Astronomical and Astrophysical Transactions (*AApTr*), 2010/2011, Vol. 27, Issue 1, pp. 22–28,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Dark matter, dark energy and COINS

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Received 23 October, 2008

Cosmological data provide evidence for internal time-independent covariant symmetry that unifies cosmic quarks (baryons), leptons (electrons, neutrinos and antineutrinos), gauge bosons (CMB photons), dark matter and dark energy into a regular set with a conserved quantity common for all the five energy ingredients.

Keywords: Cosmology; Dark matter; Vacuum

1 Introduction

The standard model of particle physics is the best theory currently available to answer the question 'What is the world made of?'. However the three generations of quarks and leptons, together with force carrier gauge bosons of the model account for only a tiny $\simeq 5\%$ of the entire energy of the observed Universe. Recent observational findings in cosmology indicate that the major cosmic constituents are dark energy ($\simeq 70\%$) and dark matter ($\simeq 25\%$). The physical nature and microscopic structure of dark energy and dark nature remain obscure. A naive extrapolation of the standard model predicts a value of the dark energy density which is 50–120 orders of magnitude higher than the observed one [1]. There are no particles in the standard model which would be suitable for the role of dark matter particles.

The cosmic energy mix with 95% of mysterious stuff may look preposterously complex, strange or even absurd. I will show, however, that its recipe is simple and regular, if a proper way is defined to compare the cosmic energy ingredients. In the recipe, a sort of internal symmetry (COINS) reveals itself that unifies the five ingredients into a set with a common conserved quantity [2].

2 Five cosmic energies

In standard ΛCDM cosmology, quarks (Q), leptons (L), gauge bosons (B), dark matter (DM) and dark energy (DE) are considered at the macroscopic level as gases or fluids having their densities and pressures. Quarks are represented by 'baryonic matter'

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which is a gas of protons and neutrons; the gas is non-relativistic in all of the history of the Universe since the epoch of Big Bang Nucleosynthesis (BBN). At present, Q mass density is $\rho_{\rm Q} = \Omega_{\rm Q}\rho_{\rm c}$, where $\rho_{\rm c} \simeq 1 \times 10^{-29}$ g cm^{-3} is the cosmological critical density now and $\Omega_{\rm Q} \simeq 0.04$. Since the total cosmic density is nearly or exactly equal to the total cosmic density (according to the recent WMAP data), the value of $\Omega_{\rm Q}$ gives the relative fraction of quarks. The total mass of all quarks in the observed Universe

$$M_{\rm Q} \simeq 10^{54}\ {\rm g} \sim 10^{60} M_{\rm P}. \tag{1}$$

Hereafter natural units are used in which the speed of light, the Boltzmann constant and the Planck constant are all equal to unity: $c = k = \hbar = 1$. The ('reduced') Planck mass $M_{\rm P} = (8\pi G/3)^{-1/2} \simeq 10^{-6} \sim 10^{18}$ GeV. To be exact, $M_{\rm Q}$ is the Q mass in the observed patch of the Universe ('our cosmic domain' or Metagalaxy) which is usually defined as a spherical volume V_0 with the present Hubble radius $R_0 \sim 10^{60} M_{\rm P}^{-1}$. Since Q density scales redshift as $\rho_{\rm Q}(z) \propto (1+z)^3$ and $V(z) = V_0(1+z)^{-3}$, the mass $M_{\rm Q}$ is conserved with time.

