Cosmological Implications from Observations of Type Ia Supernovae

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Abstract

The evidence for an accelerated expansion of the universe comes from the distance measurements of type Ia supernovae. Cosmological distances are notoriously difficult to obtain reliably and the use of the light curve shape for type Ia supernovae has resulted in a major breakthrough. The discussion now concentrates on possible contaminating effects of the observed signature. A primary contaminant could be evolution of the supernovae peak luminosity. Unfortunately, our current knowledge of the explosion physics and the radiative transport limits firm conclusions. Simulating supernova explosions and their observables represents some of the most challenging numerical problems to date.

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1. Introduction

Cosmology is the study of the global parameters of the universe. Since the discovery of the cosmic expansion and within the framework of general relativity the research has concentrated on determining the values of the expansion rate, the total energy/matter content, and the age of the universe. Other constituents are generally not regarded as important for the current universe, e.g. radiation e.g. [50,29]. The Big Bang theory is well established through the measurement of the cosmic microwave background radiation (hereafter CMB), the Hubble expansion, the dynamical interpretation of the red shift, the nucleosynthesis predictions, which have been confirmed by recent observations of deuterium [31,26], and the general evolution of galaxies as a function of lookback time.

The inconsistency between the dynamical age of the universe as derived from the measured expansion rate, Hubble's constant H_0, the (pressureless) matter density and the oldest known stellar objects was generally believed to stem from measurement uncertainties of either the Hubble constant or the matter density. Another discrepancy arose from the prediction by inflationary theories of a flat space-time geometry and the determination of the mean matter density, which amounts to only about one third of the required critical density.

The last few years have seen spectacular progress in the observations of the CMB fluctuations, which set a physical scale at a red shift of about 1000. These measurements indicate a flat geometry for the universe [8,35,46]. For the total energy density to amount to the critical density, as implied by the flat geometry, an additional energy source must be found.

An alternative way to determine the energy density of the universe is to measure the deceleration of the expansion due to the gravitational action of its matter content. But the effect on the change of the universal expansion rate depends on the nature of the energy component. The decay from a false vacuum during the inflationary period led to a dramatic *increase* of the expansion rate e.g. [23].

Type Ia supernovae (hereafter denoted SNe Ia), the thermonuclear explosion of a compact, small star, are currently the best known distance indicators which reach beyond the local supercluster. They have been widely used to pin down the value of the Hubble constant [7,6,47,43,15]. Remaining discrepancies in H_0 can be traced back to the local calibration of the absolute luminosity of SNe Ia.

Observations of distant SNe Ia by two groups have yielded strong evidence that the expansion rate in the past has been accelerated [39,32]. Several interpretations of this result are possible and range from astrophysical explanations, such as obscuration by intergalactic dust or evolution of the supernovae, to the need for a cosmological constant, i.e. an energy contribution by the vacuum.

This paper briefly discusses the observations. It will then concentrate on the possible interpretations and additional observations, which address the known weaknesses. In the following a discussion of the current understanding of SNe Ia will be given. As it turns out, the theory of the explosion as well as of the radiation escape from the supernovae is not terribly well understood, which has serious implications for the cosmological interpretation of the distant supernovae. Recent reviews on this topic have been published [38,22].

2. Observations

The cosmic expansion is measured as the ratio of two distances at two distinct red shifts. This provides the relative change of the expansion rate. The trick is to have a good distance indicator. Type Ia supernovae have become the prime cosmological distance indicator over the past decade. They have several advantages: they are extremely bright and their maximum luminosity can be normalized by their light curve shape for a review see [21], and they are point sources, which makes their measurement less complicated than for extended sources like galaxies. A further advantage is the ease by which they can be classified and as a group distinguished – through spectroscopy – from other luminous, variable objects.

The change of the expansion rate can be established from the determination of relative distances. There is still an ongoing debate about the absolute peak luminosity of SNe Ia, which is reflected in the uncertainties of the Hubble constant [43,15].

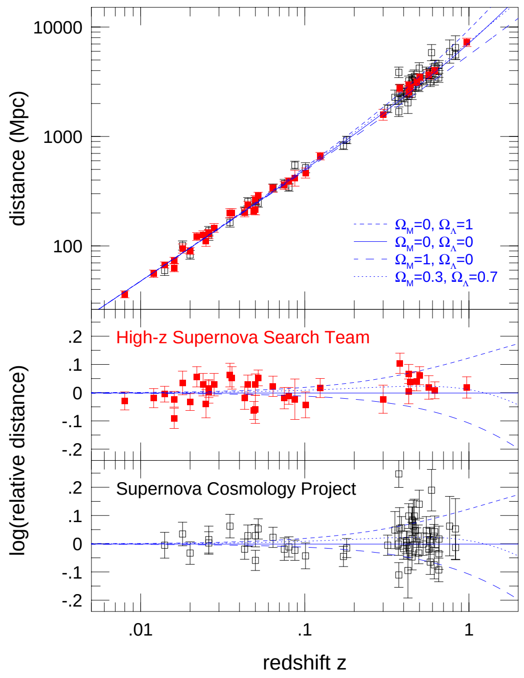

Fig. 1. Hubble diagram of type Ia supernovae. The upper panel shows the classical Hubble diagram with distance *vs.* red shift. Note that this figure shows observables and no derived quantities. The lines indicate the loci of standard candles for various combinations of the cosmological parameters. Ω_M denotes the fraction of the matter density in the critical density, Ω_Λ the contribution from a cosmological constant, i.e. the vacuum density. The lower panels have been normalized to the expansion in an empty universe.

