

# A large mass of iron in supernova 1991T

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## ABSTRACT

We present quantitative intensity measurements of several forbidden transitions of Fe II and Fe III in the spectrum of the type Ia supernova 1991T at age 1 yr. The two species account for virtually the entire observed optical and near-infrared spectrum. These data are fundamental to tests of the explosion models of supernovae, and allow a direct determination of the mass of  $^{56}\text{Ni}$  produced. The line intensities support models that require most of the white dwarf precursor to be converted to  $^{56}\text{Ni}$ .

**Key words:** line: formation – supernovae: general – supernovae: individual: 1991T.

## 1 INTRODUCTION

Type Ia supernovae are among the most energetic phenomena in astrophysics. Their high luminosity decays slowly, with an e-folding time of two or three months. Moreover, type Ia supernovae are a very homogeneous taxon, and hence make excellent standard candles. Yet we still lack a detailed understanding of the mechanism proposed to power them. A better understanding of these objects is of interest for their own sake, but additionally offers the prospect of inferring directly their luminosity, and hence distance, independent of the distance ladder.

In 1969 Colgate & McKee showed that the decay of radioactive  $^{56}\text{Ni}$  could power the optical light curve of type I supernovae (see also Arnett 1979; Colgate, Petschek & Kriese 1980; Chevalier 1981). Current conventional wisdom holds that in a type Ia supernova an accreting white dwarf exceeds the Chandrasekhar limit. The consequent rapid temperature rise results in the thermonuclear fusion of a substantial fraction of the star to  $^{56}\text{Ni}$ . This nuclear species is the most stable configuration of alpha particles (Truran, Arnett & Cameron 1967; Bodansky, Clayton & Fowler 1968). The star is completely disrupted by either a subsonic (deflagration) or a supersonic (detonation) front moving through the star (Woosley 1990).

In carbon deflagration/detonation models of type Ia supernovae  $\approx 0.7 M_{\odot}$  of  $^{56}\text{Ni}$  are created.  $^{56}\text{Ni}$  rapidly decays ( $\tau = 8.8$  d) to  $^{56}\text{Co}$ , which in turn decays with a much longer mean-life ( $\tau = 113.6$  d) to stable  $^{56}\text{Fe}$ . The light curves of all types of supernova at late times become exponential with e-folding times similar to those expected from the radioactive decay. This is deemed strong, but indirect, evidence

for the suggested  $^{56}\text{Ni}$  mechanism. Models that invoke hydrodynamical or neutrino-deposition explosions produce large ( $\sim 0.3 M_{\odot}$ ) masses of  $^{56}\text{Ni}$  only in stars with helium core masses in excess of  $8 M_{\odot}$  (Woosley & Weaver 1986), i.e. in type II supernovae. The detection of  $> 0.4 M_{\odot}$  of  $^{56}\text{Ni}$  in the ejecta of a type Ia supernova would therefore provide strong evidence for the carbon deflagration/detonation process.

In the case of SN 1987A (a type II supernova), the characteristic  $\gamma$ -ray lines from the decay of  $^{56}\text{Co}$  at 1238 and 847 keV were detected (Matz et al. 1988), so directly confirming the presence of the radioactive species. Moreover, infrared spectroscopy of SN 1987A has shown that the mass of emitting cobalt in the ejecta was two orders of magnitude greater than would be expected for stable cobalt (Meikle et al. 1989); the mass of emitting cobalt was also shown to decay with the expected characteristic time-scale (Varani et al. 1990; Danziger et al. 1991). A similar decay of the cobalt was revealed in the type Ia supernova 1972E by Axelrod (1980), providing the strongest evidence to date for the  $^{56}\text{Ni}$  hypothesis for type I supernovae. The decaying feature at 5900 Å, however, lies close to the Na D lines and its reliability as a direct test of the model has been questioned (Branch 1990).

In addition to the  $\gamma$ -rays, positrons of approximately 1 MeV energy are emitted in the decay of  $^{56}\text{Co}$ . The  $\gamma$ -rays and positrons deposit their energy in the ejecta in the form of energetic electrons which in turn ionize, excite and heat the gas. The gas is cooled through emission by collisionally excited forbidden transitions. We observe these transitions in the late-time spectra of supernovae.

For a type Ia supernova, it is believed that  $\sim 0.7 M_{\odot}$  of  $^{56}\text{Ni}$  may be created in the explosion, but the rapid decay ensures that only its daughter products will be observed.

