The cosmological parameters from supernovae

Pilar Ruiz–Lapuente
Department of Astronomy, Faculty of Physics, U. Barcelona, Spain
Max–Planck Institut für Astrophysik, Garching bei München, Germany

Abstract.
Supernovae are bright luminous stellar objects observable up to redshifts close to $z \sim 1$. They are used to probe the geometry of the Universe and its expansion rate by applying different methods. In this text, I review the various approaches used to measure the present expansion rate of the Universe, $H_0$, and the paths to determine its matter density $\Omega_M$ and the possible contribution of a non-zero cosmological constant $\Lambda$. An account is given of the numerical estimates of those cosmological parameters according to the present status of the research.

1. Introduction

The quest for three numbers $H_0$ (the present value of the Hubble parameter, i.e. Hubble constant), $\Omega_M$ (the matter density of the Universe, i.e. density parameter) and $\Lambda$ (the possible non-zero value of the cosmological constant) has become of primordial interest since the beginning of modern cosmology. The type of Universe in which we live is described by those numbers, and its evolution is related to them.

Original attempts to determine those values (see Weinberg 1973, for a review) involved the selection of a number of astrophysical objects which could be observed due to their brightness up to very large redshifts, and with properties of intrinsic luminosity well understood –i.e. either homogenous in luminosity or following a well-known correlation with a measurable observable.

Supernovae (SNe) were depicted as one of those objects, and their observed brightness along redshift space (also called Hubble diagram) suggested a way to trace the geometry and expansion of the Universe.

Along the following decades of research on these objects, very much has been learnt about their physical nature and observational properties such as spectra and light curves. We know that there are two ways in which a star can explode giving rise to what we know as a supernova. For massive stars the explosion occurs through the gravitational collapse of their core at the end of their evolution. This class constitutes the “gravitational collapse SNe” which includes the phenomenological Types II and Ibc (SNe II and SNe Ibc). A second way
in which stars explode is through a thermonuclear runaway of their degenerate core. This occurs for stars of low mass in binary systems which end up their lives as C+O degenerate cores: white dwarfs (WDs). If those stars belong to a close binary system, and accrete matter from the companion, the growth in mass produces an increase in density and temperature of the core which finally leads to the thermonuclear runaway. The “thermonuclear supernovae” correspond to the phenomenological class of Type Ia SNe (SNe Ia).

Being both SNe II and SNe Ia very bright events, a number of methods have been proposed to use their luminosity for cosmology purposes. Some of them have a purely empirical basis and some others involve a theoretical perspective. SNe Ia are more homogeneous than SNe II. This placed them as more favorable objects to be used as “standard candles” for cosmological purposes. I will restrict the discussion to what is being learnt through SNe Ia, actively used nowadays not only for the $H_0$ determination, but for that of $\Omega_M$ and $\Lambda$ as well.

2. Dispersion and relationships of Type Ia supernova luminosity

A standard candle to be used in the determination of the cosmological parameters should be able to depict the geometry of the Universe and its expansion rate with as much accuracy as possible. Ideally such a precise indicator would be a kind of “Cepheid” observable up to very large redshifts: an object whose magnitude could be predicted or known with very low intrinsic dispersion, its empirical relation with other observable properties being well understood. In Cepheids, the zero–point of the period–luminosity (P–L) relationship is known with a 0.1 mag of accuracy, and the dependence of the P–L relation with metallicity has also been well studied and can not be larger than 0.05 mag (Feast & Walker 1987).

We do not have objects so well–known in magnitude as Cepheids, which could be discovered and observed at redshifts close to $z \approx 1$. However, Type Ia supernovae are likely, among the existing distance indicators, the closest one to a “long–distance Cepheid” that we can find: the understanding of their intrinsic magnitude, and its correlation with observable properties such as the shape of the light curve and the spectral characteristics reduce the intrinsic dispersion in the predictable luminosity of those candles to $\sigma = 0.2$.

