THE ASTROPHYSICAL JOURNAL, 426:L89–L92, 1994 May 10

# EVIDENCE FOR $^{56}$Ni → $^{56}$Co → $^{56}$Fe DECAY IN TYPE Ia SUPERNOVAE

MARC J. KUCHNER AND ROBERT P. KIRSHNER
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138;
kuchner@cfa.harvard.edu, kirshner@cfa.harvard.edu

PHILIP A. PINTO
Steward Observatory, University of Arizona, Tucson, AZ 85721; pinto%aristarchus@as.arizona.edu

AND

BRUNO LEIBUNDGUT
European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany; bleibund@eso.org
*Received 1993 December 30; accepted 1994 March 1*

## ABSTRACT

In the prevailing picture of Type Ia supernovae (SN Ia), their explosive burning produces $^{56}$Ni, and the radioactive decay chain $^{56}$Ni → $^{56}$Co → $^{56}$Fe powers the subsequent emission. We test a central feature of this theory by measuring the relative strengths of a [Co III] emission feature near 5900 Å and a [Fe III] emission feature near 4700 Å. We measure 38 spectra from 13 SN Ia ranging from 48 to 310 days after maximum light. When we compare the observations with a simple multilevel calculation, we find that the observed Fe/Co flux ratio evolves as expected when the $^{56}$Fe/$^{56}$Co abundance ratio follows from $^{56}$Ni → $^{56}$Co → $^{56}$Fe decay. From this agreement, we conclude that the cobalt and iron atoms we observe through SN Ia emission lines are produced by the radioactive decay of $^{56}$Ni, just as predicted by a wide range of models for SN Ia explosions.

*Subject headings:* supernovae: general

## 1. INTRODUCTION

Conventional wisdom (Woosley & Weaver 1986) holds that virtually all of the energy emitted by Type Ia supernovae (SN Ia) is produced in the radioactive decay of $^{56}$Ni → $^{56}$Co → $^{56}$Fe (Pankey 1962; Colgate & McKee 1969). In successful models of these explosions, a C-O white dwarf explodes, burning a significant fraction of the star to $^{56}$Ni, which decays to $^{56}$Co with a half-life of 6.10 days, and then to stable $^{56}$Fe with a half-life of 77.7 days (Browne & Firestone 1986). The positrons and gamma rays produced in these decays are trapped in the expanding ejecta, heating and ionizing it; their energy is eventually reemitted at optical and infrared wavelengths (Axelrod 1980a, b; Pinto 1988).

At early times, spectra of supernovae show a lumpy continuum with broad, strong P Cygni lines of intermediate-mass (Kirshner et al. 1973; Wheeler & Harkness 1990 and references therein). This partially burned material and its distribution in velocity provide important clues to the details of nuclear burning as revealed by analysis of the photospheric spectra. About 50 days after explosion, however, the supernova debris begins to become transparent. At later times, a small and ever-decreasing fraction of the decay energy is converted into thermal energy; most escapes directly as gamma rays (Leibundgut & Pinto 1992). The expanding shell is cooled mainly through emission in forbidden Fe and Co lines produced from excitation of the same nuclei that are daughters of the original $^{56}$Ni (Kirshner & Oke 1975; Axelrod 1980a, b).

Spectral synthesis calculations in the nebular phase test important details of particular models for the explosion, but they require a detailed description of the chemical and physical structure of the ejecta (Axelrod 1980a, b; Pinto 1988; Eastman & Pinto 1994; Ruiz-Lapuente 1992). The complexity of the physical processes and the detail of the atomic data which must be invoked make a simpler approach worth pursuing when we seek generic information.

The presence of [Fe III] and [Co III] in nebular spectra suggest a test for the $^{56}$Ni decay paradigm which does not depend on the details of a specific SN Ia model or employ complex spectrum synthesis calculations. We have studied a feature at 5900 Å which is primarily [Co III] and a feature at 4700 Å which is mostly [Fe III]. We show that the ratio of the Fe flux to the Co flux reveals the evolution of $^{56}$Co and $^{56}$Fe abundances in the ejecta, providing a simple check on the fundamental idea that cobalt and iron in SN Ia result from nickel produced in the explosion.

