Cosmological Implications of the Fifth Force

Yasunori Fujii
Institute of Physics, University of Tokyo-Komaba
Meguro-ku, Tokyo, 153 Japan

Abstract

A brief review is given on the present status of the "fifth force", followed by the study of its cosmological consequences. If the force is indeed mediated by a massive vector field, we expect a period $t \lesssim 10^{-13}$sec in which the universe cooled down like $T \sim t^{-1}$.

I begin with giving a phenomenological definition of what is called the 5-th force. The 5-th force if there is any is characterized by the following three properties:

(i) The coupling strength nearly comparable with or somewhat weaker than the ordinary gravitational interaction.

(ii) Finite force-range somewhere between cm and km.

(iii) Composition-dependence, unlike Einstein's gravity.

So the static potential between two point masses may be put into the form:

$$V_{ij}(r) = -G_{\infty}\frac{m_i m_j}{r}(1+\alpha_{ij}e^{-r/\lambda}), \quad |\alpha_{ij}| \lesssim 1, \quad \mathrm{cm} \lesssim \lambda \lesssim \mathrm{km}.$$

The Yukawa potential represents the 5-th force. It arises from an exchange of a particle of mass $\mu = \lambda^{-1}$, with the spin probably 0 or 1, and the coupling constant f. It is simply unlikely that the strength

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is exactly proportional to the total mass of a system.

The property (i) translates into $f^2 \lesssim 10^{-38}$. Why is the coupling so weak? Is the strength comparable with gravity simply a coincidence? I have my own reason why I expect the coupling of this weak. The coupling constant $f \sim 10^{-19}$ is precisely a number that gives a mass scale of typical elementary particles (masses of quarks, leptons, or W, Z bosons or QCD mass scale, electroweak mass scale and so on) in terms of a product $m \sim fM_{P\ell}$. As a crude estimate I choose $m \sim$ GeV, allowing a few orders of latitudes in both directions. In fact one can think of a scalar field theory in which the vacuum expectation value is $\sim M_{P\ell}$ that generates particle masses through the coupling constant f. Also the mass μ is simply given by $\mu \sim fm \sim f^2 M_{P\ell}$ and hence yielding a value $\sim 10^{-19}$GeV $\sim 10^{-10}$eV, or $\lambda \sim 10^5$cm. These were the motivations on which I suggested the possible presence of a force of this kind in the early 70's.[1] In place of a scalar field theory one can also invent a vector field theory based on Kaluza-Klein theory.[2] In any case the 5-th force will have something to do with the hierarchy problem, namely the presence of mass scales of low-mass elementary particles in unified theories characterized by a huge mass $M_{P\ell}$. However, other types of theories have also been proposed.

Now what about the experiments? Not so many are available yet. Most remarkable was a geophysical experiment due to Stacey and his group.[3] By measuring the gravity gradient in a mine shaft they claimed to discover an anomaly which can be explained by an additional Yukawa potential with the parameters $\alpha = -0.0075 \pm 0.0035$ and $10\ \mathrm{m} \lesssim \lambda \lesssim 1000\ \mathrm{m}$. A negative α implies a repulsion. It is true that $\alpha = 0$ is only 2σ away, and also the result depends crucially on their estimate of the local average rock density which they determined to the accuracy 0.38%.

But this was the result that prompted Fischbach et al to publish their paper [4] entitled "Reanalysis of the Eötvös experiment." They claimed that the data shown in the original paper by Eötvös et al had revealed a non-null result which was consistent with the force discovered by Stacey. More specifically, they suggested the force due

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to a vector field coupled to the baryon number. After the dust settled, however, what is now widely accepted is the following: The Fischbach et al's reinterpretation of the Eötvös experiment is not consistent with Stacey et al's force. Also the original Eötvös experiment suffered most likely from many systematic errors due to unknown local mass distributions among others, and hence was not accurate enough to test the effect of the proposed force. It is as if the Baron had known precisely what the limitation of their experiment was and had not dared to say anything beyond that. Nevertheless, Fischbach et al left a strong impact by pointing out for the first time that the experiment of this importance had been left unimproved for so many years.

