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MYSTERIOUS ANTI-GRAVITY AND DARK-ESSENCE

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The need of anti-gravity and dark-essence in cosmology is the greatest scientific mystery in the 21st century. This paper presents a personal view of several relevant issues, including the long-standing cosmological constant problem, the newly emerging dark radiation issue, and the basic stability issue of the general-relativity limit in modified gravity.

Keywords: Dark energy; modified gravity; dark radiation; cosmological constant problem.

1. Introduction

Cosmology is a science of the evolution, the structures and the compositions of the universe. It has recently become an experimental science driven by astrophysical observations. In addition to observations, describing and understanding our universe require an initial condition of the universe and a theory of fundamental fields/particles and interactions, such as general relativity for gravity and the standard model of particle physics for the others.

The modern version of the cosmic story told by observations is interesting and surprising. It involves the following unexpected characters.

- **Special initial condition.** The cosmic background was rather flat, homogeneous and isotropic; the primordial perturbations were rather adiabatic, scale invariant and Gaussian. The inflation scenario is doing a great job in giving such initial condition.
- **Extra gravity.** The extra attractive gravity is needed to help the cosmic structure formation. A favorite scenario of extra gravity is invoking dark matter.
- **Anti-gravity.** The repulsive gravity is needed to drive the accelerating expansion of the present universe. It invites the consideration of the energy source of anti-gravity dubbed "dark energy" and gives strong motivation for modifying gravity.

In the scenario with dark matter and dark energy, the two unknown dark components contribute 95% of the energy of the present universe, presenting us the greatest enigma in fundamental science at all times.

Anti-gravity is particularly mysterious. It may be caused by dark energy or modified gravity. The simplest candidate of dark energy is a positive cosmological constant. It was firstly introduced by Einstein and later abandoned as his biggest blunder. It is so far so consistent with the observational results and therefore has been widely considered. Nevertheless, the smallness of the cosmological constant and the coincidence problem (why the cosmic expansion just starts to accelerate recently or why the present matter and dark energy densities are comparable) in this model require fine-tuning and make this model look unnatural. The fine-tuning stems from the constant nature of the cosmological constant. To avoid the fine-tuning, a necessary condition is the time variation of the dark energy density. This invites the consideration of a scalar field as a simple phenomenological realization of dark energy with a time-varying energy density.

As to modified gravity, although there is no evidence of such modification, the above three surprising characters give strong motivation for modifying gravity. Although general relativity (GR) so far can pass all the local tests, it is still open for the cosmological tests. As an essential requirement from the success of GR in passing the local tests, in any viable modified gravity model the GR limit must exist and be stable, not just at the action level, but particularly at the solution level.

In addition to dark matter and dark energy, the recent cosmic microwave background (CMB) observations suggest one more dark component called "dark radiation" that represents the additional relativistic degree(s) of freedom. It is expected to give important effects in CMB and in Big-Bang nucleosynthesis (BBN).

The remainder of this paper will provide a simple personal view of three relevant issues: the cosmological constant problem, dark radiation, and the stability of the GR limit in modified gravity.

2. Cosmological Constant Problem

Observations have given an upper bound to the energy density of a cosmological constant: $\rho_\Lambda \lesssim 3 \times 10^{-11}$ eV^4, i.e. its energy scale $\lesssim 10^{-3}$ eV. This upper bound is much smaller than the expected contribution from the quantum vacuum, leading to the long-standing, notorious cosmological constant problem.[1]

In the framework of quantum field theory the vacuum energy can contribute to dark energy of the same form as a cosmological constant. Its size may be designated by the high-energy cut-off scale of the quantum field theory that, either the Planck scale, the electroweak scale or some other scale involved in the standard model of particle physics, is much larger than 10^{-3} eV. One may think this problem unrealistic because the physics, particularly that of gravity, around the cut-off scale is not well tested and the correct way of assessing the gravitational effect of the vacuum energy around the cut-off scale is not clear. Let us put aside the unclear high-energy cut-off scale and consider the low-energy scales such as the eV scale, i.e. the micron length scale. Even the quantum fluctuations of the eV scale can provide too large vacuum energy and ruin our universe, while the physics at such scale is well known and has been tested thoroughly. That tells the genuineness and the severeness of the cosmological constant problem.

One naive way of surviving the vacuum energy crisis is to compensate the vacuum energy with a bare cosmological constant that might be introduced at the very beginning of the universe. The size of the bare cosmological constant needs to be delicately chosen to balance the vacuum energy of quantum fields. Another naive way is to make the vacuum energies of different quantum fields cancel each other via carefully choosing the field contents and finely tuning the very details of the field theory. These two naive ways are so fine-tuning that one can hardly believe they can be a part of the grand design in nature.

Even if such fine-tuning is invoked at the beginning of the universe, the later phase transition(s) associated with spontaneous symmetry breaking (SSB), such as the electroweak phase transition, would ruin the initial fine-tuning. During a SSB phase transition, the vacuum energy may drop by an amount on the energy scale of the phase transition (e.g. ~ 300 MeV for the electroweak phase transition), thereby ruining the perfect cancellation in the initial design. If one insists to invoke the brute-force cancellation, the design would be as tedious as the following sentence: It is necessary to foresee all possible SSB phase transitions and know the very details of the vacuum energy change during each of them, as detailed as 10^{-3} eV at least, and then make the earlier cancellation imperfect, with the energy deficit on the scale of the phase transition and with the precision 10^{-3} eV or better.

