SN 1987A: Observations at Later Phases

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The last observations (until April 1993) of SN 1987A made at ESO, La Silla, are presented. Our data show that: (i) the criterion of line shifts proves that dust is still present and is absorbing more strongly than ever; (ii) the I magnitude decreases faster than the other ones after day ~1700; (iii) the 1.3mm flux is constant at about 9mJy, and comes most probably from free-free emission produced by the cooling of the former star envelope still weakly ionized. Previous analyses of the bolometric light curve until day 1444 are briefly reviewed. In spite of the large uncertainties, the flattening of the light curve, observed after day ~900, extends until our latest data points (day 2172). This can be explained by theoretical models including time-dependent effects due to long recombination and cooling times (Fransson and Kozma 1993). However, one cannot rule out the presence of a compact object such as a neutron star, radiating as a pulsar or accreting matter from a disk either continuously or intermittently.

1. The Dust

In order to understand many aspects of the observed behaviour of SN 1987A at later phases, one must appreciate the role of dust in the expanding ejecta of the supernova. Molecules such as CO and SiO were formed at a very early phase (<100 days after outburst) (Bouchet and Danziger 1993). Probably as a result of the presence of molecules, dust formed at approximately day 530 and has since continued to play a dominant role in absorbing much of the harder radiation and thermalizing it. The spectroscopic signature causing an apparent blueward shift of the peak of various broad emission lines ([O I]6300,6363, Mg I]4571 and [C I]9823,9849), together with independent photometric evidence (e.g., the appreciation that the IR excess created after dust formation had to be included in the energy budget to obtain the most plausible bolometric energy), proved beyond doubt that dust had condensated in the envelope and was not originating from an IR echo from surrounding material (Danziger *et al.* 1989, Lucy *et al.* 1989, Suntzeff and Bouchet 1990). Analyses (i) of the shape of the profiles and (ii) of the observed extinction of emission lines revealed that the dust was confined throughout the inner metal rich parts of the envelope, i.e., the ejecta, and that although amorphous silicate dust might be the dominant component, dust also existed in clumps whose optical depths could be very large (Lucy *et al.*, 1989, 1991). These dense thick clumps may still be preventing us from seeing to the centre of the supernova where a compact remnant (neutron star) is predicted to lie.

Our observations show that at day 1806 (February 4, 1992), the peak emission of Mg I]4571 had a blue shift of 810 km/s and that of [O I]6300 of 495 km/s (Fig. 1); at day 2159 (January 22, 1993), the blue shifts were of 780 km/s and 500 km/s for Mg I] and [O I], respectively. This proves that, within the uncertainties, there has been no significant change during this period. These shifts under the model proposed by Lucy *et al.* (1989, 1991) correspond to optical depths of 1.85 and 0.8 at the 2 wavelengths, at least as large as any reported in the past and still indicating a colour effect due to the presence of

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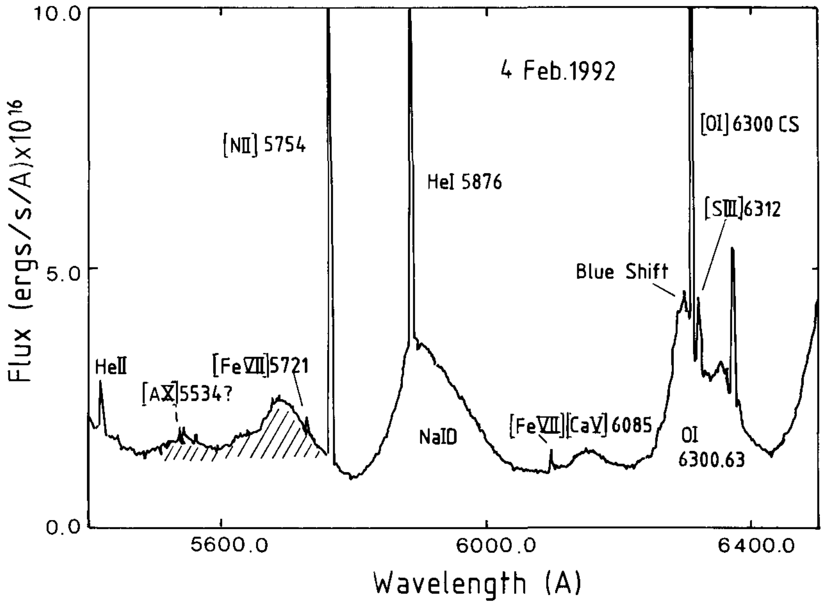

