Dark energy model building and observational issues

Anjan A Sen
Center for Theoretical Physics, Jamia Millia Islamia, New Delhi 110025, India
E-mail: aasen@jmi.ac.in

Abstract. In this short review, I shall discuss the issues relating to dark energy and late time acceleration of the Universe. I shall give a brief overview of the possible model building approaches for the late time acceleration of the Universe as well as different observational issues regarding dark energy.

1. Introduction
The most pathbreaking discovery in cosmology in recent years is the observation of cosmological acceleration in our Universe. Starting in the year 1999 when two independent observational efforts relating to the Type-Ia supernova first pointed out that the Universe may be accelerating recently, it has now been confirmed by a variety of cosmological observations [1]. The big picture that has now emerged from a host of very accurate cosmological observations are as follows: we are living in a Universe which is homogeneous and isotropic on large scales. This Universe is well described by a flat FRW Universe on large scales. The visible part of the Universe constitutes only 5 percent of the total energy budget of the Universe. The rest of the Universe is dark with 25 percent constitutes with non-relativistic dark matter, while the rest 70 percent of the Universe is given by a smooth relativistic component having a negative pressure whose magnitude is comparable to its rest energy density. This component with negative pressure is called the dark energy which is responsible for the accelerating Universe.

To understand the effect of dark energy in simple terms, let us write the equation of motion in Newtonian Gravity. It is given by

\[ \ddot{R} = -4\pi G \rho, \]

where \( \rho \) is the rest energy density of the gravitating matter. As this is always positive, the negative sign in the rhs of the above equation (which is due to the attractive nature of gravity) ensures that we have always deceleration. But when we write the same equation in Einstein General Relativity (GR), this equation gets a crucial modification. Due to the fact that pressure also gravitates in Einstein GR, this equation becomes:

\[ \ddot{R} = -4\pi G (\rho + 3p), \]

where we assume that space part of the Universe is homogeneous and isotropic and \( p \) is the pressure in all three directions. The remarkable property of the equation is that if \( \rho + 3p < 0 \)
(also known as violation of strong energy condition), then $R > 0$ and the Universe will accelerate. Hence to accelerate the Universe, we need a dark component which has negative pressure such that $\rho + 3p < 0$.

Let us see the possible ways one can explain the late time acceleration of the Universe. The Einstein equation is given by

$$G_{\mu\nu} = 8\pi GT_{\mu\nu}$$

With this if we assume a FRW metric to describe our Universe in cosmological scales, there is essentially two ways to explain the late time acceleration. If we concentrate on the rhs of the Einstein equation, we have already explained above that one needs to have negative pressure for acceleration. And as no normal component that we know has negative pressure, one has to include some additional exotic component having a negative pressure (we call it Dark Energy) to explain the late time acceleration. On the other hand if we keep normal components in the rhs of the Einstein equation, then one has to modify the lhs of the equation in such a way so that any departure from simple $G_{\mu\nu}$ term will mimic the negative pressure component that we require to add in the rhs of the equation to explain the acceleration [2].

There is a third way out. In this case, one retains the Einstein equation as it is, also keep the normal component in the rhs, but give up the idea that Universe is described by a FRW metric. In this review I shall only describe the first approach that is to say that we need to add some exotic component with negative pressure in the energy budget of the Universe to explain the late time acceleration.

Now how to probe this mysterious dark energy? In simple terms, there are three possible ways. One is to probe its effect on background cosmological expansion. This includes geometric quantities like distances, angles, volumes etc. The observables for this are standard candles like Sne-Ia, standard rulers like Acoustic Oscillations in Baryon-Photon fluid before decoupling. The second one is the direct or indirect effect of dark energy on structure formation of the Universe. The observables in this case are linear and non linear clustering, the Integrated Sachs-Wolf effect in temperature anisotropy in CMB, redshift space distortion, weak lensing etc.

2. Dark Energy Models

Simplest example for dark energy is a cosmological constant which is described by the equation of state $p = -\rho$. The cosmological constant together with the normal non relativistic matter (known as the concordance $\Lambda$CDM model) describes perfectly all the cosmological observations till date. But this is plagued by problem of unnatural fine tuning as well as the cosmic coincidence problem [1]. Also the observational data allow models different from $\Lambda$CDM where at least the cosmic coincidence problem can be addressed successfully.

