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INFRARED OBSERVATIONS OF SN 1987A FROM 5.3 TO 12.6 MICRONS: EVIDENCE FOR AN EARLY DUST ECHO

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ABSTRACT

Supernova 1987A was observed spectroscopically in the wavelength range 5.25–12.6 μm from the Kuiper Airborne Observatory on two nights, approximately 60 days after the initial outburst and about 25 days before maximum light. Significant spectral features superposed on the 5500 K photospheric continuum were seen on both flights. Strong Huβ and Pfα emission lines were observed from the extended hydrogen envelope above the photosphere of the supernova. In addition to these emission lines, an infrared excess emission was observed from 7 μm to at least 11.5 μm. This excess emission may represent evidence for an infrared echo from dust grains heated by the supernova outburst.

Subject headings: infrared: sources — nebulae: supernova remnants — stars: supernovae

I. INTRODUCTION

The occurrence on 1987 February 23 of a supernova in the Large Magellanic Cloud presented an opportunity to study such an object at relatively short range. Guidelines for the behavior of the new supernova may be obtained from previous observations of distant supernovae and from theoretical predictions. The presence of hydrogen lines and the light curve of SN 1987A are roughly consistent with previous Type II supernovae. The observed deviations of SN 1987A from typical Type II light curves are discussed by Woosley *et al.* (1987) in terms of a compact progenitor. Other authors, Arnett (1987) and Hildebrand *et al.* (1987), have also shown that such a star would produce a fainter than normal supernova closely matching the behavior of SN 1987A. The compactness of the object was ascribed to mass loss by the progenitor and/or low metallicity of the progenitor by these authors.

Previous Type II supernovae have had continuum emission longward of 2 μm which was a combination of emission from the expanding atmosphere of the exploding star and thermal emission from dust. The temperature and brightness of the atmosphere drops as its expands, while the dust emission becomes more prominent (cf. Dwek *et al.* 1983). Two explanations for the dust emission have been put forward: condensation of ejected material and a dust echo from existing material around the supernova. Both Dwek (1983) and Graham and Miekle (1986) argue that the excess infrared emission observed in previous supernovae can, in cases observed so far, be explained as due to an echo and in at least one case, Graham *et al.* (1983) showed unambiguously that the infrared excess emission from SN 1982E was due to an echo. The infrared dust echo in SN 1987A has been observed by us and by Aitken and Smith (1987). Our data (Fig. 1) show an excess emission from the new supernova which can be attributed to emission from dust.

II. OBSERVATIONS

SN 1987A was observed on two nights, 1987 April 21 and 27, with the Kuiper Airborne Observatory. Infrared spectra were obtained from 5.25 μm to 12.6 μm on the first night. Observations on the second night were hampered by high clouds and after reaching clear skies there was time to observe only the shorter wavelengths from 5.25 μm to about 9 μm. All observations were made at an altitude of 41,000 feet (~12.5 km). Atmospheric correction and flux calibration were obtained from the stars α Hydra and σ Libra which were observed either before or after the supernova on each flight.

The spectra were taken with a 24 channel grating spectrometer which has been described elsewhere (Witteborn and Bregman 1984). The resolving power of the spectrometer was nominally equal to 75 corresponding to about 4000 km s^{-1} velocity resolution. All observations were made using a 22″ aperture on the sky. Four grating settings were required to cover the complete spectral range of 5.3–12.6 μm and on the second flight, short wavelength spectra were taken at a one-half channel spacing requiring a fifth grating setting. Wavelength calibration was derived from absorption in polystyrene film and from emission lines from the bright H II region G333.6 − 0.2.

a) Discussion: Hydrogen Line Emission

Three spectral emission lines can be identified in the spectra of SN 1987A shown in Figures 1, 2, and 3. Figure 2 shows the Pfα (5–6), Huβ (6–8) line blend at 7.5 μm with a measured flux of $(9.6 \pm 0.5) \times 10^{-18}$ W cm^{-2}, and Figure 3 shows the Huα

