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Creating a legacy and learning about dark energy

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Some publications are a guaranteed success. The paper by Pierre Astier et al. on the first-year results from the Supernovae Legacy Survey (SNLS) was such an instant classic. It reported early results of a transformational experiment with wide-reaching consequences for cosmology and astrophysics. By measuring distances to type Ia supernovae (SNe Ia), they could confirm and further constrain the nature of a new component necessary for the cosmological models – dark energy. Determining the nature of "dark energy" is considered one of the most important problems in today's physics and one of the main topics in the cosmology of the early 21st century (Frieman et al. 2008). Because of a nearly complete lack of theoretical guidance, it has become extremely important to observationally constrain the parameters of dark energy. Massive surveys of distant type Ia supernovae, together with surveys looking for the growth of structure and mapping the cosmic microwave background, have become the tool of choice for characterizing the effects of dark energy.

The use of SNe Ia as distance indicators had been explored for several decades and they had proved extremely useful for mapping out the local expansion field and the Hubble constant. These cosmic explosions are thought to be the thermonuclear explosions of white dwarfs near the Chandrasekhar mass limit (Hillebrandt & Niemeyer 2000), and they can be calibrated to provide excellent cosmological distances. In the prevailing paradigm of the end of the 20th century, the change in the cosmic expansion rate should be governed by the amount of matter in the universe, encapsulated in the deceleration parameter. Cosmology then consisted essentially in determining the two numbers for the Hubble constant H_0 and the deceleration parameter q_0 (Sandage 1988). By observing distant supernovae, the change of the expansion rate would provide this second parameter. Much to everybody's surprise, the expected deceleration, hence shorter distances than in a freely expanding universe, was not found, but the distant supernovae appeared to be farther away than predicted for even an empty universe (for early reviews see Riess 2000; Leibundgut 2001). Clearly something was amiss. The simplest extension of the field equations of general relativity was introduced by Einstein himself as the cosmological constant in a failed attempt to stabilize the cosmological models derived from his theory of gravity. As it turns out, introducing the cosmological constant can explain the apparent acceleration; however, it had been shunned in physics for eight decades as unmotivated, unnecessary, and not understood (Carroll et al. 1992).

The SNe Ia indicated elegant solutions to enlarging the dynamic age of the universe to encompass the oldest stars and to comply with the best available measurements of the Hubble constant, as well as to increase the energy density in the universe enough to provide a global geometry, which would lead to the flat space-time geometry favored by theoretical models of inflation. The global geometry had been determined from the measurements of the fluctuation scales in the cosmic microwave background by balloon experiments almost at the same time as the accelerated expansion was found. The price to pay was to introduce new components into the cosmological models. A major problem with the then existing sample of distant SNe Ia was that they are extremely limited both in size and quality of the measured supernova light curves and spectra.

It was in this context that the French and Canadian astronomical communities decided to dedicate over 450 dark nights of the Canada-France-Hawaii Telescope (CFHT) in five years to a set of surveys meant to solve some of the outstanding astrophysical problems. The MegaCam instrument was specially built for wide-area photometry and large and deep sky surveys. By dedicating a majority of the most valuable telescope time to such surveys, these communities resolved to make significant contributions to burning problems. In addition, classification of the supernovae and determination of their redshifts require detailed spectroscopy. Hence, a concerted effort combining the largest existing telescopes with orchestrated observations over several years was established. The SNLS is in competition with another supernova survey, the ESSENCE project (Miknaitis et al. 2007; Wood-Vasey et al. 2007). While the SNLS set out to measure around 1000 distant SNe Ia, the ESSENCE project attempted to observe about 200 SNe Ia with the CTIO 4m Blanco telescope. The resulting publications combine data from the CFHT (or the CTIO Blanco telescope for ESSENCE) for photometry and spectroscopy obtained at the ESO VLT, the Keck telescopes, the Gemini telescopes, and the Magellan telescopes for the vital classification of the supernovae (Lidman et al. 2005; Howell et al. 2005; Garavini et al. 2007; Bronder et al. 2008; Ellis et al. 2008). The large SNLS collaboration is reflected in the authorship of the Astier et al. paper – 42 authors from 18 different institutions in 7 countries – and is the result of the large work force needed to turn the observations into timely results. Supernova work requires that the discovery and follow-up spectroscopy are done in nearly real time. Since the SNLS is working as a "rolling search", i.e. observations during every dark lunar period, it means that a sizable team must be organized and working continuously.

Astier et al. also highlight some of the changes that astrophysical research is experiencing. The move to dedicate whole telescopes to specific problems, the rise of surveys, and the increase in the size of the collaborations are all marks of a new generation of astrophysicists. Tackling big problems involves strong efforts and investments using significant resources.

