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RESEARCH ARTICLE

The dynamics of quintessence, the quintessence of dynamics

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Abstract Quintessence theories for cosmic acceleration imbue dark energy with a non-trivial dynamics that offers hope in distinguishing the physical origin of this component. We review quintessence models with an emphasis on the dynamics and discuss classifications of the different physical behaviors. The pros and cons of various parameterizations are examined as well as the extension from scalar fields to other modifications of the Friedmann expansion equation. New results on the ability of cosmological data to distinguish among and between thawing and freezing fields are presented.

1 Introduction

Understanding the acceleration of the cosmic expansion is a landmark problem in physics, impacting gravitation, high energy and quantum physics, and astrophysics, and likely to revolutionize one or more of these fields. The direction in which to look for a solution is almost wholly unknown currently. Though there is no shortage of suggestions, most are far from a first principles explanation of how such physics arises.

Perhaps the simplest proposal—Einstein's cosmological constant Λ [25]—is correct, though even so we have as yet no understanding of why it would arise, with the magnitude needed to explain acceleration occurring near the present epoch. That puzzlement can be broken into two severe problems [12,71,91]: the fine tuning problem of how Λ appears with a magnitude (energy density or energy scale) so far from the natural (Planck) scale defined by fundamental constants, and the coincidence problem of why acceleration appears in our recent past, at a cosmic scale factor within 2 of

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the present value out of perhaps 10^{28} since inflation. The cosmological constant is addressed in far greater detail in the articles by [8,72] in this special volume.

To paraphrase Winston Churchill speaking about democracy, it may be that the cosmological constant is the worst form of accelerating physics, except for all those other forms that have been tried from time to time. Nevertheless, this article addresses those other forms, specifically dynamical physics that aims to ameliorate the coincidence, and/or fine tuning, problems. We concentrate on the dynamics, the time evolution of the cosmological expansion physics, (mostly) from a canonical scalar field, given the name quintessence. See [15] for a particle physics perspective.

Section 2 provides a brief historical perspective on the development of quintessence theories. Section 3 reviews key elements of the dynamics of quintessence and the physical origins of structure in the phase space, defining classes of models. Efficient representation of the dynamical behavior through parameterization or principal component analysis is discussed in Sect. 4, and we investigate in detail thawing models, those which approach cosmological constant behavior, in Sect. 7. In Sect. 5, we consider a selection of dynamical models beyond standard quintessence, and briefly mention the effects of expansion dynamics on growth of cosmic structure in Sect. 6. We conclude in Sect. 8.

2 Origins of quintessence

The role of a dynamical scalar field for recent acceleration of the cosmic expansion certainly owes a debt to the use of rolling scalar fields for early universe inflation. A scalar field, and more generally a negative equation of state, were implemented as a substitute for the cosmological constant in a flurry of activity in the 1980s. On the theoretical side [49] proposed a simple extension from the flat potential of the cosmological constant to a tilted, linear potential, that releases the field to roll when the expansion rate of the universe decreases sufficiently, what is now called a thawing field. In 1988, two nearly simultaneous papers by [76,92] described in more detail cosmology in the presence of a quintessence field.

At the same time, considerable work on the phenomenology of energy density components with an arbitrary (including negative) pressure to density, or equation of state, ratio was being carried out. [90] discussed such generalized cosmology, and [50] then followed up on this with detailed investigation of a variety of cosmological probes of additional components with arbitrary equation of state. These included tests of the expansion dynamics through distance, age, volume, and abundance measurements. Particular attention was paid to light propagation in such a generalized cosmology, including possible inhomogeneities in the components [51] (some results occurred earlier in the unpublished thesis of [41]). General equations of state had been considered in a formal way for the growth of structure within linear perturbation theory by [43]. Implications of general equations of state for growth were presented in [29,52].

Thus high energy physics theory and cosmology were all ready in the 1980s for data exploring the expansion and growth histories of the universe. It took another 10 years for observations [73,77] to make the astonishing breakthrough that turned these