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HIGH-RESOLUTION MID-INFRARED IMAGING OF SN 1987A[1]

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ABSTRACT

Using the Thermal Region Camera and Spectrograph (T-ReCS) attached to the Gemini South 8 m telescope, we have detected and resolved 10 μm emission at the position of the inner equatorial ring (ER) of supernova SN 1987A at day 6067. "Hot spots" similar to those found in the optical and near-IR are clearly present. The morphology of the 10 μm emission is globally similar to the morphology at other wavelengths from X-rays to radio. The observed mid-IR flux in the region of SN 1987A is probably dominated by emission from dust in the ER. We have also detected the ER at 20 μm at a 4 σ level. Assuming that thermal dust radiation is the origin of the mid-IR emission, we derive a dust temperature of 180^{+20}_{-10} K and a dust mass of $(1-8)\times10^{-5}\ M_\odot$ for the ER. Our observations also show a weak detection of the central ejecta at 10 μm. We show that previous bolometric flux estimates (through day 2100) were not significantly contaminated by this newly discovered emission from the ER. If we assume that the energy input comes from radioactive decays only, our measurements, together with the current theoretical models, set a temperature of 90 K $\leq T \leq$ 100 K and a mass range of 10^{-4} to $2\times10^{-3}\ M_\odot$ for the dust in the ejecta. With such dust temperatures the estimated thermal emission is $(9\pm3)\times10^{35}$ ergs s^{-1} from the inner ring and $(1.5\pm0.5)\times10^{36}$ ergs s^{-1} from the ejecta. Finally, using SN 1987A as a template, we discuss the possible role of supernovae as major sources of dust in the universe.

Subject headings: dust, extinction — infrared: ISM — supernova remnants — supernovae: individual (SN 1987A)

1. INTRODUCTION

The circumstellar envelope (CSE) surrounding SN 1987A consists of an inner equatorial ring (ER) flanked by two outer rings (Burrows et al. 1995). These rings, created ~20,000 yr before the explosion of the supernova, form the waist and caps of an hourglass, or "bipolar," nebula ~1 pc across, enclosing an H II region and expanding into a diffuse medium that terminates in a dense shell 4 pc in radius (Crotts & Heathcote 2000).

The collision between the ejecta of SN 1987A and the ER, predicted to occur sometime in the interval 1995–2007 (Gaensler et al. 1997; Borkowski et al. 1997), is now under way. "Hot spots" have appeared inside the ER (Pun et al. 1997), and their brightness varies on timescales of a few months (Lawrence et al. 2000). In the next few years, new hot spots will continue to appear as the whole inner rim of the ER lights up, probably brightening by a factor of 1000 during the next several years (Luo et al. 1994).

The spectral energy distribution longward of 5 μm has evolved continuously in time. After day 300 a cold, dustlike component appeared (Suntzeff & Bouchet 1990; Bouchet & Danziger 1993; Wooden et al. 1993). An asymmetry in the profiles of optical emission lines that appeared at day 530 showed definitely that dust had condensed in the metal-rich ejecta of the supernova (Lucy et al. 1991). Although it was discovered via spectroscopy (Danziger et al. 1989), the presence of the dust could be easily inferred from the spectral energy distribution: as the dust thermalized the energy output, after day 1000, SN 1987A radiated mainly in the mid-infrared (Bouchet et al. 1991). Unfortunately, after approximately day 2000, the flux emitted from SN 1987A in the thermal spectral region was too weak to be detected by the instruments and telescopes available. SN 1987A was observed at day 4100 with ISOCAM, on board the ESA *ISO* satellite (Fischera & Tuffs 2000). In 2003, one of us (P. B.) reported a weak detection of the supernova at day 4300 with OSCIR at the CTIO 4 m telescope. Except for these two observations, there have been no other detections of the mid-IR emission from the ejecta/ring region of SN 1987A over the last five years.