Cosmic leptons are mostly electrons, neutrinos and antineutrinos. They are non-relativistic at present, but were relativistic at earlier epochs. The present L density fraction $\Omega_{\rm L} \simeq 0.01$. The total L mass in the cosmological domain

$$M_{\rm L} \simeq M_{\rm Q} \sim 10^{59} M_{\rm P}, \tag{2}$$

when the leptons are non-relativistic. When they are relativistic, their density scales as $(1+z)^4$ and their number density $n_{\rm L} \simeq \rho_{\rm L}^{3/4} M_{\rm P}^3$; in this case, the total number of relativistic leptons $N_{\rm L}$ is conserved in the expanding volume: $N_{\rm L} = n_{\rm L} V = Const.$

Cosmological bosons are mostly the CMB photons and (perhaps) relic gravitons. They are relativistic at any epoch, so their density scales as $(1+z)^4$. The present B fraction $\Omega_{\rm B} \simeq 0.0004$. Their particle density is rather high now: $n_{\rm B} \sim \rho_{\rm L}^{3/4} M_{\rm P}^3 \sim 10^3$ cm^{-3}. The total number of bosons in the expanding domain

$$N_{\rm B} \sim 10^{88} \tag{3}$$

is conserved.

Standard cosmology treats dark matter as invisible non-relativistic ('cold') gas of stable or long-living weakly interacting particle. The most likely version of the DM particle is hypothetical WIMP (Weakly Interacting Massive Particle) of the large mass $\sim M_{\rm EW}$, where $M_{\rm EW} \sim 1$ TeV is the electroweak energy scale. If this is so, DM is non-relativistic since the first picoseconds of cosmic history. The present DM density fraction $\Omega_{\rm DM} \simeq 0.25$. Their total conserved mass in the cosmological domain

$$M_{\rm DM} \sim 10^{61} M_{\rm P}. \tag{4}$$

ΛCDM cosmology describes dark energy as invisible medium with positive density, $\rho_{\rm DE} > 0$, and negative pressure, $P_{\rm DE} < 0$. The model accepts the simplest (and most probable) interpretation of DE relating it to Einstein's cosmological constant Λ, so that $\rho_{\rm DE} = \Lambda M_{\rm P}^{-2}$, and the DE pressure $P_{\rm DE} = -\rho_{\rm DE}$. If so, this antigravitating vacuum (see, for instance, [1]). According to the recent CMB studies, the DE density fraction $\Omega_{\rm DE} \simeq 0.7$, and its density

$$\rho_{\rm DE} = \Omega_{\rm DE}\rho_{\rm c} \sim 10^{-120} M_{\rm P}^4. \tag{5}$$

The conserved value for DE is the DE density itself.

3 Friedmann integrals

The existence of the conserved quantities comes from the Friedmann 'second' equation which is applied to each of the energy ingredients individually:

$$\frac{\dot{\rho}}{\rho(1+w)} = -3\frac{\dot{R}}{R}, \tag{6}$$

where $R(t)$ is the expansion scale factor, ρ is the density of a given energy ingredient, w is pressure-to-density ratio for each of them: $w = -1$ for dark energy, $w = 0$ for dark matter, leptons and quarks (when all the three are non-relativistic), and $w = 1/3$ for bosons and also for quarks and leptons when they are relativistic. The equation has the integral which may be written in the form:

$$A = [M_{\rm P}^{-2}\rho R^{3(1+w)}]^{\frac{1}{1+3w}}. \tag{7}$$

The positive conserved quantity A (of the length dimension) is called the Friedmann integral, and Eq. 7 is its definition. The integral is directly related to the corresponding conserved quantity for each of the energy ingredients (see Sec. 2 and below). Since four of them are defined in the cosmological domain, the scale factor of Eq. 7 is assumed to be normalized to the present-day Hubble radius: $R(z) = R_0(1+z)^{-1}$.

(Note that the isotropic and uniform cosmological model is applicable to the observed Universe at large spatial scales which exceed the size of the cosmic 'cell of uniformity' $\simeq$ 100–300 Mpc $\simeq (0.03\text{–}0.1)R_0$. On the other hand, the Universe is observed on the scales $\leq R_0$. So the range of applicability is actually measured by one (or one and a half) order of magnitude for the spatial scale. The 'truly cosmological' scale is $\sim R_0$ anyway.)