The history of how the understanding of SNe Ia has evolved and how the relationships between luminosity and other observables developed covers a long period of debates. Pskovski (1977, 1984) first suggested the relationship between absolute magnitude at maximum and rate of decline of the light curve. His assertion was objected on the grounds that it could be an effect of different intrinsic reddening (Boisseau & Wheeler 1991).

The follow–up of SNe Ia (Maza et al. 1994; Filippenko et al. 1992a,b; Leibundgut et al. 1992) confirmed that such an intrinsic dispersion in luminosity
and decline rates of the light curve were real. Extensive and accurate observations were collected by the CTIO group which allowed to build up a sort of “period–luminosity” relationship for Type Ia supernovae: a mathematical expression in which the intrinsic luminosity and the rate of decline of the light curve is established. Hamuy et al (1996a,b) expressed it as:

\[ M_{MAX} = a + b[\Delta m_{15}(b) - 1.1] \] (1)

where \( a \) and \( b \) are constants and \( \Delta m_{15} \) are the magnitudes decreased in 15 days after maximum. They found this relationship to be:

\[ M_B = -19.25 + 0.78 [\Delta m_{15}(B) - 1.1] + 5 \log(H_0/65) \] (2)

with an intrinsic dispersion of only \( \sigma \sim 0.2 \) mags.

Riess, Press & Kirshner (1995a) give an alternative way to express the intrinsic luminosity of Type Ia supernovae as related to the rate of decline of the light curve. They account for an overall shape parameter describing the evolution in luminosity before maximum to well past maximum. Their parameterization (see Figure 1), and the one by Hamuy and collaborators (1995; 1996a,b) give a comparable scale of magnitudes for specific SNe Ia. Riess, Press & Kirshner (1995a,b; 1996) have used as well the color light curve shapes to determine the reddening affecting the observed luminosity of the supernova.

Another independent line of research on SNe Ia by Tammann & Sandage (Tammann & Sandage 1995; Tammann et al. 1997, Tammann 1996) and Branch & collaborators (Branch et al. 1995) suggests that if restriction is made to those SNe Ia which fulfill a number of observable requirements from the spectroscopic point of view (Nugent et al. 1995 ), or from the colors, i.e. omitting objects redder than \( B-V = 0.2 \) (Tammann & Sandage 1995), the use of the decline–luminosity relationship is not necessary. According to those authors, the concept of spectroscopically “normal SN Ia”, also called “Branch–normal” SNe Ia is a sharp enough guidance to the luminosity of SNe Ia. The intrinsic dispersion of those “normal” SNe Ia would be of \( \sigma=0.3 \) mag.

Even within the empirical use of Type Ia supernovae for distance determinations, a spread of usages has proliferated. The final values of \( H_0 \) by various authors are still different and will be mentioned in section 6.

So far, we are discussing the prolific use of SNe Ia as candles from nearby supernovae samples (\( z \sim 0.1 \)). To derive \( H_0 \) is suitable to use a sample at \( z \) below 0.3 since at larger redshifts the contribution from the deceleration term can not be neglected. SNe Ia at \( z \geq 0.3 \) serve to determine \( \Omega_M \) and \( \Omega_\Lambda \). Those uses will be addressed in section 7.

In the following section, I would like to contrast the empirical usage of Type Ia supernovae with the theoretical expectations.
Figure 1. The use of light curve shapes to calibrate SNe Ia luminosities, from Riess, Press & Kirshner (1996).
3. Boundaries on $H_0$ from WD explosions

The absolute magnitude of an exploded WD has a limit established by the maximum mass of any WD which explodes: the Chandrasekhar mass $M_{Ch} \approx 1.38 M_\odot (Y_e/0.5)^2$, where $Y_e$ is the number of electrons per nucleon. A WD accreting mass beyond the Chandrasekhar mass would either undergo a gravitational collapse forming a neutron star, or it would form a exploding Chandrasekhar mass object plus an envelope of some mass around. The former would be an underluminous explosion, and the second would not imply significantly different absolute magnitudes than the bare exploded C+O WD.

