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SPECTRAL LINE PROFILES OF NICKEL AND ARGON IN SUPERNOVA 1987A: EXPANSION VELOCITY AND ELECTRON SCATTERING EFFECTS

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ABSTRACT

Spectra of SN 1987A showing the Ni II 6.634 μm and Ar II 6.983 μm fine-structure lines were obtained from the Kuiper Airborne Observatory in 1988 April. The signal-to-noise ratio of 100 near the peaks and resolving power of 200 are sufficient to show the average velocity of expansion from the core of about 1400 km s^{-1} and to indicate the range of velocities. An asymmetry in the profiles of both lines and a redshift of the line centroids of about 440 km s^{-1} above the 280 km s^{-1} recessional velocity of the LMC can be explained in terms of scattering of the photons by electrons in the expanding hydrogen envelope of the supernova. A mass of 0.0030 $M_{\odot}$ of Ni II can be deduced from the line strength of the Ni II line and a mass of 9×10^{-4} $M_{\odot}$ of Ar II from the Ar II line strength.

Subject headings: line profiles — stars: supernovae

I. INTRODUCTION

SN 1987A has been observed in the 5–8 μm range during three deployments of the Kuiper Airborne Observatory (KAO). These were in 1987 April and November and most recently in 1988 April, respectively 60, 260, and 415 days after core collapse. Low resolving power spectra obtained in 1987 April (Rank *et al.* 1988*a*) showed mainly a photospheric continuum with a few minor features in the 5–8 μm range. Spectra obtained in 1987 November (Rank *et al.* 1988*b*) revealed lines from core ejecta including the Ni II (6.634 μm), Ar II (6.983 μm), and Co II (10.52 μm) lines. The Ni II line strength in 1987 November provided a lower limit of 0.002 $M_{\odot}$ to the mass of Ni II and 0.008 $M_{\odot}$ to the mass of Co II.

Measurements of the expansion velocities of core ejecta are essential for determining the amount of mixing between core products and the photospheric envelope. Although the early appearance of X-rays from SN 1987A has been cited as evidence for mixing (Itoh *et al.* 1987), direct evidence is needed to verify the presence and determine the extent of such mixing. Consequently, during one of our three KAO flights in 1988 April, we employed a relatively high resolving power (about 200) over a short spectral range to provide information about the velocities of the nickel and argon ions that we had observed 5 months earlier. These lines are particularly well suited for such study because they are bright and do not overlap other lines expected to be significant in the supernova spectrum. In this paper we report on the profiles of these two lines and the implications for mass motion and structure in the exploding material.

II. INSTRUMENT, OBSERVATIONS, AND CALIBRATION

The spectra were obtained with a liquid helium–cooled, grating spectrograph employing an array of 24 bismuth-doped-silicon detectors. The original system was described by Witteborn and Bregman (1984). It now incorporates an externally driven grating rotator and an externally driven aperture and order-sorting filter selector. This grating has 210 grooves mm^{-1} and is blazed for 4.3 μm in first order. Two detectors near either end of the array were inoperative. The wavelength intervals lost were either covered by overlap of adjacent grating settings or were placed in continuum regions adequately measured by adjacent channels. The spectrometer entrance aperture was 1 mm in diameter (13."6).

The SN 1987A observations were made from 8:25 to 10:40 UT on 1988 April 14. The results described here were made with three overlapping grating settings displaced by one-third of a channel, so that the actual spectrum would be oversampled had the image of the star filled the 1 mm aperture. Prior to the supernova observations, the first calibraton star, α Canis Majoris, was measured at each of the grating settings used for the supernova. Each setting was verified and calibrated by obtaining a spectrum of a polystyrene sheet which had been carefully calibrated using a Nicolet Fourier transform spectrometer referenced to a HeNe laser. After the supernova observation, spectra of another standard star, α Bootis, were obtained at each of the three grating positions. Thus the two standards sampled the atmospheric absorption at either end of the flight path from which the supernova was observed. Water vapor monitors measured the zenith water vapor emission during the observations. The precipitable water vapor equivalent depth varied from 8 μm to 15 μm during observations of the first standard, from 7 μm to 16 μm during SN 1987A observations and from 11 μm to 15 μm during observations of the second standard. Spectra were also obtained of the strong, narrow Ar II (6.983 μm) line in the Galactic H II region G333.6−02 to provide a measure of the instrument function under the same conditions that the other observations were made and to establish the rest wavelength of the Ar II line.

