Experimental Limits on Any Long Range Nongravitational Interaction between Dark Matter and Ordinary Matter

Christopher W. Stubbs
Department of Physics, University of California, Santa Barbara, California 93106
and Center for Particle Astrophysics, University of California, Berkeley, California 94720
(Received 31 July 1992)

Much of the mass of the Universe is thought to reside in some as yet unidentified dark matter. This view is based on the analysis of trajectories of luminous "tracers" that map out the local potential, assuming that gravity is the only long ranged interaction between ordinary and dark matter. This assumption should be tested experimentally if possible. Laboratory tests of the weak equivalence principle can constrain (at an interesting level) any exotic coupling between ordinary and dark matter when analyzed as a test of the uniformity to free fall towards the center of the Galaxy.

PACS numbers: 04.90.+e, 04.80.+z, 95.30.Sf, 95.35.+d

There is strong observational evidence [1,2] that the rotational properties of spiral galaxies cannot be accounted for by the gravitational effects of luminous matter. The stars and gas found interior to some galactocentric radius r do not appear in sufficient quantity to exert the gravitational force needed to support the observed rotational velocity. Clusters of galaxies also seem to have more mass than the luminous material would indicate [3]. A number of ideas have been put forth to address this "missing force" problem. The currently favored scheme appeals to an extensive spherical galactic halo of nonluminous ("dark") matter that exerts enough gravitational force to make up the observed deficit. In our own Galaxy the dark matter is thought to be distributed with a density $\rho(r)$ given approximately by [4]

$$\rho(r)=\rho_0\frac{b^2+r_0^2}{b^2+r^2}\,, \tag{1}$$

where b and r_0 are the core radius and solar system's galactic radius, respectively, and $\rho_0=\rho(r_0)$.

A wide variety of candidates have been put forth as possible constituents of the dark matter (DM), ranging from low-mass stars to exotic particles [4]. The standard dark matter scenario assumes that gravity is the only interaction between dark and ordinary matter. This minimal picture is appealing in that it appears to account for the observations, but it is important that this underlying assumption be tested if at all possible.

The possibility of an exotic nongravitational coupling to particle dark matter is not without motivation. In general, elementary particle candidates for the dark matter (weakly interacting massive particles, axions, massive neutrinos, etc.) lie outside the standard model and long range couplings can arise in a wide variety of pictures of the world beyond the standard model [5,6]. In particular, if the DM is a fundamental particle that is rendered stable by some conserved quantum number, one might imagine an associated U(1) coupling [7]. Any interaction of this sort could play an important role in our understanding of the dark matter problem.

The main point of this paper is that current experimental data can set interesting limits on any nongravitational long range interaction between ordinary and dark matter.

Virtually all scenarios that give rise to a new interaction exhibit composition dependence at some level (i.e., it is very difficult to construct a model that features an interaction mediated by an exchange particle that couples identically to *mass*), and hence would generate apparent violations of the weak equivalence principle [5].

In considering any new long range nongravitational coupling in this context, three cases are of interest: (1) interaction purely in the DM sector, i.e., exotic DM-DM couplings, (2) any exotic coupling between DM and ordinary matter, and (3) the exotic coupling between ordinary material that must come about if ordinary matter participates in the interaction.

The first of these has been explored recently by Frieman and Gradwohl [8] and will not be discussed here. Note, however, that a significant vector (and hence repulsive) self-interaction of the dark matter is ruled out if it is bound to the halos of galaxies.

Case (2) is the main focus of this paper, as any nongravitational long range coupling between dark matter and ordinary luminous matter would lead us to draw invalid conclusions from the observed motions of luminous "tracer" material in spiral galaxies and clusters. If case (2) exists then case (3) must also, but the stringent bounds on exotic long range couplings (between ordinary materials) from the recent "fifth force" experiments [5] do not address directly the possibility of a nongravitational coupling between ordinary and dark matter.

