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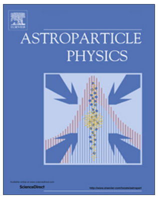

The emergence of cosmic repulsion

Gregory Ryskin

Robert R. McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL 60208, United States

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ABSTRACT

In cosmology based on general relativity, the universe is modeled as a fluid. The transition from the Einstein field equation to its large-scale (cosmological) version is thus analogous to the transition, for a system consisting of a large number of molecules, from the molecular/kinetic description to thermodynamics and hydrodynamics. The cosmic fluid is an effective continuum defined on the cosmological scales (only); for such a continuum, the appearance of new emergent properties should be expected. (Emergence of space–time and gravity is not discussed here.) When these new properties are calculated, the following predictions result: (a) the universe is spatially flat; (b) its expansion is accelerating; (c) dark energy makes up 75% of the total energy density of the universe; (d) the pressure of dark energy is equal and opposite to its density. All of these are in good agreement with the observational data. Also in favor of the present model are the absence of adjustable parameters, and consistency with the second law of thermodynamics. The distance–redshift relation predicted by the model is in good agreement with the Hubble diagram of Type Ia supernovae.

1. Introduction

In cosmology based on general relativity, the universe is modeled as a fluid. The transition from the Einstein field equation to its large-scale (cosmological) version is thus analogous to the transition, for a system consisting of a large number of molecules, from the molecular/kinetic description to the effective-continuum description of thermodynamics and hydrodynamics. An important consequence of such transitions – changes of the level of description – is the appearance of new emergent properties such as temperature or pressure, which have no meaning before the transition.

An instrument suitable for measuring macroscopic variables does not "see" the molecules, whereas a microscopic instrument (or an imaginary being), capable of measuring the velocities of individual molecules and the forces between them, would not be able to "feel" the pressure. "A precise determination of temperature is incompatible with a precise determination of the positions and velocities of the molecules" – Niels Bohr [1]. Concepts that are well defined on the macroscale become meaningless on the microscale, and vice versa.

These purely classical issues were discussed by Niels Bohr when he was developing the concept of complementarity in quantum theory; he used the term "complementarity" in reference to these classical issues as well [2]. The two types of complementarity are, of course, entirely distinct. The present discussion does not involve quantum theory in any way.

The cosmic fluid that serves as the model of the universe is an effective continuum defined on cosmological scales (only); for such a continuum, the appearance of new emergent properties should be expected. (Emergence of space–time and gravity is not discussed in the present work.) The "microscale" in this case includes everything from atoms and molecules to galaxy clusters; thus the emergent properties of the cosmic fluid will not be directly accessible to laboratory experiments or astronomical observations, but will be manifest only through their effect on the dynamics of the universe as a whole.

When these new properties are calculated, the following predictions result: (a) the universe is spatially flat; (b) its expansion is accelerating; (c) dark energy makes up 75% of the total energy density of the universe; (d) the pressure of dark energy is equal and opposite to its density.

All of these are in good agreement with the observational data. The above summary of the results is phrased in terms of dark energy solely for convenience; in fact, the present model eliminates the dark energy concept altogether – the emergent properties of the cosmic fluid suffice to explain the dynamics of the universe.

The present model differs fundamentally from the standard model of cosmology (ΛCDM), whatever the choice of the parameters in the latter. (The present model has no adjustable parameters.) For example, the present model implies that the expansion

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E-mail address: ryskin@northwestern.edu

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has been accelerating ever since the end of the radiation-dominated era. In the standard model, such a scenario would preclude the growth of structure that eventually led to the formation of galaxies. Not so in the present model: the growth of structure does occur, and its rate is in reasonable agreement with the data (Section 8).

As mentioned above, the present model is in good agreement with all the major conclusions of observational cosmology. Detailed comparison with observations will become possible after a complete cosmology is built on the new basis; this is far beyond the scope of the present work. One comparison that can be made now – with the Hubble diagram of Type Ia supernovae – shows good agreement (Fig. 1 and Section 6).

Assuming the data continue to support it, the present model has a number of attractive features. These include the absence of adjustable parameters, and the elimination of the dark energy concept. The model resolves three problems of cosmology – the flatness problem, the cosmological constant problem, and the coincidence problem. Its consistency with the second law of thermodynamics explains the large-scale homogeneity of the universe. It even sheds new light on the origin of inertia.

The analysis (Sections 2–4) is based entirely on general relativity, without the cosmological constant. No additional fields are invoked or introduced; quantum aspects are not discussed. The mean-field approach, borrowed from statistical physics, leads to the desired result with a minimum of calculation. The predictions of the model are compared with observational data in Sections 6 and 8; consistency with the second law of thermodynamics is discussed in Section 11. A closely related statistical-physics problem is reviewed in the Appendix.

