Evidence for the fifth element
Astrophysical status of dark energy

Alain Blanchard

Received: 3 June 2009 / Accepted: 11 December 2009 / Published online: 29 June 2010
© Springer-Verlag 2010

Abstract Evidence for an accelerated expansion of the universe as it has been revealed 10 years ago by the Hubble diagram of distant type Ia supernovae represents one of the major modern revolutions for fundamental physics and cosmology. It is yet unclear whether the explanation of the fact that gravity becomes repulsive on large scales should be found within general relativity or within a new theory of gravitation. However, existing evidences for this acceleration all come from astrophysical observations. Before accepting a drastic revision of fundamental physics, it is interesting to critically examine the present situation of the astrophysical observations and the possible limitation in their interpretation. In this review, the main various observational probes are presented as well as the framework to interpret them with special attention to the complex astrophysics and theoretical hypotheses that may limit actual evidences for the acceleration of the expansion. Even when scrutinized with skeptical eyes, the evidence for an accelerating universe is robust. Investigation of its very origin appears as the most fascinating challenge of modern physics.

Keywords Cosmology · Dark energy · Cosmological models

1 Introduction

Modern cosmology has achieved remarkable progresses during the last 50 years. The general picture originally designed as the “Primeval atom” by Lemaître and which has become the “Big Bang” model according to the word of one of its most famous opponent, F. Hoyle, is now recognized as the successful scientific representation of the
world at the large scales (in space and in time) we can measure. Construction of this picture has necessitated the successive abandonment of philosophical and scientific ideas, some of which are not only those of physicists but are also shared by the more general public. Maybe the first to be given up was the idea that it is hopeless to try to figure out a global picture of the universe. Although heroic pioneers can be traced back since a long time ago, undoubtedly Einstein is the first one to directly address the question of handling the universe as a single physical object with an appropriate tool in hands, general relativity (GR). The fact that one of the very first applications of his theory was Cosmology is an evidence that the cosmological question was central in his thoughts. This is reinforced by the fact that he proposed to modify the initial formulation of his theory given the problems he encountered. It is commonly said that Einstein introduced the cosmological constant to obtain a static universe because he was reluctant to the idea of an expanding picture. This formulation is inappropriate: it merely suggests that Einstein was willing to avoid an expanding universe, while he actually wanted to find at least one solution to the cosmological problem with an initial formulation which assumes the universe to be stationary, there is no indication in his seminal paper that he wished to reject a non-stationary universe: he actually started his paper by discussing the problem of having mass at large distances in the Newtonian approach, noticing that this leads to divergence of the potential. He insisted that this would lead to unacceptably large velocities for stars. He also quoted that this can be cured by assuming a correcting term to the Newtonian potential equation:

\[ \nabla^2 \phi - \lambda \phi = 4\pi G \rho \]  

and then proposed to modify his initial theory with the addition of the cosmological term \( \Lambda \). This allowed him to construct the first relativistic cosmological model, the Einstein solution, which is spatially closed (because being spherical) and static. In 1919, de Sitter discovered a new solution to Einstein equation which was written in a stationary form and contains no matter (but a non-zero cosmological constant). It is only a few years after, in 1925, that Lemaître identified the de Sitter solution to an homogeneous expanding universe (Lemaître 1925). Friedmann (1922, 1924) found the general homogeneous solutions, providing the equation for the scale factor \( R(t) \) and recognisee their expanding nature. It is somewhat surprising that his work has remained totally unnoticed, despite a controversy with Einstein. During this period it is clear that the nature of the redshift of what Hubble had identified as extragalactic nebulae became a question addressed by many astronomers. Slipher’s discovery was probably much more intriguing now that the nature of nebulae had been identified.

---

1 It is fair to say that few scientists are still opposed to the “Big Bang” picture. Most of the serious opponents try to demonstrate that some observational facts, most often only one, which are coming in support of the Big Bang may be interpreted in a different way and therefore the whole construction has to be questioned. It is useful to remember that the success of a scientific model is—in some sense—measured by the number of predictions it leads to and how many are successful. Newton theory of gravity is wrong, but nevertheless it remains a high quality scientific theory because of its past (and present) successes. It is in this sense that modern cosmology should be regarded as successful, and this will remain in the future, even if it might be regarded as being “wrong”…

2 The choice of the coordinates system lead to a form of the metric for which the coefficients are constant.