Because both $^{56}$Fe and $^{56}$Co are daughters of $^{56}$Ni, the distribution of these elements in the ejecta, and the temperature and electron density surrounding typical Fe and Co ions, should be identical. In addition, these elements have similar atomic physics. The first ionization potentials of Fe and Co are virtually the same (7.90 eV for Fe and 7.87 eV for Co), and the second ionization potentials differ by only 5% (16.19 eV for Fe and 17.08 eV for Co; Fuhr, Martin, & Wiese 1988). We expect the ionization balance for Fe and Co to be nearly the same over a wide range of physical conditions.

The oscillator and collision strengths of the relevant transitions are not so similar, producing different Sobolev optical depths and critical densities for these transitions. Since the flux ratio does not, by itself, indicate the elemental abundance ratio, we constructed a straightforward multilevel atom model to predict emission-line ratios from elemental abundance ratios, for a range of reasonable physical conditions.

A similar analysis of late-time spectra of the Type II supernova SN 1987A by Varani et al. (1990) used ratios of Co and Fe lines in the infrared. Axelrod (1980a, b) studied the 5900 Å cobalt feature in the Type Ia supernova SN 1972E, and found that its decline matched that expected from $^{56}$Co decay. A more powerful test based on gamma-ray emission lines from $^{56}$Ni has been performed for SN 1987A (Palmer et al. 1993), but no SN Ia has been near enough to apply this technique

(Ruiz-Lapuente et al. 1993a). To our knowledge, no previous study has directly used the ratio of flux in Fe and Co emission lines to analyze the $^{56}$Co → $^{56}$Fe evolution in several Type Ia supernovae.

## 2. SPECTRA AND MEASUREMENTS

Figure 1 shows spectra of SN 1981B taken 95, 116, and 271 days past maximum light. These spectra show the evolution of the measured features and illustrate the apparent decline of Co relative to Fe as the supernova ages by several $^{56}$Co half-lives. The broad emission centered at 5900 Å is primarily due to [Co III] λλ5890, 5908 in the $a\,^4F$–$a\,^2G$ multiplet, which arises from the gound state. There is a small contribution at earlier epochs from $a\,^2P$–$a\,^2F$, λλ5841, 5943. The blend of lines between 4500 and 4800 Å results from [Fe III] transitions in $3d^6\,^5D$–$^3F$, with Fe III transitions between higher lying levels contributing weakly at early times.

There has been some controversy over the origin of the 5900 Å feature (e.g., Wheeler, Swartz, & Harkness 1993). Mustel (1971) pointed out that the Na I D doublet (λλ5890, 5896) could contaminate any Co feature there. Unfortunately, there are no other strong Na lines to gauge the presence of Na in the spectra of SN Ia. However, sodium seems unlikely on theoretical grounds: it is not produced in any quantity in SN Ia explosion models, and significant abundances of Na in the supernova ejecta would present grave problems for our present understanding of galactic nucleosynthesis. Also, there is no need to invoke sodium to understand the observations: we show that the behavior of this feature is completely consistent with the expected evolution of cobalt alone.

At Harvard we have routinely acquired spectra of supernovae using the 1.5 m at Mount Hopkins, the Multiple Mirror Telescope, and other facilities. We examined these spectra, together with some data from CTIO, Texas, Berkeley, and other observatories, and we culled 35 spectra from 13 supernovae at least 48 days past maximum which covered the Co and Fe features with adequate signal-to-noise ratio. Information about the 13 supernovae appears in Table 1.

SN 1981B, SN 1986G, SN 1989B, SN 1990N, SN 1991T, SN 1991bg, and SN 1992A have well-established light curves and well-determined dates of maximum light. For the other supernovae, we use dates of maximum as listed in the Asiago supernova catalog (Barbon, Cappellaro, & Turatto 1989) determined using incomplete light curves and comparisons with photospheric spectra of well-studied supernovae. We assume uncertainties of ±20 days in the phases of spectra from supernovae without complete light curves.

