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Energy Production in a ^{56}Ni Star

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Abstract

We make some reality checks on Type Ia SNe, consisting of (a) simple observations about risetime and (b) the relationship of our Leibundgut light template to the power production of an initial ^{56}Ni star. On very general grounds, the radius of the supernova must be of the order of 100 AU at the time of maximum light, and this radius cannot be reached in less than tens of days from the time of the explosion, or several ^{56}Ni halflives. Although the observed transition from a rapid fall to a long tail resembles the transition from ^{56}Ni decay to ^{56}Co decay, it occurs perhaps 20 days later. It seems unlikely that we can associate any readily measured feature of the light curve with radioactive lifetimes, and hence unlikely that we can set limits on the time variability of G_F without excessive model dependence.

1. Size and risetime considerations

A Type Ia SN has a maximum brightness comparable to that of the host galaxy, or of order 10^{10} $L_\odot$.† If it were approximately a black body with the sun's temperature, then its radius would need to be about $10^5 R_\odot$. The sun subtends almost exactly 0.01 radians in the sky, so its radius is 0.005 AU. The radius of our SN at maximum light is therefore about 500 AU, or 7.5×10^{10} km.

If the effective temperature were (more reasonably) 10^4 K, then the radius would be about three times smaller for the same luminosity. And for our present purposes we have only guesstimated the luminosity. The point is that if the object is to be nearly as bright as an entire galaxy in optical light, then its radius is 100 or more AU.

Expansion velocities are 10,000 to 15,000 km/s, so that a radius of 7.5×10^{10} km is reached in about 5×10^6 s, or about 60 days. For 100 AU, the result would be 12 to 18 days. According to David Branch [1], the detailed model calculations give risetimes of 15–20 days in *e.g.* blue light. We see that this is physically reasonable, and that there is no credible way to get a significantly faster turnon.

Our photometry errors are about 10% of the maximum signal, so by turnon we must mean an increase by a factor of 5 or 10 (1.7 to 2.5 magnitudes)—not far from the 10% to 90% risetime definition some of us are used to. Early data indicates an increase of 1 magnitude from -10 days to max. If we approximate earlier behavior as linear in magnitude, an increase of 0.7 to 1.5 magnitudes in 5 to 10 days means a slope of 0.07 to 0.3 mag/day This is consistent with Saul's nominal turnon slope of 0.33 mag/day, obtained by extrapolating Leibundgut's B template [2] to early times. It would be hard to justify the steeper slopes we have experimented with. We must find some other explanation for "stretch factors" of less than unity.

† The luminosity of a star with radius R and surface temperature $T_{\rm eff}$ is $4\pi\sigma R^2 T_{\rm eff}^4$. Alternatively, this serves to define $T_{\rm eff}$, which is 5770 K for the sun.

2. Nickel and cobalt decay

According to model calculations, a large fraction of the collapsing white dwarf's mass is converted to ^{56}Ni by the thermonuclear burning of light "alpha-cluster" light isotopes. This isotope decays by e capture with a halflife variously reported as 5.9 and 6.1 days (Fig. 1, Ref. 3). The ^{56}Co daughter decays with a 77.27 day halflife, 51.2% of the time by e^+ emission and the remainder by electron capture (Fig. 2). The initial thermonuclear explosion occurs in a second or so, but much of its energy powers the expansion of the star. The supernova we observe is presumably powered by the more leisurely radioactive decay chain.

What relationship does the time profile of this well-defined decay chain have to the observed light curve? It is straightforward to calculate the radioactive decay "light curve."

To simplify notation, we let the subscript "1" refer to ^{56}Ni and the subscript "2" to ^{56}Co. It is useful to define the decay constants λ_1 and λ_2, where $\lambda = \ln 2/t_{1/2}$.

As can be seen in Fig. 1, ^{56}Ni decays exclusively to a 1.720 MeV level of ^{56}Co, which then cascades to the ground state by various routes. The Q value is 2.136 MeV, but the ν carries off nearly all of the energy difference. We thus assume that each ^{56}Ni decay contributes $E_1 = 1.720$ MeV to the star's energy.

