TYPE Ia SUPERNOVA COUNTS AT HIGH $z$: SIGNATURES OF COSMOLOGICAL MODELS AND PROGENITORS

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ABSTRACT

Determination of the rates at which Type Ia supernovae (SNe Ia) occur in the early universe can give signatures of the time spent by the binary progenitor systems to reach explosion and of the geometry of the universe. Observations made within the Supernova Cosmology Project are already providing the first numbers. Here it is shown that, for any assumed SNe Ia progenitor, SNe Ia counts up to $m_{\theta} = 23–26$ are useful tests of the SNe Ia progenitor systems and cosmological tracers of a possible nonzero value of the cosmological constant, $\Lambda$. The SNe Ia counts at high redshifts compare differently with those at lower redshifts depending on the cosmological model. A flat, $\Omega_m$-dominated universe would show a more significant increase of the SNe Ia counts at $z \sim 1$ than a flat, $\Omega_m = 1$ universe. Here we consider three sorts of universes: a flat universe with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 1.0$, $\Omega_\Lambda = 0.0$; an open universe with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$; and a flat, $\Lambda$-dominated universe with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$. On the other hand, the SNe Ia counts from one class of binary progenitors (double-degenerate systems) should not increase steeply in the $z = 0–1$ range, contrary to what should be seen for other binary progenitors. A measurement of the SNe Ia counts up to $z \sim 1$ is within reach of ongoing SNe Ia searches at high redshifts.

Subject headings: cosmology: miscellaneous — supernovae: general

1. INTRODUCTION

Supernovae are bright stellar explosions that can now be observed up to redshifts of $z \sim 1$. Several programs (Perlmutter et al. 1997, 1998; Schmidt et al. 1996; Garnavich et al. 1998) are presently devoted to discovering high-redshift supernovae for cosmological purposes. The goal is to determine the geometry of the universe through the effect that have on the magnitude-redshift relationship of Type Ia supernovae (SNe Ia). The same programs provide rates of explosion up to large redshifts through the proper evaluation of control time and the efficiency of detection. Indeed, the Supernova Cosmology Project has already achieved the first results after evaluating the data collected in its 1995 and 1996 discovery runs (Pain et al. 1996, 1998). In this Letter, we outline the theoretical background for the prediction of those number counts for different geometries of the universe and for various SNe Ia progenitors. The pace at which stars formed in the past (the star formation rate [SFR]) and the evolutionary clock rate of explosion for those binary supernovae are reflected in the counts. The evolutionary clock spans, in the case of SNe Ia (as opposed to SNe II), an important fraction of the age of the universe. SNe Ia counts extending up to apparent red magnitudes $m_{\theta} \sim 23–25$ could provide a good test of the SNe Ia binary progenitor systems. We also find that SNe Ia counts should be sensitive to a $\Lambda$-dominance in our universe through a larger increase at $z \sim 1$. Refinements in the determination of the global SFR and continued SNe Ia searches at large redshifts should furnish an accurate enough basis for both tests in the near future.

2. MODELING

The global SFR recently derived for high-redshift galaxies in the Hubble Deep Field (HDF) by Madau et al. (1996) has been extended to lower redshifts (Madau 1998), in accordance with the results of Lilly et al. (1995, 1996). It peaks at $z = 1.5$ and has been observed, for $z > 2$, from the UV luminosity density along the redshift. Rowan-Robinson et al. (1997) have also derived an SFR$(z)$ from infrared observations of galaxies in the HDF from the Infrared Space Observatory. The general shape agrees well with Madau’s (1998) data, but the inferred values are higher, maybe implying that about of star formation at high $z$ has taken place shrouded by dust. In a different approach, Pei & Fall (1995) have dealt with the determination of the global star formation history by tracking the evolution of the global H I contents of the universe as measured from Ly$\alpha$ QSO absorption-line systems. The results of Madau et al. (1996) agree with those from that very different approach. Prospects to explore further the global SFR include the number counts of SNe II discovered at high redshift, which should trace the activity of star formation in the universe along $z$. Such numbers on SNe II are obtainable in current high-z SNe searches. Given the continuous improvement in the determination of the global SFR, we base the present calculation of SNe Ia number counts on the most recent empirical results. We evaluate the rate of explosion of SNe Ia by convolving their time to explosion with the SFR. The rate can then be calculated as

