^{56}Ni Mass in Type IIP SNe: Light Curves and Hα Luminosity Diagnostics

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Summary. We analyze late-time observations, available photometry and spectra, of a sample of type II plateau supernovae (SNe IIP). The possibility of using Hα luminosity at the nebular epoch as a tracer of ^{56}Ni mass in this class of objects is investigated, yielding a consistency with the photometry-based estimates within 20%. Interesting correlations are found and their impacts on our present understanding of the physics of core collapse SNe are discussed.

1 Results and Discussion

The study of SNe IIP (i.e., optical properties, asymmetry, clumping, nucleosynthesis and yields) provides constraints on the explosion models and pre-supernova parameters. In particular, the ^{56}Ni mass is one of the crucial parameters since it presumably depends on the presupernova structure and the explosion model [1].

   We select a sample of type IIP SNe on the basis of available photometry and spectra, especially at latter epochs. In Fig. 1(left) we display the absolute $V-$light curves of the SNe sample together with that of SN 1987A. We adopt unique distance determination methodology, namely using the recession velocity of the host galaxy corrected for Local Group in fall onto the Virgo Cluster and assuming a Hubble constant H$_0$=70 km s^{-1}Mpc^{-1}. Galactic extinction is removed using the map of galactic dust extinction by Schlegel et al. [7], while the host galaxy reddening is estimated from the "$B - V$" and "$V - R$" color excess compared to the intrinsic color curves of SN 1987A. This is based on the fact that at the late photospheric phase, through the end of the recombination phase, SNe IIP seem to follow color evolution similar to SN 1987A [8].

   The computed late time decline slopes, in the $150 - 400$ d time range, are consistent with the radioactive decay of ^{56}Co and consequent trapping of the gamma-rays. Indeed a mean value of about $< \gamma^V > \ \simeq \ 0.99$ (± 0.13) for the sample SNe is measured.

   Once we fix the points related to the extinction and distance, which are crucial when dealing with a SN-sample study, we proceed with computing the amounts of ejected ^{56}Ni using the absolute $V-$light curve of SN 1987A
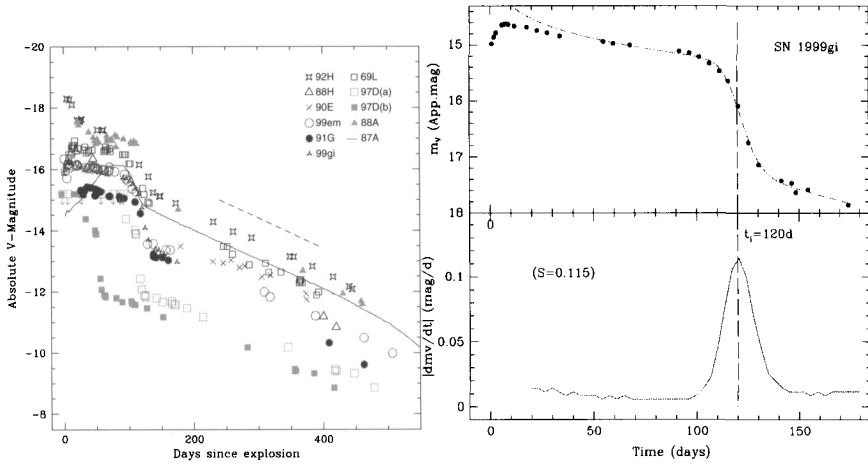
Fig. 1. Left: M_V light curves of the SNe sample. The dashed line shows the slope for ^{56}Co decay. Right: determination of the steepness and inflection time for the case of SN 1999gi (data from Leonard et al. [6]).

as template (in the $120-400$ days time range). We found a range from lower values for SN 1999eu and SN 1997D to a higher one for SN 1992H ([0.003 − 0.13] $M_\odot$), with an average of about 0.05 $M_\odot$. These results combined with the emergence of the extremely faint and bright events (see also the chapters by Pastorello and by Hamuy in these Proceedings) tend to change the general belief about the ^{56}Ni production in type II SNe (i.e. all eject $\sim 0.07\ M_\odot$). The above facts are extremely important for modeling the chemical evolution of galaxies since they impose constraints on the iron production.

