Memo 2.2.1: TYPE Ia SUPERNOVAE AS STANDARD CANDLES

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This memo provides a brief introduction to Type Ia supernovae (SNe Ia). It addresses the basic issues of how SNe Ia are defined and what sorts of stellar populations produce them; why they are so valuable as distance indicators for cosmology; and the nature of the standard physical model for SNe Ia.

CLASSIFICATION AND STELLAR POPULATIONS

Supernovae are classified primarily on the basis of their optical spectra. Those that show obvious hydrogen lines are called Type II. Those that lack obvious hydrogen lines but that do develop obvious He I lines are Type Ib. Neither hydrogen nor He I lines are conspicuous in supernovae of Type Ic. Most if not all events of Types II, Ib, and Ic are thought to result from core collapse in massive stars. The envelopes are ejected as the cores form neutron stars or black holes. The appearance of the optical spectra depends on the extent to which the progenitor stars retain (Type II) or lose their hydrogen layers (Type Ib), or even lose their helium layers (Type Ic), by the time of core collapse. The observed tendency for events of these three types to occur only in star-forming regions of galaxies is strong evidence that they come from massive stars that exist so briefly ($\lesssim 3\times10^8$ years) that they die where they were born.

The spectra of Type Ia supernovae (SNe Ia) lack hydrogen and He I lines but unlike Type Ic events they do include among other distinguishing characteristics a deep absorption feature near 6100 Å that is produced by blueshifted Si II $\lambda\lambda$6347, 6371. Given a good observed spectrum that extends as far as 6100 Å in the supernova rest frame, deciding whether it is or is not a spectrum of a Type Ia is practically always straightforward. (If the spectrum isn't of high quality and it doesn't extend to 6100 Å the classification may be uncertain.) For a recent review of supernova spectral classification that includes illustrations of the the spectra of each type, see Filippenko (1997).

Supernovae for which spectra aren't available are sometimes classified as Type Ia on the basis of their photometry (broad–band light curves and colors), but this must be done with caution and only with good data because some of the core–collapse events have photometric characteristics that are not so different from those of SNe Ia. Supernovae that appear in elliptical galaxies are commonly assumed to be of Type Ia because so far not a single event in an elliptical galaxy has been found to be otherwise.

Although SNe Ia occur in elliptical galaxies, which contain only old ($\sim 10^{10}$ years) stellar populations, they also occur in spiral galaxies, at a rate that is correlated with galaxy color: the bluer the galaxy — and by inference the higher the star formation rate during the last 10^9 years — the higher the SN Ia rate. This means that most SNe Ia are produced by stars that were born moderately massive (but < 8 $M_\odot$) and last $\sim 10^9$ years.

STANDARD CANDLES

The possibility that the peak luminosities of SNe Ia have only a small disperison, making SNe Ia valuable as "standard candle" estimators of distances to their parent galaxies, began to be discussed on empirical grounds during the late 1960s by Pskovskii and Kowal and it slowly gained further observational support and credence during the following two decades. The situation as of the early 1990s was reviewed by Branch & Tammann (1992), who strongly emphasized the observational homogenity of SNe Ia. A few of the events in the extant observational sample were recognized to be conspicuously peculiar, both photometrically and spectroscopically, but the mild apparent photometric differences among normal SNe Ia were not larger than the observational errors in the data available at that time. (Spectroscopic differences among even the normal SNe Ia were more apparent.) The intrinsic dispersion in the blue and visual absolute magnitudes, $\sigma(M_B)$ and $\sigma(M_V)$, after correction for extinction by intervening interstellar dust in our Galaxy and the supernova parent galaxies, was estimated to be no more than 0.25 mag, which corresponds to a dispersion in luminosity of 26 percent and therefore a dispersion of only 13 percent in distance when SNe Ia are used as standard candles. This luminosity homogeneity, together with the extremely high luminosity of SNe Ia (approaching 10^{10} $L_{\odot}$) that makes them detectable across the universe, plus the fact that unlike galaxies supernovae are observed as point sources which facilitates accurate photometry, make SNe Ia extremely attractive as distance indicators for cosmology.

Branch & Tammann expressed optimism that SNe Ia would become valuable for measuring the value of the Hubble constant, for exploring departures from pure Hubble flow (i.e., parent–galaxy peculiar velocities), and for demonstrating the time dilation of the light curves of high–redshift SNe Ia that must occur if the universe is really expanding. They also concluded that among the methods that had been proposed to measure the cosmic deceleration parameter, high–redshift SNe Ia as standard candles offered the best hope. As discussed at length elsewhere in this document, observational developments in the 1990s have been rapid, and great progress has been made in all of these applications of SNe Ia to cosmology. The large amount of effort (and *Hubble Space Telescope* time) that has been devoted to measuring the Hubble constant with SNe Ia has been reviewed by Branch (1998). Peculiar velocities have been measured (Riess et al. 1997). The time dilation has been established (Goldhaber et al. 1997; Leibundgut et al. 1996; Goldhaber et al. 2001). The startling discovery that the expansion is accelerating rather than decelerating (Riess et al. 1998; Perlmutter et al. 1999) has been reviewed by Riess (2000). The implications have been discussed by, e.g., Perlmutter, Turner, & White (1999). Recently, evidence for the early epoch of deceleration that is expected to have preceded the acceleration has been presented (Riess et al. 2001). The primary goal of the proposed SNAP experiment is, of course, to use SNe Ia to dramatically advance our ability to probe the history of the cosmic expansion.