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Moreover, at early times the spectrum is dominated by photospheric emission, and only a fraction of the ejecta is directly observable. The detection of a large mass of iron in the ejecta of a type Ia supernova would therefore provide further strong evidence for the proposed mechanism. The late-time optical spectra of type Ia supernovae are dominated by [Fe II], [Fe III] and [Co III] (Axelrod 1980; Branch 1990), but suffer from such severe line blending as to prohibit unambiguous identifications and quantitative analysis. Between 1 and 2  $\mu\text{m}$  strong lines of [Fe I] and [Fe II] are accessible and sufficiently isolated to prevent blending even when highly Doppler broadened. At late times these transitions are unlikely to suffer from optical depth effects. They are negligibly affected by reddening.

Graham et al. (1986) used the 1.644- $\mu\text{m}$  [Fe II] line in the type Ib supernova 1983N to infer that 0.3  $M_{\odot}$  of iron was present in the ejecta. Their interpretation relied on the model of Axelrod (1980). The conclusion was challenged by Oliva (1987), who attributed the line to [Si I] instead. Late-time infrared spectra of the type Ia SN 1986G did not conclusively show [Fe II] emission (Spyromilio 1989). Thus the direct demonstration of the expected presence of iron in the infrared spectra of type I supernovae has remained elusive. Iron-group elements were identified in SN 1991T by Ruiz-Lapuente et al. (1992), who modelled its pre-maximum optical spectrum, but they were unable to determine the mass of iron present. In contrast, in SN 1987A a plethora of iron-group elements has been revealed by infrared spectroscopy, confirming the creation of 0.08  $M_{\odot}$  of  $^{56}\text{Ni}$  (Meikle et al. 1989 and references therein).

## 2 OBSERVATIONS

Supernova 1991T was discovered in NGC 4527 on 1991 April 13, a week before maximum light, by four independent groups (IAU Circ. 5239). The absence of hydrogen lines in the spectrum and the development of the characteristic absorption at 6150 Å due to Si II allowed a classification of the supernova as type Ia (Phillips & Hamuy 1991).

We observed SN 1991T on 1992 March 31 at the 3.8-m United Kingdom Infrared Telescope on Mauna Kea, using the infrared spectrograph CGS4 (Mountain et al. 1990). We used a 75 line  $\text{mm}^{-1}$  grating to give a spectral resolution of  $\sim 500$ . The detector was a  $62 \times 58$  InSb array. Sky subtraction was effected by alternating regularly between two positions along the slit. The spectrum was fully sampled by moving the detector array by half a resolution element. We oriented the slit at PA  $109^\circ$ , along the spiral arm of NGC 4527 in which the supernova lies, to minimize the gradient of background light along the slit. Three wavelength settings were used to cover the long end of the *J* (1.2  $\mu\text{m}$ ), and the entire *H* (1.6  $\mu\text{m}$ ) and *K* (2.2  $\mu\text{m}$ ) windows.

On 1992 June 4 SN 1991T was observed in service time at the 3.9-m Anglo-Australian Telescope by Raylee Stathakis and Elaine Sadler using the Cassegrain spectrograph. Two spectra were obtained using the 25-cm camera and the faint-object red spectrograph to cover the wavebands 3200–6000 and 5500–10 000 Å respectively. The slit was set to the parallactic angle to minimize losses due to atmospheric dispersion. As a result, continuum flux from the parent galaxy was introduced into the spectrum. The optical and near-infrared spectra are shown in Fig. 1.