A good job of solving the vacuum energy crisis should not be as tedious as the brute-force cancellation. A satisfactory solution to the cosmological constant problem is yet to be found and the appropriate scenario for the solution is also not yet clear. The final solution may be associated with the reconciliation between gravity and quantum, while such ultimate paradigm is still in the mist.

3. Dark Radiation

Dark radiation is the additional relativistic degree(s) of freedom suggested by the recent CMB observations. It may be the only surprise so far in the 21st century in cosmology. In the 20th century there were several salient surprises in cosmology, such as the cosmic acceleration, dark energy, dark matter, etc. In contrast, in the 21st century the ΛCDM model fits the observational results so far so well, except the observational indication of dark radiation.

Conventionally cosmologists invoke the following fitting formula of the radiation energy density to fit data.

$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma\,. \tag{1}$$

Here $N_{\rm eff}$ can be regarded as the effective number of the neutrino species, i.e. the number of the degrees of freedom of the relativistic neutrino-like particles (weakly interacting or even non-interacting fermions), or, phenomenologically, it parametrizes the energy density of the relativistic degrees of freedom additional to the CMB photons. Radiation is important in the early universe. With different amount of radiation, i.e. with different $N_{\rm eff}$, the early universe has different looks, particularly regarding the CMB spectra and the BBN prediction of the light element abundance such as the ^{4}He abundance. Accordingly, the CMB and the BBN-related observations can give essential constraints on $N_{\rm eff}$.

In the standard model of particle physics the contribution from neutrinos to $N_{\rm eff}$ is close to 3. In contrast, the recent CMB observations, together with the observations of large-scale structures and the measurements of the Hubble parameter, suggest 1 or 2 more degrees of freedom, i.e. $N_{\rm eff} = 4$–5, and the standard model value 3 is 2σ away from the best fit (see Refs. 2–4). As to BBN, the BBN theory with $N_{\rm eff} = 4$–5 is consistent with the observational results of the light element abundance (see Ref. 5). In the future the Planck observation of CMB is expected to give more precise information about $N_{\rm eff}$ with the precision $\delta N_{\rm eff} \simeq 0.26$.

Thus, in addition to dark matter and dark energy that contribute 95% of the energy density of the present universe, we may need to invoke one more dark component, dark radiation, that changes the early-time expansion history, thereby helping to explain the CMB and BBN data related to the early universe. Although dark radiation and dark energy provide very different functions, they provide the functions at two different epochs: one modifies the early-time expansion history and the other drives the late-time acceleration. Therefore, it is possible to combine them, i.e. with one single energy source that behaves like dark radiation at early times and like dark energy at late times. In this scenario the dark energy information may also be encoded in the early-time events such as CMB and BBN, in addition to the late-time events such as type Ia supernovae and structure formation. This distinct feature makes this possibility particularly worthy of further investigations.

4. Stability of the GR Limit in Modified Gravity

Since GR passes all the local tests, a viable model of modified gravity should behave very similar to GR at the local scales, particularly in the solar system. In addition, since the standard cosmology based on GR fits the observational results about CMB and BBN so far so well, people expect a viable modified gravity model should mimic GR at the early times relevant to CMB and BBN. Thus, the GR limit should exist and should be stable in modified gravity at the local scales and at the early times.

People may explore the existence of the GR limit at the action level. However, this is not good enough. The more essential is the existence and the stability at the solution level, because it is the solution but not the action that directly describes our universe. Around the GR limit people may treat GR as a good approximation of the modified gravity theory. Nevertheless, this may not be true when the GR limit is not stable.

This issue is particularly serious in the modified gravity theories with higher-order derivatives such as the $f(R)$ theory. The gravitational field equations of such theories are higher-order (higher than 2) differential equations while the Einstein equations in GR are 2nd-order differential equations. In this case, using GR to approximate modified gravity is to utilize the 2nd-order differential equations to approximate the higher-order differential equations, the validity of which is doubtful.

In this approximation a significant portion of the solution space is abandoned, and the remaining solution space is approximated by another simplified solution space. To verify the validity of this approximation, people need to show that the abandoned solution space is not important and the simplified solution space is truly a good approximation of the remaining solution space. Unfortunately this is not always true. In many cases the abandoned solution space is not negligible but may play an important role, and the simplified solution space as an approximation may be no good in a long run. That is, even if at the beginning the real solution is in the neighborhood of the simplified solution space, later it may leave away from the simplified solution space and even go deeply into the abandoned solution space. (For more details and for a heuristic demonstration of this issue, see Ref. 6.)

Thus, in addition to the existence, the stability of the GR limit at the solution level needs to be carefully examined for any modified gravity model to be viable.

5. Summary

Anti-gravity and dark-essences of the universe have been strongly suggested by astrophysical observations. They are the most mysterious in physics and cosmology. Their nature and origin are the most important unsolved puzzles in the 21st century. This paper presents a simple personal view of several relevant issues, particularly the cosmological constant problem, dark radiation, and the GR limit of modified gravity.

The cosmological constant problem may guide us to the final reconciliation between gravity and quantum. Dark radiation may be the early-time manifestation of dark energy, with which the nature of dark radiation indicated by the CMB and BBN observations can provide important information about dark energy. As to modified gravity, the need of anti-gravity in cosmology gives a strong motivation and the cosmological observations provide important tests. In addition to performing the tests, the even more essential is to examine not only the existence of the GR limit at the action level but also its stability at the solution level.

The clarification of these issues may help to solve the puzzle about the need of anti-gravity and dark-essences in cosmology. Hopefully the solution to this great puzzle will lead us to a new revolution in physics in the 21st century and bring us an unprecedentedly complete picture of our universe.

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