Naturally their work inspired experimenters to propose new ideas. So far two reports have been published. One is Thieberger's experiment [5] and the other is due to Stubbs et al.[6] Thieberger picked up a composition-dependent force which, arising from a cliff, acted to water and a hollow copper ball that floated in the water. The result can be interpreted in terms of α and λ which are consistent with those given by Stacey et al. On the other hand, Stubbs et al simply modernized Eötvös's torsion balance placed now on a slope. They compared forces acting to Be and Cu. They found nothing anomalous and put an upper bound of α which is an order smaller than Stacey et al's. One might suspect some systematic errors whose real nature is not yet known exactly. But I point out that the above conclusion of inconsistency is based on the assumption that the 5-th force couples exclusively to the baryon number. One may relax this assumption slightly to allow a coupling to the lepton number as well. A general analysis [7] shows that the three experiments and also the old Kreuzer experiment can be consistent with each other if the force couples to $\simeq(B - 0.2L)$ and the force-range λ is $\lesssim$ 50 m, though I cannot exclude λ $\lesssim$ 20m from these experiments. The overall coupling constant is estimated to be $f^2 \simeq 2.5\times10^{-41}$. I find that the 5-th force between two electrons separated within the force-range is then $\sim$ 530 times as large in magnitude as the Newtonian force; it is as if the electron mass were

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$\sim$ 12 MeV, though repulsive.

The forthcoming experiments include a free-fall experiment by Kuroda et al [8] who use a laser interferometer to measure the difference between accelerations of two falling objects.

Now I am going to discuss what implications the 5-th force would have in cosmology. Probably the first thing to do is to ask if the particles associated with this force field can be part of the dark matter. However, the mass is so small $\sim$ peV, or equivalently 10^{-5}K that it is just hopeless to expect this. Does it decay giving observable effects? It may decay into a number of photons or neutrinos if the latters are sufficiently light. But in any case the lifetime $\sim$ $(f^2\mu)^{-1}$ would be longer than 10^{18}yr. It is virtually stable and completely penetrable. It may be produced as a decay product of other particles. But again the partial decay rate would be prohibitively small. One might still concern if the particles are produced by Compton-like processes inside steller objects and carry away energies too rapidly, in much the same way as axions or Higgs particles have been suspected to do. This might be particularly important if leptons can contribute. The rate of the energy loss was calculated and compared with the energy generation rate of main-sequence stars and red-giants.[9] The obtained upper bounds for f^2 is $10^{-26} \sim 10^{-28}$, much larger than the expected value $\lesssim 10^{-41}$. The 5-th force particle is highly elusive.

The effect to the steller structure is found to be rather moderate.[10] It also seems quite unlikely that the 5-th force plays a major role in strange quark nuggets.

I now turn to a more fundamental question how a finite-range force affects the way the universe expands. I first find that, since the coupling strength of the 5-th force is almost comparable with gravity, the effect would be significant only if the horizon size of the universe is as small as the force-range. And it was around $t \sim 10^{-2}$sec when the horizon was about 100m large. This is rather close to $t \sim$ 10^{-4}sec when the quark-hadron transition is supposed to have taken place. This transition is characterized by the QCD mass scale $\sim$ 100

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MeV, or roughly close to $\sim$ GeV, and one can easily convince oneself that the above near agreement is not a coincidence.

I next emphasize that the 5-th force is simply part of the matter system in general relativity. Consequently Einstein's equation remains unchanged. The only change one expects to occur is in the equation of state. And probably the first reasonable thing to do is to appeal to the mean field approximation.[11] I consider a system of an abelian massive gauge field that couples to the baryon number of Dirac fields for the quarks, for example. The result is simple: The energy density ε is given by

$$\varepsilon \sim Aa^{-6} + \text{quark term}, \quad A = (f^2/2\pi^2\mu^2)M^2,$$

where f is the gauge coupling constant and μ is the mass of the gauge field, M the quark mass, and a(t) is the scale factor of the universe of k = 0, for simplicity. The quark term is the usual Fermi energy but calculated in a fully relativistic manner. So in the low-density limit the quark term dominates ε, and we get the dust behavior $\varepsilon \sim a^{-3}$ and hence $a(t) \sim t^{2/3}$. In the high-density limit, on the other hand, the extra contribution from the vector field is much larger, giving $a(t) \sim t^{1/3}$. This corresponds to the equation of state $p = \varepsilon$.[12] So one of the qualitative features arising from the 5-th force is to make the cosmic fluid extremely stiff at the very early stage of the universe. But the expansion $a(t) \sim t^{1/3}$ leads to $T(t) \sim t^{-1}$ and differs dangerously from the conventional radiation-dominated universe, $a(t) \sim t^{1/2}$ and $T(t) \sim t^{-1/2}$, based on which most of the cosmological scenarios have been founded. If one goes back to the past, the temperature would go up much faster. Now the question is how strong the effect would be.