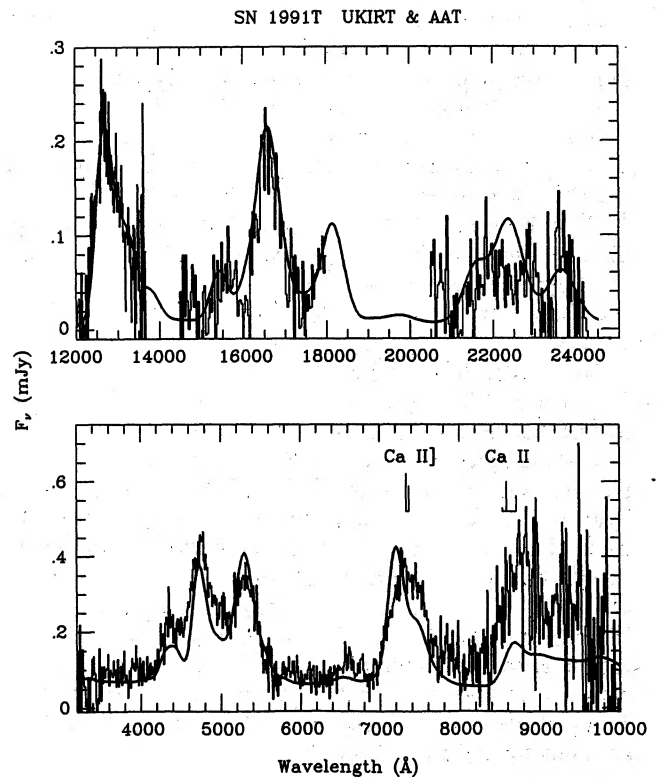


Figure 1. Observed spectrum of SN 1991T between 3200 and 25 000 Å. The optical spectrum in the lower section has been scaled by a factor of 2.45 to compensate for the different epoch. The solid line is a model fit. The locations of  $\text{Ca}^+$  transitions that are not included in our model are indicated.

## 3 A SPECTRAL MODEL

The pre-maximum spectrum of SN 1991T differs from that of another well-studied supernova, SN 1990N (Filippenko et al. 1992; Phillips et al. 1992). SN 1991T was brighter than the average type Ia supernova in the Virgo cluster. Phillips et al. argue that the parent galaxy is on the near side of the cluster and the maximum luminosity of SN 1991T was typical of its class. This conclusion is not shared by Filippenko et al., who argue that SN 1991T was 0.6 mag more luminous than the average type Ia supernova. Spectra of SN 1991T taken after maximum are very similar to those of the well-studied type Ia supernovae SN 1989B and 1990N (Phillips et al. 1992).

To combine our optical and infrared spectra, we backdated the former by 65 d assuming a decay rate of 0.015 mag per day (Barbon, Cappellaro & Turatto 1984). The validity of this approach relies on a minimal change of the spectral characteristics over this period. Models of the supernova ejecta at late epochs (Axelrod 1980; Meyerott 1980; Spyromilio 1989) do not predict rapid changes in the ionization structure or temperature over the period under consideration. The optical spectrum of SN 1991T is not dramatically different from that of other type Ia supernovae at similar epochs, which indeed exhibit stable spectra (e.g. Kirshner & Oke 1975). We therefore believe that the backdating technique is justified.

Because of line blending, the spectrum must be modelled. We used non-LTE models for  $\text{Fe}^+$  and  $\text{Fe}^{++}$ . For  $\text{Fe II}$ , transition probabilities were taken from Nussbaumer & Storey (1988), and collision strengths from Nussbaumer & Storey (1980). For  $\text{Fe III}$ , transition probabilities came from Garstang (1957) and collision strengths from Berrington et al. (1991). Collision strengths for the high-excitation transitions of  $[\text{Fe II}]$  were not available, so we adopted approximations discussed in detail by Graham, Wright & Longmore (1987) and Spyromilio & Graham (1992). We convolved our model spectrum with a Gaussian line profile of  $10\,000\text{ km s}^{-1}$  FWHM.

Our model, which includes *only* iron emission, accounts for virtually the entire observed spectrum. The complex feature between  $4000$  and  $5500\text{ Å}$  is due to emission by several multiplets of  $[\text{Fe II}]$  and  $[\text{Fe III}]$ . At least 70 per cent of the peak near  $4700\text{ Å}$  is due to  $[\text{Fe III}]$ . At  $7200\text{ Å}$ , emission by the  $a^4\text{F}-a^2\text{G}$  ( $14\text{F}$ ) multiplet of  $[\text{Fe II}]$  dominates the spectrum, although we cannot exclude a contribution from  $\text{Ca II}$  ( $^2\text{S}-^2\text{D}$ , multiplet  $1\text{F}$ ). Between  $8400$  and  $10\,000\text{ Å}$  multiplet  $a^4\text{F}-a^4\text{P}$  ( $13\text{F}$ ) of  $[\text{Fe II}]$  is blended with the  $\text{Ca II}$  triplet ( $^2\text{D}-^2\text{P}^0$ , multiplet  $2$ ). The features in the  $12\,000$ – $13\,500\text{ Å}$  region arise from multiplet  $a^6\text{D}-a^4\text{D}$  of  $[\text{Fe II}]$  and those between  $15\,000$  and  $18\,000\text{ Å}$  almost exclusively from multiplet  $a^4\text{F}-a^4\text{D}$  of  $[\text{Fe II}]$ . The  $^3\text{G}-^3\text{P}$  multiplet of  $[\text{Fe III}]$  accounts for most of the flux around  $22\,000\text{ Å}$ , although a contribution from  $\text{Na I}$  cannot be excluded.