There exist very few mid-IR observations of supernovae in general. Therefore, SN 1987A, the closest known supernova in 400 yr, gives us an opportunity to explore the mid-IR properties of supernovae and their dust, with the help of the newest generation of large-aperture telescopes and sensitive mid-IR instrumentation.

2. OBSERVATIONS

The new Thermal Region Camera and Spectrograph (T-ReCS) mid-IR imager/spectrometer at the Gemini South 8 m telescope offers a combined telescope and instrument

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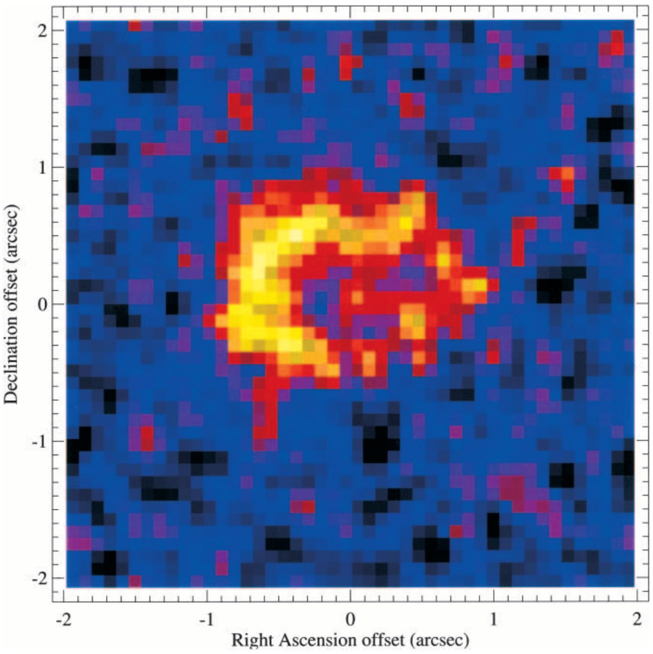

FIG. 1.—SN 1987A seen with T-ReCS at day 6067 in the *N*-band filter ($\lambda = 10.36$ μm). The image is smoothed to 2 pixel (0$''$.18) resolution. Note, in particular, the central point source that corresponds to the ejecta of the supernova.

with diffraction-limited imaging (0$''$.3 resolution) and superbly low thermal emissivity. On 2003 October 4 (day 6067), we imaged SN 1987A with T-ReCS as part of the instrument's system verification program. In a 23 minute on-source, co-added image in the *N*-band filter ($\lambda = 7.70-12.97$ μm), we were easily able to detect and resolve the ER (Fig. 1). This image shows several luminous hot spots distributed over the ring. The calibrated flux density integrated within an aperture of 1$''$.3 radius is 9.9 ± 1.5 mJy. This absolute calibration has been made using $\lambda_{\rm eff} = 10.36$ μm. No color correction was applied; doing so would most likely increase the flux density. The standard star used for this and all calibrations was HD 37160, whose flux density was taken to be 8.77 Jy in the *N* band. On 2003 December 1 (day 6125), a short exposure of the supernova in the *Qa* band ($\lambda = 17.57-19.08$ μm) led to a 3.7 σ detection of the resolved ER with a flux density of 50.6 ± 6.6 mJy (this image will be published when reinforced by improved signal-to-noise ratio images). We used α CMa, with a flux density of 44.3 Jy at 18.30 μm, for the flux calibration of that observation.

In Figure 2, we compare our 10 μm data with data we obtained in the He I line at CTIO at day 5749 (Fig. 2*a*) and in the F656N filter, as observed by the *Hubble Space Telescope* (*HST*) at day 5555 (Fig. 2*b*; ESO/ST-ECF Science Archive Facility). This filter includes the Hα and [N II] λ6583 lines. Our mid-IR image is also compared with the *Chandra* X-ray image obtained at day 5791 (Fig. 3*a*; Park et al. 2004b) and the Australian Telescope National Facility (ATNF) 18.5 GHz (12 mm) maximum entropy restored image at day 6002 (Fig. 3*b*; Manchester et al. 2003). There is good agreement in shape and size between our mid-IR image and images obtained at other wavelengths. The mean radii and approximate surface brightness distribution (brighter on the east side) of the ring are similar over the range from X-ray to radio wavelengths, demonstrating that the dust is coextensive with the gas components. The origin of that brightness asymmetry may be related either to the asymmetric distribution of the ejecta and/or the density variation in the circumstellar matter (CSM; Park et al. 2004b, 2004c) or to a time-dependent effect caused by the tilt of the ER, as discussed by Panagia et al. (1991).

