Reopening the window on charged dark matter

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Abstract: We reexamine the limits on charged dark matter particles. We show that if their mass and charge fall in the range $100(q_X/e)^2 \lesssim m_X \lesssim 10^8(q_X/e)$ TeV, then magnetic fields prevent particles in the halo from entering the galactic disk, while those initially trapped inside are accelerated through the Fermi mechanism and ejected within about 0.1 – 1 Gyrs. Consequently, previous constraints on charged dark matter based on terrestrial non-observation are invalid within that range. Further, we find that charged massive particles may simultaneously solve several long-standing astrophysical problems, including the underabundance of dwarf galaxies, the shallow density profiles in the cores of the dwarf galaxies, the absence of cooling flows in the cores of galaxy clusters, and several others.

Keywords: dark matter theory, galaxy formation
1. Introduction

That most of the mass in the Universe is comprised of unknown non-baryonic particles has been in the mainstream of cosmology for almost a generation. Yet attempts to detect these particles only succeeded in excluding many attractive candidates. Recently, underground detectors have also produced strong constraints on the weakly interactive massive particles (WIMPs), limiting their interaction cross-section with nucleons to about $10^{-43}$ cm$^2$ [1, 2]. However, in this paper we show that the reason for non-detection might not be the low interaction strength, but rather the depletion of dark matter from the galactic disk. This could occur if dark matter particles were charged and their charge-to-mass ratio fell into a specific range. Furthermore, we find that charged massive particles (CHAMPs) may simultaneously solve several long-standing astrophysical problems, including the underabundance of dwarf galaxies (known as the missing satellite problem), the too shallow density profiles in the cores of the dwarf galaxies, the absence of cooling flows in the cores of galaxy clusters, and several others [3, 4, 5, 6, 7, 8, 9].

It was proposed long ago that a stable particle with a unit charge can act as nearly collisionless dark matter if its mass is sufficiently high [10]. However, subsequent experiments using both terrestrial and satellite data failed to detect any traces of such particles in our vicinity (see e.g., Dimopoulos et al. 1990). The less appealing option of dark matter particles with fractional charge [11] is also subject to strong observational constraints [12]. However, as shown by our calculations, if the charge and mass of CHAMPs fall in the

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range $100(q_X/e)^2 \lesssim m_X \lesssim 10^8(q_X/e)$ TeV, then their absence in the galactic disk (and hence non-detection on Earth) can be naturally explained by their interaction with galactic magnetic fields. In brief, galactic magnetic fields, which are observed to be parallel to the disk, prevent halo CHAMPs from penetrating the disk. ¹ At the same time, interactions with expanding supernovae (SN) remnants boost the kinetic energy of CHAMPs initially present inside the disk, leading to their expulsion on a time-scale of 0.1-1 Gyrs. This mechanism is similar to the one that produces cosmic rays, however, it is much more efficient due to the largely dissipationless nature of the CHAMPs.

The paper is organized as follows: In §2 we consider the chemistry of CHAMPs, baryons, and electrons. In §3 we describe the mechanism for CHAMP ejection from the Milky Way disk. In §4 we describe the changes CHAMPs would introduce into galaxy formation process. We summarize our results in §5.

2. CHAMP chemistry

CHAMPs may recombine with baryons and electrons, which would affect their charge state, and hence their interactions with electromagnetic fields and their mean-free-path. Depending on the initial charge, we can group CHAMPs into three categories.

I: The chemical properties of CHAMPs with positive unit charge would be very similar to protons. Consequently, in the interstellar medium the fraction of free CHAMPs ($X^+$) and CHAMPs recombined with electrons ($X^+e$) would mirror the local ionization state of hydrogen. Likewise, CHAMPs with integer charge greater than unity would mirror the behavior of heavier elements.

II: Following nucleosynthesis, CHAMPs with negative unit charge can recombine with baryons, forming neutral or positively charged particles ($X^-p$ or $X^-\alpha$). Since the binding energy increases with the mass and charge of the baryon, at later epochs some of the CHAMPs can undergo charge-exchange reactions, such as $X^-p + \alpha \rightarrow X^-\alpha + p$ or $X^-p + Li \rightarrow X^-Li + p$. Unfortunately, these reaction rates are very uncertain, so at present most of these particles could be either free, bound to the helium ions, or bound to protons [13].

