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Dark energy model building: theory and observations

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Abstract. I shall discuss the issues in dark energy model building and briefly review the approaches for explaining the late time acceleration of the Universe. I shall also discuss in short the possible ways one can probe individual dark energy model as well as measuring the evidences for different models.

Keywords : cosmology: theory – cosmology: observations

1. Introduction

The discovery of late time acceleration in our Universe is one of the most significant cosmological observations in recent years. First pointed out by two independent observations measuring the apparent luminosity of the Supernova Type-Ia (SN-Ia) (Perlmutter et al. 1999, Riess et al. 1998), it is now confirmed by many other cosmological observations (Li et al. 2011, Sahni & Starobinsky 2000, Carroll 2001, Pebbles & Ratra 2003, Padmanabhan 2003). The standard cosmological picture of our Universe now says that we are living in a Universe which is spatially homogeneous and isotropic at cosmological scales and is also spatially flat. It has only five percent visible matter; the rest ninety five percent of our Universe is made of invisible components. Thirty percent of this invisible component is non-relativistic and is termed as "dark matter", while the rest of the invisible component is highly relativistic with large negative pressure (comparable to its rest energy) and is smooth at cosmological scales. This smooth component with negative pressure, dubbed as "dark energy" causes the Universe to accelerate at late times.

One can understand this acceleration in simple way. In a FRW spacetime, we have the Raychaudhuri equation (Raychaudhuri 1955):

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p), \tag{1}$$

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where p is the pressure in all three directions, ρ is the rest energy density and a is scale factor of the Universe. The appearance of pressure p in this equation is typical in General Relativity and is crucial as with $\rho + 3p < 0$ (also known as violation of strong energy condition), we can have $\ddot{a} > 0$ and the Universe accelerates. Hence to accelerate the Universe, we need a component which has negative pressure such that $\rho + 3p < 0$. So one has to look for some exotic form of matter as no normal form of matter (like radiation or dust) can have negative pressure.

One can also modify the above equation in such a way that without the presence of any exotic component, one can accelerate the Universe. These are so called "modified gravity" models where gravity is modified at large cosmological scales to explain the late time acceleration (Tsujikawa 2011).

One may also relax the assumption of FRW metric to describe our Universe and include the effect of inhomogeneity that is present in our Universe. In such a scenario, it may also be possible to explain current cosmological observations that demand the existence of an exotic component in a FRW spacetime (Buchert 2000, Rasanen 2009, Biswas & Notari 2008).

In this review, I shall discuss the first approach where one has to include some exotic dark component with negative pressure to explain the late time acceleration of the Universe.

2. Different approaches for dark energy model building

Simplest example for dark energy is what Einstein himself introduced 100 years back to get a static Universe. It is a cosmological constant (Λ) which has an equation of state $p = -\rho$. A concordance ΛCDM model is perfectly consistent with all cosmological observations. But theoretically it has inconsistencies due to the fine tuning as well as coincidence problems.

On the other hand, observational data also allow models different from ΛCDM where at least the coincidence problem can be addressed. This can be achieved with scalar fields with sufficiently flat potentials (Copeland et al. 2006). For a simple scalar field with canonical kinetic energy and minimally coupled to gravity, the equation of motion is given by,

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\partial V}{\partial \phi}. \tag{2}$$

The dynamics of this scalar field is governed by the interplay between the Hubble friction and the slope of the potential and depending upon how these two terms compete with each other, one categorizes the scalar field models into two classes namely "thawing" and "freezing" (Caldwell & Linder 2005). For the thawing models, the scalar field is initially at the flat part of the potential and is frozen due to large Hubble friction and hence it mimics Λ at early times. But as the Hubble friction decreases with time, the scalar field slowly thaws away from this frozen state and evolves towards $w > -1$. In this model, the equation of state is always close to $w = -1$ irrespective of the form of the potential but one has to fine tune the initial condition to get the right amount of dark energy at present. For the freezing models, on the other hand, the scalar field is initially in the fast roll phase and can mimic the background cosmology for certain class of the potentials. As the Universe evolves, the scalar field enters the flat part of the potential and starts behaving like Λ. In this model, although one can solve the coincidence problem with tracker like evolution, one has to fine tune the form of the potential.

One can also consider more complicated scalar field as a candidate for dark energy. Although the underlying equations are more complicated, they are certainly well motivated and can have interesting cosmological signatures. One such example is the Galilean field, which may arise in the effective 4 dimensional gravity action from certain type of five dimensional theories. The effective 4-dimensional action in these theories is given by: (See Hossain & Sen 2012 and references therein):

$$\mathcal{S} = \int d^4x \sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2\left(1 + \frac{\alpha}{M^3}\Box\phi\right) - V(\phi)\right] + \mathcal{S}_m. \tag{3}$$

In the Minkowski background, the scalar field part of the action is invariant under the Galilean transformation $\phi(x) \rightarrow \phi(x) + a + b_\mu x^\mu$. Here α is strength of the higher dimensional operator that is present in the action and M is fifth dimensional Planck's mass. Interestingly, although the action contains higher derivative operators, the equations of motion are still of second order.

3. Observational issues

The next question is how to probe these scalar field models cosmologically. Secondly whether one can say a particular model is better described by the data than the others.

To answer the first question, there are essentially two possible ways to probe any dark energy model. First, one has to see its effect on the background expansion of the Universe. This can be done using geometrical probes like distance, angle and volume measurements as well as the measurement of the age of the Universe. The observables for this purposes are standard candles like SN-Ia, standard rulers like Baryon Acoustic Oscillations etc. Secondly one has to study the direct or indirect effect of the dark energy on the structure formation of the Universe. The observables for this purpose are linear and nonlinear matter fluctuations, integrated Sachs-Wolfe effect, redshift space distortions weak lensing etc. For a nice review on dark energy observables see (Li et al. 2011).

To compare different models observationally, one can use the Bayesian evidence formalism. The Bayesian evidence is defined as (Liddle et al. 2006)

$$E = \int P(\theta)\mathcal{L}(\theta)d\theta \tag{4}$$

where θ's are the model parameters, $\mathcal{L}$ is the likelihood function and $P(\theta)$ is the prior probability distribution for the parameters θ's.

One can calculate Bayesian Evidence for different models to compare; higher evidence value signifies that the particular model is observationally preferred.

As an example, one can calculate the Bayesian Evidence for Galileon model and compare it with that for the standard scalar field with canonical kinetic term (without any higher derivatives in the action) using different observational data. It has been shown that for linear and quadratic potentials there is very strong evidence for the Galileon model in comparison to standard scalar field models, whereas for exponential and inverse quadratic potential both are equally favored (Hossain & Sen 2012).

4. Conclusion

To summarize, the late time accelerated expansion of our Universe is confirmed by various observations. The challenge is to build models which not only explain the observations but which are also theoretically well motivated.

A simple cosmological constant is most suited model for all the observations but is plagued by many theoretical issues. This motivates people to look for other alternatives. Scalar field models are the simplest ones. One can also construct more complicated models which are also theoretically well motivated. But the challenge is to distinguish different models observationally. Techniques like estimating Bayesian Evidence can be useful for this purpose although one needs to build efficient numerical routines to calculate such evidences.

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