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Bounds on Halo-Particle Interactions from Interstellar Calorimetry

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We constrain, from the observed properties of diffuse interstellar clouds, the interactions of halo particles with atomic hydrogen.

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The light from distant stars makes cartography of the luminous material within galaxies possible, the simplest observation being the distinctive shape of the galaxy. In spiral galaxies, for example, most of the light emanates from a small central nucleus and an extended disk-shaped region. In addition to the obvious density information this light provides, by examining the optical and 21-cm spectral lines we obtain "rotation curves," maps of the orbital velocities of the components of a galaxy as a function of their distance from the center. From this we deduce that the *total* mass distribution in spiral galaxies is approximately that of an isothermal sphere: The mass density falls as r^{-2}, where r is the distance from the center of the galaxy.[1] The gravitational potential and the mass inferred from these rotation curves is in conflict with the distribution of luminous matter observed—gravitating matter outweighs luminous matter by a factor of 3 to 10. This discrepancy is observed in elliptical galaxies as well. The resolution of this paradox lies in "dark matter," nonluminous, gravitating, material in spherical halos surrounding galaxies.

Many suggestions[1] have been made as to the form this matter might take, from "condensed matter" such as substellar size macroscopic objects made of baryons, to a diffuse collection of some species of "elementary" particles such as axions or massive neutrinos. It has generally been assumed that if the galactic halo is composed of elementary particles, then these halo particles must be *weakly* interacting; otherwise, it is argued, they would be dragged into the disk of the galaxy as ordinary matter collapses.

Recently, De Rújula, Glashow, and Sarid[2] have pointed out that this reasoning could be false: If halo particles are very massive, they may not lose energy fast enough to collapse into the disk with baryons during the formation of the galaxy. Moreover, if halo particles interact relatively strongly with ordinary matter, they will not show up in traditional searches for dark matter which rely on the particles interacting weakly enough to penetrate the Earth.[3] In particular, the authors of Ref. 2 propose that the halo of our Galaxy could be composed of CHAMPs, charged particles with a mass of between a few tens to 10^4 TeV.[4]

In this Letter we show that the existence of neutral interstellar clouds constrains the interaction of any particulate dark-matter candidate with atomic hydrogen to be quite small. We show that, even for a halo particle of mass 1 PeV (10^6 GeV), the cross section with hydrogen must be smaller than the typical atomic cross section that we expect for a positively charged particle bound to an electron. This argument eliminates such positively charged particles as a dark-matter possibility, as well as any other object that has a similar cross section.

In outline, the argument is simple: If the clouds are in equilibrium, the rate at which energy is deposited by collisions with dark-matter particles must be smaller than the rate at which the cloud can cool. In the remainder of this paper we use this argument to constrain the interaction cross section of dark matter with hydrogen, and conclude with some remarks on the general viability of charged dark matter.

If the dark-matter particles which form the galactic halo interact with hydrogen, neutral or ionized, their interactions will be largely *elastic* as the relative velocity is of order of the average velocity of a halo particle (here we assume a spherical halo with a Maxwellian velocity distribution having an rms velocity v_h of approximately $9\times10^{-4}c$) and is less than $\alpha_{\mathrm{em}}c$, the typical "velocity" of an electron bound to a proton. The recoiling hydrogen atom or proton will gain a momentum less than or of order $m_p v_h$ and will quickly share most of its energy through *elastic* collisions with other hydrogen atoms and protons. Therefore, most of the energy deposited by the interactions of a halo particle will go into heating the interstellar medium and will not be quickly lost in radiation.