III. OBSERVATIONAL RESULTS

The line profiles measured for Ni II and Ar II in the SN 1987A spectrum of 1988 April 14 are shown in Figure 1. Each

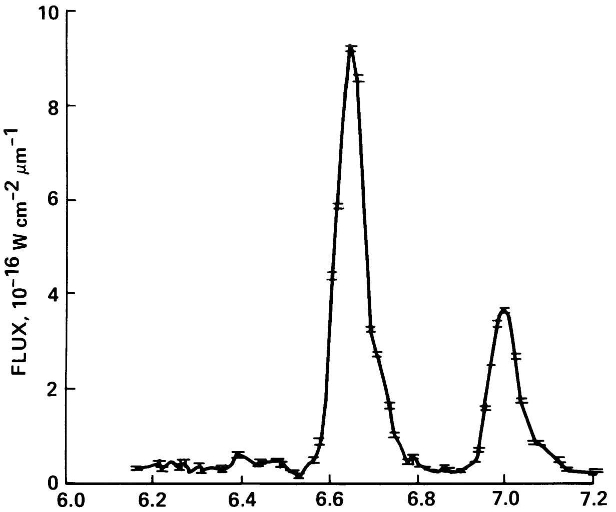

FIG. 1.—Spectrum of SN 1987A. The 1 σ error bars are typically $\pm 5 \times 10^{-18}$ W cm^{-2} μm^{-1}. The flux calibration star was α Bootis.

of the three supernova spectra was divided by an Alpha Bootis spectrum obtained at the same grating setting. The flux values were assigned by multiplying the divided spectral data points by the corresponding flux for α Bootis, which was assumed to be a blackbody at a temperature of 4200 K normalized to an 8.7 μm flux of 3.9×10^{-15} W cm^{-2} μm^{-1} (Hanner *et al.* 1984). The assumption of blackbody behavior in the 6–7 μm range was checked by dividing the α Bootis spectrum by the α Canis Majoris spectrum. The resulting ratio of the spectra of these two stars of quite different spectral type (KS III and A1 V, respectively) was flat and featureless to $\pm 4\%$, suggesting that both are well approximated by blackbodies. The three separate spectra were normalized to yield the same integrated value over the common spectral range.

IV. VELOCITY MEASUREMENTS

The supernova line profiles are clearly much wider than the line profile of Ar II in G333.6−0.2 (Fig. 2). We can safely assume the latter to be a measure of our instrument profile. Gaussian fits to these profiles give 2900 ± 100 km s^{-1} FWHM (corresponding to 0.070 μm) for the main portions of the Ni II and Ar II supernova lines and 1700 km s^{-1} FWHM for the Ar II line in G333.6−0.2. An additional Gaussian, roughly 10% of the amplitude of the peak, must be added to each supernova profile to match their asymmetrical long-wavelength wings. The amplitude-weighted centroid of the Ar II line in the supernova is displaced from that in G333.6−0.2 by 0.018 μm which corresponds to an apparent velocity difference of 770 km s^{-1} ± 100 km s^{-1}. McGee and Newton (1981) have found the recession velocity of G333.6−0.2 to be −45.3 ± 0.03 km s^{-1} (heliocentric). Thus, the apparent recession velocity of the Ar II in SN 1987A is 725 km s^{-1}.