^{56}Co decay is more complicated (Fig. 2), since half the decays involve $e^+\nu$ emission to three dominant ^{56}Fe levels. These average about 2.8 MeV above the ^{56}Fe ground state, but another 1 MeV is produced by the e^+ annihilation. Since the Q for the transition is 4.5 MeV, we conclude the electron has an average of about 1 MeV in kinetic energy. The e capture half goes to states centered around 4.0 MeV. Without doing a detailed calculation, we conclude that $E_2 \approx 4.4$ MeV is contributed to the star's energy by each decay.

After its production at essentially $t = 0$, the ^{56}Ni decays with time constant $1/\lambda_1$, while ^{56}Co is produced at the same rate and decays with time constant $1/\lambda_2$,

$$\begin{aligned} \frac{dN_1}{dt} &= -\lambda_1 N_1 \\ \frac{dN_2}{dt} &= \lambda_1 N_1 - \lambda_2 N_2 \ , \end{aligned} \tag{1}$$

so that

$$\begin{aligned} N_1 &= N_{10} e^{-\lambda_1 t} \\ N_2 &= N_{10} \frac{\lambda_1}{\lambda_1 - \lambda_2} \left(e^{-\lambda_2 t} - e^{-\lambda_1 t} \right) \ . \end{aligned} \tag{2}$$

The energy production rate is then given by

$$\frac{dE}{dt} = E_1 \lambda_1 N_1 + E_2 \lambda_2 N_2 \ . \tag{3}$$

(Note that dN_2/dt includes the production term $\lambda_1 N_1$, which does not contribute to this expression.)

The magnitude corresponding to the function given by Eq. (3) is plotted in Fig. 3, with arbitrary normalization. Note that $t = 0$ is the moment of conflagration, 15 to 20 days before light maximum. For comparison, we have plotted our Leibundgut template for blue light [2], with light maximum at $t = 20$ days.

It is immediately obvious that the sharp peak in the observed luminosity does not directly reflect the ^{56}Ni decay, since the peak occurs about three halflives after the ^{56}Ni is produced. The

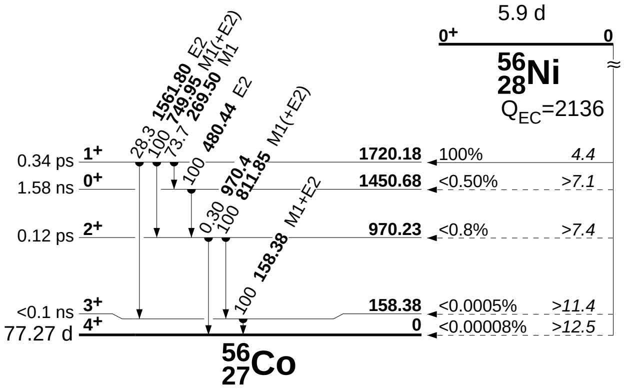

Figure 1: ^{56}Ni decay scheme [3].

