Relic signal produced by the annihilation of dark matter particles

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Abstract. We discuss the possibility to observe the products of dark matter annihilation that was going on in the early Universe. Of all the particles that could be generated by this process we consider only photons, as they are both uncharged and easily detectable. The earlier the Universe was, the higher the dark matter concentration $n$ and the annihilation rate (proportional to $n^2$) were. However, the emission from the very early Universe cannot reach us because of the opacity. The main part of the signal was generated at the moment the Universe had just become transparent for the photons produced by the annihilation. Thus, the dark matter annihilation in the early Universe should have created a sort of relic emission. We obtain its flux and the spectrum.

In the second part of the article we consider in greater detail the instance the dark matter is constituted by Weakly Interacting Massive Particles (WIMPs), which is one of the most popular hypotheses. It is shown that in this case we may expect an extragalactic gamma-ray signal in the energy range 0.5 - 20 MeV with a maximum near 8 MeV and there is evidence that an experimentally observed excess in the gamma-ray background at 0.5 - 20 MeV is created by the relic WIMP annihilation.

1. Introduction

In this report, we consider the dark matter annihilation in the epoch near the relic radiation formation ($z \sim 1000$). At that time, the average dark matter particle concentration $n \propto (z + 1)^3$ was nine orders higher than now and four orders higher than in our Galaxy near the Sun system. So we may expect that the annihilation, the rate of which is proportional to $n^2$, was very intensive in that epoch. Of all the particles that can be generated by the dark matter annihilation we will consider only photons, as they are both uncharged and easily detectable. Uncharged particles do not interact with the magnetic field of the Galaxy, which allows one to measure the extragalactic background reliably enough.

The earlier the Universe was, the higher the DM density and the annihilation rate were. However, the emission from the very early Universe cannot reach us because of the opacity. The main part of the signal was generated at the moment the Universe had just become transparent for the photons produced by the annihilation. Later the dark matter density rapidly dropped, decreasing the signal. The moment (and its redshift) depends, of course, on the characteristic energy of the photons, in other words, on the nature of the dark matter. Thus, the DM annihilation in the early Universe should have produced a sort of relic emission. We obtain its flux and the spectrum.
2. Calculations

In case of the homogeneous isotropic Universe the number of photons of the above-mentioned relic emission that come to the local observer from unit solid angle per unit time per unit of area per unit energy interval can be represented [1] as

\[ \dot{Q}(\varepsilon) = \int Q(\varepsilon, \beta) f(\beta) \, d\beta \]  

(1)

where

\[ Q = \frac{\langle \sigma v \rangle n_0^b \varepsilon \beta \sqrt{\varepsilon}}{8 \pi H_0 \sqrt{\Omega_m} \varepsilon^2 / \varepsilon^2} \exp \left( -\frac{2 \pi \kappa n_0^b}{3 H_0 \sqrt{\Omega_m} \varepsilon \sqrt{\varepsilon}} \right) \beta \sqrt{\varepsilon} \]  

(2)

Here \( n_0 \) and \( n_0^b \) are present dark matter particle and baryon concentrations respectively, \( \langle \sigma v \rangle \) is the annihilation cross section of dark matter particles, \( \kappa \) is the averaged cross-section of the interaction of photons generated by the annihilation with the baryonic matter.

Strictly speaking, the annihilation cross-section and the relative contribution of various channels depend on the energy of the DMPs collision, which can be important, if the annihilation occurs, for instance, near a black hole [3]. However, in the considered case the relative velocity of the DMPs is very small, and we may neglect this effect.

If we make a very natural supposition that the DMPs were in thermal equilibrium with other particles in the early Universe, we can estimate their annihilation cross section [2, 6]:

\[ \langle \sigma v \rangle \simeq \frac{2 \cdot 10^{-27} \text{ (cm}^3 / \text{s})}{\Omega_{DM} h^2} \]  

(3)

For the present value [4] of \( \Omega_{DM} h^2 = 0.113 \) we obtain \( \langle \sigma v \rangle \simeq 2 \cdot 10^{-26} \text{ (cm}^3 / \text{s}) \). These are the telling reasons to believe that the dark matter consists of Weakly Interacting Massive Particles (WIMPs). They are expected to annihilate into fermion-antifermion or gauge boson pairs with a large fraction of quark-antiquark pairs. A WIMP pair annihilation finally leads to 30 – 40 photons generation (in the fragmentation process, mainly from \( \pi^0 \) decays). A greater part of the photons has energy in the range from 2 to 4 GeV [5, 6].