The five Friedmann integrals that come from Eq. 7 represent five energy ingredients in the Friedmann 'first' equation which gives the expansion scale factor $R(t)$ as a function of time:

$$\dot{R}^2 = (A_{\rm DE}/R)^{-2} + (A_{\rm DM} + A_{\rm L} + A_{\rm Q})/R + (A_{\rm B}/R)^2. \tag{8}$$

The key part that the integrals play in cosmology is seen quite clearly from Eq. 8. Historically, the quantity A appeared first in 1922 in Friedmann's first paper on cosmological expansion as a length-dimension positive constant of integration that represented non-relativistic 'dust-like' matter in the theory of the expanding universe.

By their origin from Eq. 7 as constants of integration, the values of the five integrals are completely independent of each other *a priori* and not restricted by any theory constraints (except for trivial ones). For instance, in the cold Universe (a model with zero initial temperature which was discussed before the discovery of the CMB background) the integral for bosons (radiation) is zero; in the model with zero dark energy density (which was the standard view a decade ago), the integral for vacuum is infinitely large. Therefore, the whole interval from zero to infinity is, generally, open for these quantities.

Let us now calculate the values of the integrals. With the use of the data of Sec. 2, we have:

$$A_{\rm DE} = M_{\rm P}\rho_{\rm DE}^{-1/2} \sim 10^{61}M_{\rm P}^{-1}. \tag{9}$$

$$A_{\rm DM} = \frac{3}{4\pi} M_{\rm P}^{-2} M_{\rm D} \sim 10^{60} M_{\rm P}^{-1}, \tag{10}$$

$$A_{\rm L} = \frac{3}{4\pi} M_{\rm P}^{-2} M_{\rm L} \sim 10^{58} M_{\rm P}^{-1}, \tag{11}$$

$$A_{\rm Q} = \frac{3}{4\pi} M_{\rm P}^{-2} M_{\rm Q} \sim 10^{59} M_{\rm P}^{-1}, \tag{12}$$

$$A_{\rm B} \simeq [\frac{3}{4\pi}]^{1/2} M_{\rm P}^{-1} N_{\rm B}^{2/3} \sim 10^{58} M_{\rm P}^{-1}. \tag{13}$$

As we may see, the five integrals have the values which are nearly equal within 3 orders of magnitude. Thus, we may write approximately in round numbers:

$$A_{\rm DE} \sim A_{\rm DM} \sim A_{\rm L} \sim A_{\rm Q} \sim A_{\rm B} \sim 10^{60} M_{\rm P}^{-1}. \tag{14}$$

It is worthwhile to compare the accuracy (3 orders of magnitude) of the empirical identity of Eq. 14 with the 50–120 orders of magnitude of the error in the theory prediction for DE density (see above).

In Eq. 14, the quantities $A_{\rm DE}, A_{\rm DM}, A_{\rm Q}, A_{\rm B}$ are determined by the Friedmann second equation of Eq. 7 and conserved since the BBN, at least. As for the quantity $A_{\rm L}$, it is determined above for the epoch, when electrons, neutrinos and antineutrinos are non-relativistic. It is easy to see, however, that the integral estimated for leptons when they (or some of them) are relativistic, has the value near $A_{\rm B}$ which is not far from the values of the other integrals. Thus, although the values of the five integrals are calculated with the use of the data related to the present-day state of the Universe, the integrals and their approximate identity are valid at least since the first minutes or seconds of the cosmological expansion. Moreover, Eq. 14 may possibly be extrapolated to the epoch of TeV temperatures – which is the edge of the applicability of the standard model of particle physics – with no contradiction to cosmological observational data (see below).

The near identity of the integrals for radiation and 'dust-like' non-relativistic matter was first found [3, 4] soon after the CMB discovery; with the discovery of dark energy and dark matter, the identity was extended to the dark cosmic ingredients [1].

4 Cosmic internal symmetry

The near identity of the five quantities in Eq. 14 seems hardly to be a simple arithmetical accident. It is rather a real regularity in the energy balance of the Universe. The relation of Eq. 14 comes from an empirical analysis of the cosmological data, and it reflects, most probably, an essential internal correspondence among the five energy constituents of nature. Actually it is the simplest time-independent recipe of the cosmic energy mix written in terms of the Friedmann integrals.