$$ r_{\text{SNe Ia}} (t) = \int_0^t R (t - \tau) \text{SFR} (\tau) \, d\tau, $$

where $R(t)$ is the SNe Ia rate after an instantaneous outburst, and $t$ and $\tau$ are in the SN rest frame. Depending on the progenitor systems, in some cases we would have SNe Ia with a peak rate of explosion at 10$^9$ yr. In other cases, there can be some SNe Ia exploding only a few 10$^9$ yr after star formation, thus becoming the brightest optical events at $z \gg 1$. The SFR$(\tau)$ is derived from the global SFR$(z)$ (Madau et al. 1996; Madau 1998). The adopted SFR$(z)$ (for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 1.0$, $\Omega_\Lambda = 0$) is shown in the top panel of Figure 1, along
The dependence on cosmological parameters of the comoving volume derivative \(dV/dz\) differs from one model of the universe to another. A different cosmological effect is the age-redshift \([f(z)]\) relationship for different model universes, which changes the \(z\) at which the SNe Ia rates peak. The results are tightly linked to the reliability of the global SFR. An estimate of its current uncertainty can be obtained by looking at the data points in the top panel of Figure 1. Increasingly accurate SFRs should steadily improve the SNe Ia rate predictions. There is also increasing evidence of universality in the slope of the initial mass function (IMF) from tests in different metallicity and age environments. Such a "universal" mass function would be well represented by the Salpeter (1955) power law with \(x = 0.86 \pm 0.23\). Both the overall trend to convergence in the estimate of the global SFR\((z)\) and the near constancy of the IMF favor the possibility of deriving global values for the SNe Ia explosion rates.

### Stellar clock: binary progenitors

All evolutionary models for SNe Ia progenitors involve the accretion of mass by a C + O white dwarf (WD) from a companion in a close binary system. Current research on SNe Ia has discarded some formerly proposed SNe Ia scenarios. The two classes of binary systems considered here as the most likely systems giving SNe Ia are (1) the merging of two white dwarfs, also called the double-degenerate (DD) scenario, and (2) the accretion by the WD of H from a less evolved star in a close binary system, a single-degenerate (SD) scenario. We call this second case a cataclysmic-like system (CLS). The time evolution of the SNe Ia rates after star formation differs from one family of progenitor systems to another, and there are variations within each family. We have modeled the SNe Ia rates by means of the same Monte Carlo code as in previous works (Ruiz-Lapuente, Burkert, & Canal 1995, hereafter RBC95; Ruiz-Lapuente, Canal, & Burkert 1997; Canal, Ruiz-Lapuente, & Burkert 1996, hereafter CRB96), and we have adopted different prescriptions for each evolutionary path and for the initial binary parameters. We have also compared our predictions with those of other authors: (1) The physical input for the merging of two C + O WDs is modeled both as in Iben & Tutukov (1984) and as in

with the measured data points and their error bars. Note that the data points from Connolly et al. (1997) for the 1 \(\lesssim z \lesssim 2\) range fall somewhat below the adopted curve, whereas those from Rowan-Robinson et al. (1997) for the 0.6 \(\lesssim z \lesssim 1\) range are significantly above the adopted curve.

The SFR \((z)\) is transformed according to the geometries of the model universes considered. Here we restrict this presentation to three favored models of the universe: (1) model A, a flat universe with \(H_0 = 65\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 1\), \(\Omega_{\Lambda} = 0\); (2) model B, an open universe with \(H_0 = 65\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.3\), \(\Omega_{\Lambda} = 0\); and (3) model C, a flat universe with \(H_0 = 65\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.3\), \(\Omega_{\Lambda} = 0.7\).