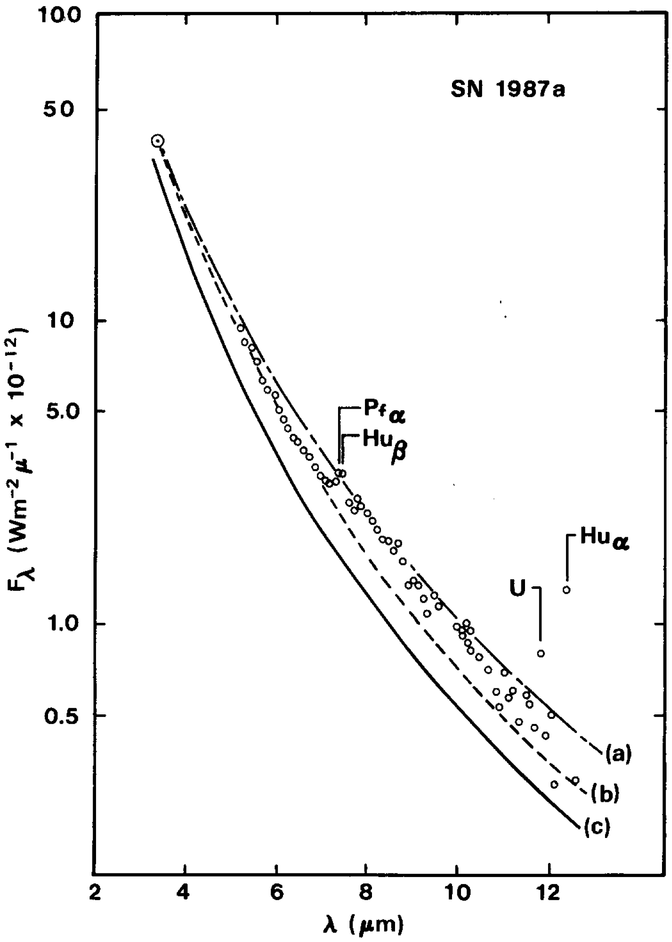

FIG. 1.—5.25–12.6 μm supernova spectrum compared to graybody curves: (*a*), 5500 K plus 1500 K graybody normalized to the SN spectrum at 2.2 μm and 3.4 μm; (*b*), 5500 K graybody normalized at 3.4 μm; (*c*), 5500 K graybody normalized at 2.2 μm. The photometric data at 2.2 and 3.4 μm (*dotted circle*) is from Menzies *et al.* (1987), and it has been extrapolated about 7 days to the date of the KAO observations. The good fit to the data between 3 μm and 7 μm shown by curve (*b*) is expected from the Type II supernovae models of Hershkowitz *et al.* (1986*a*).

(6–7) line at 12.4 μm with a flux of (9.7 ± 3) × 10^{-18} W cm^{-2}. The hydrogen lines shown in the figure are expected to be formed in a zone of H II recombination above the photosphere of the supernova, and their presence assures us that our data describe a relatively pure hydrogen recombination above the photospheric continuum spectrum from 5 μm to 12.6 μm.

Such a spectrum should be typical of Type II supernovae in their early phase of expansion. Unfortunately the signal-to-noise ratio of the Huα line is not high enough to make a reliable comparison with the expected line strengths of Pfα (5–6) and Huβ (6–8) from recombination theory and our data alone. Aitken and Smith (1987) measured Huα from the ground in mid-April and determined a flux of 4.5 × 10^{-18} W cm^{-2} in the line. This flux is in general agreement with a measurement by Blanco *et al.* (1987) of the Brγ (4–7) line intensity of 1.5 × 10^{-17} W cm^{-2} made about 1 month prior to our observations. Scaling this Brγ line intensity to Huα using Einstein A coefficients for hydrogen would give a flux of 3.4 × 10^{-18} W cm^{-2} for Huα, in good agreement with Aitken and Smith. It is possible that our measurement of the Huα flux is in error by about +2 σ since it is also inconsistent with the flux predicted from the Pfα, Huβ blend in our data on the basis of recombination theory (Seaton 1959). Line fluxes of Pfα = 6 × 10^{-18} W cm^{-2}, Huβ = 3 × 10^{-18} W cm^{-2}, and Huα = 5 × 10^{-18} W cm^{-2} are consistent with our data and the reported observations of other observers, provided that we choose the 2 σ lower limit for our measurement of Huα.

b) Discussion: Continuum

The observed LW IR emission of SN 1987A shown in Figure 1 generally fits a 5500 K graybody curve inferred by optical and near-IR measurement. The photospheric effective temperature T_e and angular size at the time of our observations, which are derived from the graybody spectral flux density of the SN, are 5500 K and 7 × 10^{-9} rad, respectively (Menzies *et al.* 1987).