Analyzing the absolute light curves of the sample events, we introduce a new parameter, called "*steepness*" and defined as $S = -dM_V/dt$, which describes the shape of the light curves and provides a way to measure the decay rate at the inflection point. The light curves in the transition period from plateau to radioactive tail are approximated by a sum of plateau and radioactive terms:

$$F = A\frac{(t/t_0)^p}{1 + (t/t_0)^q} + B\exp(-t/111.26),\tag{1}$$

where A, B, t_0, p and q are parameters derived by the χ^2 minimization technique in the sensitive interval $t_i \pm 50$ days. Fig. 1(right) demonstrates the behavior of S and determination of the inflection time t_i for the case of SN 1999gi.

The correlation between the ^{56}Ni mass and plateau M_V found by Hamuy [5] is confirmed (Fig. 2, left), and the linear fit is described by the equation:

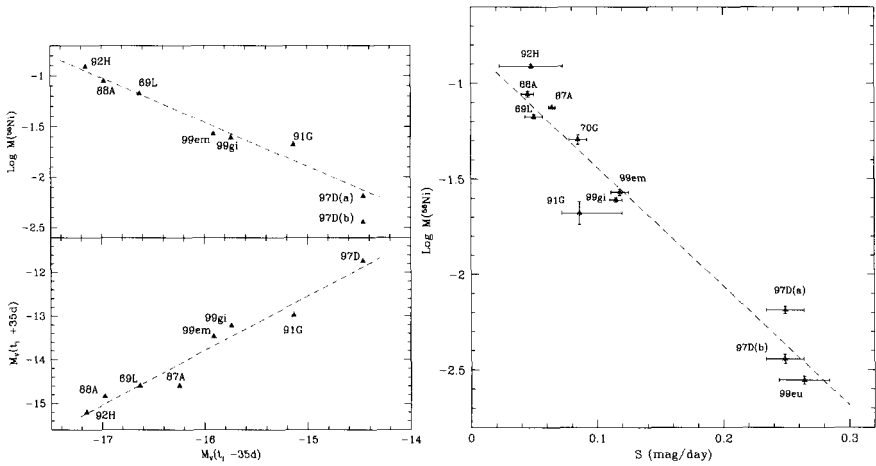$$\log M(^{56}\text{Ni}) = -0.438M_V(t_i - 35) - 8.46.\tag{2}$$

Fig. 2. Left: the correlation between M_V magnitudes of plateau and of radioactive tail. Upper panel shows the correlation between M_V at the moment $(t_i - 35\mathrm{d})$ and ^{56}Ni mass derived from the tail magnitudes. Lower panel shows directly the correlation of plateau magnitude $M_V(t_i - 35\mathrm{d})$ and tail magnitude $M_V(t_i + 35\mathrm{d})$. Right: the correlation between ^{56}Ni mass and steepness S. Case "a" of SN 1997D is adopted for the fits (dashed lines).

Furthermore an interesting by-product of the sample photometry analysis is the correlation found between ^{56}Ni mass and the steepness parameter S. The correlation is quantified on the basis of the available data (Fig. 2, right), and the best linear fit reads:

$$\log M(^{56}\mathrm{Ni}) = -6.2295\,S - 0.8147 \tag{3}$$

The correlation is such that the steeper the decline at the inflection point the lower is the mass of ^{56}Ni. Although the interpretation of this correlation requires hydrodynamical modeling with different amounts of ^{56}Ni and degrees of mixing, it may well be that somehow the increase of the ^{56}Ni mass in SNe IIP ejecta favors the larger radiative diffusion times at the end of the plateau and, therefore, a less steep transition from plateau to the radioactive tail, or that the increase of the ^{56}Ni mass is accompanied by the growth of the degree of mixing which favors a less steep decline. This correlation is interesting in the sense that, if confirmed, it will provide distance and extinction independent estimates of the ^{56}Ni mass in SNe IIP.

We construct then a "$two-zone$" model of the Hα luminosity in SN IIP to explore the sensitivity of the Hα behavior to variation of model parameters. The primary purpose of the upgraded model is to specify better the early nebular phase compared to the previous version [2]. We found that if mass, energy and mixing conditions do not vary strongly among SNe IIP (less than factor 1.4) then with an accuracy better than 10% Hα luminosity is
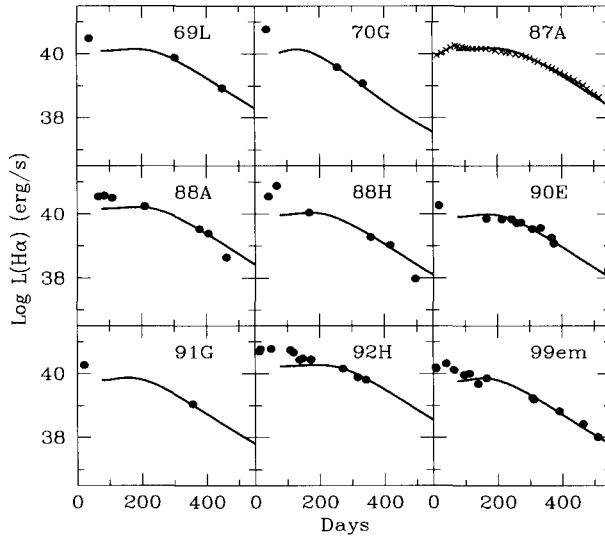
Fig. 3. The Hα luminosity evolution in different SN IIP. Models (*solid lines*) are over plotted on the observational data *dots*.