The SFR \((z)\) derived for each case is next transformed into SFR\((t)\) using equation (1) and integrated over the comoving volume to obtain the expected SNe Ia counts (yr\(^{-1}\) sqdeg\(^{-1}\)) as a function of \(z\). We integrate over \(dV\):

\[
dV = \frac{d\Omega}{[1 + \Omega_m H_0^2 d_m^2]^{1/2}} d\Omega \frac{d\Omega}{d\Omega}.
\]

where \(d_m\) is the proper motion distance and \(\Omega_m = 1 - \Omega_m - \Omega_{\Lambda}\) is the fractional contribution of the curvature to the expansion (Carroll, Press, & Turner 1992). \(d_m\) is related to the luminosity distance \(d_L\) through \(d_L = (1 + z)d_m\) (Weinberg 1972); \(d_L\) is calculated as

\[
d_L = \frac{(1 + z)}{H_0 \Omega_m^{1/2}} \sin \left(\Omega_m^{1/2} \right)
\times \int_0^{z} \frac{(1 + z)^2 (1 + \Omega_{m} z) - z (2 + z) \Omega_{\Lambda}^{1/2} dz}{z^2}.
\]

where "sinn" stands for "sinh" if and for "sin" if \(\Omega_m > 0\) and for "sin" if \(\Omega_m < 0\) [both sinn and the \(\Omega_m\) terms disappear from eq. (3) if \(\Omega_m = 0\), leaving only the integral times \((1 + z)/H_0\)]. The integration is performed numerically.

The SFR is calculated as

\[
SFR(z) = \int_0^z \frac{d\Omega}{d\Omega} d\Omega.
\]

where \(\Omega_m\) stands for \(\sinh\) if and for \(\sin\) if \(\Omega_m > 0\) and for \(\sin\) if \(\Omega_m < 0\).
RBC95. We allow for a number of different physical descriptions of the binary evolution, and we try different values of the common envelope parameter $\alpha$ (a measure of the efficiency with which orbital energy is used in envelope ejection). (2) The physical modeling of the explosion of a C + O WD when it reaches the Chandrasekhar mass by accretion and burning of H from a main-sequence, subgiant, or giant companion is modeled as in the early work of Iben & Tutukov (1984), as in CRB96, and finally including the most recently proposed variation of the binary evolution by Hachisu, Kato, & Nomoto (1996), who find a “wind” solution for fast hydrogen accretion by a WD from a red (sub)giant companion, but we apply the same evolutionary constraints as Yungelson et al. (1996).

Particularly relevant to the modeling are the slope of the IMF, the distribution of mass ratios $q$ of the secondary to the primary, and the distribution of initial separations $A_{in}$ in the progenitor binary systems, together with the prescriptions for mass transfer. By trying various physical approaches adopted by different modelers and exploring different values of the initial binary parameters (IMF, $q$, and $A_{in}$ distributions) and assumptions as to the mass transfer rates, we obtain the characteristic behavior of each stellar clock and the uncertainties in the absolute scale of the rates. In Figure 1, a comparison of $R(t)$ (in equation (1)) with those from other authors (middle panel: different IMF, $q$, and $A_{in}$ distributions; bottom panel: different assumptions as to the allowed mass transfer rates) is made. From such a comparison, we concluded in our previous work that the evolution of the SNe Ia rates (rise, peak, decline) along cosmic time, for a given class of systems, has broad common features shared by the predictions from different authors (Iben & Tutukov 1984; Tutukov & Yungelson 1994; Yungelson et al. 1996; our own modeling), which basically describe the clock of the corresponding systems. The Hachisu et al. (1996) solution, here called CLS(W), would allow us to have some relatively young SNe Ia in the CLS scenario, and the SNe Ia rate would increase faster with redshift. On the other hand, the DD scenario predicts a flatter increase of the rate from $z = 0$ to $z = 1$, in all model universes. In all cases, the $R(t)$ shown here would give, for our own Galaxy and the present time, SNe Ia rates that are within the current error bars of the observational estimates.

