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CLAYTON, COLGATE, & FISHMAN'S DETERMINATION OF GAMMA-RAY LINES FROM SUPERNOVA REMNANTS

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The paper "Gamma-Ray Lines from Young Supernova Remnants" by Clayton, Colgate, & Fishman (1969) introduced a realistic observational target for a new wave band of astronomy: nuclear gamma-ray lines that can identify newly synthesized nuclei. The 847 and 1238 keV gamma rays following ^{56}Co decay to ^{56}Fe, thereby creating that abundant daughter nucleus, presented exciting targets to the research groups that were initiating astronomy at gamma-ray energies. All one needed was a nearby young supernova remnant! The half-life of ^{56}Co is 77 days, requiring sufficiently rapid thinning of the supernova structure if the gamma rays are to emerge, but also presenting a bright rate of emission. Several research groups almost immediately undertook plans to search for these (Haymes at Rice, Jacobson at JPL, Leventhal at Bell Labs, Teegarden at NASA Goddard, Fishman and colleagues at NASA Marshall, Kurfess and Johnson at NRL, and several other groups that followed). The wait for the appropriate supernova was to be 18 years.

A major readjustment in nucleosynthesis theory was occurring at the time of Clayton, Colgate, & Fishman's study. Emphasis in 1968 was switching from the hydrostatic nuclear evolution of stars to the rapid burning that accompanies the shock wave that causes the ejection from supernovae. A key issue was whether ^{56}Fe was synthesized as itself or as a radioactive ^{56}Ni progenitor. For more than 20 years it had been believed that the nuclear properties of iron were the ones that determined iron's abundance. Hoyle (1946) had reached that conclusion in a historic paper demonstrating that the appropriate temperatures and densities for nuclear equilibrium are achieved in advanced stellar evolution. In their influential description Burbidge et al. (1957) repeated Hoyle's picture for the nucleosynthesis of iron isotopes. Hoyle & Fowler (1960) and Fowler & Hoyle (1964) vigorously defended that same picture, arguing that the new conserved–vector-current theory of weak interactions was validated by the time required for the nuclear matter to achieve sufficient excess of neutrons by weak decay. The neutron excess of about 7% would be required for ^{56}Fe to dominate equilibrium within the supernova. For a fuller history of this detour in the development of nucleosynthesis theory, see Clayton (1999).

A more plausible picture of iron nucleosynthesis arose from understanding the way in which silicon transforms into nickel by way of a sequence of restricted equilibria (called "quasi-equilibrium" by Bodansky, Clayton, & Fowler 1968) and from improved measurements of the mass of the ^{56}Ni nucleus (see Clayton 1999). The new view became that ^{56}Ni and ^{57}Ni progenitors of abundant ^{56}Fe and ^{57}Fe were synthesized in seconds (Truran, Arnett, & Cameron 1967) and explosively ejected from supernovae. The entire abundance pattern between Si and Ni was shown to support this view. Since that time a leading issue has remained the extent to which nucleosynthesis occurs during the hydrostatic evolution of the presupernova and the extent to which it occurs in the final second after passage of the core-bounce shock wave. A major goal of Clayton et al. (1969) had been clarification of that debate by new observational opportunity.

In 1987 a core-collapse supernova occurred in the Large Magellanic Cloud (SN 1987A). The detection of radioactive ^{56}Co by the 847 and 1238 keV lines that Clayton et al. (1969) had predicted demonstrated that in such Type II supernovae the ejected ^{56}Fe was created in that last second in the form of radioactive ^{56}Ni. Share at NRL found ways to use the Gamma Ray Spectrometer on *Solar Maximum Mission* to record gamma rays from SN 19897A. NASA also launched an armada of balloon-borne detectors to record the gamma lines. In late 1987, a conference was held (Gehrels & Share 1988) that reported nuclear line detections from SN 1987A by several groups. It was the first occasion on which radioactive nuclei were shown to have been produced by a single explosive event.

The potential observability of the lines identified by Clayton et al. (1969) elevated enthusiasm for a special NASA mission for gamma-ray astronomy, which Frank McDonald had championed. This writer, owing to the Clayton, Colgate, & Fishman paper, became spokesperson to assemble scientific support for a Gamma Ray Observatory (see Kniffen & Gehrels 1997, p. 529). The success of this campaign led in 1979 to the recommendation by the Space Science Board (NAS) for the *Compton Gamma Ray Observatory*. Three of its initial five instruments (later reduced to two of four) targeted the radioactive cobalt lines. Both instruments succeeded in first detections despite the delay of *CGRO* launch until 1991: OSSE of ^{57}Co in SN 1987A (Kurfess et al. 1992) and COMPTEL of ^{56}Co in SN 1991T (Morris et al. 1995). SN 1991T was the first Type Ia supernova to reveal the ^{56}Co gamma lines. These were also expected from their light curves, which Colgate & McKee (1969) had interpreted in terms of the thermal power endowed by the ^{56}Ni decay. Both core-collapse and explosive supernovae are profoundly radioactive. More precise measurements of the gamma-ray lines from Type Ia supernovae will resolve the long-standing confusion about the explosive mechanism. The ^{56}Ni abundance required to power the light curves already confirms that this type of supernova also ejects ^{56}Ni rather than ^{56}Fe. Type Ia supernovae are the major iron-producing machines of our universe. Cosmology's standard candle is radioactive ^{56}Ni and ^{56}Co, which power the late-time light curves.

Clayton et al. (1969) called attention also to the nucleosynthesis of ^{44}Ca as its radioactive progenitor ^{44}Ti. Its 60 year half-life suggests that, given a rate of about three supernovae per century, about six remnants having ages less than about 200 yr should be observable in the Galaxy from its gamma-ray line emissions. The COMPTEL instrument aboard *CGRO* detected ^{44}Ti lines from the 310 year old Cas A supernova remnant (Iyudin et al. 1994). Flamsteed's 6th magnitude star has become an important astrophysics laboratory (Hartmann et al. 1997). Still another nearby remnant may be visible in the Vela region; it is too early to be sure. But a contemporary puzzle is the lack of the expected sources within the inner Galactic 180° within the past two centuries (Leising & Share 1994). Europe has constructed the *INTEGRAL* mission as a follow-up to the *CGRO* spectrometry for launch in 2002. Because of its increased sensitivity beyond that of *CGRO*, advances in the known ^{44}Ti sources and in the

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distributed ^{26}Al sources are eagerly anticipated. What has become evident is that a bonanza of science lies at sensitivities roughly 50 times better than those of OSSE and COMPTEL, and several groups now plan such sensitive line spectrometers for NASA's next gamma-ray line mission. The paper by Clayton, Colgate, & Fishman can be seen to have identified key targets for a new field of astronomy, one that has already confirmed underpinnings of nucleosynthesis theory and that has an even richer science future just around the corner.

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