Hershkowitz, Linder, and Wagoner (1986*a*) have calculated the emergent flux density from model atmospheres typical of Type II supernova photospheres. They found that the dominance of scattering over absorptive opacity in such atmospheres leads to a slow increase of the effective radiation temperature of the photosphere across the near-IR visible and UV portion of the spectrum. Thus these supernova models predict a spectrum which is broader and falls off more slowly in the near-IR than that of a simple blackbody radiating at the effective temperature of the photosphere: Curve (*c*) in Figure 1 shows the decline in flux density of a 5500 K blackbody normalized to the flux of SN 1987A at 2.2 μm. Curve (*b*) provides a much better fit to the observed data from 5 to 7 μm with the Rayleigh-Jeans portion of a 5500 K blackbody normalized to the supernova flux at 3.4 μm. The apparent increase in IR flux density indicated by curves (*b*) and (*c*) of Figure 1 generally agrees quite well with the Type II model calculations of Hershkowitz, Linder, and Wagoner (1986*b*) for an effective photospheric temperature of 6000 K and an atmospheric scale height of 10^{13} cm. Accurate comparison of their model to supernova 1980K gave effective temperature = 8500 K and a scale height of the photosphere = $\frac{1}{3}$ × 10^{13} cm. The continuum emission from SN 1987A extending from about 7.0 to 11 μm cannot be produced by a hot photosphere since it does not have the slope of a 5500 K blackbody as shown in curve (*b*) of Figure 1. Significant excess emission above that expected from the expanding stellar photosphere is clearly indicated in the figure. The emission excess extends from about 7.0 to 12.0 μm representing a 20%–30% enhancement in spectral flux density throughout the region. Excess emission by solid grain material in this spectral band is common in the spectra of stars and H II regions where dust temperatures can range from 200 K to 700 K. The excess emission from the supernova vicinity appears quite similar to such circumstellar grain emission and may arise from material present prior to the supernova. Such emission is not expected in Type II SNs at early times according to present models of supernova ejecta (Weaver and Woosley 1986). Solid particles could form in the expanding envelope of a SN only after a period of 200 days from the initial explosion. Models of Type II supernovae with circumstellar dust shells (Dwek 1983) also indicate that excess emission due to dust particles will appear much later in the evolution of the SN and that the "signature" of the circumstellar dust will first appear at shorter wavelengths due to an indicated characteristic temperature of 1000 K or larger.

An LW IR tail is predicted for Type II SNs by these models; however, the excess emission appears 1–2 yr after detonation. The evidence for a hot dust component in the spectrum of SN

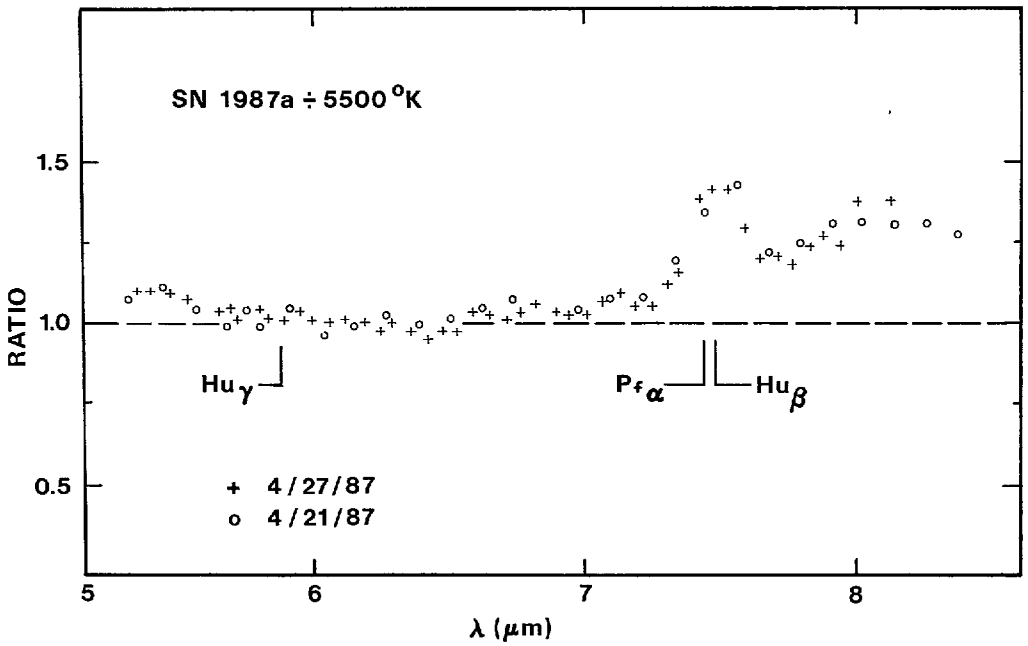

FIG. 2.—Comparison of observed spectra on two flights in the region of the Huα (6–9), Huβ (6–8), and Pfα (5–6) lines 5.25–8.0 μm. Circle data points were sampled at a frequency equal to the spectral resolution of the instrument. Plus data points were sampled at twice the instrumental resolution. Both spectra are divided by a 5500 K graybody spectral flux density.