In the thermonuclear explosion of a Chandrasekhar WD, the generated kinetic energy, $E_{kin}$ and the radioactive energy $E_{56Ni}$ are linked. The larger the radioactive energy from $^{56}Ni$, providing the luminosity, the highest expansion velocities $E_{kin}$ have the ejecta. A fast expanding ejecta traps less efficiently the radioactive energy: thus a self–constraining play on the final absolute magnitude is obtained in explosions of different energies to favor a maximum absolute magnitude which a Type Ia explosion could achieve. That limit corresponds to a final minimum $H_0$ of about 50 km s$^{-1}$ Mpc$^{-1}$.

An upper limit to the value that $H_0$ is provided by the discussion of the minimum mass of a exploding WD, and if that could correspond to what we see as SNe Ia. The exploration of the range of possible exploding WDs by various proposed mechanisms suggests that the range of what we can observe if a whole range of WDs below the Chandrasekhar mass explode is much wider that the objects we actually identify as SNe Ia. This argument disfavors $H_0$ larger than 75 km s$^{-1}$ Mpc$^{-1}$ (see sections 4 and 5).

4. Theoretical uses of Type Ia supernova through light curves

The first estimates and the use of theory of Type Ia supernovae to determine their absolute magnitude are found in Arnett, Branch & Wheeler (1985) who made a prediction of that value from the light curve of a exploded WD at the Chandrasekhar limit. That evaluation was based in the power of $^{56}Ni$ and the trapping of its radioactive decay energy to provide the peak of luminosity of a Type Ia supernova. Soon a number of difficulties appeared related to this approach: the calculation of the bolometric (overall) luminosity of a Type Ia supernova can be undertaken with moderate efforts. However, most of the observed light curves are given in broad–band filters: B, V, R & I. To make predictions of how the energy is distributed in the different colors requires to make calculations taking into account detailed opacities and NLTE effects, among others. One could address the problem trying to estimate a bolometric correction to transform the blue and visual light curves into bolometric light curves. Some authors have attempted this, but the bolometric corrections can easily become a bag of errors, if not sustained by light curve calculations, and the luminosity of SNe Ia go beyond any reasonable value.

The problem of calculating the color light curves was addressed in a number of papers by Höflich and Khokhlov (1995). They predict B, V, R, I light curves
for Type Ia supernovae, and attempt a simultaneous determination of reddening. Chandrasekhar explosions with differences in burning propagation could, according to their calculation, account for the intrinsic dispersion in SNe Ia light curves. Assigning to each individual supernova a reduced set of Chandrasekhar explosion realizations (in which differences arise from burning propagation or variation in envelope conditions), distances to those supernovae are derived.

A second caveat of the method of predicting the absolute magnitude of Type Ia supernovae is formulated in the question of what if the models considered for Type Ia supernovae are not correct after all. Arnett & Livne (1995) addressed this issue by considering a different mechanism for the explosion of a WD as a Type Ia supernova: the edge–lit detonations below the Chandrasekhar mass, and predicting how those light curves would be, and what would be the dispersion and absolute magnitude reached in those explosions. They found that the absolute maximum–rate of decline relationship can be easily accounted for if WDs encompassing a wide range of masses explode below the Chandrasekhar mass. Höflich et al (1997), on the contrary, argued against that possibility by pointing that those sub–Chandrasekhar explosions give too–blue light curves as compared with observations. They favor the explanation of the intrinsic dispersion of Type Ia supernovae by variations within the Chandrasekhar–mass model (Höflich et al. 1997).

Recently, Pinto & Eastman (1996) argue that a number of different effects playing into the light curve physics have not been addressed so far in calculations. They suggest that Chandrasekhar models do not give the sort of correlation between maximum brightness and rate of decline observed among SNe Ia.

5. The absolute magnitude of Type Ia supernovae and the density diagnostics

A different approach towards the absolute magnitude of Type Ia supernovae is linked to the possibility of obtaining density diagnostics of the object which explodes. This lead us to the discussion on the mass of the object that we see reflected in light curves and spectra.

