

# Radioactive Decay and Its Manifestations in Core-Collapse Type IIP Supernovae

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## Abstract

We use observable properties of Type IIP (core-collapse) supernovae to obtain improved insight into the type of star which explodes, the range of masses of radioactive material produced and its effect on other observable properties. Because we now have a small sample of reasonably frequently observed Type IIP SNe we have used the light curves to obtain the mass of  $^{56}\text{Co}$  produced, a method exploited for the well observed SN 1987A. With these determinations we can demonstrate a correlation between the mass of  $^{56}\text{Co}$  and the rate of decline of the visible light curve (V) from plateau to exponential decay. This provides a distance-independent method for determining the mass of  $^{56}\text{Co}$ . The availability of spectra in the phase interval 200-400 days allows us to demonstrate a good correlation between the luminosity of  $\text{H}\alpha$  and the  $^{56}\text{Co}$  mass. More observed SNe with improved sampling would strengthen these conclusions.

*Key words:* Radioactivity, Decay, Nucleosynthesis, Light curves

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## 1 Introduction

A brief but thorough account of the history of the powering of supernovae by radioactive decay has been given by Arnett *et al.* (1989) and not repeated here. These authors also give an account of the earlier predictions of  $\gamma$ -ray production as a result of radioactive decay. The most pertinent in the context of this observationally oriented paper are those papers by Burbidge *et al.* (1956) and Colgate & McKee (1969). The former suggested that radioactive decay of  $^{254}\text{Cf}$  powered the late-time light curve of the Type Ia SN 1937C because the decay times were similar. The general idea was correct but the coincidence was misleading because the increasing loss with time of  $\gamma$ -rays

from SNIa envelopes, owing to their low mass, produced this coincidence. The latter authors consolidated the idea that  $^{56}\text{Co}$  decay into  $^{56}\text{Fe}$  was the important mechanism for powering light curves. The occurrence of SN 1987A and the accurate measurement of its bolometric light curve, together with IR measurements of lines of [CoII] and the expected  $\gamma$ -rays have placed this prediction beyond doubt.

In the work described below we make use of the luminosity of the light curves on the exponential tail,  $^{56}\text{Co}$  decay prevailing, to determine the mass of this radioactive species. In reality, what aids this procedure is the fact that, by coincidence, for Type IIP SNe the V light curve tracks the decay line (e-folding time 111.3 days) of  $^{56}\text{Co}$  quite closely. By assuming that the bolometric correction is the same at these late epochs for all SNe in our sample, we avoid the necessity of having bolometric light curves which in any case are very difficult to obtain. The following work has been elaborated by Elmhamdi *et al.* (2003).

## 2 V-band Light Curves and Masses of $^{56}\text{Co}$ for the Sample

We have assembled V light curves for a sample of 12 Type IIP SNe, where we include SN 1987A to provide the template for scaling the other light curves. Flux calibrated spectra in the phase interval 120-400 days were also available. The quality and frequency of both types of observation are inevitably variable from one object to another. All observations have been corrected for reddening and absolute magnitudes and luminosities have been derived with a Hubble constant  $H_0 = 70\text{km/s/Mpc}$ .

Under the assumption that the V luminosity on the exponential tail in the interval 150-400 days scales linearly with mass of  $^{56}\text{Co}$ , we have determined this mass by least squares fitting to the V light curve for SN 1987A whose mass of  $^{56}\text{Co}$  has been taken to be  $0.075M_\odot$ . For objects in common with Hamuy (2003), differences are primarily due to the adopted distances even if the methodologies are somewhat different. There is a large uncertainty in the case of SN 1997D because two quite different explosion times have been proposed. The range in derived masses of  $^{56}\text{Co}$  is quite significant, resulting from  $0.123M_\odot$  for SN 1992H and  $0.0028M_\odot$  for SN 1999eu.

## 3 Light Curve Decline

The rate of decline of the various light curves for SNIa correlates with absolute magnitude at maximum in the sense that brighter SNe decay more slowly. This suggests an investigation of similar phenomena in Type IIP SNe because

they also seem to belong to a relatively well-defined class.

