Quintessence and the Rest of the World: Suppressing Long-Range Interactions

Sean M. Carroll*
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
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A nearly massless, slowly rolling scalar field ϕ may provide most of the energy density of the current Universe. One potential difficulty with this idea is that couplings to ordinary matter should lead to observable long-range forces and time dependence of the constants of nature. I explore the possibility that an approximate global symmetry serves to suppress such couplings even further. Such a symmetry would allow a coupling of ϕ to the pseudoscalar $F_{\mu\nu}\widetilde{F}^{\mu\nu}$ of electromagnetism, which would rotate the polarization state of radiation from distant sources. This effect is fairly well constrained, but it is conceivable that future improvements could lead to a detection of a cosmological scalar field. [S0031-9007(98)07343-8]

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Recently a number of pieces of evidence, especially studies of the Hubble diagram for type-Ia supernovae [1], have lent support to the idea that the Universe is dominated by a smooth component with an effective negative pressure, leading to an accelerating expansion. While the most straightforward candidate for such a component is the cosmological constant [2], a plausible alternative is dynamical vacuum energy, or "quintessence" [3,4].

A number of models for quintessence have been put forward, the most popular of which invoke a scalar field in a very shallow potential, which until recently was overdamped in its evolution by the expansion of the Universe. For generic potentials the requisite shallowness implies that excitations of the field are nearly massless, $m_\phi \equiv \sqrt{V''(\phi)/2} \leq H_0 \sim 10^{-33}$ eV. To provide the necessary energy density, the present value of the potential must be approximately the closure density of the Universe, $V(\phi_0) \sim (10^{-3}\ \mathrm{eV})^4$, so the field itself will typically be of the order of $\phi_0 \sim 10^{18}$ GeV $\sim M_{\mathrm{Pl}} = (8\pi G)^{-1/2}$, where M_{Pl} is the reduced Planck mass. (These estimates can be dramatically altered in models with more complicated dynamics [5].)

The exchange of very light fields gives rise to forces of very long range, so it is interesting to consider the direct interaction of the quintessence field ϕ to ordinary matter. Although it is traditional to neglect (or set to zero) the couplings of this light scalar to the standard model, we expect that our low-energy world is described by an effective field theory obtained by integrating out degrees of freedom with momenta larger than some mass scale M, in which case it is appropriate to include nonrenormalizable interactions suppressed by appropriate inverse powers of M. For example, ϕ can couple to standard-model fields via interactions of the form

$$\beta_i \frac{\phi}{M} \mathcal{L}_i \,, \tag{1}$$

where β_i is a dimensionless coupling and $\mathcal{L}_i$ is any gauge-invariant dimension-four operator, such as $F_{\mu\nu}F^{\mu\nu}$ or $i\bar{\psi}\gamma^\mu D_\mu \psi$. In the absence of detailed knowledge about the structure of the theory at high energies, the couplings β_i are expected to be of order unity.

The mass parameter M, meanwhile, represents the energy scale characterizing the phenomena which we have integrated out to obtain the low-energy description. We cannot specify it with precision, but it should not be higher than the scale where quantum gravity becomes relevant—not only may there be new particles at this energy, but exotic effects such as wormholes and virtual black holes become relevant [6]. With this in mind, the limits in this paper will be quoted in terms of the reduced Planck mass $M_{\mathrm{Pl}} \sim 10^{18}$ GeV, but cases could be made for values as high as the traditional Planck mass $G^{-1/2} \sim 10^{19}$ GeV or as low as the unification scale $M_{\mathrm{unif}} \sim 10^{16}$ GeV (for example, in the phenomenologically attractive regime of M theory compactified on an interval [7]).

The scalar force mediated by ϕ will not obey the equivalence principle (which is compatible only with forces mediated by spin-two fields), and hence is constrained by Eötvös-type experiments. Su *et al.* [8] have found that the differential acceleration of various test bodies, in the direction of the sun, is less than 10^{-12} times the strength of gravity. Such limits can be translated into constraints on the dimensionless couplings β_i; for example, we may calculate the charge on a test body due to a coupling $\beta_{G^2}(\phi/M)\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu})$, where $G_{\mu\nu}$ is the field strength tensor for QCD (cf. [9]). Although it is difficult to compute QCD matrix elements to high precision, the Su *et al.* results can be used to place a conservative upper limit

$$|\beta_{G^2}| \leq 10^{-4}\left(\frac{M}{M_{\mathrm{Pl}}}\right). \tag{2}$$

Similar considerations constrain other couplings, although typically not quite as well (see, e.g., [10]).