FIGURE 1. A spectrum of SN 1987A taken at day 1806 at ESO, La Silla with the New Technology Telescope (NTT). Narrow lines from the CS gas are identified as are some broad features formed in the expanding envelope. Other broad features with hatching are yet unidentified.

amorphous silicates. While great caution is now required in using this model because the original assumptions may be overstrained, there remains ample evidence of the presence of copious amounts of dust.

2. The ESO data

2.1. *The visible:*

At later phases, the observations of SN 1987A have became very difficult, due to the faintness of the supernova and the contamination of the neighbouring stars. Therefore, even with the ESO New Technology Telescope (NTT) which is well known for providing very good images, observations can only be conducted under very good seing conditions. Moreover, a careful analysis of the data is necessary in order to reduce the contamination from the companions (ROMAFOT has been used for the reduction of our data). Fig. 2 shows the UBVRI lightcurves obtained at ESO and at CTIO (courtesy N.B. Suntzeff; see also Suntzeff *et al.* 1992). It has to be stressed that 70% of the errors in the broad band photometry arise from the uncertainty in the determination of the extinction correction, due to the various volcanoes which have exploded during the past years, and which have spread in the sky a large amount of dust (The Pinatubo in The Philippines being the most prejudicial). These errors are estimated to be $\leq$0.05 magnitude for V, R and I, and $\leq$0.10 magnitude for B. Fig. 2 shows that the I magnitude decreases faster than the other ones after about day 1700. The reason for this behaviour is still unclear, although it is most probably due to the relative absence of emission lines in this band.

2.2. *The infrared:*

The same difficulties as for the visible arise for the near-IR photometry. Moreover, the detectors available for this spectral region are less sensitive. The accuracy in the K band is estimated to be $\leq$0.10 mag. At later phases, the supernova is too faint in L(3.8μm)

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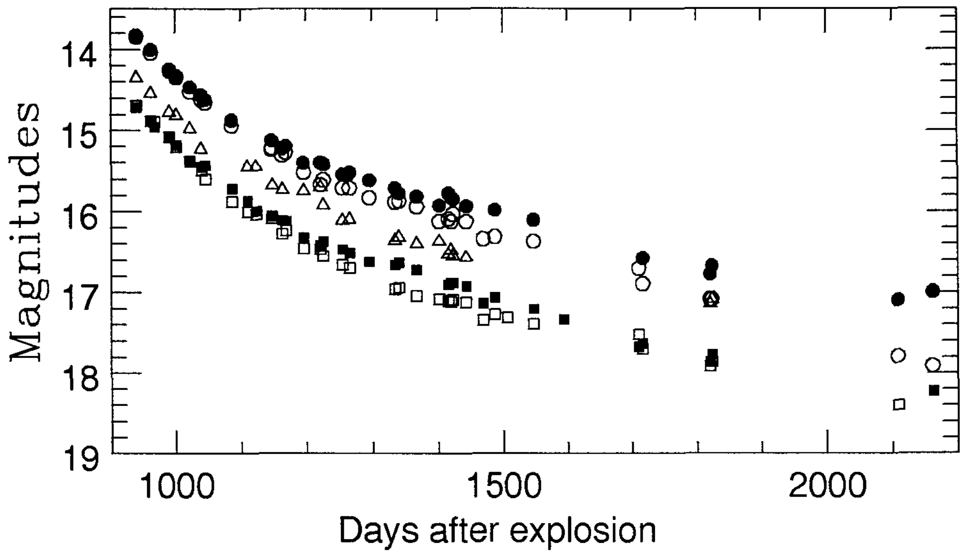

FIGURE 2. The U (open triangles), B (open squares), V (filled squares), R (filled circles) and I (open circles) lightcurves from CTIO and ESO. Note the faster decrease in the I band.