We will adopt a picture where any new interaction is mediated by a Yukawa particle in a backdrop of spacetime. It is then useful to parametrize a new long ranged interaction as a modification to the gravitational interaction between two point objects,

$$V(r)=\alpha G\frac{(q/\mu)_1(q/\mu)_2 m_1 m_2}{r}e^{-r/\lambda}\,, \tag{2}$$

where the dimensionless number α characterizes the strength of the interaction, G is Newton's gravitational constant, m_1 and m_2 are the object's masses in amu, (q/μ) represents their relevant effective "charge" per amu, and $\lambda = \hbar/m_{ex}c$ is the range of the force (determined by m_{ex}, the mass of the exchange boson that mediates the new interaction). Of course α is a universal constant independent of whether the objects are ordinary or dark matter, but the charge content q/μ of the two would in general differ.

Two materials with a difference $\Delta q/\mu$ in charge-to-mass ratios will accelerate at different rates when acted upon by a "source" with nonvanishing q/μ. The experimental signature of a composition-dependent long ranged interaction would then mimic a violation of the weak equivalence principle (WEP). Tests of the WEP have been conducted by comparing the free fall rates of different materials. The results of these WEP tests can be cast (for interaction ranges λ much larger than the scale of the experiment) as a dimensionless number $\Delta a/g$, where Δa and g are the measured acceleration difference and the average gravitational acceleration towards a source. In terms of the parameters of Eq. (2), in the limit of large λ

$$\Delta a/g = \alpha(\Delta q/\mu)_{\rm det}(q/\mu)_{\rm source}, \quad (3)$$

where the subscripts refer to the detector materials and the source, respectively. A number of sensitive experiments have searched for apparent WEP violation using the Earth, the Sun, and the various man-made objects as the "source" for the experiment [5]. Of these, torsion balance experiments have achieved the greatest sensitivity to date for long ranged composition-dependent interactions ($\Delta a \sim 10^{-11}$ cm s^{-2}). Virtually all such experiments have produced null results [5].

By interpreting these existing WEP data as an upper bound on differential acceleration towards the galactic center (or other cosmological-scale mass inhomogeneities) rather than towards the Earth or Sun, interesting limits can be placed on the possibility of any long ranged composition-dependent coupling between ordinary and dark matter. This approach exploits the fact that on galactic scales the DM constitutes a significant fraction of the attracting mass. On cosmological scales at least 90% of the mass is thought to be DM.

An astronomical source at a declination δ generates an interesting signal in a torsion balance placed at a latitude l on the Earth. The torsion pendulum is most sensitive to sources that lie in the plane normal to the torsion fiber, and this plane sweeps through the sky as the Earth rotates. The normalized accelerations A_W and A_N towards the West and North in the plane normal to the fiber are

$$A_W = a_W/a_{\rm ff} = \cos(\delta)\sin(\omega t),$$
$$A_N = a_N/a_{\rm ff} = -\cos(\delta)\sin(l)\cos(\omega t) + \sin(\delta)\cos(l), \quad (4)$$

where the $a_{\rm ff}$ is the free-fall acceleration of a test object towards the celestial source, which achieves its upper culmination at $t=0$. The time-independent N component arises from the projection of the acceleration that is parallel to the Earth's spin axis. This component maintains a constant direction in the laboratory frame. The acceleration orthogonal to the Earth's spin axis adds a modulated component with a period of one sidereal day, $\tau_{\rm sid} = 1/\omega = 86\,164.1$ s. (A signal of solar origin would instead have a period of a solar day.) Sources with $|\delta| > (90° - l)$ are circumpolar and never pass through the torsion balance's plane of highest sensitivity, so only a torsion balance on the equator would achieve full-sky coverage at maximum sensitivity. A continuously rotating torsion balance of the sort developed by Adelberger *et al.* [9] would detect both the stationary and time-dependent components of a WEP-violating signal from a celestial source, provided the balance turned sufficiently rapidly, and is well suited to this task (see Smith *et al.* [10]). Figure 1 shows the time evolution of A_N and A_W arising from a celestial source at $\delta = -29°$ (corresponding to the galactic center), for a torsion balance at $l = 45°$.