A related phenomenon is the time variation of the constants of nature. For the dynamical nature of ϕ to be relevant today, we expect a change in ϕ of the order of M_{Pl} over cosmological time scales $t_0 \sim H_0^{-1}$.

In that case, a coupling such as $\beta_{F^2}(\phi/M)F_{\mu\nu}F^{\mu\nu}$ will lead to evolution of the fine structure constant α. Various observations constrain such variation. For example, isotopic abundances in the Oklo natural reactor imply that $|\dot{\alpha}/\alpha| < 10^{-15}$ yr^{-1} over the past 2×10^9 yr [11]; this leads to the limit

$$|\beta_{F^2}| \leq 10^{-6}\left(\frac{MH_0}{\langle\dot{\phi}\rangle}\right), \tag{3}$$

where $\langle\dot{\phi}\rangle$ is the average rate of change of ϕ in the past 2×10^9 yr. [There has also been a claimed detection of a difference between the fine structure constant today and at a redshift $z \geq 1$ [12]; given the preliminary nature of the claimed detection, it is safest to rely on the limit (3).] Again, changes in other couplings are also constrained.

There is clearly good evidence against the existence of a nearly massless scalar field coupled to the standard model via nonrenormalizable interactions with strength of the order of $1/M_{\mathrm{Pl}}$. It would be premature, however, to conclude that the idea of quintessence is ruled out, as we may consider imposing symmetries which prevent the couplings considered thus far. An exact continuous symmetry of the form $\phi \rightarrow \phi + \text{const}$ is clearly not appropriate, as it would not allow for a nontrivial potential $V(\phi)$. An alternative possibility is a discrete symmetry, for example, of the form $\phi \rightarrow -\phi$; this would forbid terms linear in ϕ and could arise from spontaneously broken gauge symmetries [13]. However, in the case at hand, discrete symmetries appear to be ineffective, as they themselves are spontaneously broken. (The field ϕ is expected to be displaced from the fixed point of the symmetry, so an effective linear term will be unsuppressed.)

We are therefore left with the possibility of approximate global symmetries of the form $\phi \rightarrow \phi + \text{const}$. Indeed, such symmetries are invoked in pseudo-Goldstone boson (PGB) models of quintessence [4], as an explanation for the naturalness of the small mass m_ϕ: in the limit as the symmetry is exact, this mass goes to zero. This same effect could explain the small values of the dimensionless couplings β_i. In this sense, the PGB models are more likely than those based (for example) on moduli fields; in the latter set of theories, the scalar field represents a flat direction which typically does not generate any symmetry with a potential generated solely by nonperturbative effects. There is no apparent reason for the β_i's to be small in such models.

An objection to this scenario is that quantum-gravity effects do not respect global symmetries. It is known, for example, that there are no unbroken global symmetries in string theory [14]. Furthermore, the induced interactions mentioned above from wormholes and virtual black holes are constrained solely by gauge symmetries [6]. These symmetry-breaking effects have been suggested as problems for axion and texture theories [15].

Nevertheless, although our current understanding of quantum gravity and string theory leads us to believe that global symmetries are generically violated, it is insufficient to say with confidence that the resulting violations are in some sense large (in our context, that the parameters β_i are of order unity). For example, although string theory has no exact global symmetries, it does have axionlike fields with an approximate Peccei-Quinn symmetry. It may also be the case that pure quantum-gravity effects are nonperturbative and suppressed by e^{-S}, where the action S can be large in specific models. Kallosh *et al.* investigated this possibility in the context of axions in the presence of wormholes [16]. They found that the action was sensitively dependent on the structure of spacetime on small scales, and there could be sufficient suppression of global-symmetry violating effects to salvage axions as a solution to the strong CP problem (which is a much greater suppression than that necessary to satisfy the bounds on the β_i's above).

Evidently it is hard to estimate reliably the degree to which an approximate global symmetry can consistently be invoked in a world with gravity. Given the tentative character of our current understanding, we should take seriously the possibility that the quintessence field has avoided direct detection because the couplings considered above are suppressed by such a symmetry.

