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16. Summary/Notes

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ABSTRACT

From theoretical considerations of the behaviour of gamma ray line fluxes occurring after a supernova explosion, the 1.156 and 0.847 MeV lines are seen to be the most likely to be observed. The 1.156 MeV line has been previously observed by other investigators. ~~We report here~~ Observations of the 0.847 MeV line, and 1.332, 1.173 and 0.059 MeV lines using a Ge(Li) telescope aboard a stratospheric balloon which was flown in Brazil in 1977 are reported. ~~We also report~~ The observation using a NaI(Tl) detector of a line in the energy interval 1.5 - 1.6 MeV, which may be due to O^{18} (p, p') O^{18*} reaction is also reported.

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1. INTRODUCTION

From stellar evolution theory, it is known that a star having mass $M \leq M_\odot$ will evolve to the white dwarft stage. However, stars with a few solar masses may reach the silicon burning stage, with temperatures about 5×10^9 K and densities in the range $10^7 - 10^9$ g cm^{-3} (Clayton et al., 1969). The nuclear reactions, occurring at this stage, may drive the iron core of the star to collapse within a few seconds. This sudden collapse gives rise to a Supernova (SN).

During the moment of collapse many radionuclides with long lifetimes are synthesized and the synthesis process may continue as the shock wave propagates through the nearby interstellar medium. The explosive nucleosynthesis process, taking place in Supernovae (SNe), seems to be mainly responsible for the synthesis of the elements in the mass range $28 \leq A \leq 57$.

Later, when the expanding shell has become optically thin to the gamma radiation, produced by the decay chains of these nuclides, a strong discrete source of nuclear gamma ray lines will remain.

Study of these lines should lead to a better understanding of the process which produce SNe phenomena. However, detection of these lines with a statiscally significant level of confidence is presently a difficult problem.

Assuming a quasi-adiabatic expansion of the shell surrounding a type I SN one obtains that the nebula is opaque to the gamma radiation for times less than 0.3 year. This conclusion is also valid for Supernova Remnants (SNR) with mass ~ 10 $M_\odot$ (from SN type II), according to Arnett (1976).

Using a Monte Carlo method, Brown (1973) calculated the gamma ray flux emitted by an expanding shell of a type I SN. His results showed that Compton scattering may produce a strong background continuum radiation, masking any nuclear gamma line below 0.8 MeV.

In addition to the lines due to decay chains, there would exist gamma lines produced by nuclear de-excitation of nuclides, interacting with highly energetic cosmic particles present in the shell of a SN (Ramaty and Boldt, 1971).

2. PRINCIPAL GAMMA RAY LINES AND POSSIBLE OBSERVATIONS

Clayton et al. (1969) calculated variations in the strength of the expected main decay lines as a function of the time after the explosion.

They supposed a type I SN, 1 Mpc away, at the silicon burning stage producing Ni^{56}, and that the gas envelope is expanding with a speed of about 10^4 km s^{-1}.

In Figure 1, from Lingenfelter and Ramaty (1978), we show the expected gamma ray flux emitted by a type I SN with the above characteristics located 10 kpc away, i.e., a source localized near the Galactic Center, as a function of time.

The estimates of the fluxes shown in Figure 1 are based on the calculations by Clayton et al. (1969) and Clayton (1973), with the hypothesis that all Fe^{56}, Fe^{57}, Ca^{44} and only 2% of Ne^{22} observed presently are decay products of the nuclides produced in SNe, with both types (I and II) contributing equally for the nucleosynthesis of these elements.

Table I gives the main decay chains associated with SNe phenomena which produce gamma ray lines. Table II lists the gamma ray lines which are due to de-excitation of nuclides excited by nuclear interactions of highly energetic particles with the gas of the expanding shell. Presently, there exists no estimate for the expected flux of these lines.

The flux of the gamma ray lines at 0.847 MeV, produced by the decay chain $Co^{56} \rightarrow Fe^{56}$, shown in Figure 1, is above the background radiation for nearly 3 years. This means that it is possible to observe the 0.847 MeV line during 10% of the lifetime of a supernova event, assuming a birth rate for galactic SNe of order 1 SN per 30 years (Tamman, 1974).

The most probable gamma ray line to be detected at any time (lifetime $\simeq$ 68 years), according to theoretical calculations, is the 1.156 MeV line from the $Sc^{44} \rightarrow Ca^{44}$ decay chain.

