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Supernova: Status and Perspective

M. Rigault[*][†]
Laboratoire de Physique de Clermont, Clermont-Ferrand, France
E-mail: `m.rigault@ipnl.in2p3.fr`

Type Ia supernovae are powerful probes of dark energy. In the first part of this proceeding, we briefly review the status of supernova cosmology presenting the importance of understanding systematics associated to this probe. In a second part, we focus on an important issue in curent Supernova analysis: the influence of the SN host environments in measurement of cosmological distance with Type Ia supernovae and their consequences on derivation of cosmological parameters.

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[*] Speaker.

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The accelerated expansion of the Universe was discovered in the late 90s using Type Ia Supernovae (SNeIa) revealing for the first time the existence of dark energy [Perlmutter et al.(1999), Riess et al.(1998)]. Its existence has now been confirmed with high precision [Betoule et al.(2014), Planck Collaboration et al.(2016)], and today, one of the main goals of modern cosmology is to understand its nature. Among the different probes, SNeIa distance indicators remain essential. This technique is based on the derivation of relative distances through the comparison of observed fluxes of objects with intrinsically similar brightnesses. SNeIa are especially powerful for probing the recent expansion history of the Universe ($z < 0.5$), which is driven by dark energy. They consequently provide the greatest constrain on the derivation of properties of this energy [Betoule et al.(2014), Scolnic et al.(2018)]. The latest state-of-the-art SN compilation derives a dark energy equation of state parameter w of -1.026 ± 0.041 [Scolnic et al.(2018)], which is compatible with the prediction of Einstein's cosmological constant, i.e., a pure vacuum energy with $w = 1$. Yet, the expected scale for vacuum energy based on the standard model of particle physics is too large by at least 56 orders of magnitude in energy. Therefore, while it is tempting to settle for a cosmological constant as the explanation for the accelerating expansion of the universe, it is physically unmotivated. Moreover, a number of theories developed to explain dark energy predict an observed $w \approx -1$ today but deviate as to the past behavior. To distinguish between competing models, the change with redshift w_a must thus be measured. The result may fundamentally change our understanding of how gravity behaves or may uncover new fields.

Only Type Ia Supernovae can directly probe the recent accelerated expansion of the Universe. The SNIa technique is highly complementary to the alternative techniques. The baryon acoustic oscillations (BAO) trace the expansion in the distant Universe ($z>0.5$) but is limited by cosmic variance at lower redshifts. The cosmic microwave background (CMB), weak lensing, and cluster growth constrain the influence on matter of the dark energy's anti-gravitational property. Deviation between these two aspects of dark energy would be a strong indication that we should modify Einstein's theory of gravitation. SNeIa play an additional key role in the direct measurement of the Hubble Constant H_0, which represents the current expansion rate of the Universe [Riess et al.(2009), Riess et al.(2016)]. The Hubble Constant recently became the center of attention as this measurement disagreed with predictions based on CMB data. This could be a first sign of new physics [Riess et al.(2016)], or a non-accounted astrophysical bias in the SNIa measurements [Rigault et al.(2015), Rigault et al.(2018)].

The 2020-generation of surveys will be soon launched. The Zwicky Transient Facility (ZTF) in 2017, followed by LSST, Euclid and WFIRST in the early/mid 2020s, will increase the amount of SNeIa used to probe the expansion of the Universe by several order of magnitudes. In that context, the SNIa technique will continue to be "a leading probe of dark energy for the next decade and beyond" [Kim et al.(2015)]. However, using the larger statistics of future missions requires a major effort to reduce the systematic uncertainties that already dominate the error budget of w (w_a) today. In that context, the three main challenges of modern Supernova cosmology are: calibration, photo-typing and photo-redshift and astrophysical biases.

In the rest of this proceeding we will focus on the astrophysical biases issue. For calibration, we invite the reader to consider, [Astier et al.(2013), Betoule et al.(2014), Scolnic et al.(2018)] and references therein. And for photo-typing and photo-redshift, and invite the reader to consider [Kunz et al.(2007), Jones et al.(2018)a] and references therein.

The natural SNIa magnitude (mag) dispersion is ≈ 0.40 mag. This can be significantly reduced to 0.15 mag by using two empirical relations between the SN-lightcurve peak luminosity and the lightcurve shape and color [Phillips(1993), Tripp(1998), Guy et al.(2010)]: the redder SNe are fainter and decline more quickly. However, despite the success of SN cosmology and decades of studies, the true nature of this astrophysical object remains largely unknown and the standardization process still is purely empirical ; see [Maeda & Terada(2016)] for a recent review.

We know the SN Ia event involves the thermonuclear disruption of a Carbon-Oxygen white dwarf, but the reason of this explosion (overflow companion, white dwarf mergers, etc.), and more importantly, the influence of intrinsic properties of the progenitor star (like its age or its metallicity) on the observed SN magnitudes is unclear. Since the mean properties of stars and galaxies – hence of the SN's progenitor and its environment – evolve with time, the SNIa explosion mechanism must at some level be influenced by this evolution. Altogether, astrophysical systematic errors arising from this lack of knowledge are, together with the instrumental calibration uncertainties, the dominating the errors budget on SN cosmology [Betoule et al.(2014), Ponder et al.(2016)] and by far the least studied.