Forbidden line emission is an excellent tracer of the density profile of an exploded object. In particular, ratios of lines of $[\text{Fe}^+]$ and $[\text{Fe}^{++}]$ inform us on the electron density of the exploded object. Density profiles, mass of the WD which explodes and luminosity are linked properties of the explosion. The most dense the WD the most easily will trap the $\gamma$–ray photons of the decays $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ which power the luminosity.

Through the density diagnostics provided by the late emission of SNe Ia it is possible to conclude on the correct model of explosion, and its luminosity (Ruiz–Lapuente 1996). The long–wavelength spectral comparison provides also a way to determine the reddening E(B-V) affecting the SN light (Ruiz–Lapuente & Lucy 1992).
Figure 2. Top: Distance scale favored by sub–Chandrasekhar and Chandrasekhar explosions and the discrimination through emission line. Bottom: Sensitivity of line emission to mass diagnostics. From Ruiz–Lapuente (1996).
That sort of analysis suggests that explosions below the Chandrasekhar mass (less dense explosions) fall outside the $n_e$–$T_e$ plane (electron density and temperature) suggested by the observations of normal SNeIa. That produces discrepancies between the predicted relative luminosities of the lines and those displayed by the SN. The top panel of Figure 2 shows the spectrum of a SN Ia from a Chandrasekhar WD at 300 days after explosion, compared with a spectroscopically normal SNIa, and a comparison of the same SN with a sub–Chandrasekhar model. The bottom panel gives the sensitivity of the emission lines to electron density.

6. Contrasting values of $H_0$ from SNe Ia

The initial discussion on the absolute magnitude of SNe Ia swept the wide range of values going from the mean value of absolute magnitude -18. to -20.5, having very different consequences for the value of the Hubble constant. The enormous progress made during the recent years has allowed to reduce considerably the uncertainty in that value.

From the empirical point of view the advance has come through the better study of the light curves of a large sample of supernovae and from the possibility of using distances to individual galaxies obtained through Cepheids to establish the zero point in the calibration of the absolute magnitude of Type Ia SNe (Sandage et al. 1994). From the theoretical point of view the improvement has come from the increasing sophistication in the calculations and the exploration of several mechanisms for the explosion of WDs. The path already covered has been amazing and a convergence of views can be foreseen.

To bring the story up to date, I will just compare some of the values preferred by the authors.

Tammann et al. (1996) have estimated the absolute magnitude of 7 SNe Ia from distances obtained from Cepheids in the HST programme. They list mean absolute magnitudes of $< M_B(\text{max}) > = -19.53 \pm 0.07$ and $< M_V(\text{max}) > = -19.49 \pm 0.05$ for “spectroscopically normal” SNe Ia, and thereby $H_0 = 56 \pm 3$ (Tammann et al. 1996). Branch et al. (1997) formulate that for spectroscopically normal SNe Ia, (bluer colors than B–V=0.2) the empirical calibration gives:

$$ M_B \simeq M_V = -18.6 - 5 \log(H_0/85) \quad (3) $$

These values can be contrasted with theoretical approaches. Höflich et al. (1997) obtain as a mean value for the absolute magnitudes of SNe Ia: $< M_B(\text{max}) > = -19.40 \pm 0.2$ and $< M_V(\text{max}) > = -19.37 \pm 0.18$. The absolute magnitudes from the forbidden emission approach using late–time SNe Ia spectra suggest a mean $< M_B(\text{max}) > = -19.2 \pm 0.2$ for “spectroscopically normal” SNe Ia and $< M_V(\text{max}) > = -19.2 \pm 0.2$. Thus, a mean shift of 0.2 mag in the central values compared with Tammann et al. (1996) results (overluminous SNeIa such as SN 1991T would reach -19.5). That 0.2 mag difference shifts from fifties to sixties the value of the Hubble constant. The method of light curves by
Höflich et al. (1997) favors $H_0 = 64 \pm 10$, and the late-emission method favors $H_0 = 68 \pm 6\,(\text{stat}) \pm 7\,(\text{external})$ (Ruiz–Lapuente 1996). Both approaches are independent from the zero–point calibration from Cepheids.