The most likely source of mid-IR radiation is thermal emission from cool dust (see discussion below), whereas the X-radiation is thermal emission from very hot gas (Park et al. 2004a, 2004c). The radio emission is likely to be synchrotron radiation, as is the case for Cas A (Dunne et al. 2003); those authors claim that if the dust were at a temperature of 100–150 K, it could be heated by collisions with fast-moving electrons and ions in the hot gas seen with *Chandra*. Park et al. (2004c) argue that until 2002 May 15, hard X-ray and radio emissions were produced by fast shocks in the circumstellar (CS) H II region, while the optical and soft X-ray emissions came from slower shocks in the denser ER. Park et al. (2004a, 2004b) report morphological changes in their last *Chandra* image, which is an indication of the blast wave now appearing to encounter the ER in the western side a few years after it

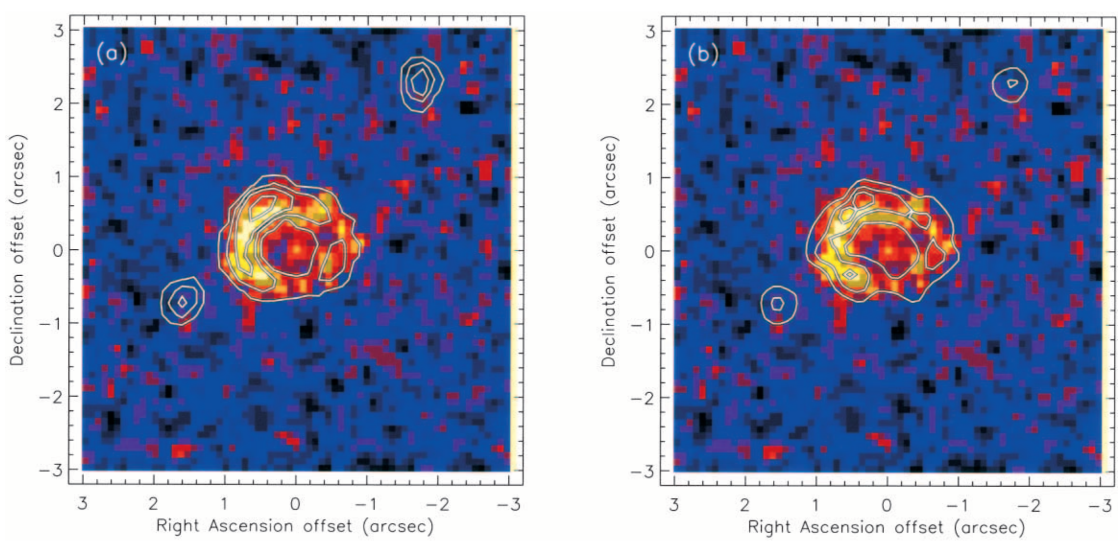

FIG. 2.—T-ReCS 10 μm images of SN 1987A, smoothed to 2 pixel (0$''$.18) resolution, overlaid with contours of the images obtained (*a*) in the He I line (1.083 μm) with OSIRIS at the CTIO Blanco telescope at day 5749 and (*b*) through the F656N filter (Hα and [N II] λ6583) with *HST* at day 5555. The *HST* image is smoothed to 1.5 pixel (0$''$.15) resolution. The central source is not seen in any of the two overlays, whereas it is detected at 10 μm.