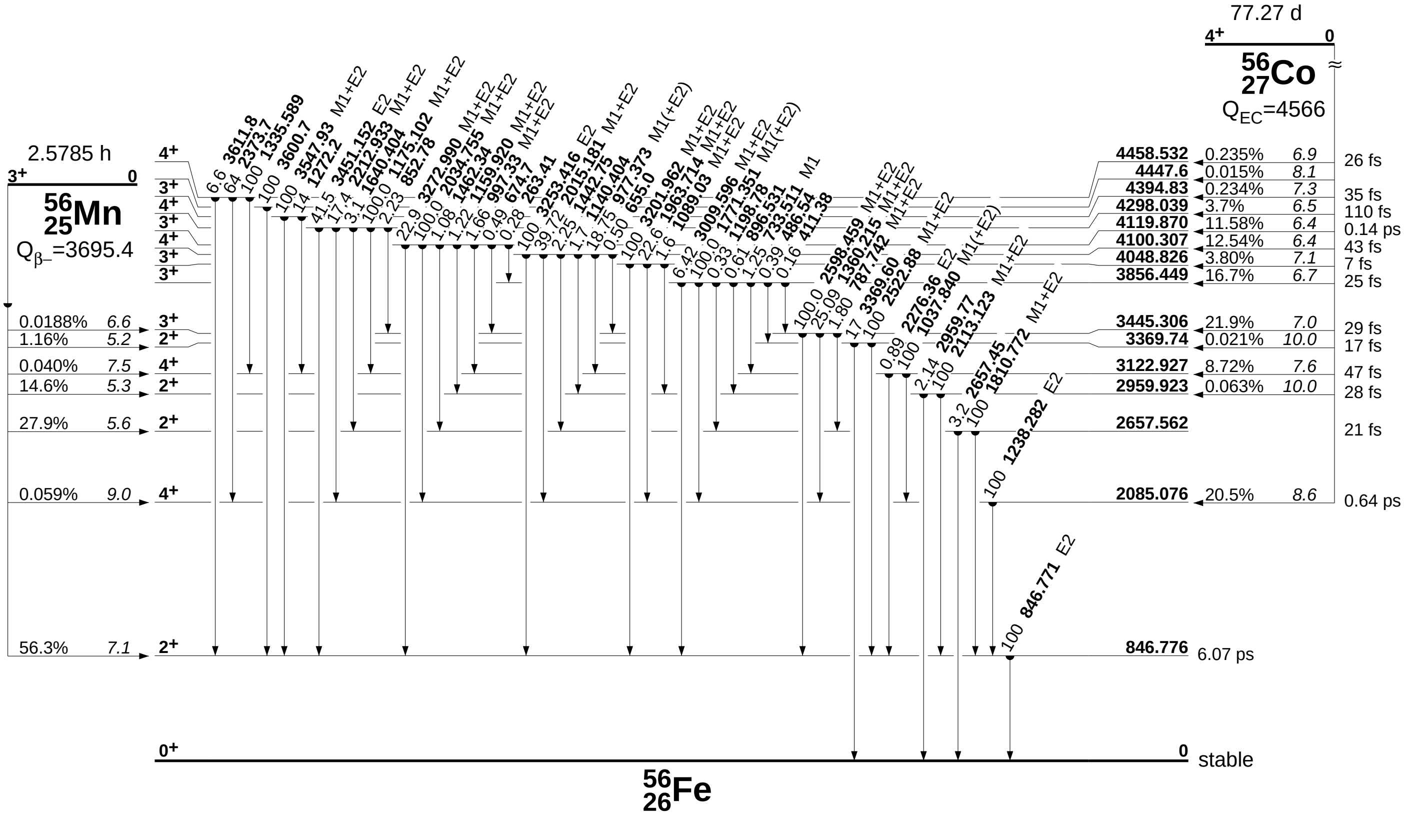

Figure 2: ^{56}Co decay scheme [3].

^{56}Ni decay just contributes energy which appears as luminosity many days later. The shape of the light curve near maximum is governed by radiation transport in a rapidly changing star.

However, one might expect to see the effects of ^{56}Co decay at late times, when the star is more transparent and time constants are long compared with 20 days. Here the problems are twofold: The light output shown is for one color band, while the star is rapidly cooling. In addition, there is no precise data after the star is 70 days or so past maximum, even for "nearby" objects. The template shown is just a linear extrapolation.