In order to obtain an objectively reproducible measure of the decline rate, we define this to be the measure when the decay rate  $S = -dM_V/dt$  at time  $t_i$  is a maximum. To obtain this we represent the V light curve of a SN in the transition region  $t_i = \pm 50$  days by the sum of 2 expressions, one representing the plateau phase and the other the exponential phase. It has the form:

$$F = A \frac{(t/t_0)^p}{1 + (t/t_0)^q} + B \exp(-t/111.3). \quad (1)$$

where A, B,  $t_0$ , p and q are parameters obtained by a minimization fitting technique.

We construct plots of S versus t and record S at the inflection point  $t_i$ . This is therefore the maximum S which we seek. It is particularly sensitive to the degree of sampling of the light curve. We also have a useful reference time  $t_i$  at this point which for some purposes replaces an uncertain explosion time. Here we use it to define points on the plateau  $t_i-35$  days and points on the exponential part  $t_i+35$  days. From the earlier discussion we would expect  $M(^{56}Co)$  to correlate with  $t_i+35$  days, and it does. In addition  $M(^{56}Co)$  correlates with  $t_i-35$  days revealing therefore a correlation between absolute luminosity and mass of  $^{56}Co$ , a new result.

An interesting further correlation is that between mass of  $^{56}Co$  and the steepness parameter S. The reasons for this correlation, which qualitatively resembles a similar effect in Type Ia SNe, are not obvious. An interpretation would require detailed hydrodynamical modelling varying both mass of  $^{56}Co$  and degree of mixing, lacking at the present time.

Confirmation of this effect with more better quality data would make it possible to measure the mass of  $^{56}Fe$  produced in any such supernova without a knowledge of its distance. The result is illustrated in Figure 1.

#### 4 The mass of $^{56}Co$ and the $H\alpha$ luminosity

The radioactive decay of  $^{56}Co$  in a weakly ionized gas causes ionization and  $H\alpha$  emission dependent on the deposition rate and hence the total mass of  $^{56}Co$ . If high density effects remain insignificant a proportionality between the two quantities might be expected. The model SN envelope discussed here is an improved version of an earlier one presented by Chugai (1990) and consists of two zones, namely an inner mixing one with metals and helium and an outer hydrogen-rich one. All the  $^{56}Co$  resides in the inner region with a clumpy distribution surrounded by cocoons of metals. By varying the various parameters describing this model one can envisage the sensitivity of  $H\alpha$  emission to each of them. In brief it has been shown that the luminosity of  $H\alpha$  is

not sensitive to the mass of the envelope, the kinetic energy of the explosion, the metal mixture, the degree of mixing and the temperature, provided that these parameters remain within a factor 1.4 of those adopted for SN 1987A where a good fit had been made. However it is clear that the luminosity of  $H\alpha$  is proportional to  $M(^{56}Co)$  in the phase 200-400 days.

Having established the above dependence of  $H\alpha$  luminosity on  $^{56}Co$  mass we can then derive quantitative measures of  $^{56}Co$  mass from the actual measurements of  $H\alpha$  luminosity in two ways. By analogy with determination of  $^{56}Co$  mass from fitting V light curves to the SN 1987A template light curve, we could fit  $H\alpha$  light curves to that of SN 1987A assuming direct proportionality between  $H\alpha$  emission and  $^{56}Co$  mass. The other method was to fit each  $H\alpha$  light curve with a particular model. There is, as would be expected good agreement between the results from the 2 methods. This is illustrated in Figure 2.

The case of SN 1970G requires special attention because it had a very short plateau and therefore may not be a bona fide Type IIP. SN 1997D also required special attention because of a claimed difference in the age at time of discovery of 45 days reported in two separate publications. This results in two different models, one with an envelope mass of  $18M_{\odot}$  and another with  $6M_{\odot}$ . Model fitting for both options produces different but low values of  $^{56}Co$  mass. This work suggests significant differences in mixing and temperature for the two models but does not by itself resolve the problem of the progenitor mass. The  $H\alpha$  luminosity method has been applied to three Type IIP SNe lacking late-time photometry. It results in reasonable values for  $^{56}Co$  mass clustered around  $0.050M_{\odot}$ .

## 5 Conclusions

From this work the following results may be summarized.