Versions CLS and CLS(W) in the bottom panel of Figure 1 illustrate the range of uncertainty in the time of start of the explosions in the SD scenarios. For the DD progenitors, we have chosen the most favorable physical assumptions, those that enhance the numbers of SNe Ia at high $z$, in order to best reproduce the first observational results. Any other choice would give lower numbers. In fact, the observed numbers seem to be above the predictions for this type of binary progenitor system (but one should stress here the uncertainty in the global SFR). A clear feature of the DD scenario is not only that the SNe Ia rates do not increase faster toward higher redshifts but also that they are lower than those predicted for the SD progenitors. We should note here that we are assuming the universality of the distributions of binary parameters determined for the solar neighborhood (Duquennoy & Mayor 1991). We have explored, however, the effects that plausible changes in the initial $q$ and $A_{in}$ distributions would have on the outcome and have found them to be only moderate (see below).

Counts as a function of magnitude.—We compare the model counts with the observations by deriving the dependence of the number counts on $m_b$, the apparent magnitude of the SNe Ia in the $R$ photometric band. In fact, in this transformation the intrinsic dispersion in brightness of the SNe Ia is not a key factor, since we are using the $N$-magnitude relationship measured in intervals of 0.2–0.5 mag for our tests (we could also use $N_z$, thus avoiding the transformation to magnitude). The intrinsic dispersion in magnitude is, in contrast, very important for cosmological tests using $m(z)$. We assume the SNe Ia to have an average absolute blue magnitude $M_b = -18.52 + 5 \log (h/0.85)$, where $h \equiv H_0/100$ (Perlmutter et al. 1997). The distance modulus for each $z$ is calculated from the luminosity distance $d_L$. The apparent $m_b$ at maximum as a function of $z$ is determined from

$$m_b = M_b + 5 \log d_L(z) - 5 + K_{corr},$$

where $K_{corr}$ is taken from Kim, Goobar, & Perlmutter (1996) (it includes the full transformation from $B$ into $R$ magnitudes). We finally calculate the variation of the SNe Ia rate ($\text{yr}^{-1} \text{sq} \text{deg}^{-2} \text{M} \text{ag}^{-1}$) with apparent red magnitude $m_b$ (we take $\Delta m_b = 0.5$ mag). The results are displayed in the four panels of Figure 2. The data points currently available (Pain et al. 1996; R. Pain 1997, private communication) are shown in the figure. The dips in the curves are entirely due to the shape of the $K$-corrections. The different slopes of the curves from one family of progenitors to another mainly reflect how fast the SNe Ia rate declines after reaching its peak value plus the time elapsed between star formation and the peak [steeper decline and longer time delay for the CLS and CLS(W) models than for the DD model; see the middle and bottom panels of Fig. 1], and the absolute values of the rates at low redshift ($m_b = 20–21$) are sensitive to the ages of the corresponding model universes [$t_f(A) < t_f(B) < t_f(C)$]. The slopes of the
rates, when comparing different models of the universe, are sensitive to the contribution of a nonzero $\Lambda$. The faster increase of the rates with magnitude (redshift) along the model sequence $A-C$ corresponds to the increasing comoving volume derivatives ($dN/dz$) in the respective model universes. Such a derivative is large if $\Omega_\Lambda$ gives a significant contribution to $\Omega$. As a check on the sensitivity of the results to the choices of the binary model parameters, we have also calculated the $dN/dm-z_m$ relationship, for the DD progenitor, adopting different $q$ and $A_0$ distributions (the dotted line in the middle panel of Fig. 1): the final curve is not very sensitive to the various choices of the distributions explored in this work (the model is shown by the continuous line in the four panels of Fig. 2).