The heating rate per nucleon due to halo-particle interactions may be computed in terms of the transport cross section σ_{tr} for hydrogen–halo-particle or proton–halo-particle scattering,

$$\sigma_{\mathrm{tr}}=\int d\Omega(1-\cos\theta)\left[\frac{d\sigma}{d\Omega}\right]_{\mathrm{elastic}} . \tag{1}$$

Integrating over a Maxwellian velocity distribution and assuming the transport cross section varies only slowly with velocity, we find the heating rate per nucleon

$$\gamma_h = 1.2(n_h \sigma_{\mathrm{tr}} v_h)(\mu^2/m_p) v_h^2 , \tag{2}$$

where

$$n_h \approx 4\times 10^{-7} \left(\frac{1\ \mathrm{PeV}}{M} \right) \mathrm{cm}^{-3} \tag{3}$$

is the local number density of halo particles of mass M [here we assume a local halo density of 0.4 GeV/cm^3 (Ref. 1)], m_p is the proton mass, and μ is the reduced mass of the hydrogen-halo-particle system.

If the interstellar medium is in equilibrium, the rate of energy deposition due to halo-particle interactions must not exceed the rate at which the medium can cool. The best bound, therefore, is derived from regions with the lowest cooling rate: interstellar H I regions.[5] These objects consist largely of atomic hydrogen, and are observed to have the following properties:[6] (1) hydrogen number densities of 10–200 cm^{-3}, and (2) temperatures T of 30–80 K. At these temperatures cooling proceeds largely by deexcitation of $C^{*+} \equiv C^{+}(^2P_{3/2})$ formed by the processes $e + C^{+}(^2P_{1/2}) \rightarrow e + C^{*+}$ and $H + C^{+} \rightarrow H + C^{*+}$.[7]

From measurements of the uv absorption by C^{*+}, one can deduce the column density of C^{*+} along the line of sight to a bright star.[8] Along a given line of sight the cooling rate per nucleon due to deexcitation of C^{*+} is

$$\lambda = AE\,N(C^{*+})/N(H) , \tag{4}$$

where $A = 2.4\times10^{-6}\ \mathrm{sec}^{-1}$ is the Einstein coefficient for the C^{+} fine-structure transition, $E = 7.9\times10^{-3}$ eV is the energy of the transition, $N(C^{*+})$ is the column density of C^{*+}, and $N(H)$ is the column density of hydrogen (ionized, atomic, and molecular). Pottasch, Wesselius, and van Duinen[8] find cooling rates along nine lines of sight using International Ultraviolet Explorer and Copernicus uv data and find an average energy loss per nucleon of $\lambda = (8.1 \pm 4.8)\times10^{-14}$ eV/sec. We take the average as representative of the cooling rate of H I regions. This value is in agreement with calculated cooling rates based on the observed compositions and temperatures.[7]

If we require $\gamma_h \leq \lambda$, we find the constraint

$$\sigma_{\mathrm{tr}} \lesssim 8\times10^{-18}\ \mathrm{cm}^2 \left(\frac{m_p}{\mu} \right)^2 \left(\frac{M}{1\ \mathrm{PeV}} \right) . \tag{5}$$

We could require that heating due to halo-particle interactions *plus* heating due to conventional sources be less than the cooling rate. It seems likely that grain photoelectric heating[9] is the primary conventional heating mechanism for these regions. The actual photoelectric heating rate, however, is uncertain and we therefore satisfy ourselves with the less stringent condition (5). This constraint on the hydrogen-halo-particle transport cross section must be obeyed by all dark-matter candidates. Accordingly, we plot the excluded region in cross section as in Fig. 1, for a local halo density of 0.4 GeV/cm^3.

In addition to the heating constraint, we have also graphed the region of cross section excluded on the basis of silicon-detector[10] measurements near the top of the atmosphere. These measurements are sensitive to dark matter which interacts weakly enough to penetrate the atmosphere above the detector and strongly enough to interact with the nuclei of silicon in the detector. The precise form of the silicon-detector constraint depends on the relationship between the dark-matter cross section on silicon and on hydrogen. We have plotted the constraint for two possibilities: a geometric cross section [$\sigma(\mathrm{Si}) \approx (28)^{2/3}\sigma(\mathrm{H})$], and a completely coherent[11] cross section [$\sigma(\mathrm{Si}) \approx (28)^{4}\sigma(\mathrm{H})$]. We show the excluded cross-section regions for these cases in Fig. 1. We see that most of the region for particles interacting more strongly than WIMPs (Ref. 12) is ruled out, with a small window remaining. Of course, without knowing the interaction responsible for the cross section, we cannot definitely relate the hydrogen and silicon cross sections. For example, if dark matter couples to spin, the cross section on silicon would be *very* small and all bounds from Si disappear.