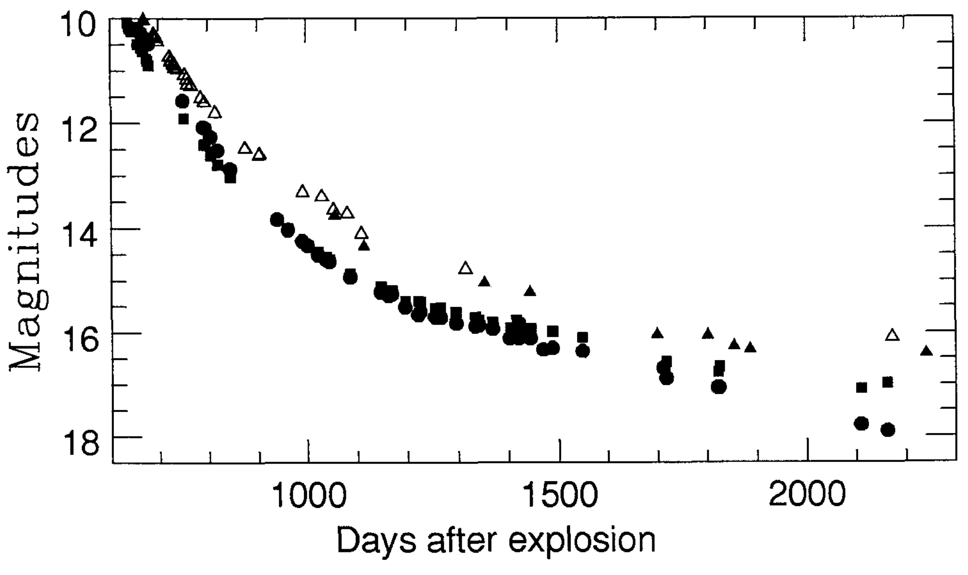

FIGURE 3. The K lightcurves from CTIO (filled triangles) and ESO (open triangles). The R (filled squares) and I (filled circles) lightcurves are also displayed for comparison.

and M (4.6μm) to be measurable. Photometry at 10 and 20μm is also difficult to achieve, and gives high uncertainties. Note that after day ~1500, under very good atmospheric conditions, 5 hours of integration time give about a 3-σ detection only! Fig. 3 and 4 shows the light curves obtained at ESO and CTIO (courtesy N.B. Suntzeff; see also Suntzeff *et al.* 1992). It is well known that discrepancies exist between the results from ESO and

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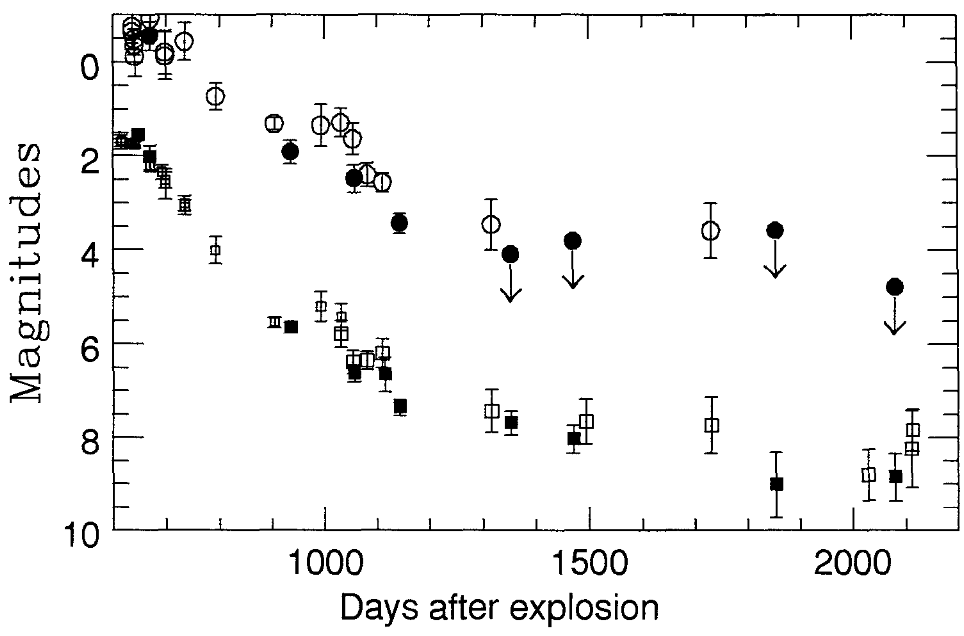

FIGURE 4. The 10 (squares)and 20 μm (circles) lightcurves from CTIO (filled) and ESO (open).

