2-15-1974

Line ^{57}Co Gamma Rays: New Diagnostic of Supernova Structure

Donald D. Clayton

Clemson University, claydonald@gmail.com

Follow this and additional works at: https://tigerprints.clemson.edu/physastro_pubs

Recommended Citation

Please use publisher's recommended citation.

This Article is brought to you for free and open access by the Physics and Astronomy at TigerPrints. It has been accepted for inclusion in Publications by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.

LINE ^{57}Co GAMMA RAYS: NEW DIAGNOSTIC OF SUPERNOVA STRUCTURE

DONALD D. CLAYTON

Department of Space Physics and Astronomy, Rice University, Houston, Texas 77001

Received 1973 July 6

ABSTRACT

The nuclear gamma-ray lines emitted when ^{57}Co decays to ^{57}Fe should be detectable for several years following Galactic supernovae, and the time structure of their intensity relative to those emitted following the ^{56}Ni and ^{56}Co decays can reveal the structure of the exploding star. An analysis of a simplified analytic model is presented as an example.

Subject headings: gamma rays — nuclear reactions — supernovae

I wish here to point out that γ -ray lines following the decay of ^{57}Co should be detectable around new Galactic supernovae. Because these γ -rays have considerably lower energy (0.136 and 0.122 MeV) than the ones following ^{56}Co decay (Clayton, Colgate, and Fishman 1969), they will suffer greater attenuation. Therefore, observations of the growth and decay of lines from both species can measure the supernova structure. I will illustrate these features with a simple analytic example following general remarks.

Radioactive ^{57}Co is expected because natural ^{57}Fe is synthesized in the explosions as ^{57}Ni , just as ^{56}Ni is the parent of ^{56}Fe (Bodansky, Clayton, and Fowler 1968; Woosley, Arnett, and Clayton 1973). Although the yield of ^{57}Ni is only about 1/42 that of ^{56}Ni , its flux is greater after about 2 years because the ^{57}Co half-life (270 days) is longer than the ^{56}Co half-life (77 days). Because the supernova may not become transparent during the first 2 years, the ^{57}Co lines could even be the strongest ones from the beginning.

If I assume (Clayton 1971, 1973) that the entire Galactic abundance of iron was synthesized in 1.7×10^9 identical events, the flux of gamma rays at a distance R , if the remnant were completely transparent, would be

$$F_i'(^{56}\text{Co}) = g_i \frac{2.6 \times 10^3}{R^2(\text{kpc})} e^{-(t/111 \text{ d})} \text{ cm}^{-2} \text{ s}^{-1}, \quad (1)$$

$$F_i'(^{57}\text{Co}) = g_i \frac{18}{R^2(\text{kpc})} e^{-(t/390 \text{ d})} \text{ cm}^{-2} \text{ s}^{-1}, \quad (2)$$

where the prime indicates that attenuation is neglected and where g_i is the number of photons of type i emitted following each decay.

The supernova is initially opaque and does not expose the radioactive nickel until a considerable expansion has occurred. The observed flux can be written

$$F_i(t) = T_i(t) F_i'(t), \quad (3)$$

where $T_i(t)$ is the fraction of photons of energy E_i that emerge without absorption or degradation of energy by Compton scattering. The value of $T(t)$

clearly depends upon the supernova structure, but it approaches unity as the object expands to negligible column opacity.

The time t_i^{max} at which F_i has its maximum is obtained by setting $dF_i/dt = 0$, giving

$$dT_i/dt = \lambda_i T_i \quad \text{at} \quad t = t_i^{\text{max}}. \quad (4)$$

The transparency at that time is growing at the radioactive decay rate. Since the latter are known, a constraint upon the expanding structure results for each line i .

If the line flux can be followed as a function of time, its second derivative at t_i^{max} gives another simple constraint:

$$\frac{1}{F_i} \frac{d^2 F_i}{dt^2} = \frac{1}{T_i} \frac{d^2 T_i}{dt^2} - \lambda_i^2 \quad \text{at} \quad t = t_i^{\text{max}}. \quad (5)$$

Viewed quite generally, one sees that equation (3) yields $T_i(t)$ fully if $F_i(t)$ can be fully measured. This unprecedented situation in astronomy occurs because the source of photons $F_i'(t)$ has known exponential time dependence.