Wampler and Richichi (1988) have measured the velocity of the narrow emission lines presumed to arise in the wind given off by the progenitor star Sk −69°202 while it was a red supergiant. This apparently provides a measurement of the pre-explosion radial velocity of the supernova's center of mass, with their reported value of 286.3 ± 0.8 km s^{-1} (heliocentric), most of which is just the recession velocity of the LMC. When this is subtracted from the 725 km s^{-1} recession "velocity" determined from the supernova's argon line center, we find a difference of ~440 km s^{-1} between the center of mass of the presupernova star and that of the postexplosion ejecta.

If explosion-induced mass motion with respect to the LMC is to account for both the redshift of the Ar II line centroid and the asymmetry in the profile, then a third, unobserved mass would have to be moving toward us to conserve momentum. Pinto and Hartmann (1989) argue that a grossly asymmetric explosion is unlikely in light of other evidence such as the apparent lack of observed shifts in many optical lines (M. M. Phillips, private communication) that such an explosion would produce. Instead, they suggest that Thompson scattering (in the ejecta) of photons emitted in the heavy-element core will produce *both* the line center shifts and the broad red wings that we have observed. The redshifts arise from those collisions in which photons are scattered *toward us* by electrons that are receding *from us*, more rapidly than the core.

By 1988 April, the supernova had expanded four orders of magnitude in radius, and its expansion can be expected to be very nearly homologous (i.e., at any instant $v \sim r$). In such an expansion, each point is receding from all others, and thus all scatterings produce a redshift in a photon's observer-frame. Because photons rarely traverse the envelope more than once while scattering out of the ejecta, the maximum extent of the resulting profiles' red tails is given by the maximum expansion velocity of the electrons, $v_{\max}$. The wavelength at which the line profile reaches zero intensity therefore gives a measurement of this quantity. The flux in the tails consists of light scattered into the line of sight and is thus exponentially dependent upon, and gives a measure of, the scattering optical depth.

In Figure 3, the Ar II line observations are compared with line profiles resulting from Thompson scattering in a simple model of the supernova's ionization structure. In the model it is assumed that the Ar II is contained in a constant-emissivity shell with inner and outer velocities of 500 and 1800 km s^{-1}, respectively. The outer velocity was determined by optimizing

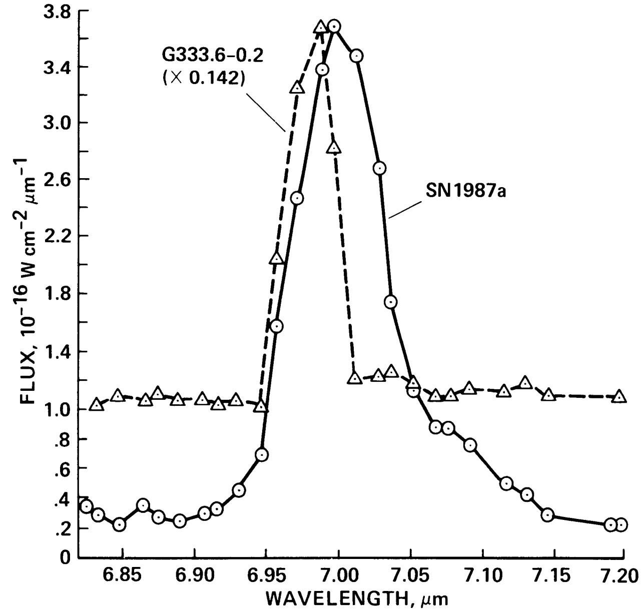

FIG. 2.—The spectrum of G333.6−02 (*dashed line*) is plotted on the same wavelength scale as the Ar II line of SN 1987A (*solid line*). The redshift of the supernova profile is clearly seen.