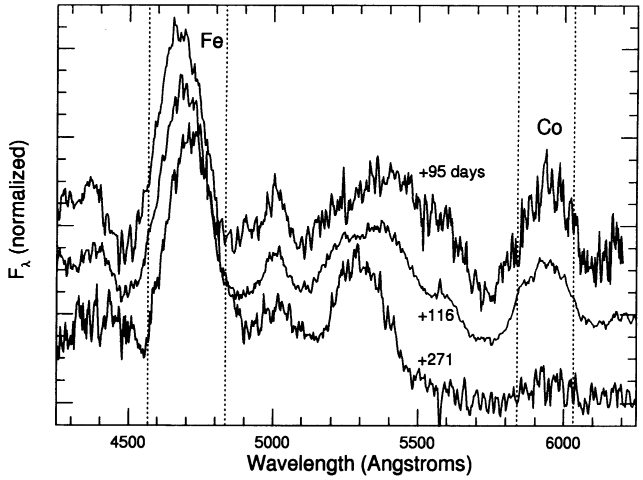

FIG. 1.—Normalized spectra of SN 1981B taken 95, 116, and 271 days after *B* maximum. Dotted lines indicate the limits of integration which define the Fe and Co features we measured. As the supernova ages, the decline of the cobalt feature relative to the iron feature is conspicuous.

SN 1991T and SN 1991bg displayed spectral and photometric peculiarities. We include them in our study because we are interested in the fundamental explosion mechanism of atypical as well as typical cases. For a discussion of SN 1991T see Filippenko et al. (1992b), Phillips et al. (1992), and Ruiz-Lapuente et al. (1992). The very unusual characteristics of SN 1991bg are described by Filippenko et al. (1992a), Leibundgut et al. (1993), and Ruiz-Lapuente et al. (1993b).

We present spectra from 48 days after maximum to 310 days after maximum, the epoch of the latest available spectrum which showed evidence of a cobalt feature. To measure the strengths of the Fe and Co features, we integrated the flux, assuming zero underlying continuum. We chose an integration

TABLE 1

TYPE Ia SUPERNOVAE

| SN | Galaxy | Radial Velocity (km s$^{-1}$) | Epoch of Maximum (UT) | Number of Spectra Measured | Data Source[a] |
|---|---|---|---|---|---|
| 1981B ....... | NGC 4536 | 1800 | 1981 Mar 7 | 4 | 1, 2 |
| 1986G ....... | NGC 5128 | 530 | 1986 May 11 | 2 | 3 |
| 1986N ....... | NGC 1667 | 4600 | 1986 Nov | 3 | 2 |
| 1986O ....... | NGC 2227 | 2241 | 1986 Dec 20[b] | 2 | 2 |
| 1987L ....... | NGC 2336 | 2172 | 1987 Jul 27[b] | 2 | 2 |
| 1988F ....... | MCG+02-37-15a | 5274 | 1988 Jan/Feb | 2 | 2 |
| 1989B ....... | NGC 3627 | 730 | 1989 Feb 5 | 6 | 4 |
| 1989D ....... | NGC 2963 | 6538 | 1989 Feb | 1 | 2 |
| 1989M ...... | NGC 4579 | 1540 | 1989 Jun | 2 | 2 |
| 1990N ....... | NGC 4639 | 980 | 1990 Jul 10 | 4 | 2 |
| 1991T ....... | NGC 4527 | 1740 | 1991 Apr 28 | 3 | 5 |
| 1991bg ...... | NGC 4374 | 1000 | 1991 Dec 14[c] | 6 | 6, 7, 8 |
| 1992A ....... | NGC 1380 | 1309 | 1992 Jan 19.2 | 1 | 2 |

[a] (1) Branch et al. 1983; (2) CfA archive; (3) Phillips et al. 1987; (4) Wells et al. 1994; (5) Phillips et al. 1992; (6) Filippenko et al. 1992a; (7) Leibundgut et al. 1993; (8) Ruiz-Lapuente et al. 1993b.

[b] Approximate.

