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Supernovae and Dark Energy

Inma Domínguez

Dpto. de Física Teórica y del Cosmos, Universidad de Granada,
E-18071 Granada, Spain

Eduardo Bravo

Dpto. de Física i Enginyeria Nuclear, Universitat Politécnica de
Catalunya, Diagonal 647, 08028 Barcelona, Spain

Luciano Piersanti, Oscar Straniero and Amedeo Tornambé

Osservatorio Astronomico di Collurania-INAF, Via Mentore Maggini
47, 64100 Teramo, ITALY

Abstract.

A decade ago the observations of thermonuclear supernovae at high-redhifts showed that the expansion rate of the Universe is accelerating and since then, the evidence for cosmic acceleration has gotten stronger. This acceleration requires that the Universe is dominated by dark energy, an exotic component characterized by its negative pressure.

Nowadays all the available astronomical data (i.e. thermonuclear supernovae, cosmic microwave background, barionic acoustic oscillations, large scale structure, etc.) agree that our Universe is made of about 70% of dark energy, 25% of cold dark matter and only 5% of known, familiar matter. This Universe is geometrically flat, older than previously thought, its destiny is no longer linked to its geometry but to dark energy, and we ignore about 95% of its components.

To understand the nature of dark energy is probably the most fundamental problem in physics today. Current astronomical observations are compatible with dark energy being the vacuum energy. Supernovae have played a fundamental role in modern Cosmology and it is expected that they will contribute to unveil the dark energy. In order to do that it is mandatory to understand the limits of supernovae as cosmological distance indicators, improving their precision by a factor 10.

1. Concordance model

A decade ago two independent teams, *the High-z Team* (Schmidt et al. 1998; Riess et al. 1998) and the *Supernova Cosmology Project* (Perlmutter et al. 1999) observed Type Ia supernovae (SNe Ia) at high redshifts (z∼0.5) with the aim of measuring the deceleration of the expansion rate of the Universe due to the gravitational effects. Surprisingly, they got the opposite result, SNe Ia were dimmer/further than expected, and the SNIa Hubble diagram was consistent with an acceleration of the Cosmic expansion. Some *repulsive* component had to counterbalance gravity and moreover, accelerate the expansion rate.

This exotic component was the missing piece in our understanding of the Universe. Finally, several observational evidences converged to an interpretation: the Cosmic Microwave Background radiation (Spergel et al. 2007) favors a flat geometry, therefore the total density (matter and energy) of the Universe should be close to the *critical density*, Ω_T=1 [1], X-rays from Clusters of Galaxies, Gravitational Lensing and Large Scale Structure, all sensitive to gravitation, are consistent with a low density-matter Universe $\Omega_m \sim 0.3$. Note that only ~5% of this 30% is known, familiar matter (i.e. atoms), while ~25% is unknown-matter, candidates are WIMPS (weakly interacting massive particles).

A 70% of *a component* withouth gravitational effects was needed and this is what the observations of SNe Ia required. In fact, for Ω_λ=0 the above independent set of observations should contain severe systematic errors (Schmidt et al. 2005). SNe Ia alone show $\Omega_\lambda \neq 0$ at 99% confidence level (Riess et al. 2007). These results are summarized in Table 1.

Table 1. Concordance Model

	Familiar Matter	Cold Dark Matter	Dark Energy
Relative Amount	5%	25%	70%
Nature	Atoms	WIMPS ??	vacuum energy ??

Additionally, if the expansion rate is accelerating, the Universe is older (~14500 Myr assuming a Hubble constant of 65 km/s/Mpc) as compared with a decelerating Universe: the Universe used to be younger than the oldest globular clusters !!

In all these years, evidence for cosmic acceleration has gotten stronger and nowadays all efforts focus on characterizing the dark energy equation of state (EOS). This equation relates pressure and density by a parameter, $P = w\rho$; w may be constant or may vary with redshift. Up to now, observations have not provided any evidence that $w \neq$-1, so a strong candidate for the dark energy is the energy related to the quantum vacuum.

2. Touching the void

Maybe we are *Touching the void* (this is a mountaineering book by Joe Simpson, 1989, his own survival adventure at the Peruvian Andes).

Quantum theory requires empty space to be filled with particles and antiparticles being continually created and annihilated, existing for very brief time. This leads to a net density of the vacuum. However, current estimations of the corresponding vacuum energy are too many orders of magnitudes (~50) out of what is needed to explain acceleration (Table 2).

Matter dilutes as the Universe expands while the vacuum energy, linked to the space itself, remains constant; hence, the matter term dominated in the

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[1] All cosmological densities in the text are normalized to the critical density, that is the density needed for a flat geometry. To give an idea, it would be equivalent to 6 protons per cubic meter (this value depends on the Hubble constant).

past while vacuum energy will completely dominate in the future. SNIa Hubble diagrams, which currently includes more than 300 SNe up to z = 1.8, show at z>0.5 the expected change from the matter-domain to the dark-energy domain (Riess et al. 2007) at 99% confidence level.