We see no evidence of the strong  $[\text{Fe I}] a^5\text{D}_{9/2}-a^5\text{F}_{11/2}$  transition (at  $14\,430\text{ Å}$ ) whose red wing would be covered by our data and whose excitation potential is  $200\text{ cm}^{-1}$  lower than that of  $12\,570\text{ Å}$   $[\text{Fe II}]$ . Nor do we see the  $15\,350\text{ Å}$  line from the same upper level. Using atomic data from Grevesse, Nussbaumer & Swings (1971), we limit the mass ratio of  $\text{Fe}^0/\text{Fe}^+$  to below 10 per cent, and ignore this species in our fit. Transitions of  $[\text{Fe IV}]$  do occur in our spectral range, but they arise from energy levels with excitation potentials higher than  $32\,000\text{ cm}^{-1}$  and are expected to be weak. We do not identify any lines as emission by  $[\text{Fe IV}]$  and are unable to place any limits on the presence of this species in the ejecta. Emission by  $[\text{Co III}]$  at  $5900\text{ Å}$  is not observed, nor is it expected at such late times – cf. the late-time spectra of SN 1972E (Kirshner & Oke 1975).

We included a smooth continuum at optical wavelengths derived by a spline fit to regions between the emission lines. As discussed above, this continuum arises from the parent galaxy. We applied a redshift of  $1775\text{ km s}^{-1}$  to match the interstellar  $\text{Na I D}$ -line absorption by the parent galaxy (Phillips et al. 1992). Filippenko et al. (1992) derived an extinction to SN 1991T of  $A_V \sim 0.7 \pm 0.3\text{ mag}$ , which encompasses the value preferred by Phillips et al. (1992). We adopted  $A_V = 0.7$ .

We assume a uniform density for the ejecta of SN 1991T and therefore derive a single temperature and electron density for the observed emission. We determine the temperature and electron density by fitting all features due solely to  $[\text{Fe II}]$ . We assume that the same values apply to  $[\text{Fe III}]$ , and derive the ionization fraction ( $\text{Fe}^{++}/\text{Fe}^+$ ) by fitting the  $4700$ – and  $22\,000\text{ Å}$  regions. Using an electron temperature of  $6000\text{ K}$ , an electron density of  $5 \times 10^5\text{ cm}^{-3}$ , and an ionization ratio,  $\text{Fe}^{++}:\text{Fe}^+$ , of  $5:1$ , we derive the fit shown in Fig. 1. It is clear that  $[\text{Si I}]$  cannot contribute significantly to the  $16\,440\text{ Å}$  line.

#### 4 DISCUSSION

The fit yields an integrated flux in the  $16\,440\text{ Å}$  line of  $1.1 \times 10^{-14}\text{ erg s}^{-1}\text{ cm}^{-2}$ . For a distance modulus to NGC 4527 of  $30.57\text{ mag}$  (Tully, Shaya & Pierce 1992) we derive a mass of emitting  $\text{Fe}^+$ :

$$M_{\text{Fe}^+} = \frac{1.0 \pm 0.2 \times 10^{-17}}{e_{16\,440}} M_{\odot},$$

where  $e_{16\,440}$  is the emissivity of the  $16\,440\text{ Å}$  transition in  $\text{erg s}^{-1}\text{ atom}^{-1}$ . The parameters of the model fit yield a mass of  $0.5 M_{\odot}$  for the sum of  $\text{Fe}^+$  and  $\text{Fe}^{++}$ .

In determining this figure we have had to rely on several insecure numbers. For example, the extinction is not well known, and there is an uncertainty of about  $\pm 0.0024\text{ mag d}^{-1}$  (Barbon et al. 1984) in the decline between the epochs of the infrared and optical observations. While these do not directly affect the observed intensity of the  $16\,440\text{ Å}$  line, they would modify the parameters we derive for the electron gas, and hence  $e_{16\,440}$ . We achieve plausible fits to the data for a wide range of electron density and temperature. The temperature spans  $3500$ – $6000\text{ K}$  and the electron density ranges from  $10^5$  to  $10^7\text{ cm}^{-3}$ . The ionization fraction  $\text{Fe}^+:\text{Fe}^{++}$  ranges from  $1:5$  to  $1:9$ . In practice, the emissivity of the  $16\,440\text{ Å}$  line is only weakly influenced by changes in these parameters. Models having low temperatures require high densities to fit the data, and vice versa; as a result the emissivity of the transition of interest remains fairly uniform.