[c] *V* maximum.

span of 4500 km $s^{-1}$ to encompass the flux in each feature, using galaxy velocities from Huchtmeier & Richter (1989) to match the supernova rest frame. This width keeps contamination from neighboring lines low while encompassing almost all of the signal. The integration of the [Co III] line extended from 5801 to 5995 Å, while the integration of the Fe lines extended from 4589 to 4805 Å, in the rest frame. Detailed synthetic spectra show that the $3d^6\,{}^5D$–${}^3F$ [Fe III] transitions contribute over 95% of the flux in our chosen Fe band. The noisiest spectra in our collection have a signal-to-noise ratio of $\approx 1$ pixel$^{-1}$ in each feature. Even these inferior spectra have less than about a 14% error in $R$ due to statistical noise, because each feature is measured over about 100 pixels.

## 3. LINE RATIOS

To determine the Fe/Co Flux ratio expected from SN Ia, we assembled a simple model of the line formation process based on five reasonable assumptions. (1) All iron and cobalt is made in the supernova as $^{56}Ni$. The relative abundances of $^{56}Co$ and $^{56}Fe$ at a given time are determined solely by the radioactive half-lives as the decay products of $^{56}Ni$ accumulate and, in the case of $^{56}Co$, decay. (2) The temperature of the gas is constant from 50 to 350 days after explosion. Since the transitions are of nearly the same energy, and both arise out of the ground state, they are only weakly affected by changes in temperature. Physical models that compute the heating and cooling balance for nebular SN Ia show that the expected temperature range is 5000–10,000 K (Axelrod 1980a, b; Ruiz-Lapuente 1992). (3) The ionization state for the gas is constant. Observed spectra are dominated throughout this period by lines from doubly ionized iron and cobalt. Gross changes in iron-group ionization are not observed in SN Ia, with the possible exception of SN 1991bg. The transitions we observe are forbidden lines arising from the ground state near the critical density, so recombination has little effect on the emissivity. We assume that the *ratio* of the iron and cobalt ionization states remains constant. Even charge-exchange processes are likely to be similar for these elements, owing to the very large number of excited states in both systems which have similar energies. (4) The ratio of electron density to ion density is constant. (5) All densities scale as $\rho(t) = \rho_0(t_0/t)^3$. Typical densities for explosions of Chandrasekhar mass white dwarfs at age $t_0 = 20$ days are of order $10^{11}$ cm$^{-3}$.

Our calculation employs a 24 level $Co^{++}$ ion and a 40 level $Fe^{++}$ ion, which are subsets of those used by Eastman & Pinto (1994). We solve for the equilibrium population densities within these ions assuming ionization equilibrium, including the effects of line trapping in the expanding atmosphere; i.e., the downward radiative rates are modified by the Sobolev escape probability (Kirshner & Kwan 1975). We also include ionization and excitation by nonthermal electrons, as well as the usual thermal collisional processes. We then calculate the ratio of the luminosity per ion of $Fe^{++}$ to that of $Co^{++}$, and multiply this by the elemental abundance ratio determined from the radioactive decay to obtain the results in Figure 2.

The sophistication of this model is actually unnecessary. At the densities ($10^6$–$10^{10}$g cm$^{-3}$) and temperatures (5000–10,000 K) for which the iron spectra from Type Ia supernova models match the observed spectra, only collisional excitation is important. The Sobolev optical depths are much less than unity, and recombination pumping of the upper levels of the observed transitions is at least an order of magnitude slower than electron collisional rates. The critical densities of the $3d^6\,{}^5D$–${}^3F$ [Fe III] upper levels vary from (2–7) × $10^6$ cm$^{-3}$ at 5000 K to (4–13) × $10^6$ cm$^{-3}$ at 15,000 K. This is identical to the range for the [Co III] transitions, so while the iron region of a typical supernova model passes through this density range 80–100 days past explosion, it has a small effect on the line ratio.