The transmission $T_i(t)$ depends on the γ -ray energy as well as the structure. One easily sees that a whole library of information would be contained in the time-dependent fluxes of differing lines from both ^{57}Co and ^{56}Co . In particular:

1) At long times the unattenuated fluxes are exponential. Their measurement gives both the absolute yield (if the supernova distance is known) and the relative yields at $A = 56$ and $A = 57$ if the moment of explosion $t = 0$ is known.

2) Two different lines from the same decay have a known relative emission rate g_i/g_j . Therefore, the relative fluxes give the ratio of the transmissions at that moment:

$$\frac{T_i(t)}{T_j(t)} = \frac{g_j F_i(t)}{g_i F_j(t)}. \quad (6)$$

This effect is substantial; e.g., in the ^{56}Co case the opacity to the 0.84-MeV line is about 1.8 times the opacity to the 2.60-MeV line. The intensity ratio can therefore measure the optical depth accurately. If a

line of another species (e.g., ^{57}Co) is simultaneously measurable, the abundance ratio is then known even if all lines are attenuated, provided the explosion time $t=0$ is known.

3) Because of equation (4), different lines peak at different times. The time displacement measures the ratio of the obscuring mass to the square of its expansion velocity.

Let me now illustrate these features with a simple analytic example. I will take a sphere of homogeneous composition having a mass absorption coefficient $\mu_i(E_i)$ equal to that of concrete (selected for convenience) everywhere, for then I may write

$$T_i(t) = \exp(-\mu_i x), \quad (7)$$

where $x = \int \rho dr$ is the optical depth from the central nickel to the surface; i.e., I will ignore the dependence of μ_i on position. For the sake of further illustration, I will also consider the exploding star to maintain a uniform density throughout as it expands. A uniform ball of mass $mM_\odot$ expanding at the velocity $10^9 v_9$ cm s $^{-1}$ has an optical depth

$$x = \bar{\rho}(t)R(t) = 4.8 \times 10^{14} \frac{m}{(v_9 t)^2} \text{ g cm}^{-2} \equiv \frac{K}{t^2}, \quad (8)$$

so for objects of about a solar mass ($m = 1$) expanding with observed and calculated supernova velocities of about $10,000 \text{ km s}^{-1}$ ($v_9 = 1$), the optical depth falls below a typically interesting 10 g cm^{-2} for $t > 7 \times 10^6 \text{ s}$. This time is very near the half-life $\tau_{1/2}(^{56}\text{Co}) = 6.7 \times 10^6 \text{ s}$, suggesting that the more abundant $A = 56$ γ -rays may not emerge from the supernova explosions. Brown (1973) has calculated the spectrum near $2 \times 10^6 \text{ s}$, for example, and finds a significant fraction of the initial γ -rays to be degraded to a Compton tail at that time. If equation (7) is applicable, then

$$-\mu_i \dot{x} = \lambda_i \quad \text{at} \quad t = t_i^{\max}. \quad (9)$$

The additional assumption of equation (8) allows explicit solution for $t_i^{\max}$:

$$t_i^{\max} = (2\mu_i K / \lambda_i)^{1/3}. \quad (10)$$

The value of K is given in equation (8) for the special case of a homogeneous expanding sphere; however, the form $x \simeq K/t^2$ is more generally valid. For example, it obviously applies also to a thin spherical shell of matter expanding with constant velocity. It therefore also applies to any spherical object in which differing spherical shells are expanding with constant

FIG. 1.—Fluxes at Earth in four γ -ray lines from a standard-yield supernova at a distance $R = 10 \text{ kpc}$ as a function of the time since the explosion. The fluxes during this period are much greater than the resolvability limit for lines, $F_{\min} \approx 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$. One solar mass of uniform density expanding at $10,000 \text{ km s}^{-1}$ provides this model of the early attenuation, which causes the fluxes to be smaller than the unattenuated expectations shown as thin dashed lines. The ^{57}Co flux is expected to be the strongest one at times between $7 \times 10^7 \text{ s}$, when it becomes stronger than the ^{56}Co flux, and $3 \times 10^8 \text{ s}$, when it becomes weaker than the ^{44}Sc flux. The time dependence of these fluxes can reveal the supernova structure.

but differing velocities. Thus a measurement of $t_i^{\max}$ is a measure of K —in this case the ratio of the obscuring mass to the square of its expansion velocity.