CTIO at 10 and 20μm (Bouchet *et al.* 1991a, Suntzeff *et al.* 1991). The reason for that is still not understood (Bouchet *et al.* 1991b).

The commissioning of the new 10μm camera, TIMMI, at La Silla will undoubtedly increase the accuracy of the measurements. First tests, made in January 1993 under bad atmospheric conditions gave in 2 hours a detection at a 3-σ level of ~15 mJy (N= 8.3), which is very promising.

2.3. *The 1.3mm data:*

Figure 5 shows that after day 800, the flux at 1.3mm (230 GHz) seems to be constant (within unavoidably large errors) at ~8–9 mJy, although a slight increase starting after day 1800 can not be completely ruled out. Further observations will clarify this point. In this figure, data from Biermann *et al.* (1990a,b, 1992) are also shown: the unusually high point at day 1640 may be spuriously high because the next point some days later when the atmospheric conditions were excellent (resulting in a very small uncertainty) is significantly lower and consistent with all subsequent oservations.

The positive detection of the supernova at 1.3mm raises the question of the origin of this flux. Fig. 6 shows the spectral energy distribution of SN 1987A at day 2172. It can be seen from this figure that it is unlikely that dust alone radiating as a black body at ~155K be responsible for the 1.3mm flux. Furthermore, it remains to be demonstrated whether the clumped dust is an efficient emitter at this wavelength. A measurement of the spectral index of this radiation near 1.3mm would help to elucidate this problem. Thus, although clumpiness is undoubtedly a feature of the expanding envelope (Lucy *et al.* 1991), these oservations do not demonstrate this point. A synchrotron radiation

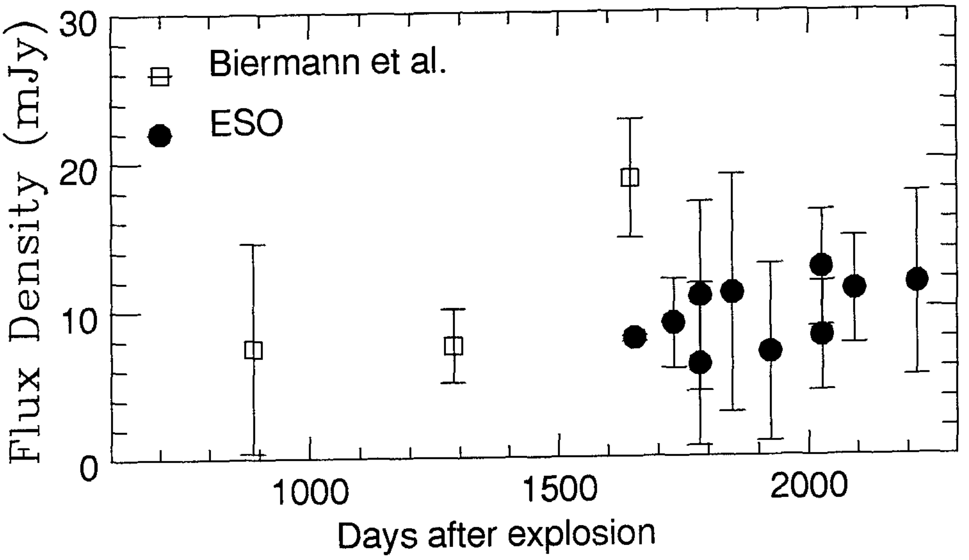

FIGURE 5. The temporal behaviour of the flux at 1.3mm measured with the SEST telescope at La Silla.