1. Masses of  $^{56}Co$  obtained from the late-time light curves reveal that a large range (more than one order of magnitude) exists.
2. The  $H\alpha$  emission luminosity in the time interval 200-400 days after outburst can provide a reliable measure of the mass of  $^{56}Co$ .
3. The rate of decline of the V light curve from plateau to exponential tail measured at the point of steepest decline, correlates with the  $^{56}Co$  mass. It therefore provides a distance-independent method for determining masses of  $^{56}Co$ .
4. The luminosity at maximum light correlates with mass of  $^{56}Co$ .
5. The above results suggest that Type IIP SNe are restricted to a relatively small parameter space possibly including progenitor masses. In fact for SN 1999em Elmhamdi *et al.* (2003) have already deduced an accurate progenitor mass of  $12-14M_{\odot}$ .

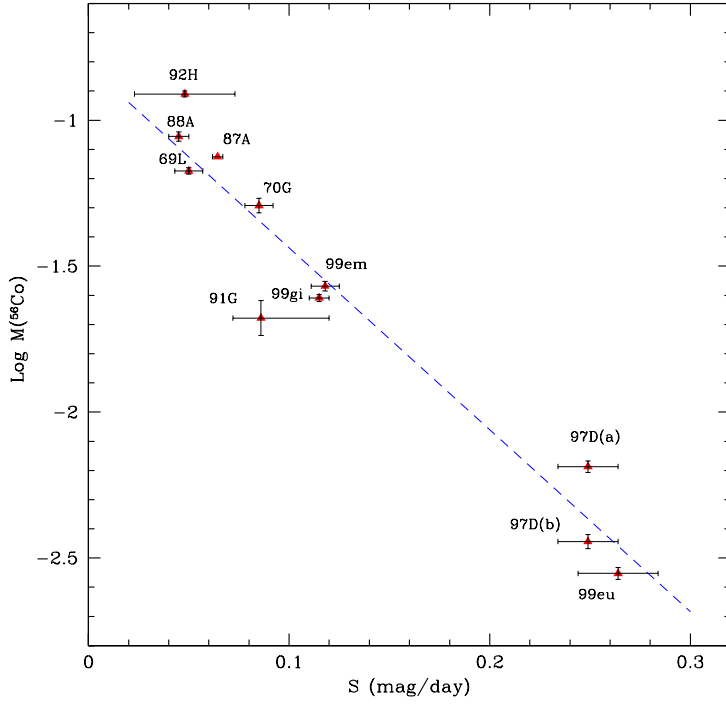


Fig. 1. The relation between the decline rate  $S$  and the mass of  $^{56}\text{Co}$  discussed in the text. The solid line is the straight line of best fit.

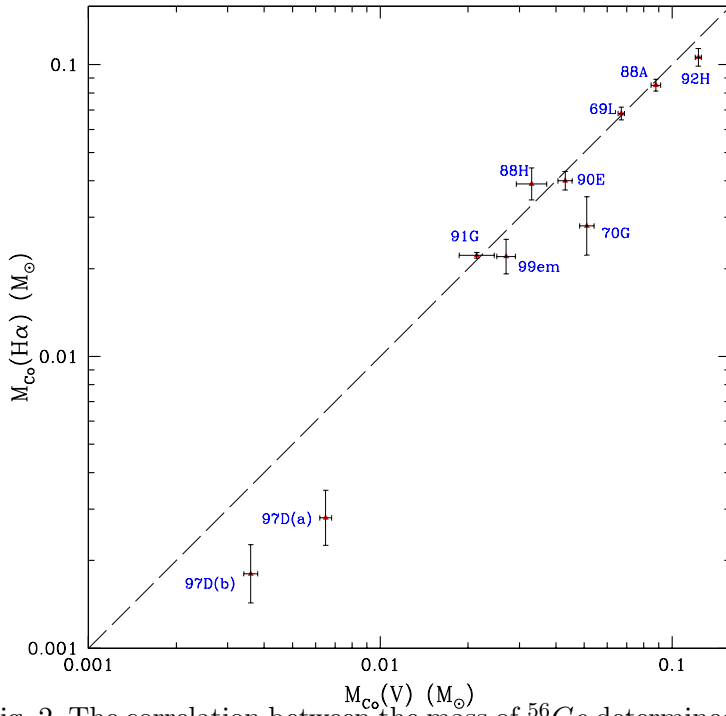


Fig. 2. The correlation between the mass of  $^{56}\text{Co}$  determined from the V light curves and that obtained from  $\text{H}\alpha$  luminosities.

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