THE STANDARD MODEL

As mentioned above, observations indicate that SNe Ia are produced by stars that are born with less than 8 $M_\odot$. However, single stars (and effectively single stars in wide binaries) in this mass range lose their envelopes non–explosively and settle down as stable cabon–oxygen white dwarfs that never explode. The standard SN Ia model appeals to a carbon–oxygen white dwarf in a close binary system that accretes matter from its main–sequence or red–giant companion until it is provoked to explode. As the white–dwarf mass approaches the Chandrasekhar limit of 1.4 $M_\odot$, its slow contraction causes its central temperature and density to rise enough to ignite carbon fusion. Because this occurs in electron–degenerate matter a nuclear instability ensues, followed by a nuclear burning front that propagates through the star and explodes it completely — no neutron star or black hole remains behind. The inner half of the white dwarf's mass is incinerated primarily to unstable ^{56}Ni, while the outer half is partially burned to intermediate–mass elements such as silicon, sulfur, and calcium, and partially ejected as unburned carbon–oxygen. The kinetic energy of the explosion, the difference between the released nuclear energy and the binding energy of the white dwarf, is about 10^{51} ergs, so the characteristic ejection velocity is 10,000 km s^{-1} (0.03c). The internal energy of the initially hot ejected matter is rapidly lost by adiabatic expansion, so if it were not for the delayed energy input provided by the gamma–ray and positron products of the radioactive decay of ^{56}Ni (6–day half–life) through ^{56}Co (77 days) to stable ^{56}Fe, the explosion would be an optical dud. The peak luminosity of an SN Ia therefore depends primarily on the mass of ^{56}Ni that is ejected, about 0.6 $M_\odot$.

The model can account for the observed wide range of time delays between star formation and SN Ia production because (1) stars of a range of masses and lifetimes end up as carbon–oxygen white dwarfs, and (2) the time between the formation and explosion of the white dwarfs depends on the time history of the rate of accretion from the companion star.

In the standard model, an obvious possible reason for the impressive homogeneity of SNe Ia is that each progenitor white dwarf must approach the fixed Chandrasekhar mass before it can explode. Possible reasons for the mild diversity that exists even among normal SNe Ia are that the range in the initial masses and compositions (especially the carbon to oxygen ratio) of the white dwarfs, and differences in the time history of their mass accretion rates, could lead to pre–explosion structural differences that cause a spread in the ejected masses of ^{56}Ni.

An alternative to the standard model is that *two* white dwarfs in a binary system spiral together owing to the loss of angular momentum by gravitational radiation and coalesce. This may be is a natural way for nature to assemble a super–Chandrasekhar mass, and the model certainly is not yet excluded, but most of those who have tackled the difficult problem of simulating a white–dwarf merger have concluded that it is more likely to collapse to a neutron star than to explode as a SN Ia. In this model a range in the total ejected mass also would contribute to the diversity of SNe Ia, and the spiral–in time would contribute to the time delay between star formation and explosion.

BIBLIOGRAPHY

Branch, D. 1998, *Type Ia Supernovae and the Hubble Constant*, Ann. Rev. Astron. Astrophs., 36, 17

Branch, D., & Tammann, G. A. 1992, *Type Ia Supernovae as Standard Candles*, Ann. Rev. Astron. Astrophys., 30, 359

Filippenko, A. V. 1997, *Optical Spectra of Supernovae*, Ann. Rev. Astron. Astrophys., 35, 309

Goldhaber, G., Deustra, S., Gabi, S., et al. 1997, *Observations of Cosmological Time Dilation Using Type Ia Supernovae as Clocks*", in Thermonuclear Supernovae, eds. P. Ruiz–Lapuente, R. Canal, J. Isern (Dordrecht: Kluwer), p. 777

Goldhaber, G., Groom, D. E., & Kim, A. 2001, *Timescale Stretch Parameterization for Type Ia Supernova B–Band Light Curves*, Astrophs. J., in press

Hillebrandt, W., & Niemeyer, J. C. 2000, *Type Ia Explosion Models*, Ann. Rev. Astron. Astrophys., 38, 191

Leibundgut, B., Schommer, R., Phillips, M. M., et al. 1996, *Time Dilation in the Light Curve of the Distant Type Ia Supernova 1995K*, Astrophys. J., 466, L21

Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, *Measurements of Omega and Lambda from 42 High–Redshift Supernovae*, Astrophys. J., 517, 565

Perlmutter, S., Turner, M., & White, M. 1999, *Constraining Dark energy with Type Ia Supernovae and Large–Scale Structure* Phys. Rev. Let., 83, 670

Riess, A. G. 2000, *The Case for an Acclerating Universe from Supernovae*, Publ. Astron. Soc. Pacific, 112, 1284

Riess, A. G., Davis, M., Baker, J., & Kirshner, R. P. 1997, *The Velocity Field from Type Ia Supernovae Matches the Gravity Field from Galaxy Surveys*, Astrophys. J., 488, L1

Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, *Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant*, Astron. J., 116, 1009

Riess, A. G., Nugent, P. E., Schmidt, B. P., et al. 2001, *The Farthest Known Supernova: Support for an Accelerating Universe and a Glimpse of the Epoch of Deceleration*, ApJ, in press