1987A is, however, clearly apparent by comparison of curve (*c*), Figure 1, with our data. Since the equilibrium blackbody temperature at a distance of 30 lt-days from the SN is about 1000 K, it is plausible that the temperature of material surrounding SN 1987A could be low enough for solid material to survive. Therefore the observed IR excess probably represents the onset of an IR echo in the supernova. Roughly $10^{-4}M$ of dust in the form of 1 μm particles could produce the observed IR excess in Figure 1. The emissivity of these particles would have to peak sharply in the region of 7.5–10.5 μm in order to suppress their emission from 4 to 6 μm. Though such particles could exist in the vicinity of SN 1987A it is still a matter of considerable surprise that an echo first appears at longer rather than shorter IR wavelengths. Clearly further observations in the 4–10 μm region are required to follow the development of the IR spectrum of 1987A.

c) *Discussion: Unidentified Spectral Features*

Figure 2 shows an unidentified spectral feature at 5.3 μm. This feature appeared in the spectrum of the supernova on

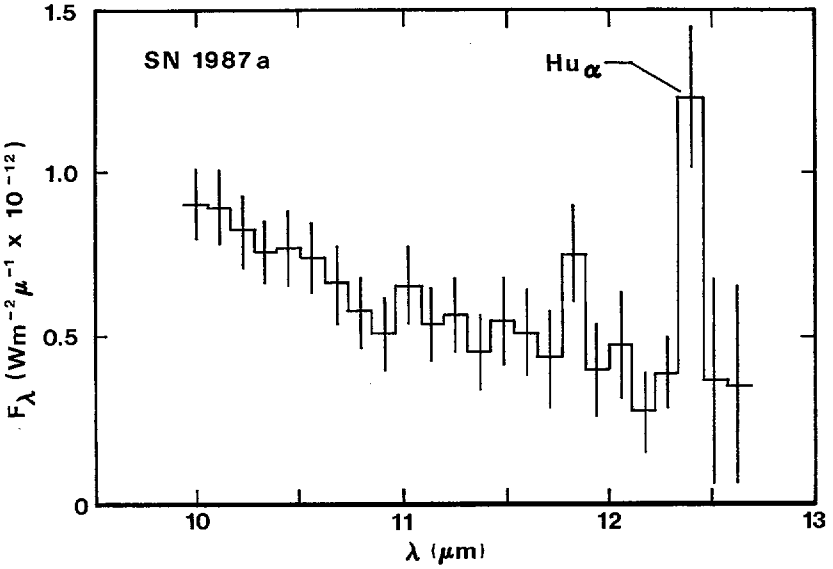

FIG. 3.—Spectrum of SN 1987A from 10 to 12.6 μm showing the Huα (6–7) line and a possible unidentified line U at 11.8 μm. The spectral flux density calibration of these data has been derived from the star α Hydra.

both nights with a signal-to-noise ratio greater than 10. The 5.3 μm feature is not the result of incomplete atmospheric correction or an instrumental artifact since the calibration stars and other sources observed on the two nights produce smooth, well-calibrated spectra from 5 to 8 μm. This feature is most probably a blend of weak lines from the supernova or possibly the result of enhanced emission from circumstellar material. A spectral line observed on one night at 11.8 ± 0.06 μm is also unidentified. The line flux of $(3 \pm 2) \times 10^{-18}$ W cm^{-2} has a marginal statistical significance and may be the result of noise in the data.

III. CONCLUSIONS

We find strong evidence for the existence of circumstellar dust grains in the vicinity of SN 1987A. This material is required to explain the infrared excess emission observed between 7.5 and 11 μm. Rough constraints can be applied to the known geometry of the supernova to provide an estimate of the amount of material which was ejected by the progenitor star. Approximately 10^{-4} $M_\odot$ of dust within a distance of 2 lt-months of the supernova would be sufficient to convert the visible and ultraviolet light of the star into the observed infrared excess radiation. Dust at greater distances along the line of sight to the supernova could in principle produce the observed IR echo; however, the rather high (larger than 500 K) apparent temperature of the dust implies that the dust is relatively close to the star. Further observations measuring the IR light curve of SN 1987A will allow more stringent constraints to be placed on both the amount and location of the circumstellar material.

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