficient mechanism that can evacuate energy from the system. Such a mechanism for example is radiation. By emitting radiation, energy escapes the system, which in turn re-virializes by contracting. Following the work of [5], we implement a dissipative model that consists of two particles: a dark electron, which is a subdominant component of DM and a dark photon. Within a DM halo, the dark electron component will lose energy via emission of bremsstrahlung dark photons. This will result to a contraction of the dark electron population and eventually it will lead to fragmentation of the dark electron halo into various self-gravitating clumps. This fragmentation process will stop as with the formation of the DSs. This process is only possible in DM halos massive enough to have a sufficiently large temperature. This implies the existence of a minimum halo mass $M_{\text{halo,min}}$, below which DSs do not have enough time to form by today and therefore do not influence the cosmological DS density.

We assume that the DS formation rate is proportional to the rate at which matter collapses into dark matter halos with masses larger than $M_{\text{halo,min}}$. The fraction of matter collapsed into halos with $M_{\text{halo}} > M_{\text{halo,min}}$ is given in the Press-Schechter model [6] by

$$f_{\text{coll}}(z) = \text{erfc}\left(\frac{\delta_c(z)}{\sqrt{2}\sigma(M_{\text{halo,min}})}\right), \tag{2}$$

where $\delta_c(z)$ is the linear overdensity at virialization and $\sigma^2(M)$ is the variance of the density field when smoothed on scale M [7]. From the collapsed fraction, we calculate the DS mass density at a given time

$$\text{DSMD}(z) \approx f_{\star,\text{DS}}\rho_{\text{DM},0} f_{\text{coll}}(z), \tag{3}$$

where $\rho_{\text{DM},0}$ is the current DM density of the Universe and $f_{\star,\text{DS}}$, can be understood as the fraction of DM in the form of DSs, which we fix to 0.5%.

2.3 Energy injection

Dark matter particles inside a DS could be annihilating into Standard Model particles, with a cross section $(\sigma v)_{\text{ann}}$, if the dark matter number is broken by two units. The rate reads $\Gamma_{\text{ann}} = \frac{1}{2}\int dV \left(\frac{\rho(r)}{m}\right)^2 (\sigma v)_{\text{ann}}$ [4]. The luminosity in gamma-rays generated by annihilations in the DS can be calculated from

$$L_{\text{ann}} = 2m f^{\gamma}_{\text{ann}}\Gamma_{\text{ann}} \simeq 1.6 L_{\odot} f^{\gamma}_{\text{ann}} \left(\frac{(\sigma v)_{\text{ann}}}{10^{-44}\,\text{cm}^3\,\text{s}^{-1}}\right)\left(\frac{R_{\text{DS}}}{10^5\,\text{km}}\right)^3\left(\frac{\rho_c}{10^3\,\text{g}\,\text{cm}^{-3}}\right)^2\left(\frac{m}{100\,\text{GeV}}\right)^{-1}\left(\frac{J_\star}{10^{-2}}\right), \tag{4}$$

where $f^{\gamma}_{\rm ann}$ is the fraction of the total energy that goes into photons and $J_\star \equiv \int_0^1 d\hat{x}\,\hat{x}^2\hat{\rho}^2(\hat{x})$ as the dimensionless "J-factor", which encompasses the difference on the choice of the particular DS solution. Here we have calculated the rate of energy injected by a single DS into its surroundings. We can now calculate the total rate of energy emitted by the cosmological DS population per comoving volume, the so-called luminosity density or in our case, the energy injection term $\left(\frac{dE}{dVdt}\right)_{\rm inj} = L_{\rm ann}\left(\frac{\rm DSMD(z)}{M_{\rm DS}}\right)$, where we have used the monochromatic approximation, in which we assume all DSs have the same mass $M_{\rm DS}$.

3. Signal of annihilating dark stars on the IGM

The DS population will produce radiation which will propagate throughout the Universe and transfer its energy into the IGM through collisions with the intergalactic gas. This transfer of energy will lead to observable effects on the 21-cm signal due to heating up of the gas and enhancement of ionization. The quantities of interest to track these effects are the IGM temperature $T_{\rm gas}$ and the ionization of the IGM $x_e \equiv \frac{n_e}{n_{\rm H}}$ (with n_e and $n_{\rm H}$ being the electron and neutral hydrogen densities respectively). The dynamical equations for x_e and $T_{\rm gas}$ are [8, 9]

$$\begin{aligned} \frac{dx_e}{dt} &= \left[\frac{dx_e}{dt}\right]_0 + \frac{1}{n_{\rm H}(z)E_i}\left[\frac{dE}{dVdt}\right]_{\rm dep,HIion} + \frac{1-C_P}{n_{\rm H}(z)E_\alpha}\left[\frac{dE}{dVdt}\right]_{\rm dep,Ly\alpha}, \\ \frac{dT_{\rm gas}}{dt} &= \left[\frac{dT_{\rm gas}}{dt}\right]_0 + \frac{2}{3n_{\rm H}(z)(1+f_{\rm He}+x_e)}\left[\frac{dE}{dVdt}\right]_{\rm dep,heat}, \end{aligned} \tag{5}$$