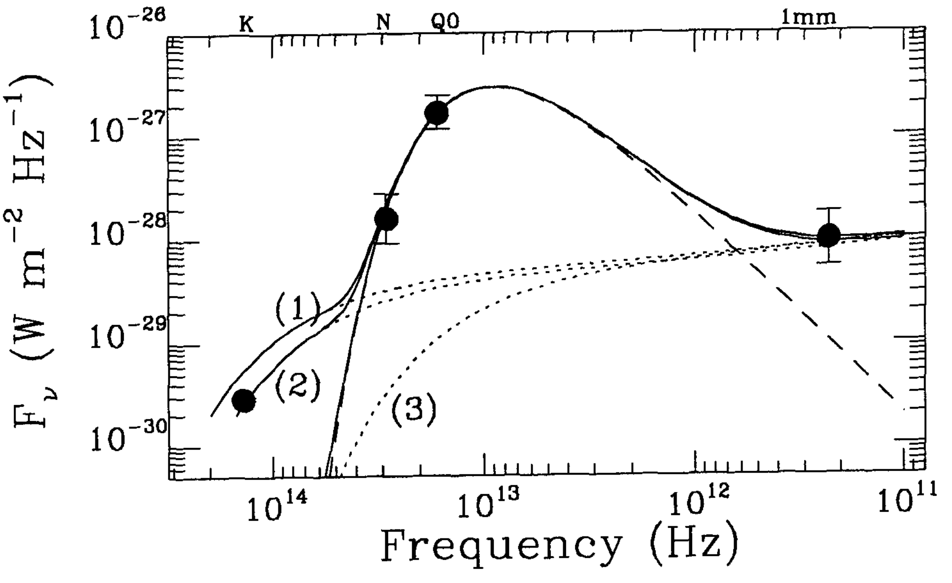

FIGURE 6. The broad band energy distribution of SN 1987A at day 2172. The dotted curves show the free-free radiation at 3000 K (1), 2300 K (2), and 500 K (3); The dashed curve represents the black body at 155 K; The plain curve is the sum of the two contributions.

from a pulsar-powered nebula has also been evoked for the origin of the 1.3mm flux (Bandiera *et al.* 1988; Salvati *et al.* 1989): that seems very doubtful due to the low level of this flux, which implies unrealistic characteristics of the eventual pulsar. The most plausible origin of the 1.3mm radiation seems to be that there is, albeit relatively faint, a component due to free-free emission underlying the black-body emission. This free-

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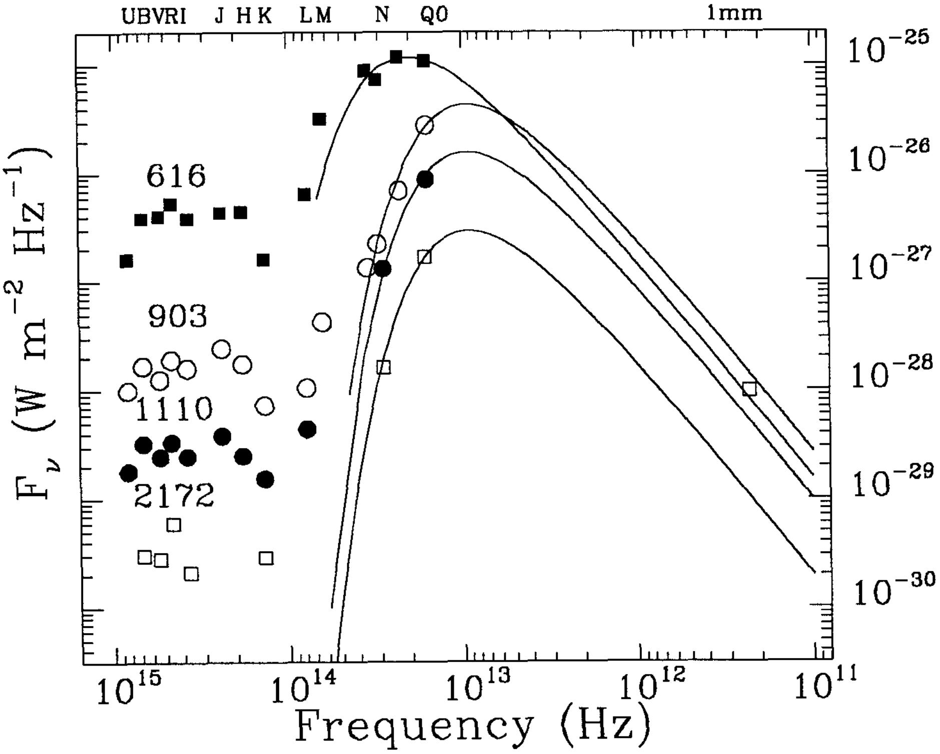

FIGURE 7. The temporal evolution of the broad band energy distribution of SN 1987A, for the indicated dates. The black bodies used for the extrapolation to the far infrared are also shown.