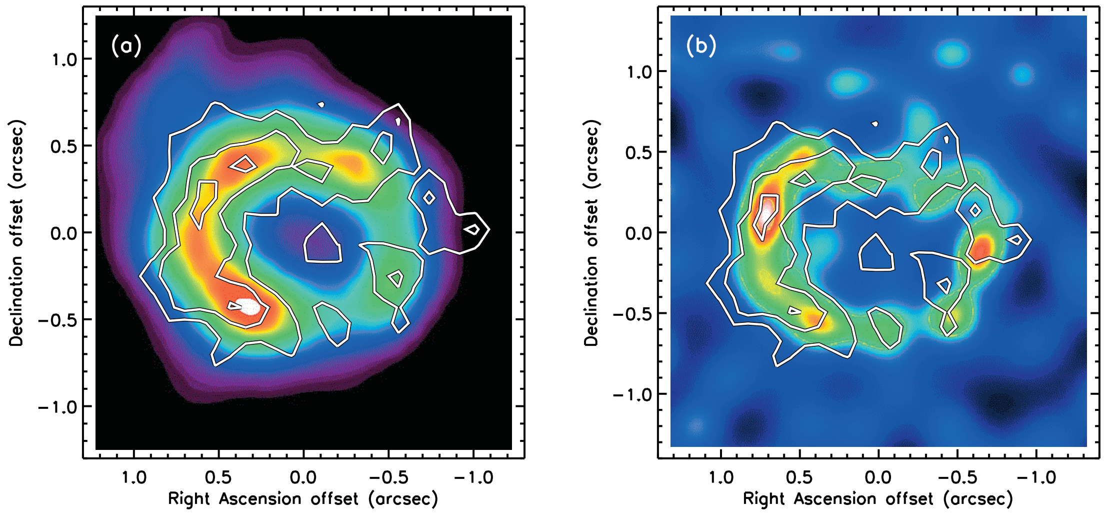

FIG. 3.—SN 1987A. (*a*) *Chandra* 0.3–8.0 keV broadband image obtained at day 5791; (*b*) ATNF 8 GHz restored image obtained at day 6002. The overlays correspond to the T-ReCS image.

reached the eastern side, and note that as of 2002 December 31 (day 5791), correlations between the X-ray and the optical/radio images are more complex than the above simple picture.

3. DISCUSSION

The origin of the 10 μm emission, for both the ER and the ejecta, may be (1) line emission from atomic species, (2) synchrotron or free-free emission, or (3) thermal emission from dust. As for the ER, its detection at 20 μm seems to suggest that the emission is thermal emission from dust. A blackbody of temperature $T_{\rm dust} = 180^{+20}_{-10}$ K can be fitted to our data. An order-of-magnitude estimate can be obtained for the dust mass from the formula

$$M_{\rm dust} = \frac{\pi D^2 F_\nu(\lambda)}{\kappa(\lambda)\pi B_\nu(\lambda, T)}, \qquad (1)$$

where D is the distance to the supernova, $F_\nu(\lambda)$ the observed flux at 10 μm, $\kappa(\lambda)$ the dust mass absorption coefficient at this wavelength, and $\pi B_\nu(\lambda, T)$ the Planck function. The approximate range for silicate and graphite grains for κ at 10 μm is 100–2000 cm^2 g^{-1}. We use $D = 51.4$ Kpc (Panagia 1999). Considering the uncertainty in the temperature, we derive from this formula a dust mass range of $(1-80) \times 10^{-6}$ $M_\odot$. Park et al. (2004b) reported a plasma temperature of $T \sim 2.8 \times 10^7$ K and a gas density $n = 235$ cm^{-3} for the hard component of their two-shock model. According to Dwek (1987), our inferred temperature indicates a high gas density ($n \geq 100$ cm^{-3}) and a large grain size in the ER and is thus in good agreement with the *Chandra* X-ray observations.