proportional to ^{56}Ni mass during the $200 - 400$ days after explosion (for more details see Elmhamdi et al. [4]). Hα luminosities are then used to derive ^{56}Ni masses of the SNe sample. This is done employing two approaches: first, using the Hα light curve in SN 1987A as template and, second, applying the model fitting (Fig. 3). Both approaches agree within 15% unless we are dealing with extreme cases such as SN 1970G (type IIP/L) and the underluminous SN 1997D. In both these cases we should possess additional information about ejecta mass and energy to derive the ^{56}Ni mass from Hα modeling. SN 1997D is indeed a special case for which two scenarios have been argued, namely: a small age scenario with a low ejecta mass (case "b" [3]) and a large age option with high mass of the ejecta (case "a" [9]).

Worth noting is the simple approach of using Hα light curve of SN 1987A as a template to estimate the ^{56}Ni mass. The ^{56}Ni mass values derived using this method agree within 20% with those from the photometry, which thus gives us confidence that Hα is a good indicator of the amount of ^{56}Ni in SNe IIP (Fig. 4). Simultaneously, this consistency suggests that parameters of SNe IIP (mass, energy and mixing) are not very different. In fact this is consistent with the uniformity of plateau luminosities and plateau lengths of SNe IIP.

This simple approach is applied then for three SNe for which we have late spectra but no photometry (SNe 1995ad, 1995V and 1995W), giving reasonable values, and thus demonstrating the usefulness of the method [4]. Generally, the approach based upon Hα may be indispensable in cases, when the photometry at the nebular epoch is absent, or when there is a problem

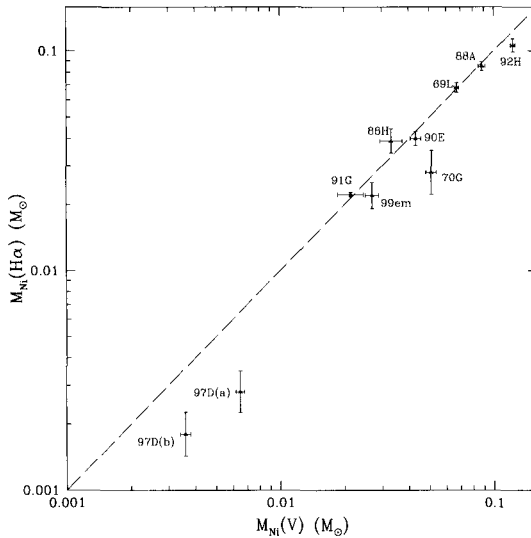**Fig. 4.** The correlation between the ^{56}Ni mass derived from the Hα luminosity, $M_{\mathrm{Ni}}(\mathrm{H}\alpha)$, and that derived from the tail M_V magnitude, $M_{\mathrm{Ni}}(V)$. The dashed line has a slope of unity. Clear deviation is seen for SN 1970G(SNP/L) and for the faint event SN 1997D.

with subtraction of stellar background (SN IIP in the bulge, or in high redshift galaxies).

On the one hand, the clustering of the points around two values of ^{56}Ni mass viz. 0.005 and 0.05 M$_\odot$ in Fig. 4 may result from poor statistical sampling, or it may be a hint that a mechanism such as fall-back is an important one in the evolution of the low-mass group.

The interesting correlations demonstrated in this class of objects point to a high degree of homogeneity and this is encouraging for the use of type IIP SNe as cosmological probes. Improved statistical samples and better sampled data are however needed to have a firmer confirmation of these correlations.

These kinds of analyses demonstrate how large sample analyses in SNe studies can provide robust results and correlations with their consequent impact for our understanding of SNe physics.

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