where $\left[\frac{dx_e}{dt}\right]_0$ and $\left[\frac{dT_{\rm gas}}{dt}\right]_0$ denote the standard evolution equations with no dark star contribution (see eg. [10] for a review), E_i and E_α are the hydrogen ionization and Lyα energy, respectively and $f_{\rm He} = 0.245$ is the number fraction of helium. The coefficient C_P is the Peeble's factor that represents the probability for an electron in the $n = 2$ state to transition to the ground state before being ionized. We have introduced the deposition energies $\left[\frac{dE}{dVdt}\right]_{\rm dep,c}$, which represent the amount of energy per comoving volume and time that is deposited into the IGM and that contributes to either ionization (HIion), excitation (Lyα) or heating (heat). To calculate them, we consider the SSCK approximation [11], which assumes that a fraction of the energy produced by the annihilating dark stars at some redshift is immediately transferred to the IGM.

The main observable in 21 cm physics is the 21 cm brightness temperature relative to the CMB δT_b, which is a measure of the difference between the CMB temperature and the temperature of a hydrogen patch at a given redshift. This quantity, neglecting spatial inhomogeneity is given by [12, 13]

$$\delta T_b \approx \frac{T_s - T_{\rm CMB}}{1+z}\tau, \tag{6}$$

where τ is the optical depth for resonant 21 cm absorption and $T_s^{-1} = \frac{T_{\rm CMB}^{-1}+x_\alpha T_\alpha^{-1}+x_{\rm coll}T_{\rm gas}^{-1}}{1+x_\alpha+x_{\rm coll}}$, is the spin temperature [14], where T_α is the color temperature of the Lyα radiation field at the Lyα frequency, x_c is the collisional coupling coefficient and x_α is the Lyα coupling [13, 15].

In fig. 2, we compare the brightness temperature as a function of redshift between the standard scenario and one with the addition of DSs. The existence of annihilating DSs can enhance the

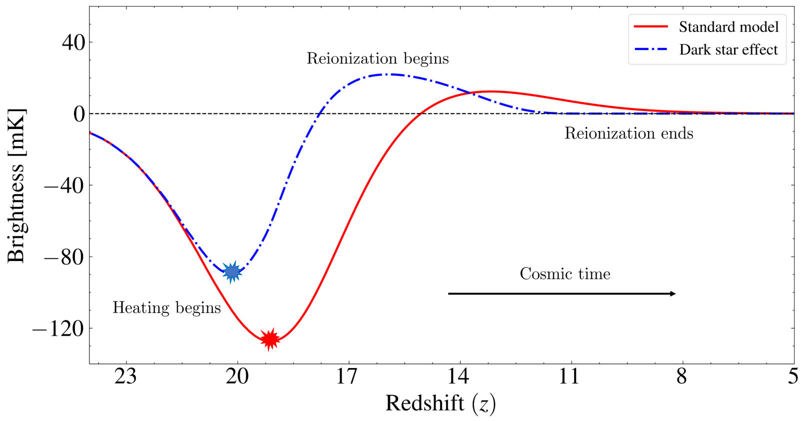

Figure 2: Brightness temperature as a function of redshift. The blue curve corresponds to the standard scenario, without inclusion of DSs. The red curve presents the effect of addition of DSs; we set $m = 10$ GeV, $m_{\gamma_D} = 100$ eV, $\alpha_D = 0.1$ and $(\sigma v)_{\rm ann} = 10^{-40}$ cm^3/s.

heating of the gas substantially shortening the depth of the plunge of the brightness temperature (counting from high redshift). One can see that although in the standard scenario full ionization takes place roughly below $z \sim 8$, dark stars can move this value up to $z \sim 12$, which makes the distinction between the two scenarios easily identified.

4. Conclusion

In this proceedings we argue that even a tiny component of DM with small annihilation cross sections can have a very dramatic effect on the 21 cm signal. A small but strongly interacting component of DM can collapse and form compact objects which can have various sizes depending on the model parameters. If this component possesses DM annihilations to photons it can lead to substantial luminosities. Although the DM annihilations will have a completely negligible effect for DM particles moving as a free gas, the high compactness and subsequently core densities of these DSs, counterbalance the smallness of the cross section. The produced DS luminosities can be significantly larger than the luminosity produced by population II and III stars, leading to dramatic changes in the shape and amplitude of the 21 cm signal as well as in the overall ionized fraction of hydrogen. DSs can heat up the IGM quite efficiently, causing a more rapid increase in the baryon temperature and an earlier ionization of hydrogen compared to the standard scenario. With the advent of more accurate experiments measuring the 21 cm signal, such DM scenarios can be easily probed despite the smallness of both the component and the annihilation cross section.

Acknowledgments

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