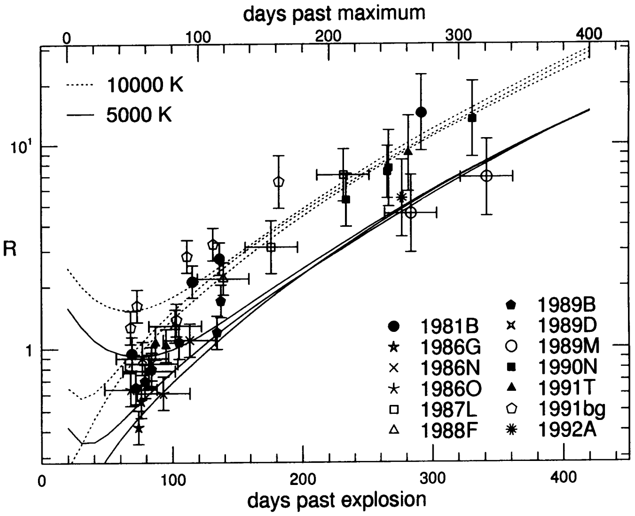

FIG. 2.—Measured Fe/Co flux ratio ($R$) plotted on a logarithmic scale against supernova phase as plotted on the upper abscissa. The solid lines show the expected evolution of this ratio in a 5000 K plasma for $n_e$ at 20 days past explosion of $10^9$, $10^{10}$, and $10^{11}$ cm$^{-3}$; the lowest density is at the top. The dotted lines depict corresponding calculations at 10,000 K. The timescale for the model was chosen on the assumption that SN Ia take 20 days from explosion to maximum light. It is marked on the lower abscissa.

## 4. DISCUSSION

Figure 2 compares the measured ratio, $R$, with our model for the Fe/Co emission ratio. Explosion models predict that small amounts of Ni, Co, and Fe isotopes other than $^{56}Ni$, $^{56}Co$, and $^{56}Fe$ are synthesized in SN Ia. A survey of typical models appears in Leibundgut & Pinto (1992). In the solar system, the abundance of all isotopes other than $^{56}Fe$ amounts to just 9%. Even if SN Ia synthesize a similar fraction of stable iron, this would not be noticeable in Figure 2.

Some SN Ia are in elliptical galaxies and have very little reddening. At the opposite extreme is SN 1986G in the dust lane of NGC 5128, with an estimated $E(B-V)$ of $\sim 1.0$ (Phillips et al. 1987). Because the lines we use are not separated by a large wavelength difference, even an unusually high color excess $E(B-V) = 1.0$ would decrease the observed value of log $R$ by only about 0.07, scarcely noticeable in Figure 2.

The calibration of the spectra is a more important source of error: we could have a 10% error in the relative flux calibration. Taking this and the noise into account, we believe that our ratios have an uncertainty in log $R$ of about 0.08. Spectra can also suffer from errors introduced in background subtraction of the sky and galaxy light along the slit. These errors tend to cancel when both features are strong and similar in size, but as the Co feature becomes small compared to the Fe feature in later epochs, the background subtraction increases errors in $R$. In the latest spectra, the error in the cobalt flux may be as much as 50%. To avoid a meretricious air of precision, vertical error bars in Figure 2 indicate a $\Delta$ log $R$ of 0.08 for data before

150 days, a Δ log $R$ of 0.13 for data from between 150 and 250 days, and a Δ log $R$ of 0.19 for data after 250 days.

Figure 2 shows that the Co-Fe evolution in our sample of supernovae is consistent with the $^{56}$Ni decay model for the origin of the Co and Fe and for the energy source of Type Ia supernovae. It also supports the identification of the 5900 Å feature as [Co III]. It is probably not wise to use this figure as evidence for temperature or density variations among SN Ia, although more precise observations and better atomic data might allow some conclusions about those important issues.

The data from SN 1991T fit the model as well as data from any supposedly normal supernova. In a spectrum of SN 1991bg from 198 days after maximum, however, the 4700 Å [Fe III] feature has vanished, making measurement of $R$ inappropriate for this spectrum. Up to that point, measurements of its spectra are matched by the $^{56}$Ni decay picture. Ruiz-Lapuente et al. (1993b) attribute the weak [Fe III] in SN 1991bg to unusually low ionization at late times. Even in these atypical cases, the evidence that cobalt and iron are the decay products of nickel seems persuasive.