It has to be stressed that the cosmic acceleration can only be determined by comparing distant to nearby SNe Ia. The nearby sample is for this measurement just as important as the distant objects. Most of the nearby supernovae have been observed by the Calán/Tololo surveys [33]. Various well-observed objects have been added to this list e.g. the CfA sample [40]. These local supernovae lie along the expansion line in the Hubble diagram, distance *vs.* red shift. These local SNe Ia define, after the light curve correction, the linear expansion of the local universe extremely well [40]. This is also proof of the accuracy of the measured distances. These nearby supernovae further 'anchor' the world model lines in the Hubble diagram (Fig. 1).

The normalized maximum brightness of the distant and local SNe Ia can then provide the distance ratio and distinguish between the various cosmological models. In Friedmann models of the universe with a Robertson-Walker metric, i.e. an isotropic and homogeneous universe, the distant supernovae appear fainter than what is expected in a freely coasting universe, i.e. one that does not experience any deceleration from gravitational action of its matter content. In fact, the SNe Ia appear even more distant indicating an accelerated expansion over the last several gigayears. They are further normalized to the nearby supernovae. Hence, the supernova results, barring any astrophysical influences, clearly reveal an additional, repulsive component of the universe.

An 'old' candidate is the cosmological constant introduced to balance the universal model [13,10]. The world view at the beginning of the 20^{th} century - before galaxies had been identified as extragalactic objects - assumed a static universe, based on stellar velocities of the order of a few dozen kilometers per second. A modern proposal to explain the acceleration is often called 'quintessence' and refers to a decaying particle field, not unlike the idea for the inflation, which is somehow coupled to the expansion [9].

3. Interpretations

One basic assumption for the supernovae is that they are good distance indicators all the way back to where they have been measured (about 6 Gyr). While this can be empirically tested in the local universe (out to about a red shift of 0.1; cf. Fig. 1), it has to be assumed for the more distant objects. This is quite a leap of faith, if one considers that a red shift of 0.1 corresponds to a lookback time of only 1.4 Gyr.

If the absolute peak luminosity of SNe Ia has changed between a red shift of 0.1 and 0.5, in particular if it decreased, the fainter supernovae would not be a signature of larger distances, but rather of an evolution of the objects. Although the SN Ia models do not necessarily favor such an evolution, they cannot exclude them (see the next section). A color change has been noted for the distant supernovae, they appear bluer than the nearby objects after correction for the red shift [22], which could indeed indicate an evolution.

Another possible explanation could be that undetected intergalactic dust dims the distant supernovae. Dust in the Milky Way is observed to preferentially absorb bluer light, which results in a reddening of objects. The distant supernovae are all corrected for such an effect [39]. Since they are presumed to be rather standard, their observed color is an indication of how much of their light has been absorbed. However, if there is dust of different composition and different grain size, i.e. different scattering properties, then the supernova color would not provide the required information. There have been extensive discussions of this effect [1,48,22]. Interestingly, the amount of the observed unresolved infrared background radiation can constrain the amount of intergalactic dust and the limits are close to exclude this explanation [1]. The observed blue color of the distant SNe Ia also disfavors dust right now [22].

There is a clear signature for a cosmological interpretation for the distant supernovae. For the currently favored cosmological parameters the expansion in the early universe would be decelerated as the effect of the cosmological constant is still negligible. Hence the evolution in Fig. 1 is predicted to be non-monotonic, while for evolution or dust a monotonic evolution is expected.

An important result in this respect is the recent observation of a supernova at a red shift of 1.7 [41]. Although a spectroscopic classification of this object is not available, it is fully consistent with an SN Ia. It also appears brighter relative to its counterparts at z=0.5, hence favoring a decelerated phase. Compared to simple, linear models for evolution or dust this supernova is discrepant by several sigma [41].

Right now, the cosmological interpretation is clearly favored. It implies that the age of the universe is fully consistent with its oldest stellar objects and the combination with matter density and the global geometry e.g. [49,4].

4. Physics of Type Ia Supernovae

How much have SNe Ia evolved from the time when the universe was about half its current age until today? Ideally, our understanding of the physics of SNe Ia should guide us in answering this question. Unfortunately, there is currently still a large uncertainty about the exact physical processes which take place in an SN Ia explosion and how the radiation from it is released see for a recent review [16].

