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Confinement of Cosmic Rays in Dark Matter clumps

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Abstract: Some part of the relic Dark Matter is distributed in small-scale clumps which survived structure formation in inflation cosmological scenario. The annihilation of DM inside these clumps is a strong source of stable charged particles which can have a substantial density near the clump core. The streaming of the annihilation products from the clump can enhance irregularities in the galactic magnetic field. This can produce small scale variations in diffusion coefficient affecting propagation of Cosmic Rays.

Introduction

The Cosmic Ray (CR) propagation in the Galactic disk is described as a resonant scattering on the magneto hydrodynamic turbulences (MHD) with the scale equal to the particle Larmor radius $k_r^{-1} \sim r_g = pc/ZeB$ in the galactic magnetic field B. The MHD turbulences can propagate in space as Alfvén waves with the velocity $v_a \sim B/\sqrt{4\pi\rho_H}$, which depends on the interstellar gas density ρ_H and is in the order of 10-100 km/s. The spectral density of the waves is usually associated with fluctuations in interstellar medium (ISM) and follows a power law $W(k) \propto k^{\alpha-2}$, where $\alpha = 1/3$ for the Kolmogorov spectrum. The MHD waves interact with the CR and ISM and can be enhanced or damped, depending on the energy flow. The kinetic equation for the spectral density $W(r,k)$ in spherical coordinates can be written as [11]:

$$\frac{\partial W}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} v_a r^2 W - \frac{\partial v_a}{\partial r}\frac{\partial}{\partial k} kW = (G-S)W \quad (1)$$

The G term describes the enhancement of turbulences due to streaming of CR particles and S represents the damping. The growth of turbulences occurs when the CR streaming velocity v_s is larger than the Alfv́en speed v_a [17]. The streaming velocity depends on the gradient of the CR density f which satisfies the diffusion equation:

$$\frac{1}{r^2}\frac{\partial}{\partial r} D \frac{\partial}{\partial r} r^2 f - V_c \frac{\partial f}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r} r^2 V_c \frac{p}{3}\frac{\partial f}{\partial p} = -q(p,r), \quad (2)$$

where $q(r,p)$ is the source function, V_c is the convection velocity and energy losses are neglected. The diffusion coefficient D at resonance is related to $W(k,r)$ as [1]: $D(r) \approx v r_g^2 B^2 / 12\pi W(k_r, r)$ and a high level of turbulences corresponds to a local confinement of particles. Since the enhancement and damping strongly depend on the local environment, this opens a possibility for large and small scale variations in propagation parameters and therefore CR density. On the large scale the MHD waves can be damped in the galactic disk of $z \sim$ 100pc, leading to a large diffusion coefficient. Outside the disk the $W(k,r)$ can be larger and propagation is dominated by convection if $V_c > D/r$ [15]. On small scales the diffusive propagation can be affected near the CR sources or in the dense gas clouds [13, 18]. In the model with isotropic propagation the locally observed CR fluxes are used to evaluate the CR distribution in the whole Galaxy and then to calculate the diffusive gamma rays [12]. The obtained size of diffusion zone of 1-4 kpc is compatible with observations of secondary CR (B,Be,subFe) but contradicts smaller angular gradients observed in diffusive gamma rays which requires larger halo [4]. The isotropic model also does not explain the excess of gamma rays in GeV range [10, 12]. The galactic rotation curve points to a large mass in the galactic halo which can be associated with the Dark Matter (DM). The DM can self annihilate and produce stable particles which will contribute to the gamma rays and CR fluxes. Here we consider how the DM can affect the galactic model.