An important consequence of this viewpoint is that interactions which are invariant under $\phi \rightarrow \phi + \text{const}$—that is, derivative couplings of ϕ—should be present with couplings β_i of order unity. The derivative term of lowest dimension that could multiply an arbitrary gauge-invariant scalar operator would be $g^{\mu\nu}\nabla_\mu\nabla_\nu\phi$; however, we would expect this dimension-three term to be divided by M^3 and hence lead to negligible effects. The other possibility is to couple ϕ/M to a total derivative, which after integration by parts is equivalent to a coupling to $\partial_\mu\phi$. The only allowed term in the standard model is

$$\beta_{F\tilde{F}}\frac{\phi}{M}F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{\beta_{F\tilde{F}}}{M}[-(\partial_\mu\phi)K^\mu + \partial_\mu(\phi K^\mu)], \tag{4}$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor, $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ is its dual, and $K^\mu = 2A_\nu\tilde{F}^{\mu\nu}$. The divergence term on the right-hand side of (4) contributes a surface term to the action, which vanishes for fields which fall off at infinity. Therefore this interaction does represent a derivative coupling, and respects the symmetry $\phi \rightarrow \phi + \text{const}$.

Such a coupling can lead to potentially observable effects. Since $F_{\mu\nu}\tilde{F}^{\mu\nu}$ is a pseudoscalar quantity, it does not accumulate coherently in a macroscopic test body and hence does not give rise to appreciable long-range forces (although one can consider tests using polarized bodies [17]). However, a spatially homogeneous but slowly varying ϕ field would rotate the direction of polarization of light from distant radio sources [18]. The dispersion relation for electromagnetic radiation in the presence of a time-dependent ϕ becomes $\omega^2 = k^2 \pm (\beta_{F\tilde{F}}/M)\dot{\phi}k$, where $\pm$ refer to right- and left-handed circularly polarized modes, respectively. If we define χ to be the angle between some fiducial direction in the plane of the sky and the polarization vector from an astrophysical source, then in the WKB limit where the wavelength of the radiation is much less than that of ϕ, the difference in group velocity for the two modes leads to a rotation $\Delta\chi = (\beta_{F\tilde{F}}/M)\Delta\phi$.

Such a rotation is potentially observable, as distant radio galaxies and quasars often have a well-defined relationship between their luminosity structure and polarization structure [19]. In the wake of a claim that a dipole pattern of rotations (in contrast to the monopole pattern expected from a homogeneous scalar field) was present in existing data [20], it was pointed out that more recent observations provide a stringent upper limit on any such effect [21,22]. It is a straightforward exercise to use these same data to place upper limits on the magnitude of a direction-independent pattern of rotations. As an example, Fig. 1 shows the data given by Leahy [21] for $\Delta\chi$, plotted as a function of redshift.

Simply taking the mean value all of the points (for which the minimum redshift is $z = 0.425$) yield $\langle\Delta\chi\rangle = -0.6° \pm 1.5°$. This implies a bound

$$|\beta_{F\tilde{F}}| \leq 3 \times 10^{-2}\left(\frac{M}{|\Delta\phi|}\right), \tag{5}$$

where $\Delta\phi$ is the change in ϕ between a redshift $z = 0.425$ and today. From the figure, it is evident that the single source 3C 9 at a redshift $z = 2.012$ (originally analyzed in [23]), with $\Delta\chi = 2° \pm 3°$, provides an interesting limit on any substantial rotation at high redshifts.

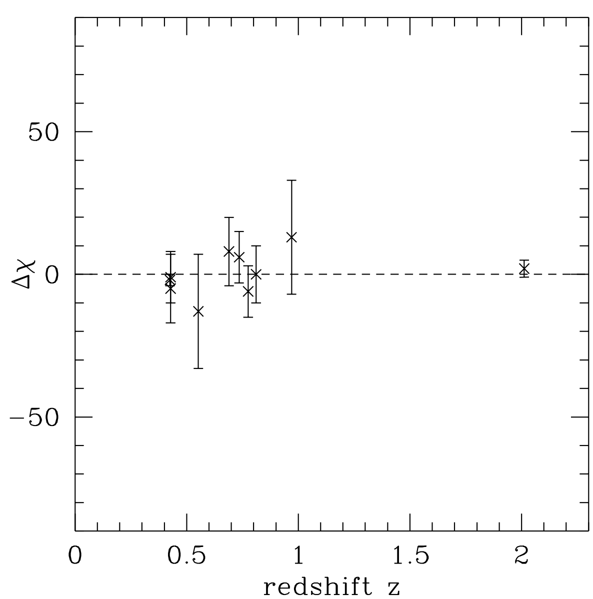

FIG. 1. Rotation of polarization vector vs redshift.