From the empirical approach, the relationship of absolute magnitude and rate of decline as derived by Riess, Press and Kirshner (1995a, 1996) and the zero–point calibration from HST Cepheids, it is found that standard SNe Ia (shape parameter zero) have $M_V(\text{max}) = -19.36 \pm 0.1$. These authors obtain a value of $H_0 = 64 \pm 6$. On his own, Hamuy et al. (1996a,b), using their parameterization of the rate of decline–brightness correlation and a zero–point calibration from four supernovae (SM 1937C, SN 1972E, SN 1981B, SN 1990N) out of the sample of HST distance–calibrated SNe Ia, obtain $H_0 = 63.1 \pm 3.4\,(\text{internal}) \pm 2.9\,(\text{external})$ km s$^{-1}$ Mpc$^{-1}$ and similar values for the mean absolute magnitude of normal SNe Ia to Riess et al. (1996). Thus, theoretical methods and empirical ones taking into account the correlation of brightness and rate of decline suggest values for the Hubble constant in the sixties range.

The way from absolute magnitudes and individual distances to a global value of the Hubble constant presents divergences among authors. It should be possible to establish the “central” value of the absolute magnitude of a SNIa: shape parameter zero for Riess et al. (1996); $\Delta m_{15} = 1.1$ from Hamuy et al. (1996a,b); a given (B-V) color according to Tammann et al. (1996) or spectral sequence (Branch et al. 1996; Nugent et al. 1996). Once the empirical correspondences are well determined there should be little room left for a disagreement on $H_0$.

On the other hand, much confidence exists on the possibilities of setting the final global value of $H_0$: It has been shown that the value of $H_0$ provided by SNe Ia at high redshift should not differ significantly from the local value obtained with a nearby sample at $z \sim 0.1$. Kim et al (1996) find $H_0^L / H_0^G < 1.10$ at a 95% confidence level. During the last years it has become more and more evident the depth of the Virgo cluster and the dangers of assuming a given galaxy to be at the core of that cluster. It has also been shown that the path of using relative distances between Virgo and Coma can be full of errors (Tammann 1996; see also the article by Hendry in this volume). These more controversial routes to the Hubble constant have not been used in the the works mentioned in this section. Despite the increasing agreement on absolute magnitudes of SNe Ia, if compared with the starting point of that discussion, the remaining difference between a $H_0$ of 50–60 and $H_0$ of 60–70 has important cosmological implications, and the discussion is not yet finished.

7. From a higher redshift

Type Ia supernovae being among the brightest objects in the Universe, soon were used to determine the deceleration parameter $q_0$ which leads us to decide whether we are in an open, flat or closed Universe. The deceleration parameter $q_0$ measures the role of the matter density in slowing down the expansion rate of the Universe, and a possible contribution of a non–zero cosmological constant accelerating the expansion.
\[ q_0 = \frac{1}{2} \Omega_M - \Omega_\Lambda \] (4)

where \( \Omega_\Lambda = \Lambda / 3(H_0)^2 \). As it can be seen in equation 4, a negative \( q_0 \) means that \( \Omega_\Lambda \) has a dominant contribution.

The relationship of observed magnitude \( m \) with redshift \( z \) for an object of constant luminosity has a dependence with \( q_0 \) which produces a bending in the \( m(z) \) diagram (the Hubble diagram). That relationship departs from a straight line at high \( z \):

\[ m = M - 5 \log H_0 + 25 + 5 \log cz + 1.086 (1 - q_0)z + O(z^2) \] (5)

Soon, Oke & Sandage (1968) realized that a practical use of that method implied to take into account the finiteness of the broad band filters in which one is collecting the light from distant objects. As the light is redshifted towards longer wavelengths in an expanding Universe and the power of energy emitted by unit time is affected by the frequency shift resulting from the expansion, a correction from the measurement of the received luminosity through a filter at the site of emission and at a site of observation far from emission has to be included. This correction, called K–correction, was pointed out by Oke & Sandage (1968) and has been applied thereafter (Kim et al. 1996).

