Gamma-ray lines - A Na-22 radioactive diagnostic of young supernovae

Donald D. Clayton

Published on: 15 May 1975 - The Astrophysical Journal

Topics: Gamma ray, White dwarf, Supernova, Stellar evolution and Stellar structure

5-15-1975

Gamma-Ray Lines: A 22Na Radioactive Diagnostic of Young Supernovae

Donald D. Clayton
Clemson University, claydonald@gmail.com

THE ASTROPHYSICAL JOURNAL, 198: 151–152, 1975 May 15

GAMMA-RAY LINES: A ^{22}Na RADIOACTIVE DIAGNOSTIC OF YOUNG SUPERNOVAE

DONALD D. CLAYTON
Department of Space Physics and Astronomy, Rice University
Received 1974 November 4

ABSTRACT

The nuclear γ-ray lines emitted following the decay of ^{22}Na should be detectable for roughly a decade following Galactic explosions of massive stars in which the helium shell is heated sufficiently to synthesize ^{19}F and ^{21}Ne from seed ^{14}N.

Subject headings: gamma rays — supernovae

My purpose here is to add another good candidate to the γ-ray line sources that may be expected to be detectable surrounding young supernovae. The detection of these lines could clarify nucleosynthesis theory and also serve as a diagnostic of the structure of the presupernova. Clayton (1974) has discussed the supernova diagnostic idea with respect to radioactive nickel. The source in question here, ^{22}Na synthesized from ^{14}N in exploding helium shells (Howard, Arnett, and Clayton 1971), will arise from quite different shells of the same source or even from a quite different object altogether, but the diagnostic ideas are the same as those outlined by Clayton (1974). A general review of other γ-ray line sources may be found in Clayton (1973*a*).

The idea of detecting ^{22}Na has been mentioned before (Clayton and Hoyle 1974), but within the specific context of explosive hydrogen burning on the surfaces of white dwarfs, leading to the nova phenomenon. The mass ejected in those cases is probably small, of order $10^{-4}\, M_{\odot}$; but even so, some young novae should be detectable for several years to distances of several kiloparsecs. In the context to be discussed here, namely, the explosion of a massive layered star, the helium shell may contain several $M_{\odot}$. This shell should be ejected in its entirety. Since it is much less obscure than the deeper layers where the radioactive nickel would be synthesized, the discovery of an abundant radioactive source of γ-rays within the helium shell can be of considerable importance. For example, if, as seems likely, both the ^{22}Na and the ^{56,57}Ni lines can be detected from a massive supernova, their relative strengths will reveal something about the relative masses of the helium shell and the deeper nickel-containing shells. Decided constraints upon a numerical hydrodynamic model will result. There is little chance in such a model of confusing the source of the ^{22}Na with that potentially synthesizable in explosive hydrogen shells, because, as Howard *et al.* (1971) showed, the hydrogen envelope of a massive evolved star rests at a density much too low for significant proton captures to occur.

One of the difficulties of evaluating this helium-shell source is that Howard *et al.* (1971), and also Arnould and Beelen (1974) who studied the problem again, showed that the yield of ^{22}Na is very sensitive to the conditions of the explosion—primarily the peak temperature and the expansion time scale. For peak temperatures about $T_8 = 6$, reaction sequences similar to and including

$$^{14}\mathrm{N}(\alpha, \gamma)^{18}\mathrm{F}(\alpha, p)^{21}\mathrm{Ne}(p, \gamma)^{22}\mathrm{Na}$$

establish large concentrations of ^{22}Na. The ^{14}N is abundant because the CNO cycle would have been responsible for the previous exhaustion of hydrogen, and the ^{22}Na yield can be a significant fraction of the ^{14}N concentration. On the other hand, the ^{22}Na yield would be small if the helium ejection is gentle enough ($T_8 < 5$). Without some additional guideline, therefore, it is difficult to know what yield to expect.