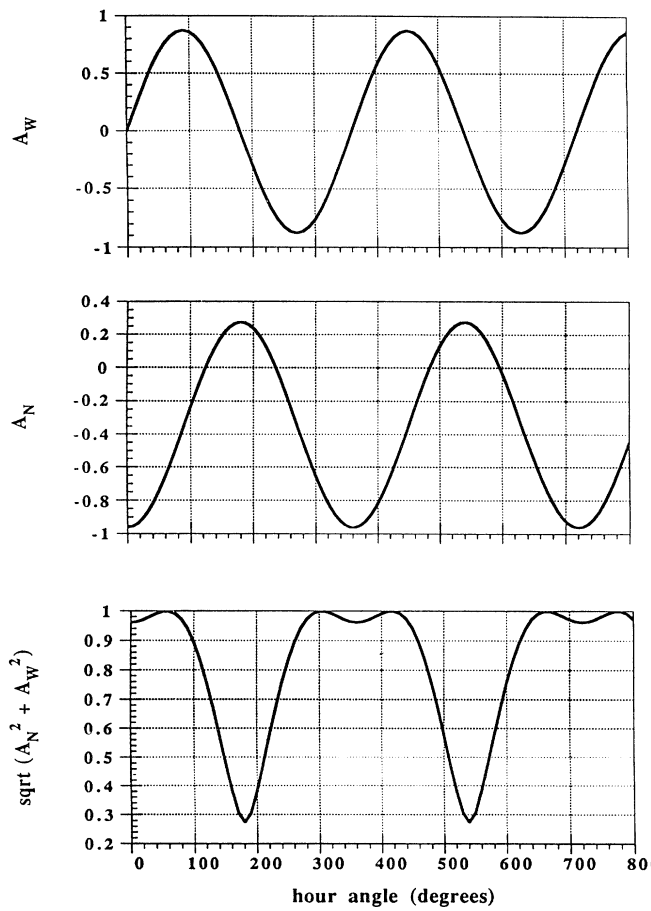

FIG. 1. The normalized components A_W (West) and A_N (North) of the gravitational acceleration towards a source at $\delta = -29°$ are shown as a function of hour angle in the upper and middle panels. The magnitude $(A_W^2 + A_N^2)^{1/2}$ is shown in the lower panel.

Table I lists the acceleration normal to the fiber of test

TABLE I. Source strengths for torsion balance experiments. The maximum acceleration a_n normal to the torsion balance fiber is listed, for a torsion balance situated at 45° latitude. Galactic values are computed using $\rho_0=0.3$ GeV/cm^3. The Virgocentric infall velocity in units of 250 km s^{-1} is v_{250}, and h_{100} is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. The third column lists the normal acceleration attributed to the dark matter content of the celestial sources. Units are cm s^{-2}.

Source	$\|a\|_n$	$\|a\|_{\rm dark}$
Earth	1.66	0
Sun	0.59	0
Galaxy ($b=2.0$ kpc)	1.85×10^{-8}	8.5×10^{-9}
Galaxy ($b=4.0$ kpc)	1.85×10^{-8}	6.6×10^{-9}
Galaxy [$b=5.6$ kpc (preferred value)]	1.85×10^{-8}	5.9×10^{-9}
Galaxy ($b=10.0$ kpc)	1.85×10^{-8}	4.8×10^{-9}
Virgo cluster	$\sim8\times10^{-11}h_{100}v_{250}$	$\sim7\times10^{-11}h_{100}v_{250}$

objects on a torsion balance (at a latitude $l=45°$) imparted by the galaxy and the Virgo cluster [11]. Values for the Earth and Sun are shown for comparison. Both the galactic center ($\delta=-29°$) and Virgo ($\delta=+12.5°$) pass through the plane of maximum sensitivity for a balance operated at a latitude of $l=45°$. Table I also lists the acceleration due to the dark matter component of the galactic and cosmological sources (neglecting the possibility that dark matter might be captured by solar system objects [12]).