Let us evaluate one numerical example. Taking $m = v_9 = 1$ in equation (8) gives $K = 4.8 \times 10^{14} \text{ s}^2 \text{ g cm}^{-2}$. Consider the fates of three separate lines—the 0.84-MeV (100%) and 2.60-MeV (17%) lines of the ^{56}Co decay and the 0.122-MeV (88%) line of the ^{57}Co decay. Graphs of the γ -ray half-thickness of concrete (Marion 1960) show the following values of concrete thickness $d_{1/2}$ necessary to reduce the number of monoenergetic quanta by a factor of 2: 0.84 MeV (9.9 g cm^{-2}), 2.60 MeV (18 g cm^{-2}), 0.122 MeV (4.7 g cm^{-2}). The mass absorption coefficient $\mu = (\ln 2)/d_{1/2}$. Inserting these values in equation (10) gives the following times to maximum intensity:

$$t_{2.60}^{\max} = 7.1 \times 10^6 \text{ s}; \quad t_{0.84}^{\max} = 8.7 \times 10^6 \text{ s}; \\ t_{0.12}^{\max} = 17 \times 10^6 \text{ s}.$$

There is a spread of almost 3 weeks between the maxima of the two ^{56}Co lines, and 13 weeks between the ^{56}Co maximum and the ^{57}Co maximum.

A graph of the anticipated fluxes in these lines is shown in figure 1, which shows equation (3) in its detail for the simple homogeneous uniform-density expanding model. This figure shows the numerical value of the flux expected for the 0.84-MeV and the 0.12-MeV lines of ^{56}Co and ^{57}Co , respectively, for an average supernova at a typical Galactic distance $R = 10 \text{ kpc}$. The ^{57}Co line peaks later and exceeds the ^{56}Co flux after $7 \times 10^7 \text{ s}$, when both remain well above the detectable flux limit $10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$. The

2.60-MeV line of ^{56}Co is for convenience shown as it would be if its value of g_i were the same as that for the 0.84-MeV line (rather than the actual $g_{2.60} = 0.17 g_{0.84}$), because this makes their asymptotic behavior the same.

I cheerfully acknowledge that the simplified analytic model used in this discussion is probably not realistic, but the various effects on the γ -ray lines will also occur in realistic models. The problem then will be to carefully calculate the transparency of a hydrodynamic model. My feeling is that this might as well wait until the lines are observed. There is such a great difference in supernova models that some careful experiments capable of the types of observations discussed here may be needed to discover the proper model. In particular, instabilities could allow the central material to burst through in streams. When a Galactic supernova comes, it will be important to have planned for the most useful observations.

In emphasizing the new discovery of the importance of the ^{57}Co lines, I do not want to forget the ^{56}Ni lines so far omitted from this discussion. They have a 6.1-day half-life and were discussed by Clayton *et al.* (1969). The sequence of half-lives 6.1 days, 77 days, and 270 days has been graciously provided us by Nature, making this important application of γ -ray astronomy possible. It affords a way in principle to see the inner structure of an exploding star.

This research was supported by the National Science Foundation GP-18335 and by the National Aeronautics and Space Administration.

REFERENCES

- Bodansky, D., Clayton, D. D., and Fowler, W. A. 1968, *Ap. J. Suppl.*, **16**, 299.
 Brown, R. T. 1973, *Ap. J.*, **179**, 607.
 Clayton, D. D. 1971, *Nature*, **234**, 291.
 ———. 1973, in *Proceedings of International Symposium and Workshop on Gamma-Ray Astrophysics*, ed. F. Stecher and J. Trombka (Washington: U.S. Government Printing Office).
 Clayton, D. D., Colgate, S. A., and Fishman, G. J. 1969, *Ap. J.*, **155**, 75.
 Marion, J. B. 1960, *Nuclear Data Tables: Part 3 Nuclear Reaction Graphs* (Washington: U.S. Government Printing Office), see fig. 47, p. 105.
 Woosley, S. E., Arnett, W. D., and Clayton, D. D. 1973, *Ap. J. Suppl.*, No. 231, **26**, 231.