According to one of the most general definitions, 'symmetry denotes that sort of concordance of several parts by which they integrate into a whole' [5]. If a symmetry does not concern spacetime relations, it is referred to as internal symmetry – in contrast to geometrical symmetries. An example of internal symmetry is the symmetry between the proton and the neutron: the particles differ in mass, electric charge, lifetime, etc., but they are unified into a regular set which is the nucleon doublet

(spacetime and internal symmetries are the carcass of the standard model of particle physics).

Having in mind Weyl's general definition [5], we may look at Eq. 14 as at a concordance relation that connects the five cosmic energy ingredients. The connection unifies the ingredients into a regular set – the multiplet (pentet) of the cosmic energies. The Friedmann integral $A \sim 10^{60} M^{-1}$ serves as a common genuine quantity for the multiplet as a whole. The concordance expressed by Eq. 14 may be referred to as cosmic internal symmetry (COINS).

The members of the cosmological multiplet are obviously different in many respects. One of them (DE) is antigravitating vacuum, while the four others are non-vacuum gravitating energies. DE is time-independent, but the other energies dilute with the cosmological expansion. Three of the energies (Q, L, B) are described by the standard model of particle physics, and the two (DE and DM) are out of the model. Among four non-vacuum energies, there are both fermions and bosons. Despite of these and many other differences, each of the five energy ingredients is a regular, equal-rank member of the multiplet.

Since the Friedmann integrals are conserved, COINS is a time-independent symmetry in the evolving Universe. It is also a covariant symmetry, since Eqs. 8–14 are given in terms of the scalar (invariant) quantities $\rho_{\rm DE}, M_{\rm DM}, N_{\rm B}, M_{\rm L}, M_{\rm Q}$. COINS is robust: it is not sensitive to fine details of the observational data.

COINS seems to be complementary to the conserved and covariant internal symmetries of the standard model of particle physics. Anyway it provides us with a clear quantitative empirical link from the cosmology dark sector to the particles of the standard model.

The physical nature of the link may be clarified (to some extent) with the use of a model [6] which assumes that both dark cosmological ingredients may be figured out in terms of only two fundamental energy scales $M_{\rm EW}$ and $M_{\rm P}$. In particular, the DM particle has a mass near the electroweak energy scale $M_{\rm EW} \sim 1$ TeV (WIMP – see Sec. 2) and the DE density must look like

$$\rho_{\rm DE} \sim (M_{\rm EW}/M_{\rm P})^8 M_{\rm P}^4 \sim 10^{-120} M_{\rm P}^4. \tag{15}$$

The magic 120 orders of magnitude appears here explicitly via a (rather high) power of the big dimensionless ratio $X \sim M_{\rm P}/M_{\rm EW} \sim 10^{15}$ well-known in particle physics as the 'hierarchy number': it characterizes a huge gap between gravity and other physical interactions.

Using Eq. 8 together with the definition of the DE integral (Eq. 7), we have:

$$A_{\rm DE} \simeq X^4 M_{\rm P}^{-1} \sim 10^{60} M_{\rm P}^{-1}. \tag{16}$$

Then, the model enables one to describe (in a standard way – see [6]) the WIMP freeze-out at the $M_{\rm EW}$ temperatures. As a result, we obtain [1]:

$$A_{\rm DM} \sim A_{\rm B} \sim X^4 M_{\rm P}^{-1}. \tag{17}$$

Together with Eq. 16, this gives:

$$A_{\rm DE} \sim A_{\rm DM} \sim A_{\rm B} \sim X^4 M_{\rm P}^{-1}. \tag{18}$$

Thus, the equality of the three Friedmann integrals appears here as an outcome of the interplay between gravity and electroweak-scale physics which controls the freeze-out kinetics in the very early Universe. The value of the integrals given via the hierarchical number is practically equal to the empirically found one (Sec. 3). Taking this result at face value, we may propose that the hierarchy phenomenon of particle physics is actually behind the concordance and symmetry of the cosmic energies.

