Figure 1 Spectra of SNe, showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339), and SN 1984L (NGC 991; 1532). In this review, the variables \( t \) and \( \tau \) represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially "AB magnitudes" as defined by Oke & Gunn (1983).

Conclusions are based on the few existing late-time spectra of SNe Ib, and no other possibly significant differences have yet been found. At this phase, SNe II are dominated by the strong Hα emission line; in other respects, most of them spectroscopically resemble SNe Ib and Ic, but the emission lines are even narrower and weaker (Filippenko 1988). The late-time spectra of SNe II show substantial heterogeneity, as do the early-time spectra.

At ultraviolet (UV) wavelengths, all SNe I exhibit a very prominent early-time deficit relative to the blackbody fit at optical wavelengths (e.g. Panagia 1987). This is due to line blanketing by multitudes of transitions, primarily those of Fe II and Co II (Branch & Venkatakrishna 1986). The spectra of SNe Ia (but not SNe Ib/Ic) also appear depressed at IR wavelengths (Meikle
twin, spectroscopically, of SN 1981b). At such late times as 264 days, the emission comes from an optically thin nebula and is composed almost entirely of emission lines of iron-group elements, particularly $^{56}$Fe and radioactive $^{56}$Co in the first and second ionization stages. The agreement with observations is again striking, confirming among other things the presence of freshly synthesized iron and cobalt in the supernova. It is important to note that the late-time spectrum is much more restrictive upon the models than the light curve or nucleosynthesis. Not only must one get the composition right, but also, especially at late times, the dominant ionization stages come from a balance of heating by radioactive energy deposition in the form of gamma rays and positrons and of cooling by collisional excitation of forbidden lines (Axelrod 1980a,b). The ionization stages are quite sensitive to the density structure as a function of time and location in the young supernova; along with the widths of various spectral features, they greatly constrain the velocity structure allowed for the asymptotic model. Helium detonations, for example, are apparently disallowed for the common event (Woosley et al. 1984).

![Composition of a carbon deflagration model for Type I supernovae (Model W7 of Nomoto et al. 1984b) as a function of interior mass in solar masses (top of figure) and asymptotic expansion velocity (bottom of figure). The composition is sampled at a time near maximum light (15 days). All of the cobalt shown will later decay to $^{56}$Fe. Figure taken from Branch et al. (1985).](image-url)
Figure 5  Bolometric light curve of Supernova 1987A. Points are inferred from data obtained at the Cerro Tololo Inter-American Observatory [CTIO (172, 306, 307)] and the South African Astronomical Observatory [SAAO (90, 91, 344)]. The dashed line would be the result of the 100% conversion of the decay energy of 0.075 \( M_\odot \) of \( ^{56}\text{Ni} \) (and later \( ^{56}\text{Co} \)) to the forms of radiation detected by CTIO and SAAO (ultraviolet, optical, and infrared). The increasing difference in slope between CTIO and SAAO values has been identified with a difference in cutoff, which allows Ca II \( \lambda 8542 \) emission lines to be included in SAAO but not CTIO (238). In what follows we graph only the SAAO data for clarity. At late times, X rays and gamma rays escape from the supernova and the data fall below the dashed line.

"echo" described in Section 7. The star expands by a factor of 10 to a radius of about 2–3 \( \times \) 10\(^{13} \) cm before a visual magnitude as bright as \( V \sim 6.5 \) can be observed. Thus, in order to accommodate McNaught's determination of \( V = 6.4 \) and \( T = 0.128 \) days (11,000 s), it is necessary and sufficient that appreciable matter travel at a velocity near 40,000 km s\(^{-1} \). "Appreciable" here means sufficient to be optically thick at 2–3 \( \times \) 10\(^{13} \) cm, or about 10\(^{28} \) g. Subsequent spectra obtained a full day later indicate line absorption above 30,000 km s\(^{-1} \), so this value for the initial photospheric expansion seems plausible.

Figure 1 showed the comparison between the first few days of optical data and the calculated visual magnitudes, normalized to an explosion at the time IMB and Kamiokande II saw the neutrino burst. If the time when energy was supplied to the star is shifted 3 hr earlier to the time of the Mont Blanc neutrino report, the model no longer fits the data.

This may be seen without a detailed model. As the shock breaks out, the kinetic and internal energies are comparable. The diffusion time for