In the interval 1 – 5 GeV the photon spectrum caused by the main \( b \bar{b} \) annihilation channel is well approximated if the distribution function \( f(\beta) \propto \beta^{-1} \exp(-0.15/\beta) \). We shall use the following \( f(\beta) \) (\( \beta \) is expressed in GeVs):

\[ f(\beta) = \begin{cases} 
26.7 \cdot \beta^{-1} \exp(-0.15/\beta), & \beta \in (1 - 5) \text{ GeV} \\
0, & \beta \notin (1 - 5) \text{ GeV} 
\end{cases} \]  

(4)

We normalized it considering that one act of annihilation generated on average 30 photons.

We use the following set of cosmological parameters: \( \Omega_\Lambda = 0.75, \Omega_m = \Omega_{DM} + \Omega_b = 0.25, \Omega_b = 0.042 \) (of course, \( \Omega_\Lambda + \Omega_{DM} + \Omega_b = 1 \)), the Hubble constant \( H_0 = 2.4 \cdot 10^{-18} \text{s}^{-1} \), the relic radiation temperature 2.725 K, the baryon-photon ratio \( \eta \equiv n_b / n_{ph} = 6.1 \cdot 10^{-10} \). We obtain the present baryon concentration \( n_0^b = 2.5 \cdot 10^{-7} \text{cm}^{-3} \). The DMP concentration, with DMP mass taken as \( M_{DM} = 50 \text{ GeV} \), is \( n_0 = 2.5 \cdot 10^{-8} \text{cm}^{-3} \). Equation (3) gives \( \langle \sigma v \rangle \simeq 2 \cdot 10^{-26} \text{ (cm}^3 / \text{s}) \).

The resulting spectrum of the relic gamma-ray background, obtained with the aid of (1), (2), grows up to \( \sim 8 \text{ MeV} \), and the bulk of the signal lies in the range from 0.5 to 20 MeV. Characteristic redshift of the relic gamma-rays is \( z \simeq 300 \).
3. Comparison with observations and discussion
The cosmic gamma-ray background reportedly (see, for instance, [8, 9, 10, 11, 12]) has a peculiarity in the energy range 0.5 - 20 MeV. A lodge-like feature is visible in the extragalactic gamma-ray spectrum (Fig. 3 in [13]). The photon index here is markedly distinct from those of the softer or harder parts of the spectrum [14, 13, 15], indicating its different origin.

Moreover, this spectral band can be formed neither by too soft emission of normal active galactic nuclei, nor by too hard blazar-type AGNs contribution (see [8] and references therein). Attempts to consider the nuclear-decay gamma rays from Type Ia supernovae as the source have not been successful: the flux expected from the supernovae is several times weaker than the observed [16, 11, 12]. It might be well to point out that the precise determination of the excess boundaries and intensity is model-dependent, and the literature values vary considerably [8, 9, 10, 11]. In any case, however, the excess becomes apparent near 0.5 MeV and disappears at the energies $\gtrsim 20$ MeV. One can see that the energy range of the feature corresponds closely to the interval characteristic for the relic gamma emission from the WIMPs annihilation. This coincidence looks promising when it is considered that the WIMP is now one of the most probable dark matter candidates.

At the same time, the relic gamma emission predicted by equations (1) and (2), is approximately five orders fainter than the observed feature. This discrepancy might result from inapplicability of the assumption of homogeneous dark matter distribution. The presence of density inhomogeneities does not affect the spectrum of the annihilation signal but increases its intensity. The modern structure of the Universe appeared from some initial perturbations that had already existed, beyond any doubt, in the epoch $z \sim 300$. Let us suppose that the spectrum of primordial fluctuations is not exactly flat, and the intensity of the fluctuations slightly builds up as their scale decreases. In the matter-dominated stage the perturbations grow as $\delta \rho/\rho \propto t^{2/3}$ and $a(t) \propto t^{2/3}$, therefore $\delta \rho/\rho \propto a$ [17]. If we assume that the small-scale perturbations left the radiation-dominated stage with amplitudes more than expected from the Harrison-Zeldovich spectrum by a factor of $\frac{200}{10^5} \approx 4$, they collapsed by the moment $z = 300$ (in so doing we imply that the amplitudes of large-scale perturbations are fixed in such a way as they reproduce the observed large-scale structure of the Universe). Considering that the largest and the smallest clump mass scales differ by more than 20 orders, even a negligible tilt of the spectrum of primordial fluctuations with respect to the Harrison-Zeldovich shape is enough to gain the factor of four.

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