Possible scenarios for the late-time mid-IR emission in Type II supernovae (Graham & Meikle 1986; Gerardy et al. 2000) are (1) dusty ejecta, (2) an infrared echo, or (3) dust heated from circumstellar interaction. In the last case, the dust could be (*a*) preexisting dust in the CSM heated by the outer blast wave, or (*b*) newly formed dust in the ejecta heated by a reverse shock traveling backward (in mass) into the supernova envelope. Our observations show that the bulk of the *received* IR flux does not originate in the metal-rich parts of the ejecta (e.g., the weak detection at the center of the ring). Moreover, these parts are expanding much more slowly than the outer parts of the H-rich envelope, and they have not yet reached the ring. As it is most unlikely that dust formed in the tenuous outer, H-rich layers of the SN interacting with the ring, we believe that the IR emission is produced by preexisting dust in the CSM heated by the outer blast wave (scenario 3*a*).

This interaction converts part of the kinetic energy into radiative output. That leads to a caveat in our reasoning: we assume that all the emission from the ER is in the form of IR emission, and we do not consider the possibility that the dust may just be reradiating a fraction of the ambient radiation if the heating mechanism were due in part to radiation and not only to collisions. However, it is most likely that the dust may be shock-heated, in which case the IR emission cools the hot plasma that gives rise to the X-ray emission as well. Indeed, Dwek et al. (1987) show that IR emission from collisionally heated dust is the dominant cooling mechanism of the shocked gas in SNRs. Dwek (1987) computes the ratio between the cooling function of the gas via gas-grain collisions and that via atomic processes as a function of the gas temperature only. Dwek et al. (1987) note that if the dust that gives rise to the IR emission occupies the same volume as the X-ray–emitting plasma (as appears to be the case in view of our Fig. 3), this cooling ratio translates into the infrared-to–X-ray flux ratio (IRX). These authors show that the observed values of this ratio are significantly larger than unity for the nine remnants that they considered and concluded that IR emission, mostly attributed to gas-grain collisions, is the dominant cooling mechanism in these remnants over large periods of their evolutionary lifetime.

Park et al. (2004a, 2004b) report that as the blast wave approaches the dense CSM, the contribution from the decelerated slow shock to the observed X-ray emission is becoming significant and increasing more rapidly than ever as of 2002 December 31. They fit their data with a two-temperature model for that epoch and find a temperature of $kT = 0.22$ keV and a luminosity of $L \simeq 1.6 \times 10^{35}$ ergs s^{-1} for the decelerated slow shock component and $kT = 2.44$ keV and $L \simeq 3.7 \times 10^{35}$ ergs s^{-1} for the blast wave shock. Combining our data with these results leads to values of IRX $\simeq 6$ and IRX $\simeq 3$, respectively. These values fall significantly below the theoretically expected ratios, at roughly the same position as the Kepler remnant in Figure 1 of Dwek et al. (1987). These authors argue that in Kepler, the low IRX ratio may mostly reflect the absence of dust in the material heated by the reverse shock. Our observations, then, suggest that little dust was formed in the ejecta during the presupernova mass-loss phase of the progenitor. We note, however, that the IRX calculations were performed for a local interstellar dust abundance and a standard dust-to-mass ratio, which might be inapplicable for SN 1987A.

The *N*-band detections of SN 1987A at days 4100 and 4300 suggested that dust was still present in the ejecta and was the dominant component of the ejecta's bolometric flux. However, the *ISO* observations were slightly nonstellar, strongly suggesting that some of the dust emission was coming from the inner ring, presumably heated by the shock front as the high-velocity material hit the ER material (Fischera et al. 2002a). EUV radiation is produced in the shock and ionizes the gas upstream of the shock front, revealing the structure and properties of the outer nebula. Fischera et al. (2002b) estimate that the CS dust is most likely a silicate-iron or silicate-graphite mixture or pure graphite. These types of grains have spectral signatures in the *N* band that were not detected in the dust that condensed in the ejecta (Bouchet 1990), most probably in the form of *X*-type SiC (Amari et al. 1992; Lucy et al. 1991).