Table 2. Toching the void: the big discrepancy

Dark energy density (needed for observed Cosmic acceleration)	~ 1
Quantum Vaccuum energy density (theoretical estimation)	$\sim 10^{50}$

3. Supernovae: Cosmological rules

Type Ia Supernovae are bright candles in the Universe, as bright as the whole galaxy in which they occur at the time of their maximum light. This is the first (1) condition to be a cosmological rule, we can see SNe Ia very far away. The second (2) is to be *standard*, we have to know their intrinsic (or absolute) magnitude (M) to estimate their distances (D) from the observed magnitude (m), $m-M = 5logD+ct$. The uncertainties related with the observed magnitudes are those related, in general, with all astrophysics standard candles: contamination with other objects and extinction. The uncertainties related with the absolute magnitude depend on the empirical relation used to obtain the absolute maximum magnitude from the light curve shape (i.e. Phillips (1993)). This relation is based on nearby objetcs, SNIa occuring in galaxies at known distances. So the third (3) condition is to be free of *evolutionary* effects: we assume that the SNIa observed at high-z (in the past) are equal to nearby SNe Ia.

Hubble diagrams in which, as Sir Edwin Hubble did, the distance is plot in function of redshift are used to derive cosmological parameters. Hubble discovered the well-known linear relation between the redshift and the distance in the local Universe. When the Hubble diagram is extended to high-z, the relation is not linear and depends on the cosmological parameters: the geometry of the Universe, the matter density and the dark energy density. These densities depend on z in different ways, making possible to quantify them independently. In Table 3 the first and the most recent observational SNIa results on dark energy are presented, note that those values are obtained assuming a flat Universe. The value $\Omega_\lambda \sim 0.7$ has been confirmed by all experiments in the past 10 years.

3.1. Systematic errors: Evolutionary effects

The results shown in Table 3 (and those not shown) have been obtained using a calibration to estimate M (and hence, D) in which the dispersion is above 0.2 magnitudes. Data are consistent with w=-1 and constant, the dark energy being the vaccum energy. However, to explore further the nature of dark energy the present dispersion has to be decreased by a factor 10 (see Table 4) (Kowalski et al. 2008). Unfortunately it is not only a question of observing thousands of SNe

Table 3. 10 years of Dark Energy based on SNe Ia

Year	SNe	Redshift	Reference	Dark Energy Ω_λ	w (EOS)
1998	1	z=0.479	High-z Team	0.6±0.4	...
1998	10	$z \leq 0.62$	High-z Team	≥ 0 (99.9%)	...
1999	42	$z \leq 0.83$	SCP	0.72	$\geq$-0.8
2006	73	$z \leq 1$	SNLS	0.737	-1.023
2007	23	$1 \leq z \leq 1.755$	HST	0.72	-0.8
2007	60	$z \leq 0.78$	ESSENCE	0.726	-1.05
2008	307	compilation	SCP	0.713	-0.969

Schmidt et al. (1998); Riess et al. (1998); Perlmutter et al. (1999); Astier et al. (2006); Riess et al. (2007); Miknaitis et al. (2007); Kowalski et al. (2008)

Ia and pin down the statistical errors, systematic errors may play a fundamental role. Among the potential systematic errors, evolutionary effects may be critical.

Table 4. SNe Ia: the precision needed for Cosmology

	(in magnitudes)
Present dispersion	0.2
Evidence of dark energy	0.2
Identify nature of dark energy	0.02

In principle, theoretical interpretation of Type Ia SNe is consistent with being free from evolutionary effects. Type Ia SNe are thermonuclear explosion of carbon-oxygen white dwarfs with a mass close to the Chandrasekhar mass. Starting from such a structure and with a proper explosion mechanism (Khokhlov 1991), most of the observed properties are reproduced (Höflich & Khokhlov 1996). However, the observed light curve diversity has been finally related with the age of the stellar populations in which they occur (Sullivan et al. 2006).

In this context we have explored the potential dependence of the light curves properties on the progenitor of the exploding white dwarf based on numerical simulations, in which we include the pre-supernova evolution, the explosion and the light curves. The results are summarized in Table 5: in the 1st column we indicate which progenitor properties we have studied and in the second column the obtained difference (upper limit) at the time of maximum light (Bravo et al. 1996; Domínguez, Höflich & Straniero 2001; Domínguez et al. 2006).

These results show that the influence of the progenitor on the light curves is within the present dispersion (Table 4), therefore the evidences for the existence of dark energy are robust. At the other side, they show how difficult it would be to decrease by a factor 10 the present dispersion. Moreover, our study is limited because the astrophysical scenario leading to the exploding white dwarf and the explosion mechanism itself are still open problems.

Table 5. Infuence of the Progenitor on SNIa maximum magnitude

	$\Delta M_{max}(mag)$
Main Sequence Mass	< 0.2
Initial Z	< 0.2
Ignition density	< 0.2
Rotation	< 0.2

4. Conclusions

To unveil the nature of dark energy is a fundamental problem in physics today. To afford this problem using SNe Ia we have to improve supernova distances by reducing a factor 10 the present dispersion in the empirical relation used to calibrate their maximum magnitudes. Nowadays efforts focus on indentifying their progenitors, on the physics of the explosion (3D simulations), the link between the observed properties and those of the progenitors, the extinction law and extending the observations to $z \geq 1$ where the early effects of deceleration may be detectable. Advances will come from different experiments and the future is promising.

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