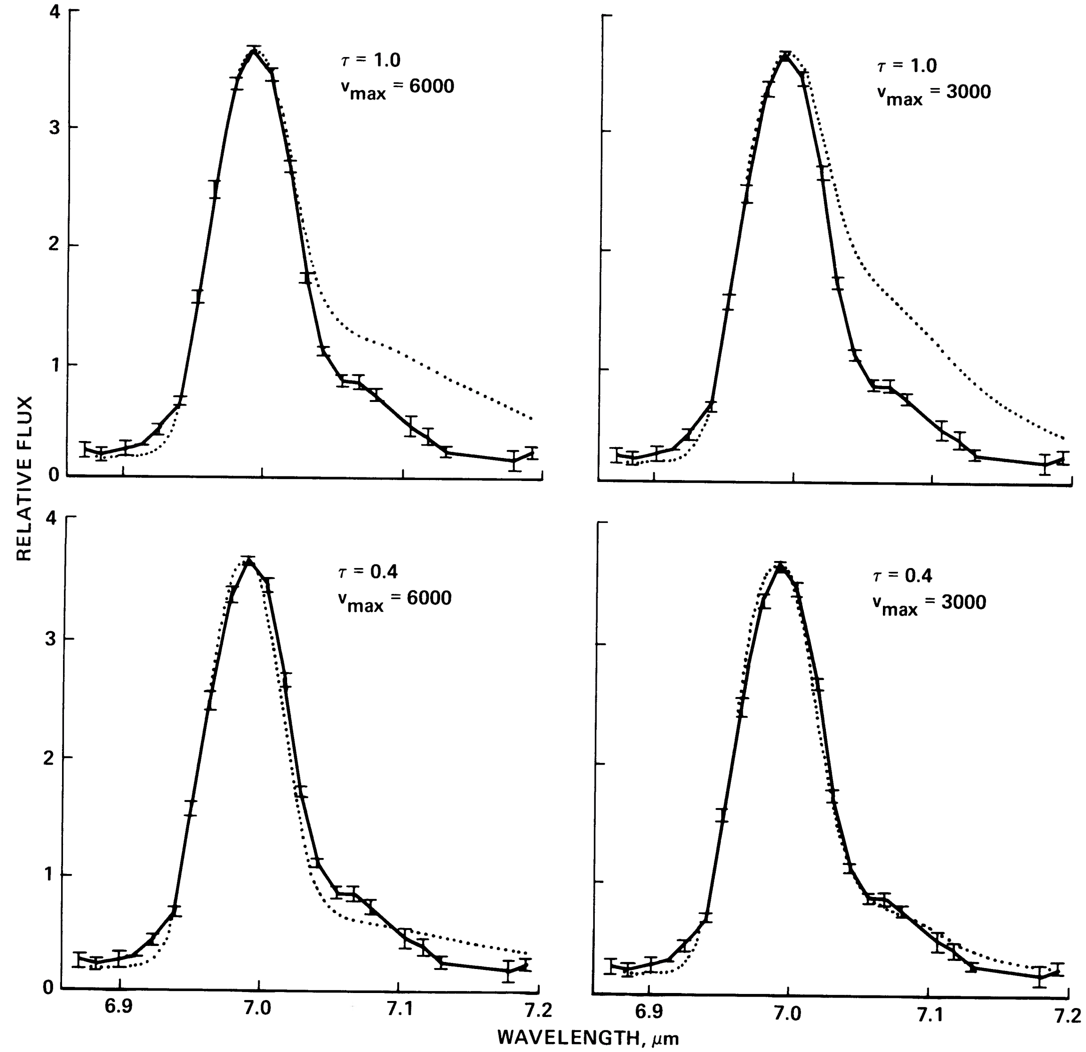

FIG. 3.—Model fits to the Ar II profile of SN 1987A. The model is the dotted line. v_{max} refers to the maximum electron velocity, a free parameter in the model. The other free parameter is τ which is the electron optical depth.

the fit to the Ar II line core (the symmetrical, upper 80%); the model depends only weakly on the inner velocity. Surrounding this photon-emitting shell is a scattering shell of electrons (mixed with ions and neutrals) with an inner velocity equal to the outer velocity of the emitters. The outer velocity, v_{max}, of the electrons and the Thompson optical depth, τ_e, of this shell are used as free parameters in fitting the observations.