Taking, at their face values, the SFR and the parameters for the SNe Ia progenitor evolution adopted, and also the two data points, the results for both the CLS and CLS(W) systems give better fits to the data than those for the DD systems, model universe $A$ being most favored and model $C$ giving the worst fit for any kind of system. But those conclusions are preliminary, and we must await the reduction of the uncertainties in the observed counts and in the global SFR for the intermediate-mass stars leading to SNe Ia. As we can see from Figure 2, at present the uncertainty in the SNe Ia counts at $m_0 = 22$ is on the order of a factor of 2. That is the same as the difference between the prediction for the DD model and the lowest one for the SD model, and it is also similar to the range covered by the two extreme predictions [CLS and CLS(W)] for the SD model. Any increase in the SFR would allow significantly shifting upward all the count predictions. At higher magnitudes, the range of predictions for the SD models becomes narrower, while the differences with the DD model increase. Thus, if we knew both the SNe Ia counts at $m_0 \approx 23$ and the global SFR to better than a factor of 1.5, we could already discriminate between the SD and DD models. The sensitivity to the cosmological parameters $\Omega_0$ and $\Omega_\Lambda$ is still low at those magnitudes. If we had determined, for instance, the DD model to be the right one, then the SNe Ia counts at $m_0 = 24.5$ (corresponding to $z = 1$) in the $C$ universe ($\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$) should be twice as large as those in the $A$ universe ($\Omega_0 = 1$, $\Omega_\Lambda = 0$), the factor of increase of $m_0 = 22$ to $m_0 = 24.5$ also being twice as large in case $C$ as compared with case $A$ (both contrasts would be sharper if the SD model were the right one). The high-$z$ SN searches to measure $\Omega_0$, $\Omega_\Lambda$ from the variation of the apparent magnitudes of SNe Ia are now almost reaching $z = 1$ (Perlmutter et al. 1998; Garnavich et al. 1998). From samples large enough to derive the SNe Ia counts at $z = 1$, the constraints on both parameters derived from the apparent magnitudes should, in principle, be tighter than those obtainable from the counts alone, but the latter could provide a supplementary test, since the method is based on a different approach: the use of a volume effect instead of a redshift-magnitude effect. Counts extending to even higher magnitudes would more clearly reveal the geometry of the universe. Suggested SN searches up to infrared magnitudes $K \sim 26-27$ (Miralda-Escudé & Rees 1997) would extend well beyond that point.

3. Conclusions and Future Prospects

The theoretical results presented here are intended to show the potential of the comparison between model predictions and the results of ongoing and future SN Ia searches. The slopes of the $dN/dm-z_m$ curves are mainly sensitive to the general characteristics of each SNe Ia model, while the absolute values depend more on model parameters and on the SFR, hence the interest in data covering a broader $m_0$ (or $z$) range than those currently available. On the other hand, the differences in the predictions from any SNe Ia progenitor assumed, for $\Omega_\Lambda$-dominated universes as compared with matter-dominated and open universes, become significant at large enough values of $m_0$. In a universe dominated by $\Omega_\Lambda$, the number counts of SNe Ia show a larger increase at $z = 1$ because of the large volume encompassed at that redshift. Useful information would be obtained by the measurement of the evolution of the SNe Ia counts up to $z = 1$ and beyond (possibly in the $K$ band for higher redshifts).

The first data obtained by Pain et al. (1996) gave a value of $34.4^{+3.9}_{-1.6}$ SNe Ia yr$^{-1}$ sqdeg$^{-1}$ in a magnitude range of $21.3 < R < 22.3$. These first results were obtained from three SNe discovered at redshifts 0.374, 0.420, and 0.354 (SN 1994H, SN 1994a, and SN 1994f), and the small-number statistics dominate this very first measurement. A larger bulk of data, already obtained, will now reduce the statistical uncertainties, and prospects to extend the observations up to higher $z$ are on the way. It is thus too soon to extract firm conclusions from the data. Our purpose here is to propose a new, useful test to be completed in the near future.

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