Walraven and Haymes (1976) made observations toward the direction $\ell = 345^{o}$ and $b = + 1.5^{o}$, with an estimated error in the position of the source within $\pm 1^{o}$ for ℓ and b, and measured a flux of about 4.2×10^{-3} photons cm^{-2} s^{-1} in the energy interval 1.054 - 1.274 MeV. This observation appear to be the first detection of the 1.156 MeV line, with a statistical level of confidence of 2.6σ above the power law background fitted to the raw data. Because of this relatively low level of confidence more observations in this direction, with better telescopes, are needed to improve the signal to noise ratio.

There were two associated SNR likely to be the sources of the observed 1.156 MeV line:

(a) An optical SNR, earlier identified by Van den Bergh et al. (1973) and at galactic coordinates $\ell = 352.05^{o}$ and $b = + 0.13^{o}$, where there is indications of a weak filamentary structure, close to an extended HII region. However, when observed in 408 MHz that SNR showed an angular diameter of about 30' arc. This implies, assuming the distance to the source to be 3 kpc, an age >> 50 years (the line lifetime above 1 MeV background) for this SNR. This SNR is therefore much too old to be the source of the observed gamma line;

(b) A radio SNR, with no optical counterpart, observed by Kesteven (1968) at galactic position $\ell = 345.34^{0}$ and $b = +1.43^{0}$. This SNR seems to be the likely source for the observed 1.156 MeV line, since it is likely to be younger than 50 years, according to Walraven and Haymes (1976).

The highly broadened gamma ray lines in the energy intervals 1-2 MeV and 4-5 MeV observed when the telescope was toward the Galactic Center (Haymes et al., 1975) may be due to nuclear de-excitation in that region.

In the 1-2 MeV energy interval, the observed line may be the result of an overlapping of several lines from de-excitation of the nuclides Ne^{20*}, Mg^{24*} and Si^{28*}, which have high relative abundances. The statistical level of confidence for this feature is about 4σ.

In the 4-5 MeV energy interval, measured with a statistical level of confidence of 3.5σ, it is likely that the origin may be the C^{12*} (at 4.44 MeV) de-excitation line, since C^{12} is relatively abundant in the interstellar medium.

From the relative abundances of the elements and from the long lifetimes (see Table I) is to be expected that the lines 1.332 and 1.173 MeV from the $Fe^{60} \rightarrow Co^{60} \rightarrow Ni^{60}$ decay chain are detectable, mainly if the origin is a type II SN, from which the flux is estimated to be higher than type I SNe.

Analyzing the measurements of gamma ray fluxes from the Galactic Center, da Costa (1979) found evidence, with a statistical confidence of $\sim 3\sigma$, of the presence of the gamma lines produced by the $Fe^{60} \rightarrow Ni^{60}$ decay chain at 1.332, 1.173 and 0.059 MeV and also the 0.847 MeV line from the $Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$ decay chain ([1]). These observations were made with a high resolution Ge(Li) telescope, which is described by Albernhe et al. (1977).

([1]) *The fluxes of these lines are about* 10^{-3} *photons* cm^{-2} s^{-1}.

The other decay chains, from Table I, are seen with less statistical confidence but the lines at 0.014 MeV from $Co^{57} \rightarrow Fe^{57}$, at 0.068 MeV from $Sc^{44} \rightarrow Ca^{44}$ and the line at 1.130 MeV from $Al^{26} \rightarrow Mg^{26}$ are not seen above the background radiation.

The fact that the observed lines are only seen when the Galactic Center is within the FWHM of the telescope, about 23^{o} at 1 MeV, indicates an extraterrestrial origin for these lines.

From measurements in December 1978, obtained with a NaI(Tl) gamma ray detector lookingat the zenith, on board a stratospheric balloon, Rao et al. (1979) observed a gamma line at 1.50 - 1.60 MeV energy interval (see Figure 2). This line showed a rapid increase in flux when the detector was looking toward $\alpha = 13^{h}$ and $\delta - 23^{o}$.

From IAU telegram n. 3221 they found a presence in the field of view of a new supernova at celestial coordinates (1950.0) $\alpha = 13^{h}\ 27.5^{m}$ and $\delta = -21^{o}\ 29'$. The new SN event occurred in 1978, May, 8. It is very likely that this extragalactic Supernova is the origin of the observed line.

One possible mechanism, producing the measured line is the O^{18} (p,p') O^{18*} excitation process which gives a line at 1.57 MeV (Lingenfelter and Ramaty, 1976). The estimated flux coming from the Supernova is about 3.62×10^{-5} photons $cm^{-2}s^{-1}KeV^{-1}$.