III: CHAMPs with fractional charge might also recombine with ordinary matter, though with smaller binding energies the combinations would be more vulnerable to dissociation. Unlike CHAMPs with integer charge, CHAMPs with fractional charge can never form neutral particles. Hence, unless their charge to mass ratio is negligible they will be unable to masquerade as neutrals.

It seems most plausible to assume that charged dark matter would be made up by the equally numerous particles and anti-particles with a unit charge ($X^-$ and $X^+$). In this case, in the interstellar medium, where hydrogen is mostly ionized, a larger fraction of CHAMPs would form charged particles (e.g., $X^+$ and $X^-\alpha$), while a smaller fraction would masquerade as neutrals (e.g., $X^-p$), which would be unaffected by magnetic fields and have a low scattering cross section. Alternatively, if CHAMPs have fractional or only

¹A direct evidence of efficient segregation of charged particles by galactic magnetic fields comes from the cosmic rays, whose typical life-time inside the disk is of order $10^7$ years, i.e., around $10^5$ times longer than would be required for their direct escape.
positive charge (the latter possibility can not be excluded, given the example of the baryon asymmetry), then charged particles can make up virtually all of the dark matter.

3. Dark matter in the galactic disk

The large-scale magnetic field in the Milky Way, with strength of order 1-10 $\mu$G, is mostly parallel to the plane of the Galactic disk. Consequently, the particles in the halo are unable to penetrate the disk and those inside it to escape, unless their gyroradius, 

$$R_g = 10^{-9}\text{pc} \left( \frac{m_X}{m_p} \right) \left( \frac{e}{q_X} \right) \left( \frac{v_X}{300 \text{ km s}^{-1}} \right) \left( \frac{B}{1\mu\text{G}} \right)^{-1},$$

(3.1)

is larger than the typical height of the disk (about 100 pc). In Eq. (3.1), $m_p$ is the proton mass, $v_X$, $q_X$, and $m_X$ are the CHAMP’s velocity, charge and mass. With the velocity dispersion in the halo of order 300 km s$^{-1}$, crossing the magnetic lines requires the CHAMP mass to be above about $10^8(q_X/e)$ TeV. (Inside the disk the energy of charged particles can increase, which may allow even lower mass particles to escape.)

The main processes affecting the energy of charged particles in the disk are interactions with dynamic magnetic fields driven by supernovae (SN) explosions (the Fermi mechanism), radiative cooling, and Coulomb scatterings, which respectively inject, dissipate, and redistribute energy in plasma. The action of the Fermi mechanism can be described as following: A charged particle traveling in the interstellar medium would repeatedly scatter off the magnetic field lines of expanding SN remnants. In each scattering the particle velocity increases, thereby decreasing the average time between scatterings. In the absence of other processes, this leads to an exponential momentum growth.

The energy injection rate from SN remnants into each particle species is roughly proportional to their thermal pressure, so the time-scale for momentum increase, $\tau_{\text{acc}} = v/(dv/dt)$ is also roughly the same for all charged species. Since injecting more energy into baryons than can be dissipated by radiative cooling would lead to a suppression of star formation, $\tau_{\text{acc}}$ must generally be close to $\tau_{\text{cool}}$, about 10 Myrs in the present-day Milky Way disk [14].

While baryons and CHAMPs receive roughly the same energy per unit mass from SNs, radiative cooling is limited to the former. Thus, energy balance may be preserved only by frequent Coulomb scatterings. For particles whose velocities are smaller than thermal velocities of electrons, scatterings with protons are dominant, with a relaxation time-scale of

$$\tau_{\text{rel},p} \approx 300 \text{ years} \left( \frac{e}{q_X} \right)^2 \left( \frac{m_X}{m_p} \right) \left( \frac{v_X}{100 \text{ km s}^{-1}} \right)^3 \times \left( \frac{n_p}{10^{-2}\text{cm}^{-3}} \right)^{-1},$$