The first attempts to discover SNe Ia at large redshift were made in the searches by Noeggaard–Nielsen et al. (1989) using the ESO 1m telescope. They resulted in the discovery of only two supernovae at high redshift in several years. A step beyond was finally achieved by the high–z supernova search by Perlmutter et al. 1996 (also called Supernova Cosmology Project) which started to discover dozens of supernovae at high redshift in discovery periods of only a few days. The Supernova Cosmology Project operates at telescopes of a number of observatories including ESO, CTIO, and La Palma Observatory, among others.

Other groups have started as well high–z SNe Ia searches: The High–z SN Search (Schmidt et al. 1996) operates at the CTIO, Mount Stromlo and Siding Spring, and Kitt Peak observatories. The Abell supernova search uses the southern hemisphere telescopes to discover SNe Ia in Abell clusters.

Follow–up of light curves and spectra (see Figure 3) is done and the decline–brightness relationship is used in the construction of the Hubble high–redshift diagram. Goobar & Perlmutter (1995) have reformulated the goal of determining the deceleration parameter by showing that it is possible to determine simultaneously \( \Omega_M \) and \( \Omega_\Lambda \). Thus, the goal is to measure the matter density of the Universe and decide whether a non–zero value of the cosmological constant is at work in our Universe. This is done through the separate contributions of both factors to the luminosity distance, \( d_L \) (see Figures 4 and 5):

\[ m(z) = M + 5 \log d_L(z, \Omega_M, \Omega_\Lambda) - 5 \log H_0 + K_c + 25 \] (6)
Figure 3. Spectra of SNe Ia at high z. The use of SNe Ia for deriving the cosmological parameters is improved by comparing distant SNe Ia spectra and those from SNe Ia in a low z sample (see Perlmutter et al. 1996; Nugent et al. 1996).

Figure 4. The m(z) relation for different choices of $\Omega_M$ and $\Omega_\Lambda$ according to Goobar & Perlmutter (1995). New values will allow to discriminate among the possibilities.
Figure 5. In this figure it is shown the the effect of the brightness-rate of decline relationship in the final diagram $m(z)$ for the early high-redshift SNe Ia sample (Perlmutter et al. 1996).
8. Number counts of SNe Ia and the geometry of the Universe

Another way to approach the evaluation of the geometry of the Universe is through the number counts of SNe Ia. The method has recently been proposed by Ruiz–Lapuente & Canal (1997), and the uncertainties and future perspectives are discussed in that work. Its basis is to predict the number counts of SNe Ia in different models of Universe. The main uncertainty there is the sort of binary scenario giving rise to Type Ia explosions: double degenerate systems where the most massive WD accretes matter from the disrupted WD companion, or single degenerate systems where a WD accretes from a main–sequence star or a giant star. The expected number of Type Ia explosions from diverse scenarios are very different depending on the type of Universe we are in (according to the various possibilities for $\Omega_M$ and $\Omega_\Lambda$), and their evolution going towards earlier cosmic times clearly points out to one scenario or another. This approach can be used to determine both the sort of explosion mechanism for SNe Ia and the sort of Universe in which they explode. The advantage of using number counts of SNe Ia in relation to that of other objects is that the luminosity corrections to apply are very limited. Uncertainties mainly come from the star formation history and the particular evolutionary uncertainties in each framework for explosion.

The first steps towards establishing a global star formation history in the Universe have been done observationally. A peak of star formation at z=2 has been detected and the shape of this function starts to become available (Madau 1996; Madau et al. 1996). On the other hand, the paths towards explosion in different scenarios have been studied and the calculations performed by various authors result in agreement on the expected behavior. The hypotheses for each evolutionary path can be contrasted with observations of the precursor objects of the finally exploding WDs, such as planetary nebulae, mass accreting X–ray sources etc. (Ruiz–Lapuente & Canal 1997).