free emission would be produced by the cooling of the former star envelope still weakly ionized (Biermann *et al.* 1990a). The measurements at K and L allows to set a maximum temperature of the free-free emission (see Fig. 6). Our data show that that maximum temperature has decreased from T =3000K at day 1316 to T =2300K at day 2172. At this point, it is worth-while to note that the analysis of the Paschen discontinuity shows that hydrogen is recombining at even lower temperature (500 to 200K) (see Kugai and Wampler, this conference). Much of the hydrogen must be in low temperature regions. Thus, as illustrated by Fig. 6, if all or most of the radiation measured in the K band is not due to the free-free, the temperature infered from the 1.3mm measurement only may be much lower than 2300K.

3. The Bolometric Light Curve

The true bolometric luminosity is the sum of:

(*a*) the "high energy" component (direct or a few times Comptonized energy from radioactive decays of nuclides produced in the supernova event),

(*b*) the UV-Optical-Infrared ("uvoir") spectrum (thermalized radiation from the high energy sources and the emerging shock-wave).

In what follows, we consider only the "uvoir" component. Due to formation of dust (or the accelerated formation of dust), ~85% of the uvoir flux by day 900, and ~97% by day 2172 comes from the infrared. Fig. 7 shows that the bulk of the radiation is inaccessible to observations from the ground (<20μm). Thus an accurate determination

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of the bolometric light curve requires not only accurate observations from 5 to 20μm, but also an appropriate extrapolation for longer wavelengths.

Although accurate measurements in N1, N2, N3, and Q0 obtained at earlier stages (when the temperature of the dust was higher) show that they can be nicely fitted with a black body curve, it has to be stressed that the step from broad-band photometry to what is computed as L_{Bol} is a *theoretical* model. Also, since the actual flux is a combination of line emissions and thermal re-radiation from dust, the computed flux from the black body is an upper limit to the thermal radiation.

3.1. *Summary of previous works:*

The bolometric light curve has been computed by several groups:

(*a*) SAAO, using U to M photometry for the period 1–880 days (Whitelock 1991, and references therein),

(*b*) ESO/CTIO, using U to Q0 photometry for the period 1–903 days (Suntzeff and Bouchet 1990),

(*c*) ESO/BOCHUM/CTIO/KAO using spectrophotometry from the visible to the 30μm region, for the period 14–432 days (Bouchet *et al.* 1991c),

(*d*) CTIO, until day 1444 (Suntzeff *et al.* 1991, 1992), and ESO, until day 1316 (Bouchet *et al.* 1991a) using the photometry at late stages.

The main results of these works may be summarized as follows:

(*a*) The sum of the early time uvoir flux and the high-energy flux is consistent with the energy released by 0.055–0.090 $M_{\odot}$ of ^{56}Co,

(*b*) After day 600, the far infrared component can be fitted with a black body of temperatures decreasing from 400 to 140 K,

(*c*) No more than 30% of the far-IR flux can be due to thermal re-radiation of energy in a cloud behind SN 1987A (the "IR ECHO") without violating the energy budget or requiring a larger fraction of high-energy photons to escape than are predicted by the models. The effective angular radius of the thermal component ($\sim$0.015$''$ after day 600) is consistent with the velocity of the emitting ejecta,

(*d*) At day $\sim$900 the bolometric light curve exhibits a significant flattening.

3.2. *The bolometric light curve at the later phases:*

At later phases, not only the photometry is inaccurate, but also the extrapolation to the far infrared relies on very few data points (in fact, in some cases, N only!). Therefore, we have to make several assumptions in order to compute the bolometric luminosity:

(*a*) at day 1731, our measurements at 10 and 20μm can be fitted with a black body of temperature $140 < T_{eff} < 160$K, which is similar to the temperature derived for day 1316 (Bouchet *et al.* 1991a). Then, for the dates at which we don't have 20μm measurements we assume that the temperature of the black body has remained constant at 150K, and we scale it with the 10μm measurement.

(*b*) at day 2172, $L_{IR} = 0.97 \times L_{Total}$, while $L_{IR} = 0.85 \times L_{Total}$ at day 1316. Then, we estimate the L_{IR}/L_{Total} ratio from the colours (V-N) and (V-R).