Several astrophysical dependencies have been confirmed and observations suggest more exist. The color correction during the SN magnitude standardization process is such an example. It has long been expected that dust in the host galaxy interstellar medium causes a wavelength dependent flux attenuation and hence causes the observed SN color variability. However, the dust absorption laws of SN-host galaxies (grain sizes) derived from SN data based on this assumption strongly differ from those observed in usual galaxies using other methods. A more realistic model would consider two reddening effects: a first caused by variation of the intrinsic SN spectral energy density (SED) and a second caused by the host dust absorption. Because the relative amplitude of both effects could vary with redshift, our inability to understand the SN color-brightness dependence is one of the main source of potential astrophysical bias. This issue is one of the most discussed topics in the Ia community for the last 20 years, e.g. [Tripp(1998), Jha et al.(2007), Burns et al.(2014)], but it has so far not been solved. The underlying cause is the lack of independent information about the host reddening in the SN light-of-sight. A second source of concern is the remaining ≈ 0.15 mag dispersion of the SN standardized brightness. While it corresponds to an exquisite precision in the distance measurement, only half of this dispersion could be explained by measurement errors and associated systematics. About 0.10 magnitudes of dispersion is thus caused by astrophysical variation of the SNe themselves and since its cause is unknown, this "intrinsic dispersion" is a nest of hidden astrophysical systematics. The LSST Science Book claims that "[...] Without understanding the physical origins of this dispersion, and whether it has systematic effects that depend on redshift, we will not be able to use the full statistical power of the tens to hundreds of thousands of SNe Ia that LSST will find." (p. 395).

Since observations of SN properties so far have failed in determining the true progenitor, some other approach is required. Early studies of Type Ia supernovae showed that the peak brightness (and stretch) varies with host galaxy type [Hamuy et al.(1996)], thus providing an important clue to the astrophysical origin. Subsequent work quantified this relation in terms of a stretch dependance on the integrated stellar mass or star formation in the host galaxy [Neill et al.(2009), Sullivan et al.(2011), Rigault et al.(2013)]. Simultaneously, the lack of a correlation between SN color and star formation (a common tracer of dust) seems to favor the existence of multiple sources of reddening [Rigault et al.(2013)].

Recent enlarged supernova samples further showed that the standardized SN magnitude (what is used for cosmology) significantly depend on the global host galaxy stellar mass [Kelly et al.(2010), Sullivan et al.(2011), Childress et al.(2013)]. This correlation is currently used as a third empirical standardization, in addition to stretch and color [Betoule et al.(2014)]. This approach, while sufficient today, is not acceptable for future surveys for at least three reasons. First, the historical method of incorporating empirical correlations as they become significant creates a worry for further, still “hidden”, correlations. Secondly, it is clear that properties of an individual object can not be directly caused by those of an integrated galaxy, and that global galaxy mass must be a proxy for the individual explosion channel, local environment, or progenitor age or metallicity. Thirdly, part of the intrinsic dispersion observed must be due to this unknown progenitor bias. Understanding the origin of SNe Ia would thus most likely provide a decreased intrinsic dispersion, even more precise distance estimates and thus improved constraints on cosmological parameters.

Recent we published a statistical analysis of SNeIa compared with their local environment [Rigault et al.(2013)]. We showed that SNe Ia in areas of strong star formation are significantly brighter. As star forming regions are more likely to host young progenitor stars (<200 Myr), this strongly suggests such progenitors lead to brighter SNe after usual standardization. Also, passive environments favor massive galaxies. Hence, our results further explains the origin of the aforementioned correlation between the host mass and the SN brightness. Furthermore, we show that SNeIa from star forming environments are significantly more homogenous with a reduced dispersion of ≈ 0.10 mag. [Kelly et al.(2015)] even claim that these SNe could have a dispersion as low as 0.08 mag. This does not only make them more precise as distance indicators but also reduces the potential of undetected systematic effects by closing the room left for intrinsic dispersion. The “age step” have since been confirmed with independent data [Rigault et al.(2015), Kelly et al.(2015), Roman et al.(2018)], and see [Jones et al.(2015)] and their follow-up analysis [Jones et al.(2018)b] where they discuss the importance of going local in environmental analysis. In addition, the relation between the mass-step and the the age-step has then been modeled in [Childress et al.(2014)].

These results hold implications for the field of SN Ia cosmology. Star formation activity is redshift dependent. Unless corrected, the age-magnitude offset will thus bias estimates of the dark energy equation of state parameter by a few percent, which is of the same scale as all the other known errors combined [Rigault et al.(2013), Betoule et al.(2014), Ponder et al.(2016), Rigault et al.(2018), Scolnic et al.(2018)]. In addition, in [Rigault et al.(2015)], we found that the SN Ia used to calibrate the average SNIa luminosity to directly measure H_0 all come from star forming environments. In contrast, they only account for half of the Hubble-flow sample, i.e., the SNeIa at higher distances – $z > 0.02$ – where the influence on redshift of the galaxy peculiar motion is negligible in comparison to the expansion rate of the Universe. The measurement of H_0 is made by matching the magnitude of the few calibrating SN with the distance measurements based on Hubble-flow SNeIa. Because of the environmental effect we discovered, the derivation of H_0 was biased by $\approx 3\%$. However, by analyzing this astrophysical effect, we are able to correct for its influence on the derivation of H_0. Prior to our correction, the direct measurement of the Hubble constant was $\approx 4\ \sigma$ higher than the one derived by [Planck Collaboration et al.(2016)] and led to the speculation of existence of a fourth neutrino family. Our corrected value of 70.6 ± 2.5kpc s^{-1} Mpc^{-1}

is compatible with the CMB measurements at the $\approx 1\ \sigma$ level [Planck Collaboration et al.(2016)]. Yet, the appropriate method for incorporating the aforementioned bias in H_0 studies is hotly debated [Rigault et al.(2015), Jones et al.(2015), Jones et al.(2018)b, Riess et al.(2016)].

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