We derive a range for the mass of *observable* iron in the ejecta of SN 1991T of  $0.4$ – $1.2 M_{\odot}$ . However, observed masses in excess of  $0.7 M_{\odot}$  result from fits with high ionization fractions. Such high ionization requires a large mass of  $\text{Fe}^{3+}$  which, as discussed above, would not contribute to our spectrum, so that the total mass of iron would exceed the Chandrasekhar limit. Although such models cannot be excluded by our data, current conventional wisdom would hold them to be unrealistic. We note that fits using low ionization fractions (and therefore lower masses) are comfortably in agreement with models of type Ia supernovae (Axelrod 1980; Meyerott 1980; Spyromilio 1989). If we adopt the ionization structure predicted by such models, which imply a small (but significant) fraction of iron in the form of  $\text{Fe}^{3+}$ , then the upper limit on the iron mass is reduced to  $1 M_{\odot}$  in the ejecta of SN 1991T.

The mass and expansion velocity we derive are consistent with models specific to SN 1991T (Yamaoka et al. 1992) that invoke a late detonation in the outer layers of the ejecta to account for the peculiarity of the pre-maximum spectrum. These models also predict  $\sim 1 M_{\odot}$  of iron to be manufactured in the explosion. As mentioned in Section 1, hydrodynamic or neutrino-deposition explosions do not result in large masses of  $^{56}\text{Ni}$  being manufactured. The large mass of iron derived here precludes such mechanisms being responsible for supernova 1991T.

We can perform two simple consistency checks on the parameters we derive. First, believing iron to provide most of the electrons, we test the electron density. The volume occupied by the ejecta after  $353\text{-d}$  expansion is  $1.2 \times 10^{50}\text{ cm}^3$ . The corresponding number density for  $1 M_{\odot}$  of iron is  $2 \times 10^5\text{ cm}^{-3}$ , which would yield a density of electrons in the range reproduced by our fit, assuming a uniform density for

the ejecta. This same argument limits acceptable ratios of ( $\text{Fe}^{++}:\text{Fe}^+$ ) to below about 10:1. Secondly, we compare the heating and cooling rates of the gas. Energy is deposited in the ejecta by the decay of  $^{56}\text{Co}$  at a rate of

$$5.80 \times 10^{-13} e^{-t/113} (f + 0.035) \text{ erg s}^{-1} \text{ atom}^{-1},$$

where  $t$  is the time in days after the explosion and  $f$  is the fraction of the  $\gamma$ -rays absorbed. Axelrod (1980) has shown that in excess of 90 per cent of this energy is deposited in the thermal electron gas. The numerical addition to  $f$  accounts for decay energy emerging in positrons, which is unaffected by expansion-induced reduction in column density. This is because small magnetic fields ensure that the positrons deposit their energy locally (Colgate & McKee 1969; Axelrod 1980). On the other hand, Colgate et al. (1980) argue that the positrons could escape the nebula without depositing their energy by following a radially combed magnetic field. If the cooling is dominated by the forbidden transitions of the iron species we observe, then at the epoch of observation it is  $\sim 2 \times 10^{-15} \text{ erg s}^{-1} \text{ atom}^{-1}$ . We thus find  $f \sim 0.1$ , in reasonable agreement with models for the energy deposition by  $\gamma$ -rays in the ejecta of type Ia supernovae at late times. This figure relies on the mass of stable iron manufactured in the explosion being of order 10 per cent that of  $^{56}\text{Ni}$ . Higher quality data are needed to distinguish between models with and without positron deposition.

## 5 CONCLUSIONS

We have provided direct confirmation that a large mass of  $^{56}\text{Ni}$  was present in the ejecta of SN 1991T. We thereby confirm the carbon deflagration/detonation models for type Ia supernovae while excluding hydrodynamical and neutrino-deposition models. We are unable to distinguish between the supersonic and subsonic models, given the uncertainties in our data. There remains some doubt about the classification of SN 1991T as entirely normal, so we have not used our measurements to give a direct determination of the Hubble constant.

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