The paper summarized the first out of five years of the supernova data collection within the SNLS and already presented the largest such data set at the time. Today, this publication still represents the largest homogeneous sample of distant supernova observations. The competing ESSENCE survey has produced a comparable number of distant supernovae, but needed three years to achieve this. The community is now awaiting the full five-year results of both teams so they can provide the definite result on the dark energy equation-of-state parameter w from SNe Ia. The full SNLS will yield over 500 spectroscopically classified SNe Ia out to a redshift of 1, while ESSENCE will be limited to about 200 objects observed with fewer filters and a more limited redshift range ($z \leq 0.8$).

In addition to the new and improved data, the Astier et al. publication introduced a new method of tackling the thorny problem of dust extinction and its coupling with the intrinsic color of SNe Ia. The paper contains an extensive discussion of systematic effects, which could affect the cosmological result. An extremely thorough explanation of the scientific method, the corrections applied to photometry, and the light curve analyses are provided as well.

Correction of the observed supernova light for intervening dust is notoriously difficult. Because of intrinsic changes in the SN Ia color, large uncertainties to the color corrections have to be introduced. By treating the color and reddening of the supernovae combined, even though they stem from entirely different physics, Astier et al. achieved a significant reduction in the uncertainty of the distance measurement and the scatter in the Hubble diagram. The larger sample and the dense sampling of the multi-filter light curves allowed them to derive a significantly different dust reddening from the normal Milky Way reddening law. This was a bold move when the paper was published, but it has become customary from independent measurements of SNe Ia with exquisite color coverage. There is, at the moment, no convincing argument for this deviation from the Milky Way reddening law other than the improved distance measurements. This clearly should be telling us something about the dust properties in other galaxies.

Astier et al. derive an uncertainty on (constant) w of less than 10% (with a slight dependence on the priors of the cosmological model), when combined with the orthogonal measurements on the dark matter content of the universe. A slightly smaller uncertainty of around 5% is derived for systematic effects, which are discussed very carefully. This also means that the existing sample does not need to be incremented dramatically. The envisaged factor of about 7 brings the statistical errors down to slightly less than the systematic errors.

There have only been few improvements since the Astier et al. paper was published. All available data have been combined into a large reference data set, which now combines over 300 SNe Ia for cosmology (Kowalski et al. 2008). A significant extension of the sample of nearby SNe Ia (100 additional SNe Ia at low redshifts) has further improved the local calibration for the cosmological application of SNe Ia (Hicken et al. 2009). Within the next couple of years, the final data sets of SNLS and ESSENCE will bring the overall number of useful SNe Ia for cosmology close to 1000.

With such a statistical sample and because the systematic errors are now the dominating source of uncertainty, future experiments will have to concentrate on improving our understanding of the astrophysical effects that influence the cosmological result. Also, it appears that the value for a constant w is very close to the expectation from the cosmological constant $w = -1$. The uncertainty will be around 5% from a combined analysis of all cosmological measurements (supernovae, baryonic acoustic oscillation, mass distribution as measured through weak lensing and cluster surveys, and the CMB fluctuations; e.g. Kilbinger et al. 2009). Currently it is not possible to meaningfully constrain any time-variable component of w, because highly accurate distances are required. Simply increasing the supernova sample statistics is not possible, contrary to the hopes for the baryonic acoustic oscillations and the weak-lensing measurements where averaging over many millions of objects could reduce the statistical errors. It remains to be seen how strongly these methods are affected by systematics. The dust absorption towards the distant supernovae and the observed intrinsic variations in the SNe Ia are the most pressing problems for further sharpening of the supernova tool for cosmology.

Several supernova surveys are either planned or already going on. They can be separated by the redshift range they target (see Leibundgut 2008 for a summary of supernova searches). Searches of nearby supernovae have to cover essentially the entire sky at nearly nightly intervals. Several very successful searches have been operating for several years, and there are many well-observed supernovae per year. Apart from producing the "anchor" for the comparison with the distant SNe Ia, they are also the most useful for improving our understanding of the supernova physics. Many SNe Ia at intermediate redshifts ($0.1 < z < 0.3$) are used to bridge the gap towards the more distant supernovae. Supernovae in this redshift range can be observed in a relatively short time interval and hence the sample characteristics can be explored. At higher redshifts, the supernovae are mostly found in deep pencil-beam type of searches. Supernovae are part of the science plans for all future survey telescopes, and numbers in the hundreds of thousands are sometime quoted. Common to all these surveys is the planning of multi-year efforts, like the SNLS, for large teams of collaborators. A future dark energy space mission will certainly include supernova investigations. They can provide the vital infrared observations, which are extremely difficult to obtain from the ground.

The SNLS has set the stage and the foundation for all future supernova cosmology projects, and the Astier et al. paper was the first glimpse of what is to come. It is also an example of the new way cosmological experiments have to be run to be successful. The coordination and orchestration of large, globally distributed teams is required to address the nature of dark energy. Astier et al. established the new standard in supernova cosmology.

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