The model line profiles in Figure 3 have been calculated by solving the transfer equation by a Monte Carlo method; for more details on the calculation and the effects of a scattering atmosphere on the profiles, see Pinto and Hartmann (1989). One can see that the profiles are sensitive to both v_{max} and τ_e and that the best fit to these observations is given by an optical depth near 0.4 and a maximum electron velocity near 3000 km s^{-1}. Comparison of a number of model calculations with the data shows that these parameters are determined to $\pm 20\%$.

If we refer to a dynamical model for the explosion which has fitted most other observations (e.g., the optical, X-ray, and γ-ray light curves and color temperatures), model 10 HMM from Pinto and Woosley (1988), we see that a velocity of 3000 km s^{-1} corresponds to a radius that defines a sphere encircling 10 $M_\odot$ of material, including 4 $M_\odot$ of the hydrogen envelope. The column density of electrons needed to produce $\tau_e \sim 0.4$ at a wavelength of 7 μm is $N_e \sim 6 \times 10^{23}$ cm^{-2}. At the time of these observations, the path length given by the model is 1200 km s^{-1} × 415 days, or 4.3×10^{15} cm. Thus, the mean electron density in this region is $\sim 1.4 \times 10^8$ cm^{-3}, corresponding to about 10% ionization of the hydrogen in this region.

While the Ni II line was not modeled, its profile is very similar to that of the Ar II line. The recession velocity of the Ni II line is equal to that of the Ar II line to within ± 150 km s^{-1} if we use 6.634 μm as the Ni II rest wavelength. The uncertainty is larger than for Ar II because no bright Galactic standard for the Ni II line's wavelength was available during our observing period.

The broadening of the bases of both Ni II and Ar II profiles on the blue side is readily interpreted in terms of a few percent of core products having radial velocities of some hundreds of km s^{-1} above the 1800 km s^{-1} cutoff used in the model. If the density of core atoms is independent of radius in the region where $500 < v < 1800$ km s^{-1}, then the average core ion ejection velocity is 1400 km s^{-1}.

V. MASS MEASUREMENTS

The integrated intensity of the Ni II (6.634) μm line is 7.7×10^{-17} W cm^{-2}. The measurement error of about 1% in relative flux is negligible compared to the 10% uncertainty in absolute flux of the standard star. If we use the Einstein *A*-value of 5.5×10^{-2} s^{-1} (Nussbaumer and Storey 1988) and assume optically thin LTE conditions (e.g., see Colgan and Hollenbach 1988), we deduce a mass of Ni II in the upper state of 7.4×10^{-4} $M_\odot$. Uncertainties in the flux, ±10%, the Einstein *A*-value, ±10% and the distance 50 kpc ± 5 kpc (see discussion, Chiosi and Pigatto 1986) combine quadratically to give a probable uncertainty in this mass of ±20%. From the shape of the photospheric continuum we estimate the temperature to be 4000 K ± 1000 K. Using the partition function and the assumption of a thermal distribution among low-lying Ni II states, we estimate a total Ni II mass of 3.0×10^{-3} $M_\odot$ ± 25%. Spectra taken during the same flight series indicate an additional nickel line at 3.116 μm in the un-ionized state. This line was also observed by Allen *et al.* (1988). Aitken (1988) determined a Ni I mass of 0.32×10^{-3} $M_\odot$ 465 days after core collapse on the basis of lines at 11.3 μm and 12.0 μm.

Similarly, from the integrated intensity of the Ar II line of 2.98×10^{-17} W cm^{-2} and its Einstein *A*-value of 5.28×10^{-2} s^{-1} (Nussbaumer and Storey 1988) we find a total Ar II mass of about 9×10^{-4} $M_\odot$ to an accuracy of ±25%.

VI. CONCLUSIONS

Line profiles of the SN 1987A core ejecta ions, Ar II and Ni II, exhibit redshifts and asymmetries that can be explained by Thompson scattering in an expanding shell of electrons. The ion ejection velocities are mostly below 1800 km s^{-1}, averaging about 1400 km s^{-1}. The radial electron velocities are mostly below 3000 km s^{-1}. The Ni II mass is slightly more than its 1987 November lower limit, and significant mass is now present as Ni I.

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