The total galactocentric acceleration was obtained from $a_{\rm gal}=v^2/r_0$ using $v=220$ km s^{-1} as the local rotational speed of the Galaxy and $r_0=8.5$ kpc as the solar system's galactic radius. The galactic dark matter's contribution to this was obtained by determining the amount of galactic halo dark matter interior to r_0 by integrating Eq. (1) from $r=0$ to r_0, giving

$$m_{\rm encl}=4\pi\rho_0(b^2+r_0^2)[r_0-b\arctan(r_0/b)]\,. \qquad (5)$$

The acceleration attributed to dark matter interior to the Earth's galactic radius can then be obtained trivially, for a spherical halo. The enclosed dark mass is linear in ρ_0 but the scaling with b, the assumed core radius, is as yet not evident upon inspection so Table I lists results for a range of core radii. The resulting DM contribution is $\sim$(25–50)% of $a_{\rm gal}$.

On a larger scale the local group of galaxies appears to be moving relative to the Hubble flow, but there is at present considerable debate [13] about the nature and origin of our local peculiar velocity. One large directly observed mass concentration that is thought to affect bulk flow in our vicinity is the Virgo cluster of galaxies. Current estimates of our Virgocentric velocity range between $v_{\rm infall}=100$ and 350 km s^{-1}, depending on whether and how other perturbations, such as the "great attractor," are incorporated in the analysis of the data. Arriving at a value for our *acceleration* towards Virgo is somewhat problematic. The local acceleration towards Virgo (in an oversimplified picture) is therefore poorly determined but is roughly

$$a_{\rm Virgo}\cong H_0 v_{\rm infall}\,,$$

where H_0 is the present value of the Hubble constant. The dark matter in the cluster is thought to dominate its mass. It is presently unclear whether cluster dark matter has the same composition as the dark matter in the halos of galaxies.

Existing WEP experiments have sufficient sensitivity to use celestial sources to set interesting constraints on the parameters of a composition-dependent coupling between dark and ordinary matter. The null results of the elegant WEP test performed by Roll, Krotkov and Dicke [14] constrain any difference in the East-West component of the free fall rates of Au and Al towards the galactic center. The data of Table V of Ref. [14] provides (with a simple coordinate transformation) a limit (95% confidence level) of $\Delta a_W<1.9\times10^{-11}$ cm s^{-2} towards the galactic center. This in turn establishes a limit on any differential acceleration towards galactic dark matter of

$$\Delta a_W/[a_{\rm DM}\cos(\delta)]<3.7\times10^{-3}\,,$$

where the preferred value of $a_{\rm DM}$ was taken from Table I.

This limit can be used to constrain the extent to which an exotic long ranged interaction could contaminate the observed acceleration of the ordinary materials (stars and neutral hydrogen) that are used as tracers of their local potential. This requires a determination of the relevant "charges" of both the detector materials and the stellar material.

The differential charge $\Delta q/m$ for two detector materials can be expressed [5] as $\Delta q/m=(\Delta A/m)\cos(\psi)+(\Delta Z/m)\sin(\psi)$, where A and Z are atomic mass number and atomic number, respectively, and ψ is a mixing angle. This is the most general expression for the vector charge of ordinary neutral matter, and is a reasonable tree-level approximation for scalar interactions as well.

Any exotic infinite-ranged coupling between dark and ordinary matter (OM) is then a fraction f of their mutual interaction, where

$$f=a_{\rm exotic}/a_{\rm DM}<(\Delta a/a_{\rm DM})(q/\mu)_{\rm OM}/(\Delta q/\mu)_{\rm det}\,, \qquad (6)$$

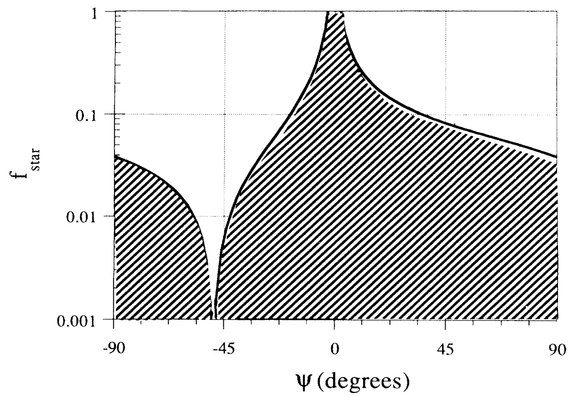

FIG. 2. Experimental constraints on exotic acceleration of stars towards galactic dark matter. The allowed region (95% C.L.) is shaded, where $f = a_{\text{exotic}}/a$ is the ratio of exotic to total acceleration towards galactic dark matter, and ψ characterizes the charge.

is a function of ψ, independent of the value of $\alpha(q/\mu)_{\text{DM}}$.