Does Eq. (5) constitute a good limit? We expect $\Delta\phi$ to be of the order of $M_{\rm Pl}$, so the factor $M/|\Delta\phi|$ is likely to be less than or of order unity. However, while 3×10^{-2} is less than 1, it is not remarkably less; we might imagine that dimensionless constants conspire to make $\beta_{F\tilde{F}}$ naturally smaller than this value even without suppression by some symmetry. For example, couplings of the form (4) can arise through triangle graphs in ordinary field theories (i.e., even disregarding the possibility of exotic quantum gravitational effects); such graphs lead to $\beta_{F\tilde{F}} = N\alpha/4\pi$, where α is the fine structure constant and N is a dimensionless factor which depends on the field content of the model. Since $\alpha/4\pi \sim 6 \times 10^{-4}$, it is by no means implausible that the interaction under consideration could exist but has evaded detection thus far. This raises the exciting possibility that improvements in the limits from radio galaxy polarization measurements could lead to a detection of quintessence. Since the relevant observed quantity is an angle, it is hard to imagine significant contamination by systematic errors, so the observation of a large number of sources can be expected to improve these limits substantially.

Unfortunately, the existence of a potentially detectable coupling of the form (4) can be avoided in certain models. This follows from noting that the analogous term for the strong interactions, $\beta_{G\tilde{G}}(\phi/M){\rm Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu})$, is not invariant under $\phi \to \phi + {\rm const}$ due to the existence of topologically nontrivial field configurations. The surface term which could be neglected in electromagnetism would receive contributions from QCD instantons, leading to a mass for ϕ proportional to $\beta_{G\tilde{G}}(\Lambda^2_{\rm QCD}/M)$ (just as for the QCD axion). As this mass is likely to be much larger than the desired value $m_\phi \sim 10^{-33}$ eV, it is incompatible with the desired properties of quintessence. In a grand unified model for which both electromagnetism and the strong interactions derive from a single simple gauge group, any gauge-singlet field which couples to $F_{\mu\nu}\tilde{F}^{\mu\nu}$ should also couple to ${\rm Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu})$ [24]. In the minimal SU(5) grand unified theory, for example, the appropriate lowest-dimension gauge-invariant operator to which ϕ could couple is ${\rm Tr}(V_{\mu\nu}\tilde{V}^{\mu\nu})$, where $V_{\mu\nu}$ is the SU(5) field strength. After spontaneous symmetry breakdown this term includes a unique linear combination ${\rm Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu}) + \frac{4}{3}F_{\mu\nu}\tilde{F}^{\mu\nu}$ with which ϕ could interact. Since the coupling to the QCD term must be suppressed, the electromagnetic coupling will be suppressed as well.

This argument undoubtedly diminishes the aura of inevitability surrounding a coupling of the form (4), but by no means precludes its existence. A simple way out is to imagine that SU(3) and U(1) are not unified in a simple gauge group, in which case there is no necessary relationship between the QCD and electromagnetic couplings. Such a scenario may be natural in string theory, where low-energy gauge fields come from compactification as well as the original gauge symmetry in higher dimensions. Another way is to include a coupling of ϕ to higher-dimensional gauge-invariant operators through interactions such as $(\phi/M^2)\mathrm{Tr}(\Sigma V_{\mu\nu}\tilde{V}^{\mu\nu})$, where Σ is the adjoint Higgs which breaks SU(5). If the mass scale v is comparable to M, such an interaction could cancel the QCD term from $\mathrm{Tr}(V_{\mu\nu}\tilde{V}^{\mu\nu})$, leaving an unsuppressed coupling to electromagnetism. However, the interaction $(\phi/M^2)\mathrm{Tr}(\Sigma V_{\mu\nu}\tilde{V}^{\mu\nu})$ is not invariant under $\phi \rightarrow \phi +$ const, so it may be noticeably suppressed.

In conclusion, the absence of observable interactions of quintessence with the fields of the standard model implies the existence of a symmetry which suppresses such couplings. Such a symmetry leaves open the possibility of a coupling to electromagnetism, which is potentially observable in polarization studies of distant radio sources. Such a coupling is not inevitable, however, so we may have to rely on conventional cosmological tests to determine whether slowly rolling scalar fields play an important role in the dynamics of the present Universe.

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*Email address: carroll@itp.ucsb.edu

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