The generally accepted picture consists of a thermonuclear explosion of a white dwarf [51]. In the explosion radioactive ^{56}Ni is synthesized in the burning to nuclear statistical equilibrium. The energy is then released in $\gamma-$radiation which is thermalized in the ejecta. The combination of energy deposition and the nuclear lifetime of ^{56}Ni (half-life of 6.1 days) and its daughter nucleus ^{56}Co (77 days), after which the chain ends with stable ^{56}Fe, determines the brightness evolution of SNe Ia.

This simple picture has been used for a long time to argue that SNe Ia are good standard candles and, indeed, as long as the nuclear physics remains unchanged the SNe Ia should display the same evolution independent of the age of the universe.

There are, however, some problems in the details. Several explosion models are currently discussed for SNe Ia. Most of them start from a white dwarf that is pushed over the Chandrasekhar mass, where white dwarfs are unstable [11]. In passing we note that no such white dwarf has been observed to date and the progenitor systems for SNe Ia are not known; there are several possible paths, but we do not yet know the correct one [24]. Some explosion models make use of sub-Chandrasekhar-mass white dwarfs, which are incinerated by a helium detonation near the surface [25].

Even for the canonical Chandrasekhar-mass models several explosion mechanisms are discussed [16]. It is generally agreed that the explosion starts as a deflagration, i.e. a subsonic flame propagation. In some models, the flame runs down a density gradient and eventually turns supersonic, a detonation. Yet another set of models has a first explosion fizzle, the star recontracts and only then detonates from the center [17].

The total explosion energy has to unbind the white dwarf and produce the observed expansion velocities of up to 20000 km s^{-1}. The regular deflagration models have so far been preferred as they produce the required intermediate-mass elements in a slow burning front, but had the disadvantage that they did not explode in numerical calculations [30,37]. They further depend on the start of the deflagration: with several off-center burning 'seeds' the explosion is more intensive. Only recently have there been successful calculations of deflagration models in three dimensions which produce healthy explosions [19,36].

Another complicated process stands between the explosion models and the observations. The release of the photons from the explosion is computationally extremely difficult to follow. The reasons are the continuous change of the energy deposition and the detailed physics of the conversion of the $\gamma-$rays injected inside the ejecta from the radioactive decays to the low-energy photons observed on the outside. The opacity changes due to the thinning of the expanding ejecta for the high-energy input, but at the same time the high velocities and the abundance of higher elements with their large number of transitions complicates the calculations e.g. [34]. The exact treatment is still debated, but it has become increasingly clear that the old assumption of a thermal input spectrum is not tenable. Even though SNe Ia display a nearly thermal 'continuum' during their peak phase, they are really dominated by the time-dependent photon distribution. The clearest demonstrations of this fact are the lack of photons at 1.2μm [45], which is due to the absence of emission lines in this wavelength region, and the occurrence of the maximum in different optical filters, 'reversed' for most supernovae, i.e. the near-IR filter curves peak before the optical ones [12,27].

Due to the large opacities in the ejecta the photon degradation proceeds through several channels e.g. [34]. Since the UV region is blocked by many velocity-broadened iron-group lines [20], the photons are progressively red-shifted until the optical depth is small enough for them to escape. This occurs first in the near-IR and hence the peak is reached earlier at these wavelengths [27,12].

Nevertheless, the optical spectrum has been modeled rather successfully even with thermal input sources. This is possible since the outer layers already encounter a pseudo-thermal input spectrum [34]. Detailed treatment of the NLTE effects has been included by several groups [18,34].

At late phases the ejecta are optically thin for optical and infrared photons and we see a spectrum dominated by collisionally excited Fe and Co lines [3,44,5]. At these epochs it has been assumed that the energy of the positrons in the ^{56}Co decay is locally deposited. This has recently been questioned because of an increased slope of the light curves [42,28]. After about 450 days a thermal instability develops in the ejecta which rapidly cool down from about 3000 K to 300 K. Excitation of optical and near-infrared transition declines rapidly and the cooling continues by fine-structure lines of Fe in the mid- and far-infrared. This is often referred to as the IR catastrophe. The predictions are that this would happen after about 500 days [14], but it has never been observed so far.

It will take a few more years until these problems can be addressed completely. A closer link between the observations and the models has been pursued by trying to understand the light curve shape correlations. The light curve decline has been modeled [18] and explained as differences in the amount of Ni produced in the explosion. The color dependence could also be explained this way. Other issues like the rise time or the occurrence of the secondary peak in the near-IR remain open. A possible interpretation of the light curve stretching during the peak phase and for the bolometric light curves links the time scales of the Ni decay, the diffusion time (for a constant opacity) and the age of the supernova [2].

5. Conclusions

The accelerated expansion has been accepted within a very short time. The supernova result together with the CMB measurements and the current estimates of the matter content of the universe are fully consistent with each other. They further predict a cosmic age that is larger than the oldest known stars. However, the size of the cosmological constant is beyond any current particle physics explanation. The possibility of a decaying field, like quintessence, is heavily investigated, but the answer is most likely coming from further supernova observations. The goal now is to map the transition phase from the decelerated to the accelerated expansion at red shifts between 0.5 and 1.2.

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