On the observational side, searches for rates of SNe at high redshifts are providing the first statistical determinations of the number of SNe exploding as a function of magnitude: SNe Ia year$^{-1}$ deg$^{-2}$ mag$^{-1}$ (see results by Pain et al. 1996). Searches conducted at different observatories will very soon provide new results.

The method is different from the one using the luminosity of SNe Ia to derive $\Omega_M$ and $\Omega_\Lambda$. The number density of explosions taking place $N(z)$ will be an indication of the geometry of the Universe instead of the observed brightness along redshift $m(z)$. Understanding the evolution in number of the SNe Ia exploding along redshift space would provide as well a step ahead to approach the chemical history of the Universe in a more certain way.

9. Contrasting values

We gave a look above to the values of $H_0$ derived by various authors. We would like to point out some of the results obtained so far through the use of Type Ia supernovae in determining $\Omega_M$ and $\Omega_\Lambda$. The last available values point towards a
Figure 6. The use of SNe Ia counts to determine the geometry of the Universe, from Ruiz–Lapuente & Canal 1997. DD stands for the double degenerate scenario for SNe Ia and CLS for the most favorable single degenerate one. The observational points are from Pain et al. 1996, and Pain 1997, private communication.
Universe with significant matter density (Perlmutter et al. 1996) and $q_0$ positive. However, the error bars are still large. Due to the fact that the early sample was clustered at $z=0.4$ it has not been possible to discriminate independently $\Omega_M$ and $\Omega_\Lambda$ (see Figure 7). The preliminary observations give an Universe with $\Omega = 0.88^{+0.69}_{-0.60}$ (for $\Lambda = 0$).

10. Measuring cosmic flows

Given the validity of SNe Ia as accurate distance indicators, they can be used to trace bulk motions in the Universe. Riess, Press & Kirshner (1995b) using the light curve shapes approach, investigated peculiar motions at moderate redshift. Analyzing the distribution on the sky of velocity residuals from a pure Hubble flow for 13 SNe Ia they found the best solution for the motion of the Local Group to be of $600 \pm 350$ km s$^{-1}$ in the direction $l = 260^0$, $b = +54^0$ (see Figure 8). This illustrates the power contained in a sample of accurate light curve measurements to constrain cosmic flows.

11. The age of the Universe, the matter density and the Hubble constant

The age of globular clusters place a constraint to the age of the Universe of 14 $\pm$ 2 Gy (Chaboyer 1995; Jiménez 1997). For $H_0$ of 60–70 and $\Omega$ larger than 0.3, the age of the Universe according to Friedmann cosmologies is shorter than 12 Gy. For $\Omega = 1$ and $H_0$ in the previous range of values, the age is shorter than 10 Gy. A non–zero cosmological constant $\Lambda$ as first introduced by Einstein (1917), could give an answer to the contradiction between observed age values and the expected range of ages of universes within the favored values of the cosmological
Figure 8. Derivation of peculiar motions from SNe Ia by Riess, Press & Kirshner (1995b). Filled/open crosses show the direction toward which the Local Group is approaching/receding according to the best fit for their SNe Ia data.
parameters. But the value of $\Lambda$ is also limited by SNe Ia observations (so far $q_0$ seems to be positive).

If, as suggested by Tammann and Sandage (1995), $H_0$ is around 50, the age of the Universe is comfortably larger and neither a non–zero cosmological constant, nor deviations from the Friedmann universes are needed.

However, if a global value of $H_0$ around 65 is confirmed, and the Universe is flat with $q_0$ close to 0.5, an alternative to the well tracked classical paths should be sought. Dabrowski & Hendry (1997), for instance, have made a reanalysis of the situation and show that in inhomogeneous universes the above values of $H_0$ and $q_0$ imply ages largely compatible with the limits on the age of the Universe resulting from the globular cluster ages. If a value of $H_0$ between 60 and 70 is confirmed, and the Universe is as dense as suggested by the preliminary Perlmutter et al. (1996) results, the door to old and new alternatives would reopen again.

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