We can apply this plot to the CHAMP scenario. For a positively charged CHAMP bound to an electron, we expect the elastic transport cross section with hydrogen to be very similar to the elastic hydrogen-hydrogen

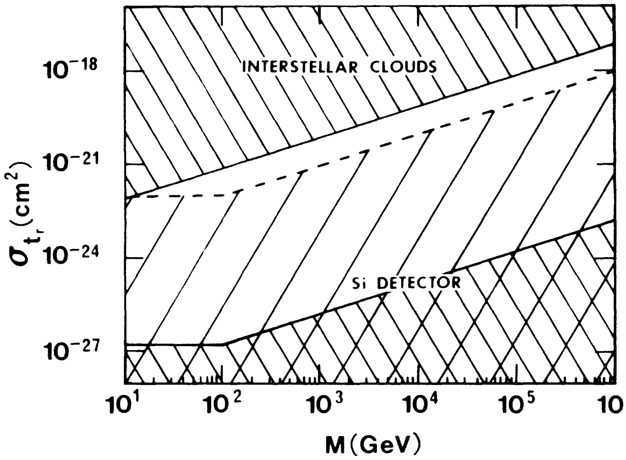

FIG. 1. The upper shaded region is excluded by limits on halo-particle heating of interstellar clouds [Eq. (5)]. We have also plotted constraints arising from silicon-detector measurements near the top of the atmosphere (Ref. 10). The precise form of this constraint depends on the relationship between the dark-matter cross section on silicon and on hydrogen. Assuming the dark-matter–Si cross section is geometric, the entire region below the dashed line is excluded, while if dark matter couples coherently to baryon number, only the cross-hatched region is excluded.

transport cross section. Naively, we would expect this cross section to be approximately geometric, like most other atomic cross sections in this energy region, $\sigma_{\rm tr} \simeq 10^{-17}$–$10^{-16}$ cm^2. Surprisingly, a calculation by Dalgarno[13] indicates that the transport cross section is, in fact, 1 or 2 orders of magnitude *larger* than this, due to the near degeneracy of the electronic levels in the CHAMP atom and the ordinary hydrogen atom. In either case, these cross sections are inside the excluded region: positively charged CHAMPs (as well as negatively charged CHAMPs bound to nuclei and having net positive charge) are ruled out.

Finally, we comment on a bound which derives from the dynamical stability of the halo. If halo particles interact sufficiently strongly with hydrogen in the galactic disk, they may become trapped in the disk and cease to form a halo. A halo particle in our Galaxy traverses the disk approximately once per dynamical time and encounters of order 1 mg/cm^2 of hydrogen when it does so. The galaxy is approximately 10^{10} yr old and its dynamical time is of order 2.5×10^8 yr, hence a typical halo particle has encountered of order 40 mg/cm^2 of hydrogen during the lifetime of the Galaxy. If we require that the cross section be small enough that 40 mg/cm^2 of hydrogen is insufficient to stop a halo particle, we find

$$\sigma_{\rm tr} \lesssim 2\times10^{-17}\,{\rm cm}^2 \left(\frac{m_p}{\mu}\right)^2 \left(\frac{M}{1\ {\rm PeV}}\right). \qquad (6)$$

Thus bounds coming from trapping halo particles in the galactic disk are somewhat less stringent than heating bound (5) discussed above.

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[12] WIMPs (weakly interacting massive particles), the generic label attached to nonbaryonic cold-dark-matter candidates, would have an elastic-scattering cross section on hydrogen of order 10^{-38} cm^2 [e.g., see M. W. Goodman and E. Witten, Phys. Rev. D **31**, 3059 (1985)].

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