The model says nothing about the integrals for quarks and leptons. It may, however, be imagined that they could be accounted for in a more general model of gravity-electroweak interplay which would include electroweak baryogenesis and leptogenesis. The symmetry relation of Eq. 14 together with Eq. 18 suggest that these processes might also be reduced somehow to the hierarchy phenomenon of particle physics. In any case, future correct theories of the cosmological origin of quarks and leptons must explain why the corresponding Friedmann integrals $A_{\rm Q}$ and $A_{\rm L}$ are close, on the order of magnitude, to each other and to the universal value $A \sim X^4 M_{\rm P}^{-1}$.

It may be expected that, if the hierarchy problem is resolved in fundamental physics, it would give a new insight into the nature of COINS and the origin of all cosmic ingredients. Presently, an interesting approach to the hierarchy problem is proposed [7] which is based on an idea of macroscopic extra dimensions. The idea assumes that there exist two finite (compactified) spatial macroscopic extra dimensions with the size λ of, say, a fraction of one millimeter. In this case, the gravity energy scale may be reduced to the electroweak scale $M_{\rm EW}$ which is seen as the 'only truly fundamental energy in this framework. Then the energy hierarchy is shifted from energy space to geometry. Not going into other details, I note that in such a model the DE density (of the correct value) is given by a very simple relation with no sign of hierarchy at all [8]:

$$\rho_{\rm DE} \sim \lambda^{-4}. \tag{19}$$

Then the Friedmann integral

$$A \sim \lambda^3 M_{\rm EW}^2. \tag{20}$$

The two ideas by Arkani-Hamed et al. are simple and what is most important, they will be proved or disproved in laboratory or/and LHC experiments soon.

5 Conclusion

COINS offers a common ground for better understanding of a number of problems in cosmology (and perhaps in particle physics as well) that otherwise seem unrelated. I give here only one example; see more in [8–10].

It has been long mentioned in cosmology that the densities of all the five energy components are most close in their values just at the present epoch, not at any other epoch in the future or in the past of the Universe. Why is this so? The question known as the 'coincidence problem' in cosmology. It seemingly indicates that a very fine tuning is needed in the initial conditions for densities at BBN or at any earlier epoch. However such an unpleasant conclusion is not unavoidable. If the initial conditions are formulated in terms of the Friedmann integrals – at any time in the cosmic history, a robust equality of the integrals is enough [11]. Indeed, the approximate equality of

the integrals given 'from the very beginning' guarantees the rough coincidence of the five densities just at present.

Indeed, taking the approximate identity of the Friedmann integrals as a basic relation, we have for the five densities:

$$\rho_{\rm DE} \sim (M_{\rm P}/A)^2, \;\; \rho_{\rm DM} \sim (A/R^3)M_{\rm P}^2, \;\; \rho_{\rm Q} \sim (A/R^3)M_{\rm P}^2, \;\; \rho_{\rm L} \sim (A/R^3)M_{\rm P}^2,$$
$$\rho_{\rm B} \sim (A^2/R^4)M_{\rm P}^2. \qquad (21)$$

Let us notice also that the scale factor, as we defined it, is equal to the Hubble radius at present, and the latter, in its turn, is near the value of the Friedmann integral: $R_0 \sim A$ – this is a clear indication on a special character of the present epoch [12]. Then we see from Eq. 21 that the five densities become nearly identical, when $R \sim R_0 \sim A$, – with no need in fine tuning:

$$\rho_{\rm DE} \sim \rho_{\rm DM} \sim \rho_{\rm Q} \sim \rho_{\rm L} \sim \rho_{\rm B} \sim\sim (M_{\rm P}/A)^2. \qquad (22)$$

Let me conclude with another quotation from Weyl's book [5]: 'Symmetry, as wide or as narrow as you may define its meaning, is one idea by which man through the ages has tried to comprehend and create order, beauty, and perfection'.

Acknowledgments

The work was partly supported by the RFBR Grant 06-02-16366.

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