This expression was used to establish limits on the exotic fraction f of the acceleration of a star under the influence of galactic dark matter. The charge content of a solar-type star was evaluated in terms of the mixing parameter ψ to generate the limits shown in Fig. 2. The parameter values for neutral hydrogen look very similar.

For most of the f-ψ plane the existing data preclude the existence of any exotic long range interaction that would lead to erroneous conclusions regarding the distribution of dark matter. The assumption of the predominance of the gravitational interaction between ordinary and galactic dark matter is supported over much of the available parameter space. Only a coupling to a charge with $\psi \approx 0$ could give rise to an appreciable nongravitational acceleration that is consistent with the limits from Roll, Krotkov, and Dicke [14]. Using other detector material pairs would allow (with a modest improvement in the performance of existing experiments) this region to be probed.

Unfortunately exploring any exotic coupling to the dark matter that dominates clusters of galaxies must await significant improvements in the resolution of WEP experiments. Achieving the requisite sensitivity is of interest since (i) there is no guarantee that cluster dark matter is of the same composition as our dark galactic halo, and (ii) it would probe for exotic interactions over a different length scale.

In summary, laboratory experiments support the hypothesis that gravity is the only long ranged interaction between ordinary and dark matter.

I have enjoyed discussions with E. Adelberger, G. Bothun, K. Cook, J. Frieman, K. Griest, C. Gwinn, C. Hogan, and the participants in the Moriond Workshop (where I first presented this material). I am grateful for their insightful suggestions and comments. This work was supported in part by the NSF Office of National Science and Technology Centers, under cooperative agreement AST-8809616.

[1] V. Trimble, Annu. Rev. Astron. Astrophys. **25**, 425 (1987).
[2] S. Tremaine, Phys. Today **45**, No. 2, 28 (1992).
[3] A. Tyson, Phys. Today **45**, No. 6, 24 (1992).
[4] J. R. Primack, D. Seckel, and B. Sadoulet, Annu. Rev. Nucl. Part. Sci. **38**, 751 (1988).
[5] E. G. Adelberger, B. R. Heckel, C. W. Stubbs, and W. F. Rogers, Annu. Rev. Nucl. Part. Sci. **41**, 269 (1991). See also C. Will, *Theory and Experiment in Gravitational Physics* (Cambridge Univ. Press, Cambridge, 1981).
[6] Y. M. Cho, Phys. Rev. Lett. **68**, 3133 (1992).
[7] An important distinction should be drawn between the possibility discussed here (an exotic coupling between dark and ordinary matter) and attempts to resolve the "missing force" problem by considering a breakdown either in the law of gravitation over large distances or in Newtonian dynamics at low accelerations, without appealing to unseen matter. Both of these suggestions appear to be in conflict with observation. See R. H. Saunders, Mon. Not. Roy. Astron. Soc. **223**, 539 (1986); and G. Lake, J. Astrophys. **345**, L17 (1989).
[8] J. A. Frieman and B. Gradwohl, Phys. Rev. Lett. **67**, 2926 (1991); also B. Gradwohl and J. A. Frieman, Astrophys. J. **398**, 407 (1992).
[9] E. G. Adelberger, C. W. Stubbs, B. R. Heckel, Y. Su, H. E. Swanson, G. Smith, J. Gundlach, and W. F. Rogers, Phys. Rev. D **42**, 3267 (1990).
[10] G. Smith, E. G. Adelberger, B. R. Heckel, and Y. Su, following Letter, Phys. Rev. Lett. **70**, 123 (1993).
[11] K. Griest and C. Hogan both suggested that extragalactic sources be considered.
[12] J. Moffatt, Phys. Rev. D **40**, 2499 (1989).
[13] G. Bothun *et al.*, Astrophys. J. **388**, 253 (1992), and references therein.
[14] P. G. Roll, R. Krotkov, and R. H. Dicke, Ann. Phys. (N.Y.) **26**, 442 (1964).