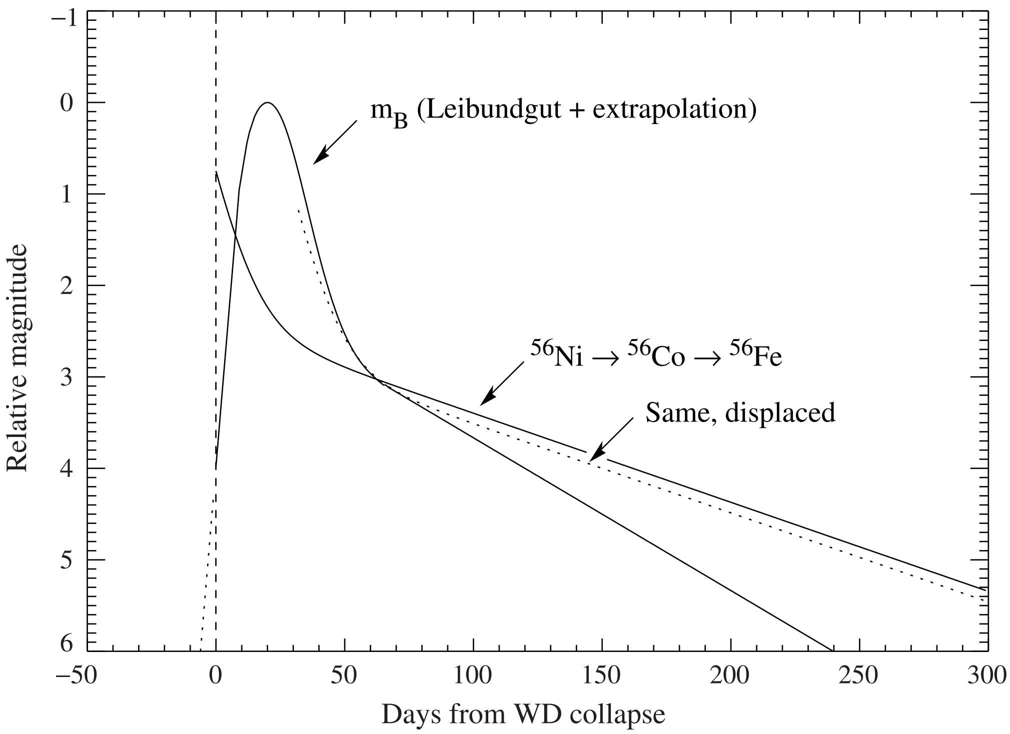

Figure 3: Energy injection rate by ^{56}Ni and ^{56}Co radioactive decay (arbitrary vertical scale) as compared with the Leibundgut template for blue light.

The dotted curve in the figure was obtained by displacing the decay power curve to the right and downward for comparison with the transition in the experimental curve. The agreement is very suggestive, particularly when reddening is taken into account. However, the conclusion that we are actually seeing such a transition in isotope decay, delayed in time by the inertia of the star's thermal capacity, would depend on detailed modeling.

It would be much better to plot the bolometric light curve for comparison purposes, but at the moment we do not have access to these data.

We conclude that while the SN may well be powered by radioactive decay, the observed light curves retain very little information about the time profile of the energy deposition. In particular, the width (our stretch factor) has little to do with the radioactive decay time constants.

3. Has the Fermi coupling constant changed over the Hubble time?

The β-decay width (essentially λ) is proportional to G_F^2. It has been suggested that our observation that light curve widths at cosmological distances are as expected from standard cosmology could be used to place limits on any possible change on G_F over times comparable to the age of the universe. Unfortunately, our conclusion in the last section is that the width of the light curve does not directly reflect the radioactive decay lifetime(s). As a consequence, our data says nothing, or at least nothing very useful, about the constancy of G_F.

There is one slender thread of hope, but at this point it is quite beyond experimental grasp: If the bolometric magnitude of the supernova could be measured at very long times, then something could be said about the lifetime of ^{56}Co at early epochs as compared with the present.

References

1. D. Branch, private communication (1995).

2. B. Leibundgut, G. A. Tammann, R. Cadonau, and D. Cerrito, *Astron. Astrophys. Suppl.*, Series 89, 537 (1991).

3. R. B. Firestone and V. S. Shirley, *8th Edition of the Table of Isotopes*, John Wiley & Sons, 1995 (in press).