One of the alternatives to $\Lambda$CDM model is canonical scalar field slowly rolling over a sufficiently flat potential at present epoch [3]. The idea is same as that of a inflation field; the only difference is that the energy scale involved is much lower ($10^{-3}$ eV). The equation of motion for a scalar field in an expanding FRW background is given by

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0.$$  (4)

The evolution of the scalar field is driven by the steepness of the potential and it is opposed by the friction term due to the expanding background. Depending upon how these two terms interplay, one can broadly classify the scalar fields into two categories: the freezing models and the thawing models [4]. For the freezing models, the scalar fields initially has a fast roll phase due to a steep potential and this helps it to mimick the background Universe. One can fine tune the form of the potential in such a way that around the present epoch the scalar field starts slow rolling and can give rise to negative pressure. On the other hand, thawing models have
sufficinetly flat potentials and is frozen to \( w = -1 \) initially due to large Hubble friction initially. As the Universe evolves, the Hubble friction decreases, and the scalar field slowly thaws away from its frozen \( w = -1 \) state. In this model, the equation of state of the scalar field is always very close to \( w = -1 \) and hence it behaves as dark energy without any fine tuning of the form of the potential, but one has to be fine tune the initial condition to get the right amount of scalar field energy density at present. One can use the different observational data to calculate the Bayesian Evidence for both thawing and freezing class of models \([5]\). The Bayesian Evidence is given by

\[ E = \int P(\theta)\mathcal{L}(\theta)d\theta \]  

(5)

where \( \theta \)'s are the model parameters, \( P(\theta) \) is the prior probability distribution for the parameters \( \theta \)'s and \( \mathcal{L} \) is the likelihood function. If one considers the dark energy to be homogeneous, there is a significant evidence in favour of the thawing class of models. But assuming the dark energy to be clustered, both thawing and freezing class of models are equally preferres by the observational data \([5]\).

One can consider more exotic fields to be considered as candidate for dark energy. One such example is the Galileon field given by the lagrangian (See \([6]\) and references therein):

\[ S = \int d^4x\sqrt{-g}\left[ \frac{M_p^2}{2}R - \frac{1}{2}(\nabla \pi)^2 \left( 1 + \frac{\alpha}{M^3} \right) - V(\pi) \right] + S_m \]  

(6)

where \( \alpha \) is strength of the higher dimensional operator that is present in the action and \( M \) is fifth dimensional Planck’s mass. The good part of the this action is that despite having higher derivative term in the action, the equation of motion is still second order. Also the field \( \pi \) respects the Galileon symmetry in the Minkowski background without the potential or with a linear potential.

One can now calculate the Bayesian Evidence for this model for different potentials and compare them with 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 potential there are very strong evidence for this Galileon model in comparison to standard scalar field, whereas for exponential and inverse quadratic potential both are equally favored \([6]\).

3. Conclusion

To conclude, the fact that our Universe is currently going through an accelerating expanding phase is now confirmed by various observations. Although a simple cosmological constant is most suited model for all the observations, the theoretical problems associated with such a set up, motivates people to look for the other options. Scalar field models are the simplest alternatives. With present observational results, one cannot distinguish various kind of scalar field models. But if one goes beyond the simple scalar fields and consider more exotics actions for these fields, present data can indeed distinguish them for some specific potentials.

Acknowledgements

I thank the organizers of the NCHEPC-2013 for inviting me to give this talk.

References

[1] Miao Li, Xiao-Dong Li, Shuang Wang, arXiv:1103.5870; V. Sahni and A. A. Starobinsky, Int. J. Mod. Phys. D 9, 373 (2000); S. M. Carroll, Living Rev. Rel. 4, 1 (2001); P. J. E. Peebles and B. Ratra, Rev. Mod. Phys. 75, 559 (2003); T. Padmanabhan, Phys. Rept. 380, 235 (2003);

[2] S. Tsujikawa, e-Print: arXiv:1101.0191 [gr-qc].

3
[3] E. J. Copeland, M. Sami and S. Tsujikawa, Int. J. Mod. Phys. D 15, 1753 (2006)
[4] Caldwell R. R. & Linder E. V., Phys. Rev. Lett. 95, 141301 (2005).
[5] S. Thakur, A. Nautiyal, A. A. Sen and T. R. Seshadri, MNRAS, 427, 988, (2012).
[6] M. W. Hossain and A. A. Sen, Phys. Lett. B., 713, 140, (2012).