Dark Matter annihilation in clumps

The N-body cosmological simulations and analytical calculations show that in the inflation scenario the smallest DM structures originate from initial primordial fluctuations. These primordial DM clumps are partially destroyed during evolution contributing to the bulk DM but 0.001-0.1 of relic DM can still reside in the clumps, depending on initial conditions [9, 8]. The density profile inside the clumps is cuspy $\rho_{cl} \propto 1/r^{1.5-2.0}$ but is probably saturated at some critical density ρ_0 forming a dense core. The clump mass distribution follows $n(M)dM \sim M^{-2}$ with the minimum mass defined by free streaming of DM particles just after kinetic decoupling $M_{cl}^{min} \sim 10^{-8} - 10^{-6} M_\odot$ [2]. The local number density distribution n_{cl} of such clumps can vary in the range of $\sim 0.1 - 100$ pc^{-3} depending on density profile and tidal destruction [2, 8]. Inside the clump, the DM of mass m_χ will annihilate producing stable particles: protons, antiprotons, positrons, electrons and gamma rays, which can be observed on top of the ordinary CR fluxes. The luminosity of the clump for a i-component is: $q_i(r,p) = \frac{\langle\sigma v\rangle Y_i(p)}{m_\chi^2}\int \rho(x)_{cl}^2 dx$, where Y_i is the yield per annihilation. For most of DM candidates the annihilation goes into fermions, predominantly quark-antiquarks, which after fragmentation will produce for $m_\chi = 100$ GeV: $\sim$3 positrons or electrons, 0.3 protons or antiprotons and 8 gamma at 1 GeV. The precise energy spectrum is well measured in accelerator experiments, for protons and antiprotons below 1 GeV the $q(p) \sim const$ and for electrons and positrons $q(p) \sim p^{-1}$. The $\langle\sigma v\rangle$ is the thermally averaged annihilation cross section which can be estimated from the observed relic DM density in time of decoupling ($T_{dec} \sim \frac{m_\chi}{20}$) $\langle\sigma v\rangle \approx (\frac{2\cdot 10^{-27} cm^3 s^{-1}}{\Omega_\chi h^2})$, where $\Omega_\chi h^2 = 0.113 \pm 0.009$ [16]. Nowadays ($T \sim 1.8K < T_{dec}$) the cross section can be the same or only smaller [6]. However the total annihilation signal can be boosted by clumpiness of DM, so called boost factor. The clumps are much denser than the bulk profile and most of the signal will come from the core of most abundant smallest clumps. The DM annihilation (DMA) signal is decreasing fast with the DM mass, at least as m_χ^2, and the boost factor is limited by $< 10^3$ [2] thus limiting the observability of heavy DM $m_\chi > 100$ GeV. Taking a clump with $M_{cl} = 2.10^{-8} M_\odot$ and 100 AU size with the average density of 100 GeV/cm^3, the total yield for GeV charged particles will be $\sim 10^{23} s^{-1}$ for $m_\chi = 100$ GeV. Assuming the isothermal distribution of clumps in the galactic halo of 20 kpc diameter and normalizing at $n_{cl}(8.5kpc) = 10pc^{-3}$, the total luminosity from the DM annihilation in GeV range in 100 years will be $\sim 10^{45}$ particles, to be compared with the SNR explosion delivering $\sim 10^{51}$ particles per explosion in the galactic disk. Despite small luminosity the DM clump is a compact and constant source and the local density of produced particles can significantly exceed the galactic average $\langle\rho_{cr}\rangle \sim 10^{-10} cm^{-3}$ producing a gradient in CR density distribution.

MHD turbulences initiated by DM annihilation

The streaming of charged DMA products from the cuspy clump will increase the level of local MHD turbulences. The amplification of MHD waves parallel to magnetic field lines can be presented as [17, 1]: $G(r,k) \approx \frac{\pi^2 e^2 v_a}{kc^2}\int\int dp d\mu v p^2 (1-\mu^2)\delta(p|\mu| - \frac{eB}{kc}) \times (\frac{\partial f}{\partial \mu} + \frac{v_a p}{v}\frac{\partial f}{\partial p})$,where μ is the cosine of scattering angle and $\frac{\partial f}{\partial \mu} \sim \frac{p^2 c^2}{4\pi^2 e^2 W}\frac{\partial f}{\partial r}$ is the anisotropic term of the CR density distribution which can be obtained from integration of diffusion equation (2). The transverse waves are averaged out along propagation path and scattering is not efficient, that is, only turbulences along local field lines will be amplified by streaming, this asymmetry is neglected in this study. The growth is reduced by different damping mechanisms. Different possibilities can be considered: a dense molecular cloud with $\rho_H \sim 10 - 10^5 cm^{-3}$, a hot plasma region and the galactic halo. The strongest damping takes place in the dense neutral gas n_H due to ions-neutral friction which dissipates energy as $S_H \sim \frac{1}{2}\langle\sigma_{col} v_a\rangle n_H$, where $\langle\sigma_{col} v\rangle \sim 10^{-9} cm^3 s^{-1}$ is the collisional cross section [**?**]. In the hot underdense gas the growth is suppressed by larger v_a and ionized gas density n_{HII} [17]. The collision of opposite waves leads to a nonlinear damping proportional to the level of magnetic turbulences $S_{nl} \approx \frac{4\pi v_t W}{B^2 r_g^2} = S_{nl}^0 W$, v_t is the gas thermal velocity $\sim v_a$ [1]. The fast magnetosonic waves with the Kraichnan spectrum can be also dumped at small scales by the CR themselves [14], this is not considered here. The simplified solution of the kinetic equation for $W(r, k = k_r)$ (1), neglecting momentum dependency for GeV particles, convection term in (2) and assuming point like source function $q(r) = q_0\delta(r)$, has a form:

$$W(r) \sim \frac{exp(-g/r - s_H r)}{r^2(C_0 + s_{nl}exp(-g/r - s_H r)/g)}$$

where $g \sim \langle\sigma v\rangle Y_{tot}\frac{\rho_0^2}{cm_\chi^2}$ is related to the total clump liminosity, $s_H = S_H/v_a$, $s_{nl} = S_{nl}^0/v_a << s_H$ are the dampings, and C_0 is a normalization factor. In the steady state it will result in an exponential increase of $W(r)$ near the clump core followed by a decrease $\propto r^{-2}$, see Figure 1. Since the spectrum of annihilated particles is limited by m_χ , the $W(k)$ distribution will be cutoff at $k \sim \frac{eB}{m_\chi}$. Thus the anisotropic streaming will create a region around a clump with small diffusion D_{in}, aligned with the local B field and with the size defined by the clump DM density, annihilation and dumping rates. The velocity of the clump proper motion and the convection speed should be below the local v_a in order to have stable environments for the growth. The turbulences will be strongly suppressed in the dense gas region although the DMA particles produced in the cusp of the clump still can be confined. In the underdense area in the galactic disk, like the Local Bubble, or in the galactic halo, the DM clump can be a substantial source of small scale MHD waves. The effect on CR propagation will be especially large if the diffusion coefficient inside clumps is much smaller than outside $D_{in} << D_{ext}$. The confinement zones with the size of r_{cl} can trap the annihilation products and CR for a time $\sim r_{cl}^2/D_{in}$ thus increasing local CR density. In a self-consistent model the zone with a large diffusion is limited by the thin galactic disk and the convection is dominant in the halo[15]. If the convection and distance between clumps are large enough, the back scattering of DMA produced particles into galactic disk can be small and will contribute a little to the observed CR fluxes, but the gamma rays and radio waves from these areas can be observed. First, the gamma rays produced directly from annihilation will produce a bump in the spectrum at $E \sim 0.1m_\chi$[7]. This can reproduce the gamma rays energy spectrum and angular gradients observed by EGRET [10, 7]. Second, the electrons and positrons trapped near the clump will contribute to the lower energy gamma rays via Inverse Compton and to radio waves by the synchrotron radiation. The DMA contributions to the charged CR will depend on the location of nearest clumps and the local environment. The local confinement combined with a large external convection and anisotropic diffusion will reduce the fluxes of antiprotons and positrons from DMA in comparison with the DMA gamma flux [3]. The secondary CR from nuclear interactions will be reduced too but can be recovered if CR are trapped in local molecular cloud structure [5].

Conclusion

The annihilation of DM in clumps can be a source of MHD waves which affect the propagation of CR with $E < m_\chi$. The growth of the MHD waves can be large for the light DM candidate, like the SUSY neutralino with $m_\chi \sim 100$ GeV which has largest annihilation cross section, and cuspy DM clump profile. The created turbulences are damped by ion-neutral interactions in the dense gas regions but in the galactic halo or underdense areas the DM clumps can produce trapping zones with increased particle density. The gamma rays from the DM annihilation in clumps can be related to the observed by EGRET excess in GeV range. The DMA gamma rays angular profiles depend upon clumps distribution in the galaxy. The abundantly produced in DM annihilation electrons and positrons will lose energy via inverse Compton and synchrotron radiation contributing to the low energy gamma rays and radio waves. The contribution of charged DMA products to the observed CR fluxes will strongly depend on the local propagation parameters and can be reduced in case of anisotropic propagation and small scale confinement.

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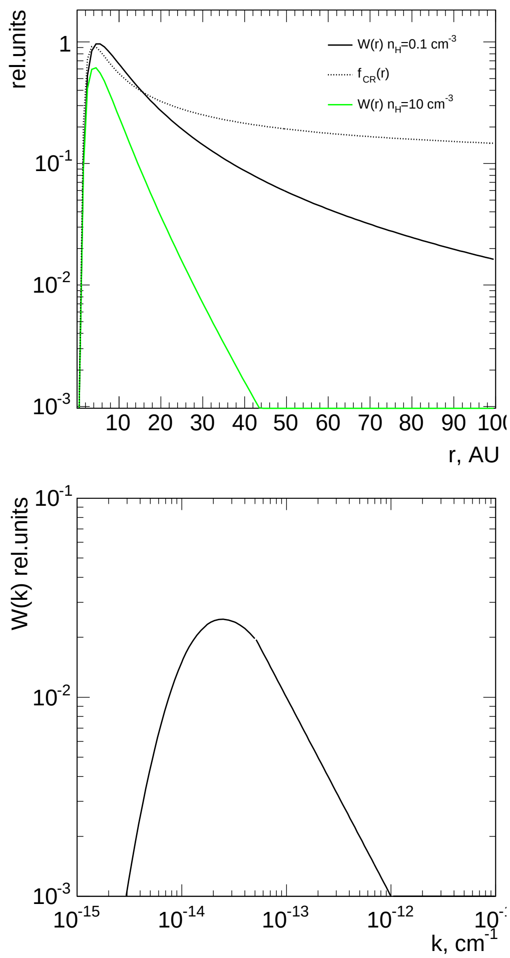

Figure 1: The $W(r)$ spatial distribution and particles distributions f_{CR} in the DM clump for GeV particles, $v_a \sim 10^6$ cm/s and $B \sim 1 \mu G$. The energy spectrum of $W(k)$ for m_χ=100 GeV.