(3.2)

where $n_p$ is the proton number density. Those with higher velocities lose energy mainly to electrons, with a relaxation time-scale of

$$\tau_{\text{rel},e} \approx 200 \text{ years} \left( \frac{e}{q_X} \right)^2 \left( \frac{m_X}{m_p} \right) \left( \frac{v_X}{1000 \text{ km s}^{-1}} \right)^3.$$
If for CHAMPs, $\tau_{\text{rel}}$ is larger than $\tau_{\text{acc}}$, the CHAMPs velocities would grow until they can no longer be contained in the disk. The escape can follow one of two routes: At early stages CHAMPs are likely to comprise a large fraction of the disk mass. If $\tau_{\text{acc}} < \tau_{\text{rel}}$, eventually their kinetic energy becomes larger than the total (CHAMPs plus baryons) binding energy of the disk and they escape from the disk, sweeping with them the magnetic field lines and the ionized gas which is tied to the magnetic field. CHAMP escape, therefore, would be accompanied by a significant depletion of baryons from the disk, as only neutral gas clouds may stay behind. At a later epoch, when the CHAMP abundance is too low to sweep baryons with them, their energy can continue to grow until it is high enough for crossing the disk magnetic field lines.

In both cases, in order to satisfy the condition for escape, $\tau_{\text{acc}} < \tau_{\text{rel}}$, CHAMP velocities must exceed a critical threshold

$$v_{\text{crit}} \sim 4 \times 10^4 \text{ km s}^{-1} \left( \frac{m_X}{m_p} \right)^{-1/3} \left( \frac{q_X}{e} \right)^{2/3} \times \left( \frac{n_p}{10^{-2} \text{cm}^{-3}} \right)^{1/3} \left( \frac{\tau_{\text{acc}}}{10 \text{ Myr}} \right)^{1/3}.$$  

(3.4)

Beyond this threshold a particle would on average gain more energy from SNs than lose in the Coulomb scatterings, so most CHAMPs would have to cross it only once in order to escape.

SN produced shockwaves with velocities comparable to the thermal velocities of protons in the hot ionized medium (about 100 km s$^{-1}$) are expected to travel across most of the galactic disk every $\tau_{\text{cool}} \sim 10$ Myr. Energy conservation in a point explosion requires that the probability of a particle being hit by a shock with velocity greater than $V_s$ scales as $V_s^{-2}$, so that shocks with $V_s \gtrsim 1000$ km s$^{-1}$ are expected to pass about once per Gyr. From Eq. (3.4) we see that at the present-day conditions of the Milky Way disk $V_s \sim 1000$ km s$^{-1}$ would be sufficient to launch the exponential acceleration of CHAMPs with mass $m_X \gtrsim 100(q_X/e)^2$ TeV, which in about 100 Myrs would lead to their escape from the disk. Since the SN activity seems to be much higher in past and $\tau_{\text{acc}}$ respectively shorter, this is likely to be a conservative estimate.

Thus, for masses in the range $100(q_X/e)^2 \lesssim m_X \lesssim 10^8(q_X/e)$ TeV, CHAMPs in the disk should have been severely depleted by SN shock acceleration, and CHAMPs in the halo will be unable to penetrate into the disk because of interactions with the magnetic field.

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2We assume conservatively that CHAMPs can escape only when their velocity is higher than the typical electron thermal velocity, i.e., when $\tau_{\text{rel}} \approx \tau_{\text{rel},e} \ll \tau_{\text{rel},p}$.

3The fact that SN shocks could make a strong impact on CHAMPs has already been noted by Dimopoulos et al. (1990). However, in their scenario they did not consider the segregation of CHAMPs from the disk by magnetic fields. Consequently, they expected that low mass CHAMPs would overheat the baryonic disk, leading to its destruction.
4. Observational signatures of CHAMPs

The interaction of CHAMPs with ordinary matter depends on its charge to mass ratio, $q_X/m_X$. Observations put severe limits on the abundance of CHAMPs with $m_X \lesssim 100(q_X/e_X)^2$ or $m_X \gtrsim 10^8(q_X/e_X)$ TeV that are not expelled from the Milky Way disk, and whose potential impact is therefore negligible. By contrast, CHAMPs in the range $100(q_X/e_X)^2 \lesssim m_X \lesssim 10^8(q_X/e_X)$ TeV can strongly affect the visible universe by interacting with ordinary matter via the mediation of magnetic fields, and, for those belonging to the lower part of this range, $100(q_X/e_X)^2 \lesssim m_X \lesssim 1000(q_X/e_X)^2$ TeV, directly by Coulomb scatterings.