After day 530 the dust emission became the dominant cooling mechanism of the ejecta of SN 1987A, radiating away the energy from the radioactive nuclides synthesized in the explosion. What happened, then, to this early dust emission? In Fig. 1, a small flux enhancement with a flux density of 0.32 ± 0.1 mJy (3 σ) can be seen in the center of the ring. It is likely that this weak feature is the remains of the dust emission from the condensates in the ejecta. Although the *N* filter contains several IR lines, such as Ar III ($\lambda = 8.99$ μm), S IV ($\lambda = 10.51$ μm), and Ne II ($\lambda = 12.81$ μm), these lines require too high an ionization state to contribute significantly to this emission. Moreover, we note from Figure 2 that the ejecta has been detected neither in the He I line nor in the Hα or [N II] lines. As the ejecta has not been detected in the radio regime either, the possibility of free-free or synchrotron emission is also ruled out. Therefore, it is likely that the weak feature detected at 10 μm is the remains of the dust emission from the condensates in the ejecta. Probably the ER and the ejecta have different dust temperatures, as was observed in Cas A (Dunne et al. 2003). We do not detect the ejecta in our *Qa*-band image, which sets a flux upper limit of 41 mJy at the 3 σ detection level at this wavelength and then a lower limit for the temperature of the ejecta $T \geq 90$ K. Fransson & Kozma (1993) showed that time-dependent effects due to long recombination and cooling times lead to a frozen-in structure of the ejecta of SN 1987A. However, Fransson & Kozma (2002) claim that freeze-out is important for hydrogen at times shorter than $\sim$3000 days and that at later stages positron input from ^{44}Ti and reverse shock heating are the major sources of energy input to the envelope. In view of their Figure 2, the bolometric luminosity of the ejecta should be of the order of $(1-2) \times 10^{36}$ ergs s^{-1}. Assuming that there is no other energy input than the radioactive decays, this luminosity is an upper limit of the IR luminosity (e.g., all the energy might not be released in the IR through dust emission). To derive this luminosity, given our 10 μm flux measurement, the dust temperature must be $T \leq 100$ K. Thus, our observations give us upper and lower limits, implying a temperature of 90 K $\leq T \leq$ 100 K for the dust in the ejecta. The dust mass derived from equation (1) is then $M = 10^{-4}$ to 2×10^{-3} $M_\odot$, considering the same approximate range for κ(10 μm), 100–2000 cm^2 g^{-1}, as for the ER.

We stress that the value given here is an upper limit of the IR luminosity, as Dwek et al. (1992) show that at day 1153

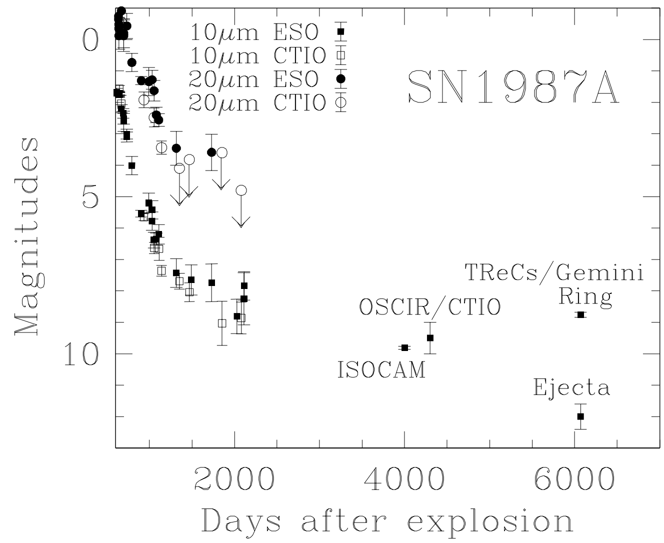

FIG. 4.—Mid-IR light curves of SN 1987A. The point called "Ejecta" derives from the weak point source near the center of the image.

line emission, mostly due to the [Fe II] 26 μm transition, and other ground-state fine-structure lines at 35, 51, and 87 μm may contribute significantly to the total luminosity. These authors find for that epoch a dust temperature of 120 K $< T <$ 160 K. We note that the same caveat given for the ER applies to our statement concerning the energetics of the ejecta: we do not consider the mechanical energy, which is in the process of being transferred to the ambient medium through the forward shock or to the ejecta itself through the reverse shock, that can power the observed IR emission. This issue will be tackled in a forthcoming paper.