The uncertainties on the distance modulus (-0.08 to +0.04 dex) and on the reddening (+0.02 dex) are negligible compared to the ones introduced by the extrapolation to the far infrared and the photometric errors. Also, lowering our Q0 by 20% (to match CTIO) gives an increase of the black body temperature of +30 to +15K, which introduces a decrease of the bolometric luminosity of -0.015 dex to -0.090 dex. Table 1 illustrates the small fraction of the actually observed flux regard to the total one, as well as the uncertainties due to the extrapolation to the far infrared and to the photometry (values between brackets have been estimated accordingly to the assumptions (i) and (ii)).

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TABLE 1. Uncertainties affecting the bolometric luminosity

Days	Range in T_{eff}	$L_{IR}^{Obs}/L_{IR}^{Tot}$	L_{IR}/L_{Tot}	Infrared extrapolation	Photometric errors
635	350–280	0.72	0.48	±0.01	±0.02
1030	180–150	0.29	0.83	±0.07	±0.03
1316	155–130	0.24	0.85	±0.08	±0.05
1493	(155–130)	0.01	(0.85)	(±0.08)	±0.18
1731	160–150	0.23	(0.90)	±0.06	±0.13
2029	(160–130)	0.01	(0.85)	(±0.08)	±0.22
2113	(160–130)	0.01	(0.95)	(±0.08)	±0.18
2172	(160–130)	0.01	0.97	(±0.08)	±0.25

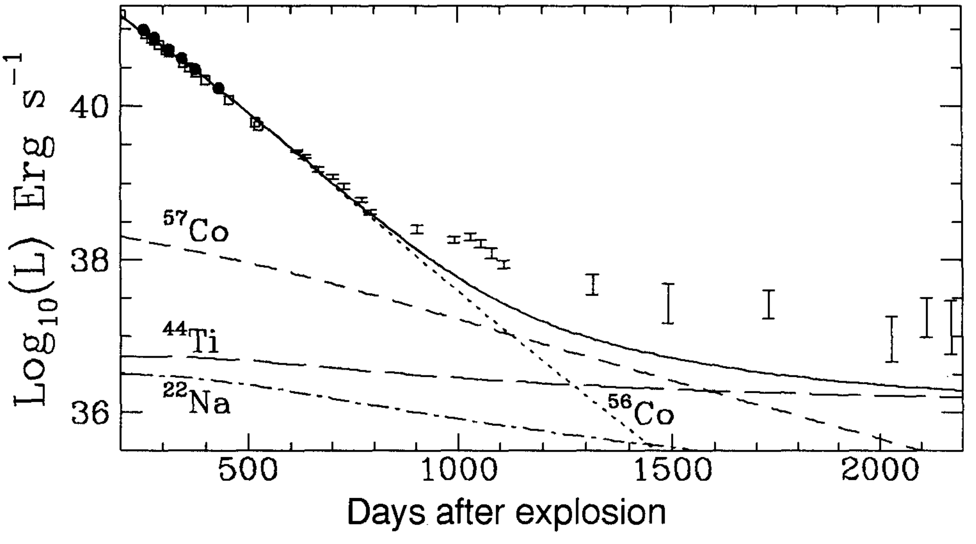

FIGURE 8. The bolometric light curve of SN 1987A; filled dots correspond to the spectrophotometric measurements, open squares to the broad-band photometric measurements. The predicted theoretical curves resulting from Woosley et al.'s model (1989) are shown. The initial ^{56}Co mass has been set to 0.069 $M_\odot$ and the column depth to 9×10^4 g cm^{-2}. The ^{57}Co/^{56}Co ratio is solar; the masses of ^{44}Ti and ^{22}Na are 1.0×10^{-4} $M_\odot$ and 2.0×10^{-6} $M_\odot$, respectively. The plain curve is the sum of all the individual contributions from radioactive decays.