If I use the values $f^2 \sim 10^{-42}$, $\mu \sim 10^{-18}$GeV ($\lambda \sim 100$ m), $M \sim 10$ MeV, then I get $A \sim 10^{-11}$, which seems pretty small. However, going back to the past, namely to a smaller a(t), one will eventually hit the region in which the A term dominates no matter how small the constant A might be. If the A term were absent, the relativistic quark term would have given a standard behavior; $a(t) \sim t^{1/2}$ for $t \to 0$, while $a(t) \sim t^{2/3}$ for $t \to \infty$. The transition between these two behaviors occurs at $t \sim 10^{-2}$sec if one chooses $M \sim 10$ MeV. If one has a nonzero A, the scale factor would deviate from this standard behavior approximately at a critical time t_1; before t_1 one has $a(t) \sim t^{1/3}$. I find $t_1/(10^{-2}\text{sec}) \sim A$. The above result $A \sim 10^{-11}$ implies $t_1 \sim 10^{-13}$sec, which is barely before the epoch of the electroweak phase transition, but still more than 20 orders later than the epoch of the GUT transition. One would face a situation that for a considerable part of time after the inflation the universe would have cooled down like $T \sim t^{-1}$, much more rapidly than usually expected. This might be a problem yet to be studied. At this moment I only raise some questions that have to be answered before going into the full details.

First, I worry whether the mean field approximation is justified or not when the horizon size becomes smaller than the force-range. As was pointed out,[12] the calculation should go over to that of a massless vector field if the size of the system is smaller than the force-range. But it is not clear if the horizon size corresponds exactly to the system size in the conventional sense.

Second, it is interesting to notice that the mass μ enters only through a combination f^2/μ^2, which is not always small only because f is very small. In fact the smallness of $f^2 \sim 10^{-42}$ has been largely offset by the smallness of $\mu^2 \sim 10^{-36}\text{GeV}^2$. Suppose we have another vector field that couples rather strongly. With $g^2 \sim 10^{-2}$, for example, and a mass $m \sim 100$ GeV, the ratio $g^2/m^2 \sim 10^{-6}\text{GeV}^{-2}$ nearly agrees with the above f^2/μ^2. In this sense the effect of the 5-th force may compete with other strong short-range forces. But this competition might be complicated if the result depends on the relations between the horizon size and the force-range.

It might be necessary to consider other microscopic forces as well, particularly a strong attraction. If one can simulate the effects by a scalar field, one can again use the simple mean field method. It turns out that at the high-density limit the scalar contribution will never win the vector contribution, and consequently might be relatively unimportant.

Finally I add a comment that the 5-th force field, if it is in fact a vector field, can be the one which plays a role in preventing the baryon number conservation from being destroyed by primordial black holes.[13]

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References

[1] Y. Fujii, Nature Phys. Sci. 234(1971)5; Phys. Rev. D9(1974) 874; Gen. Rel. Grav. 13(1981)1147.

[2] Y. Fujii, UT-Komaba 86-12(1986).

[3] S.C. Holding et al, Phys. Rev. D33(1986)3487; F.D. Stacey, et al, Rev. Mod. Phys. 59(1987)157.

[4] E. Fischbach et al, Phys. Rev. Lett. 56(1986)3.

[5] P. Thieberger, Phys. Rev. Lett. 58(1987)1066.

[6] C.W. Stubbs et al, Phys. Rev. Lett. 58(1987)1070.

[7] Y. Fujii, UT-Komaba 87-5(1987); K. Hayashi and T. Shirafuji, Kitasato 87-3 Saitama TH-87-4(1987). See, however, E.G. Adelberger et al, University of Washington preprint; P.E. Boynton et al, University of Washington preprint.

[8] K. Kuroda et al, Proc. 22nd Recontre de Moriond, 1987. See also T.M. Niebauer et al, Joint Institute for Laboratory Astrophysics preprint.

[9] J.A. Grifols and E. Masso, Phys. Lett. 173B(1986)237.

[10] E.N. Glass and G. Szamosi, Phys. Rev. D35(1987)1205.

[11] J.D. Walecka, Ann. Phys. 83(1974)491.

[12] Y.B. Zel'dovich, Soviet Phys. JETP 14(1962)1143.

[13] B. Carter, Phys. Rev. Lett. 33(1974)558; B.J. Carr, Astrophys. J. 206(1976)8.