For the purposes of defining realistic prospects for eventual measurements in nuclear γ-ray line astronomy, I think one should imagine conditions that result in appropriate yields of those nuclei whose natural abundance is attributable to explosively ejected helium shells. Howard *et al.* (1971) and Arnould and Beelen (1974) showed that these nuclei are ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne. This important discovery provides a plausible origin for those four puzzling nuclei. Concentrate on the crucial pair ^{19}F and ^{21}Ne, which both have mass fractions within a factor 2 of $X_{\odot} = 2 \times 10^{-6}$ in solar material. Review of our calculations (Howard *et al.* 1971) shows that these nuclei are synthesized in comparable amounts with mass fractions near $X = 2 \times 10^{-3}$ in the helium shell. These results show that a fraction $f = (2 \times 10^{-6})/(2 \times 10^{-3})$ of solar matter has been explosively ejected with peak helium temperatures near $T_8 = 6$. The average time between standard Galactic events ejecting $1\, M_{\odot}$ shells of He would have to be about 50 years to account for the Galactic concentration uniformly over 10^{10} years. This yield clearly contributes negligibly to the He abundance itself, although it accounts for ^{19}F and ^{21}Ne. In these plausible thermodynamic circumstances the yield of ^{22}Na is found to be of order $X(^{22}\mathrm{Na}) \approx (0.1 \text{ to } 1)X(^{21}\mathrm{Ne})$. If the appropriate mass of helium shell is taken to be $mM_{\odot}$, the flux $F_i'(t)$ if the nebula were completely transparent is

$$F_i'(^{22}\mathrm{Na}) = g_i \frac{X_0(^{22}\mathrm{Na})mM_{\odot}N_{\mathrm{A}}/22}{4\pi R^2 \tau(^{22}\mathrm{Na})} \exp(-t/\tau) \qquad (1)$$

$$\approx (0.1 \text{ to } 1)\, \frac{8\, mg_i}{R^2(\mathrm{kpc})} \exp[-8.4 \times 10^{-9} t(\mathrm{s})]\, \mathrm{cm}^{-2}\, \mathrm{s}^{-1} ,$$

where N_A is Avogadro's number and R is the distance to the supernova. The line multiplicity is $g_i = 1$ for the 1.275-MeV line and $g_i = 11/4$ for the positronium annihilation (or $g_i = 2$ if the density is so high that the positrons annihilate into two photons). The observed flux is then

$$F_i(t) = T_i(t)F_i'(t)\,, \tag{2}$$

where $T_i(t)$ is the fraction of photons that emerge without absorption or degradation of energy by Compton scattering (Clayton 1974). The transmission T_i will reach unity earlier for the expanding helium shell than it will for the radioactive nickel, provided that the layered structure is not disrupted by the explosion. If the time delay for the rise of transmission of the nickel lines relative to that of the ^{22}Na lines is measured, a clear constraint on the mass between the helium and the nickel shells is obtained (more precisely, the mass divided by the square of the expansion velocity [Clayton 1974]).

The flux suggested by equation (1) is satisfyingly large. A Galactic supernova should be detectable for a decade following the event. The 1.275-MeV line will conveniently distinguish ^{22}Na from other sources of positrons (Clayton 1973*b*). Extragalactic events, however (even in nearby M31), will probably lie below the threshold of instruments presently being contemplated. It is also unlikely that ^{22}Na will contribute much to the cosmic background, because the ^{22}Ne abundance, which is an upper limit to the entire ^{22}Na production, is only about half of the ^{56}Fe abundance; moreover, the 1.275-MeV ledge in the background (Clayton and Silk 1969) would be in practice superposed on the 1.24-MeV ledge from ^{56}Co.

Probably the worst criticism of this idea is that the ^{22}Na yield from an expanding He shell is so uncertain. On the other hand, this same strong dependence on the peak temperature does afford the possibility of a unique thermometer when a Galactic Type II event can be studied. My purpose here is simply to aid the planning for that eventuality.

This research was supported by NSF grant GP-18335 and by NASA grant NSG-7015.

REFERENCES

Arnould, M., and Beelen, W. 1974, *Astr. and Ap.*, **33**, 215.

Clayton, D. C. 1973*a*, in *Gamma Ray Astrophysics* (*NASA SP-339*), ed. F. Stecker and J. Trombka (Washington: U.S. Government Printing Office). Also in *Explosive Nucleosynthesis*, ed. D. Schramm and W. D. Arnett (Austin: University of Texas Press).

———. 1973*b*, *Nature*, **244**, 137.

Clayton, D. C. 1974, *Ap. J.*, **188**, 155.

Clayton, D. D., and Hoyle, F. 1974, *Ap. J.* (*Letters*), **187**, L101.

Clayton, D. D., and Silk, J. 1969, *Ap. J.* (*Letters*), **158**, L43.

Howard, W. M., Arnett, W. D., and Clayton, D. D. 1971, *Ap. J.*, **165**, 495.

DONALD D. CLAYTON: Department of Space Physics and Astronomy, Rice University, Houston, TX 77001