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TABLE I

GAMMA RAY LINES FROM DECAY CHAINS PRODUCED IN SUPERNOVA EXPLOSIONS(*)

DECAY CHAIN	MEAN LIFETIME (yr)	PHOTON ENERGY (MeV)
$Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$	0.31	0.847
		1.238
		2.598
		1.771
		1.038
$Co^{57} \rightarrow Fe^{57}$	1.1	0.122
		0.136
$Na^{22} \rightarrow Ne^{22}$	3.8	1.275
$Ti^{44} \rightarrow Sc^{44} \rightarrow Ca^{44}$	68	0.156
		0.078
		0.068
$Fe^{60} \rightarrow Co^{60} \rightarrow Ni^{60}$	4.3×10^5	1.332
		1.173
		0.059
$Al^{26} \rightarrow Mg^{26}$	1.1×10^6	1.809
		1.130

(*) After Lingenfelter and Ramaty (1978).

TABLE II

MAIN DE-EXCITATION GAMMA RAY LINES(*)

EMITTING STATE	MAIN PRODUCTION PROCESSES	MEAN LIFETIME (Sec)	PHOTON ENERGY (MeV)
Fe^{56*}(0.847)	$Fe^{56}(p,p')Fe^{56*}$	9.7×10^{-12}	0.847
Mg^{24*}(1.369)	$Mg^{24}(p,p')Mg^{24*}$	1.75×10^{-12}	1.369
Ne^{20*}(1.634)	$Ne^{20}(p,p')Ne^{20*}$	1.2×10^{-12}	1.634
Si^{28*}(1.779)	$Si^{28}(p,p')Si^{28*}$	6.8×10^{-13}	1.779
N^{14*}(2.313)	$N^{14}(p,p')N^{14*}$	8.5×10^{-14}	2.313
	$N^{14}(p,n)O^{14}(e^+)N^{14*}$	102	2.313
C^{12*}(4.439)	$C^{12}(p,p')C^{12*}$	5.62×10^{-14}	4.438
	$O^{16}(p,x)C^{12*}$	5.62×10^{-14}	4.438
O^{16*}(6.131)	$O^{16}(p,p')O^{16*}$	2.4×10^{-11}	6.129
Si^{28*}(6.879)	$Si^{28}(p,p')Si^{28*}$	2.5×10^{-12}	6.878

(*) After Lingenfelter and Ramaty (1978).

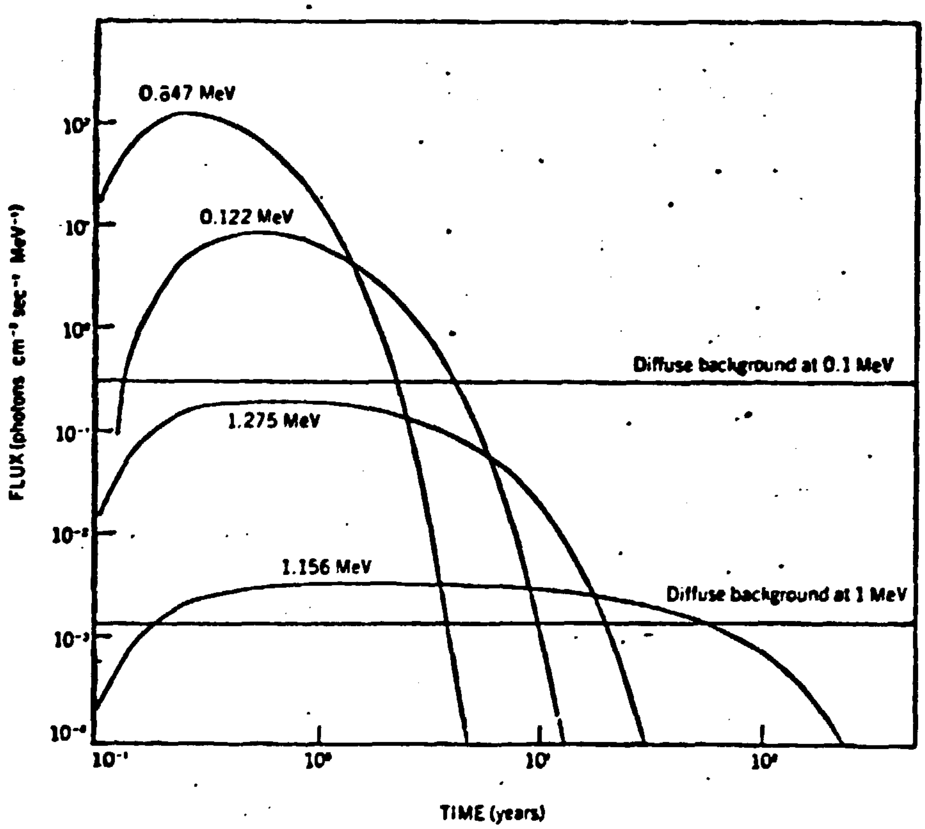

Fig. 1 - Expected gamma ray fluxes, as a function of time, emitted by a Supernova located at 10 Kpc away. (From Lingenfelter and Ramaty, 1978).