3.3. *Analysis of the bolometric light curve*

In spite of the great uncertainties, the flattening of the bolometric light curve is still observed until day 2172 (see Fig. 8). Although the degree of levelling has been a source of some debate between CTIO and ESO (due to the differences in the photometry), both observatories agree that there is in the bolometric light curve an excess above the line required by radioactive decays alone. Suntzeff *et al.* (1992) and Dwek *et al.* (1992) have argued that an amount of ^{57}Co/^{56}Co~4–6 times the solar ratio of 57/56 stable nuclides would adequately fit the observed light curve. However, the amount of

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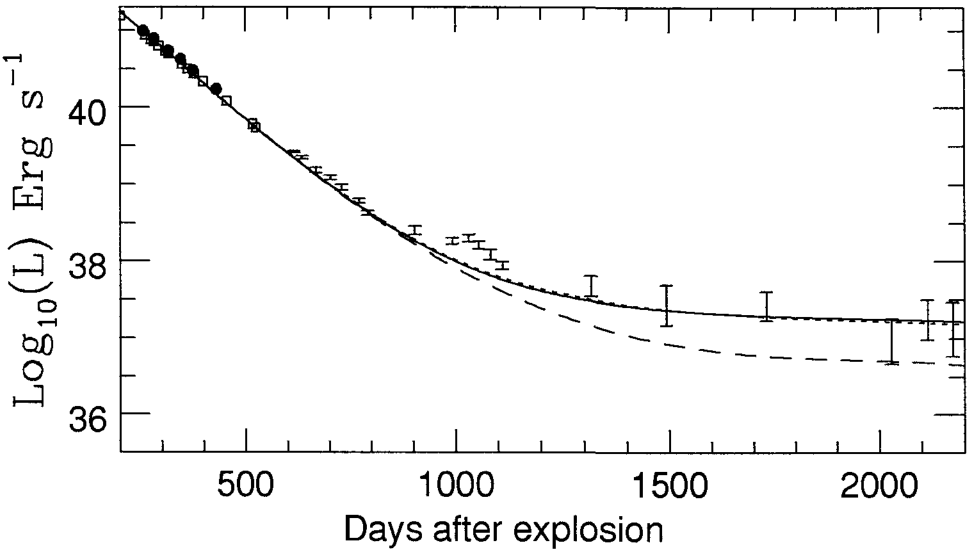

FIGURE 9. The bolometric light curve of SN 1987A as in Fig. 8. Here the $^{57}Co/^{56}Co$ ratio has been taken 2 × solar, and time dependent effects have been considered to compute the energy output from radioactive decays (dashed line) (Fransson and Kozma 1993). A central source has been added to that energy output according to Woosley *et al.* 1989: an accreting x-ray pulsator (plain) of total luminosity 2×10^{37} erg/sec, and a pulsar (dotted) of 5×10^{37} erg/sec.

^{57}Co has to be compatible with observations of the [Fe II] and [Co II] lines (Bouchet and Danziger 1993; Varani *et al.* 1990), with the failed attempts to observe the X-rays resulting from the comptonization of γ-rays from the ^{57}Co decay (Sunyaev *et al.* 1991), and with the OSSE observations of the 122 keV ^{57}Co line (Kurfess *et al.* 1992): these observations give an upper limit of 1.5 times the solar ratio. Also, the amounts of ^{44}Ti and ^{22}Na should be increased by factors 20 and 30 above that predicted by theory (Woosley and Hoffmann 1991), in order to fit the observed light curve. Such amounts of these radioactive species must be considered an unlikely possibility in view of the success of the theoretical work (Woosley 1991, Thielemann *et al.* 1991) in deriving abundances that match the observations (Danziger *et al.* 1991b).

Fransson and Kozma (1993) and Fransson *et al.* (1995) have shown that, after day ~800, time-dependent effects due to long recombination and cooling times lead to a frozen in structure of the ejecta of SN 1987A. The result is a higher bolometric luminosity, compared to models where the emitted luminosity is equal to the instantaneous energy input. Figure 9 displays the resulting theoretical light curve. Clearly, an extra energy output has still to be added in order to fit the observations. This energy could result from a compact object left at the center of the supernova, like a neutron star surrounded by an accretion disk depositing matter either continuously or at varying intervals onto the collapsed object A pulsar either beamed away from our line-of-sight or continually obscured by the dense clumps of dust is, also, still a possibility. The accreting X-rays pulsator and the pulsar models give equally good fits to the data (Fig. 9). However, it has to be stressed that no model has been able yet to reproduce the observed bump around day 1050 (at the time of the flattening). This bump is also seen in the I.U.E. data presented by Pun at this conference.

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