4.1 The Effects of Magnetic interaction

4.1.1 Dark matter density profiles

Unlike CDM halos, which remain almost static after the end of the accretion phase, CHAMP halos can undergo drastic changes following the formation of stars. Unless the CHAMP’s charge is large enough for the Coulomb scatterings to be important (the possibility discussed in the next section), the energy injection from SNs will continuously reduce the binding energy of the dark-matter halo. In large elliptical galaxies, with large binding energies and low luminosity per unit mass, the effect on the dark-matter density profiles would be moderate. In spiral galaxies like the Milky Way, the total mechanical input from the SNs is comparable to the binding energy. However, segregating CHAMPs from the stellar disk should greatly decrease the fraction of energy going into the dark matter, so the effect is again likely to be moderate. By contrast, in spherical dwarf galaxies the energy injection from SNs may drastically reduce the steepness of the dark-matter density profile, possibly leading to the expulsion of the CHAMPs from the galaxy.

This mechanism might explain the absence in dwarf galaxies of a central density cusp, which is predicted by the numerical simulations.

4.1.2 Angular momentum of the galactic disk

Scatterings of the halo CHAMPs from the magnetic field lines of the disk create momentum exchange between the disk and the halo. Since the dark-matter mass density close to the disk surface is estimated to be comparable to the baryon density, the time-scale for momentum equilibration is roughly given by

$$\tau_{\text{ang}} = \frac{R_h}{V_X} \approx 5 \times 10^5 \text{ years},$$

where $R_h \approx 100$ pc is the typical disk height and $V_X \approx 200$ km s$^{-1}$ is the tangential velocity of the CHAMPs. Since $\tau_{\text{ang}}$ is much shorter than the time-scale for momentum exchange via dynamical friction, we suspect that the history of the disk formation may be very different than in the standard model. In particular, it would be interesting to see whether numerical simulations incorporating this effect would be able to solve the so called angular momentum problem (i.e., the discrepancy between the low disk momentum produced by current simulations and the much higher observed momentum).
4.1.3 Break-off of hydrostatic equilibrium

Following the collapse into a halo, the gas and the CHAMPs gain the same amount of energy per unit mass, which should result in similar distribution profiles. However, non-gravitational processes, such as cooling, affect each component differently, leading to different dynamics. Unlike the CDM model where gas is free to settle at its new equilibrium distribution, the coupling to the dark matter via the magnetic field can support the gas against gravity when its own pressure is insufficient.

This process may explain the discrepancy between the mass estimates in galaxy clusters made independently from lensing and X-ray observations. The latter, which rely on the assumption of hydrostatic equilibrium, is in agreement with lensing observations at large radii where the cooling exceeds the Hubble time. However, at the central region the lensing often overpredicts the mass by a factor of a few [15].

4.2 Effects of collisional interactions

If the CHAMP mass is significantly above the proton mass, then following their accretion by the halo the CHAMPs would typically have much higher kinetic energies than baryons. Consequently, collisions of CHAMPs and baryons result in a net heat inflow for the gas, which can prevent its accretion unless balanced by strong cooling.

To illustrate this effect we calculate the critical temperature, $T_{cr}$, at which heating by CHAMPs is balanced by radiative cooling in halos of different size. When $T_{cr}$ is above the virial temperature, $T_{vir}$, gas is unable to collapse into the halo because of thermal pressure. Conversely, when $T_{cr} < T_{vir}$, the gas density will continue to rise, which can further increase the cooling rate.

Figure 1 shows the critical temperature in halos with different CHAMP velocity dispersions. For this example we assumed that CHAMPs have a mass of $m_X = 400 \, \text{TeV}$ and a charge +1 (i.e., most is made of $X^+$ or $X^-\alpha$). The ionization fraction of CHAMPs should be very similar to that of hydrogen. We expect the scattering cross-section of CHAMPs that recombined with electrons with hydrogen atoms to be comparable to that of hydrogen atoms, $10^{15} \, \text{cm}^2$. We consider separately the epochs prior to hydrogen and helium reionization, respectively, when collisional excitation of HI and HeII atoms were the dominant cooling processes, and the epoch when the helium is fully ionized and the metal-poor gas can cool only by Bremsstrahlung. The comparison of the critical and the virial temperatures shows that at different epochs heating by CHAMPs suppresses gas accretion in halos with velocity dispersion below about 10, 20 and 40 km s$^{-1}$, respectively. This would change the reionization history of the Universe compared to standard model since at early times because heating by CHAMPs suppresses the formation of minihalos which would shift the beginning of star formation to a later epoch, when halos with $V_X \gtrsim 10 \, \text{km s}^{-1}$ start to form. In the latter case, by contrast, heating by CHAMPs is likely to boost the formation of radiation sources. Heating by CHAMPs would significantly increase the Jeans mass,