2. The cosmological field equation

I follow the notational conventions of [3]; in particular, both the speed of light c and the Newtonian gravitational constant G are set to 1. Thus time, mass, and energy are measured in units of length; energy density and pressure have dimensions of $(\text{length})^{-2}$.

The Einstein field equation of general relativity takes the form

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}. \tag{1}$$

Here Greek indices run over 0, 1, 2, 3; the coordinate x^0 is time t; the spatial coordinates are x^1, x^2, x^3; $g_{\mu\nu}$ is the metric tensor, which determines the geometry of space–time and plays the role of gravitational field; $R_{\mu\nu}$ is the Ricci curvature tensor constructed from $g_{\mu\nu}$; $R = R_{\alpha\beta} g^{\alpha\beta}$ is the Ricci scalar; and $T_{\mu\nu}$ is the stress-energy tensor of matter, including radiation and non-gravitational fields. Summation over repeated indices is implied. The metric signature is $-+++$.

If the complete solution were known of the Einstein Eq. (1) everywhere in the universe, all the gravitational phenomena, from the fall of an apple to black holes to the expansion of the universe, would be precisely described. Such a solution will never be known. Beginning with Einstein's paper of 1917 [4], the cosmological implications of general relativity are deduced from a different (though identical in form) equation, viz.,

$$\mathrm{R}_{\mu\nu} - \frac{1}{2} \mathrm{g}_{\mu\nu} \mathrm{R} = 8\pi \mathrm{T}_{\mu\nu}, \tag{2}$$

where $\mathrm{g}_{\mu\nu}$, $\mathrm{R}_{\mu\nu}$, and R describe the *large-scale* geometry of the space–time; $\mathrm{T}_{\mu\nu}$ is the stress-energy tensor of the homogenized (smoothed-out) matter distribution.

Eq. (2) cannot be derived by averaging Eq. (1) because the left-hand side of Eq. (1) is nonlinear. (Physically, the nonlinearity means that gravitational field itself acts as a source of gravity.) Eq. (2) is thus an additional hypothesis, the cosmological field equation, modeled on the Einstein field Eq. (1). This fact is well known, and continues to be a cause of a considerable controversy; see the recent reviews [5,6] and references therein. I shall not review this literature here because my approach differs fundamentally from the previous work. The following excerpt [5, p. 4] summarizes the issue:

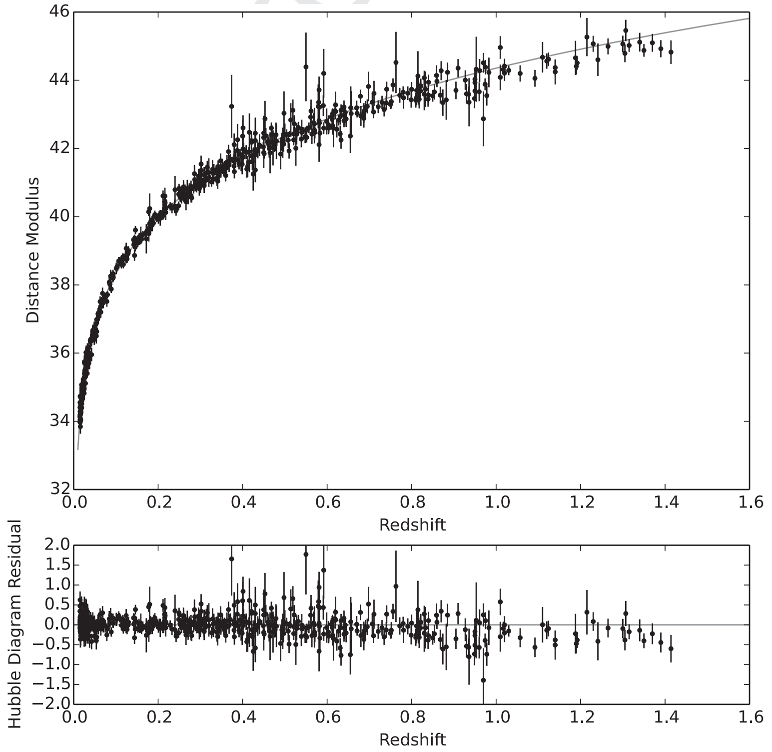

Fig. 1. The Hubble diagram (distance vs. redshift) for the Union2.1 compilation of 580 Type Ia supernovae [12]. The solid line is the prediction of the present model, Eq. (32).

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