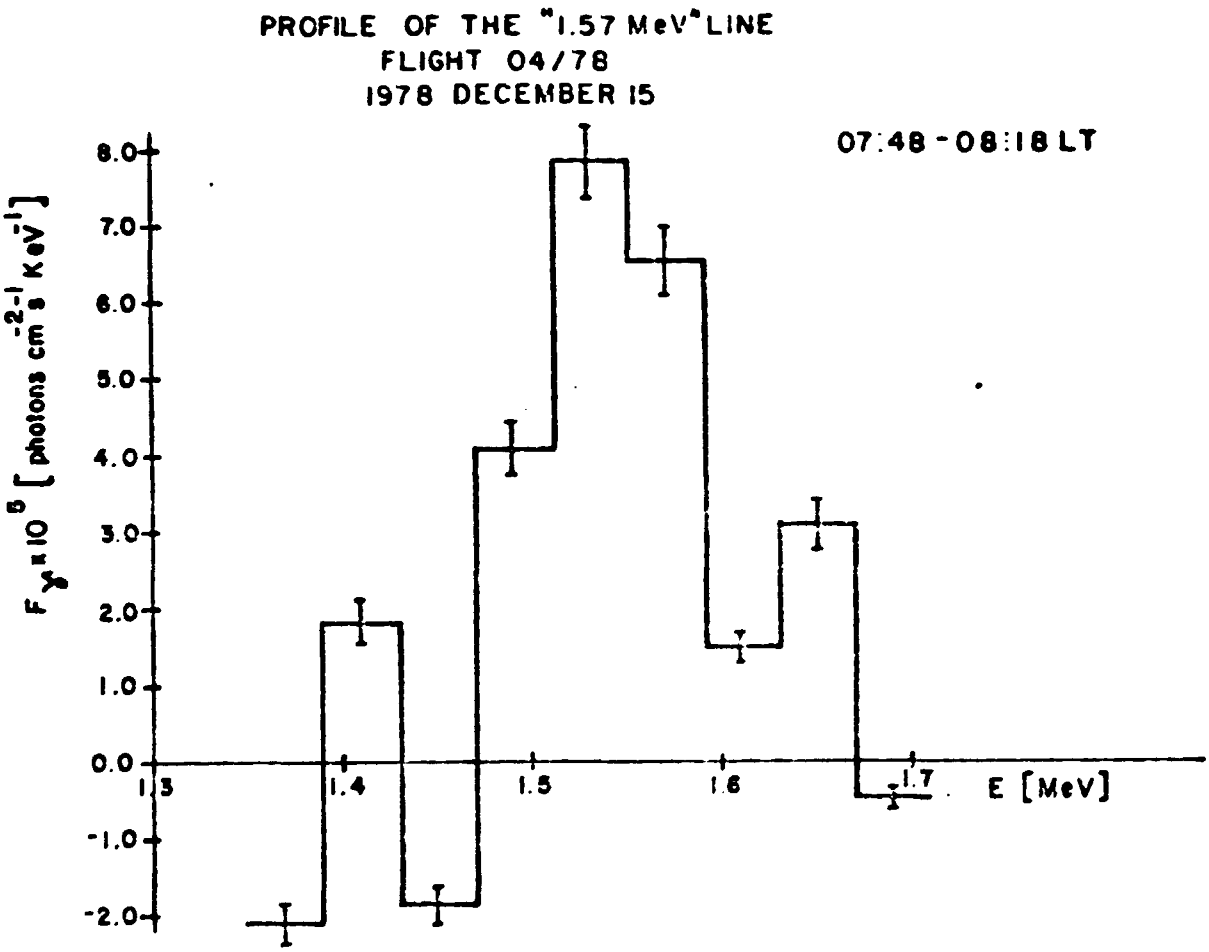

Fig. 2 - Spectrum of the possible 1.57 MeV line, due to O^{18*} de-excitation, observed by Rao et al., (1979).