\footnote{\text{It is possible that the near-degeneracy of the electron energy levels in the CHAMP and the hydrogen atom can boost the cross-section by one or two orders of magnitude, but in our case this would not make a significant change.}}
Thus biasing the first sources towards larger masses and emissivity. Since cooling in the metal-poor gas is very inefficient below 10^4 K, it is further conceivable that these halos would not be able to form stars at all, collapsing into supermassive black holes instead. This would explain the appearance of supermassive black holes already at z > 6, which would be problematic if the black holes grew by accretion starting with stellar mass seeds [16].

As reionization of hydrogen progresses, first generation halos stop forming, thus slowing the production of ionizing photons, until new halos with V_X ≳ 20 km s^{-1} start to form in large numbers. After the end of helium reionization only galaxies with V_X ≳ 40 km s^{-1} may form, with smaller halos remaining dark.

The above reionization scenario offers answers to several existing problems: The end of hydrogen reionization is observed to be at z ∼ 6, while most of hydrogen must be ionized already at z ≥ 11 [17]; present star-formation rates are insufficient to produce early reionization [23]; and the number of observed galaxies with rotational velocities below 40 km s^{-1} is much lower than expected [3, 4].

4.3 Dark matter annihilation

If the dark matter is composed of particles and anti-particles, their annihilation signature may be observable. The evolution of CHAMPs annihilation rate has several peculiar features that potentially can make its signature distinct from neutral dark matter particles.

The attractive Coulomb potential between free X^+ and X^-, increases the annihilation cross-section by a factor ∼ c/v (the Sommerfeld-Sakharov correction). Hence, after the CHAMPs become non-relativistic, their annihilation rate falls at a slower rate than for the
CDM model. By contrast, other models with Sommerfeld enhancement, where the effect is achieved by self-interaction of dark matter particles, produce an even slower decline of the annihilation rate. Since they are not collisionally coupled to radiation, their kinetic energies fall as \((1 + z)^2\), rather than \((1 + z)\) as in the CHAMPs case.

Around \(z \sim 10^6\) the CHAMPs annihilation rate is expected to decline sharply as \(X^-\) particles recombine with protons and helium ions, and the Sommerfeld-Sakharov enhancement is reduced. Similarly, the annihilation rate is likely to change significantly around \(z \sim 1000\), when \(X^+\) and \(X^-\alpha\) particles recombine with electrons. The present CHAMPs annihilation rate would be very sensitive to the fractions of \(X^-\) particles bound to different baryons.

5. Summary

We have found that CHAMPs with mass in the range between \(100(q_X/e)^2 \lesssim m_X \lesssim 10^8(q_X/e)\) TeV would be depleted from the galactic disk, which can explain their previous non-detection. Though hard to detect, CHAMPs would make a strong impact on the observable universe. In §4.2, we have shown that through their interactions with magnetic fields, CHAMPs can affect the structure and dynamics of baryonic matter. Conversely, baryons would make a strong impact on the dark matter, in particular, in low-mass galaxies where they would be able to flatten dark-matter cusps. CHAMPs with unit charge and mass of order a few hundred TeV seem especially attractive. Such particles may also be able to explain the underabundance of dwarf galaxies, the absence of cooling flows in the cores of galaxy clusters [19], the present value of \(\Omega_M\) [20], the origin of supermassive black holes, and the reionization history of the Universe.

It has been proposed that some of the problems of ΛCDM model may be solved by self-interacting dark matter (SIDM) [21]. However, since CHAMPs interact with each other mainly through the intermediate agency of magnetic fields rather than by direct scattering, they escape several problems associated with the SIDM, such as predictions of too spherical halo shapes [22], and unobserved evaporation of galactic halos inside galaxy clusters [18].

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