The observed ratio of Fe and Co lines in Type Ia supernovae changes with time just as predicted if these elements result from the radioactive decay of $^{56}$Ni. Even though we have not considered the line formation astrophysics in great detail, we have measured lines for which the effects of changes in physical conditions are likely to be both small and very similar for iron and cobalt under plausible nebular conditions. This is a simple, direct, and satisfying (if not iron-clad) confirmation of the validity of the $^{56}$Ni decay model for SN Ia.

We thank Pilar Ruiz-Lapuente and David Jeffery for their help in preparing this manuscript, and Alex Filippenko for access to his spectra of SN 1991bg. Early work on the supernova archive was carried out by Eric Schlegel. Supernova research at Harvard is supported by the NSF through grant AST-9218475 and at Steward Observatory by NASA through grant NAG52435.

## REFERENCES

Axelrod, T. S. 1980a, Ph.D. thesis, Univ. California Santa Cruz
———. 1980b, in Type I Supernovae, ed. J. C. Wheeler (Austin: Univ. Texas), 80
Barbon, R., Cappellaro, E., & Turatto, M. 1989, A&AS, 81, 421
Branch, D., Lacy, C. H., McCall, M. L., Sutherland, P. G., Uomoto, A., Wheeler, J. C., & Wills, B. J. 1983, ApJ, 270, 123
Browne, E., & Firestone, R. 1986, Table of Radioactive Isotopes (New York: Wiley)
Colgate, S. A., & McKee, C. 1969, ApJ, 157, 623
Eastman, R., & Pinto, P. 1994, in preparation
Filippenko, A. V., et al. 1992a, AJ, 104, 1543
———. 1992b, ApJ, 384, L15
Fuhr, J. R., Martin, G. A., & Wiese, W. L. 1988, Atomic Transition Probabilities (New York: AIP)
Huchtmeier, W. K., & Richter, O.-G. 1989, A General Catalog of H I Observations of Galaxies (New York: Springer-Verlag)
Kirshner, R. P., & Kwan, J. 1975, ApJ, 197, 415
Kirshner, R. P., & Oke, J. B. 1975, ApJ, 200, 574
Kirshner, R. P., Oke, J. B., Penston, M., & Searle, L. 1973, ApJ, 185, 303
Leibundgut, B., et al. 1993, AJ 105, 301
Leibundgut, B., & Pinto, P. A. 1992, ApJ, 401, 49
Mustel, E. R. 1971, Soviet Astron., 48, 3
Palmer, D. M., Schindler, S. M., Cook, W. R., Grunsfeld, J. M., Heindl, W. A., Prince, T. A., & Stone, E. C. 1993, ApJ, 412, 203
Pankey, T., Jr. 1962, Ph.D. thesis, Howard Univ.
Phillips, M. M., et al. 1987, PASP, 99, 592
Phillips, M. M., Wells, L. A., Suntzeff, N. B., Hamuy, M., Leibundgut, B., Kirshner, R. P., & Foltz, C. B. 1992, AJ, 103, 1632
Pinto, P. A. 1988, Ph.D. thesis, Univ. California Santa Cruz.
Ruiz-Lapuente, P. 1992, Ph.D. thesis, Univ. Barcelona
Ruiz-Lapuente, P., Cappellaro, E., Turatto, M., Gouiffres, C., Danziger, I. J., Della Valle, M., & Lucy, L. B. 1992, ApJ, 387, L33
Ruiz-Lapuente, P., Lichti, G. G., Lehoucq, R., Canal, R., & Cassé, M. 1993a, ApJ, 417, 547
Ruiz-Lapuente, P., et al. 1993b, Nature, 365, 728
Varani, G.-F., Meikle, W. P. S., Spyromilio, J., & Allen, D. A. 1990, MNRAS, 245, 570
Wells, L. A., et al. 1994, in preparation
Wheeler, J. C., & Harkness, R. P. 1990, Rep. Progr. Phys., 53, 1467
Wheeler, J. C., Swartz, D. A., & Harkness, R. P. 1993, Phys. Rep., 227, 113
Woosley, S. E., & Weaver, T. A. 1986, ARA&A, 24, 205