Figure 4 shows that the flux at 10 μm declines exponentially from day 2200 through day 4200 (the ISOCAM and OSCIR observations). This figure shows two data points for day 6067 (ejecta and ER). The possible ring contribution to day 4200 is unknown. However, it seems that the ejecta 10 μm flux from day 6067 lies on the extension of the exponential decline curve that roughly goes through the 10 μm flux at day 4200. If one assumes, then, that the 10 μm emission from the ejecta indeed follows an exponential decline law, that leaves no room for any ring contribution to day 4200. We conclude, therefore, that the 10 μm flux decline of the ejecta from day 2200 to 6000 is roughly 0.32 mag yr^{-1} and that the ring emission started most likely around day 4000 or later, in good agreement with Figure 5 of Park et al. (2002) for ATCA (Australia Telescope Compact Array) and *Chandra*/*ROSAT* data.

Gerardy et al. (2000) report on the detection of dust emission in the near-IR spectra of the Type IIn supernovae SN 1998S (a supernova similar to SN 1987A) and SN 1997ab and summarize dust emission in other supernovae: the IR excess observed in SN 1979C and SN 1985L is interpreted as dust forming in the ejecta, while it is attributed to dust lying in preexisting CSM in SN 1982E, SN 1982L, SN 1982R, SN 1993J, SN 1994Y, and SN 1999el (Di Carlo et al. 2002). Although it has been claimed (Dwek 1983; Dwek et al. 1983) that the near-IR emission from SN 1980K can be explained as an IR echo, we note that this supernova displayed, together with an IR excess, large blueshifts of the [O I] and [O III] lines of $\sim$3300 km s^{-1} (Fesen & Becker 1990), compared with 1870 km s^{-1} in SN 1987A, which seems to imply that dust has formed also in the ejecta of SN 1980K. In addition, Elmhamdi et al. (2003) presented clear evidence of dust formation in the Type IIP SN 1999em 500 days after explosion. Lagage et al. (1996), Douvion et al. (1999), and Arendt et al. (1999) detected a continuum consistent with silicate dust of very small pyroxene grains ($MgSiO_3$) in the youngest known Galactic SNR, Cas A.

All of the above observations of dust in supernovae may lead us to the conclusion that supernovae could be a major source for interstellar dust. Various indirect arguments (Amari et al. 1992) and theoretical calculations (Dwek & Scalo 1980; Clayton 1982; Dwek 1998) also suggest that hypothesis. Nevertheless, stellar winds from various types of stars are still considered a major source of dust production. For instance, Douvion et al. (1999) argue that supergiants and AGB stars form the bulk of the dust in the Galaxy, not supernovae. Dunne et al. (2003) argue that supernovae are at least as important as stellar winds in producing dust in our Galaxy and in galaxies at high redshifts. Morgan et al. (2003) also conclude that supernovae, or their progenitors, may be important dust formation sites.

4. CONSIDERATIONS FOR THE FUTURE

Several theoretical models predicted the presence of dust in the CSE of SN 1987A, which was produced by a wind in the supergiant phase. The CS dust is likely to be in the form of pyroxene or graphite grains, while the dust condensed in the ejecta is most probably of some type of silicon carbide. Forthcoming imaging and spectroscopic observations focusing on line versus continuum emission should determine the type of emission present, and they are required to clarify the issue of the energetics of the supernova.

Finally, in order to assess the role of SNe in the production of dust in the universe, it is clearly important to measure the presence of dust that survives into the formation of the remnants, and for this, mid-IR and submillimeter observations are critical.

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