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Astronomical gamma-ray lines predicting probable gamma-emitter nucleosynthesis sites as explosive events

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Abstract : Astronomical gamma-ray (γ) lines with energy 0.5 – 15 *MeV* have been interpreted as due to $e^+ - e^-$ annihilation and decay and de-excitation of the excited nucleosynthesis yields produced in some explosive sites and then ejected into the inter steller matter (ISM). Some explosive events e.g. X-ray outbursts and novae outbursts have been considered to study, whether these possible cosmic candidates can provide enough nuclei to explain the observed highly significant 1.809 *MeV*, 1.275 *MeV* γ-lines reported by Compton Gamma-Ray Observatory (CGRO) and other satellite experiments.

Cen *X*–4, Aql *X*–1, 1608–522, these three soft X-ray transients (SXT) during outburst can be suggested as good emitters of these two lines with emission features in observable range which may be tried with sophisticated instruments like SPI (Spectrometer INTEGRAL) on board the spacecraft INTEGRAL (International Gamma-Ray Astrophysics Laboratory) to be launched by ESA (European Space Agency) in near future.

Key words : Gamma-ray lines, soft x-ray transient outbursts, novae bursts

1. Introduction

According to J. Paul (1999) "A Golden Age of Nuclear Astrophysics" will open with the launch of the INTEGRAL spacecraft which aims mainly to observe γ-lines from varieties of cosmic sites; because, comparison between the predicted and observed emission line spectra from a celestial object and diffuse galactic γ-lines can indicate chemical as well as physical properties of the nucleosynthesis sites where the γ-emitter nuclei are produced (Schonfelder, 1999; Mc Connell et al. 1997; Knodlseder et al. 1995; Bardoloi et al. 1995, 1996; Mahoney et.al., 1982; Ramaty and Lingenfelter, 1977). Celestial γ-lines with energy 0.5 – 15 *MeV* arises due to disintegration of the radioactive isotopes produced during thermal nucleosynthesis and also they are associated with non-thermal nuclear excitations.

Here in the present work, two types of explosive cases have been considered– (I) Neutron Star (*ns*) SXT during outburst and (II) Novae— during which excited nuclei may be synthesized to emit γ–photons. We try to find out whether the ejected material from three ns SXTs i.e. Cen *X*-4, Aql *X*–1, 1608–522, during their outbursts and novae outbursts can provide enough nuclei to emit γ-lines with intensities in the observable range.

2. Case I – ns SXTs during outbursts :

Observed characteristics of three SXT outburst sources – Cen *X*-4, Aql *X*–1, 1608–522 have been explained considering them as accreting ns of mass 1.41 M⊙ in a close binary system with accretion rate $\dot{M}\sim 5.45\mathrm{x}10^{15} g\ s^{-1}$ from the accreting disk in a hot state (Bardoloi et al.,1999). The accreting matter from the companion dwarf consists of *H*, He and a small fraction of heavy nuclei (with mass fraction $X_z=4\mathrm{x}10^{-5}$). Physical conditions prevailing in the *H* shell of the accreting ns has been considered from model *C* of Wallace, Woosley and Weaver (1982). At the high temperature ($T_9=0.14$) and density ($\rho=2.85\mathrm{x}10^{6}\ g\ cm^{-3}$) prevailing in the accreted envelope of the *ns*, heavy seed nuclei *C, O, Ne* and *Mg* captures proton leading to *CNOF, NeNa, MgAlSi* cyclic reactions to occur (Fig. 1, 2, 3). These three nucleosynthesis operations are found to contribute and tally well with the observed total energy values (E_{total}), Luminosity *L*, effective temperature T_{eff}, average Luminosity L_{av} etc. (Bardoloi et al., 1999; Tanaka and Shibazaki, 1996).

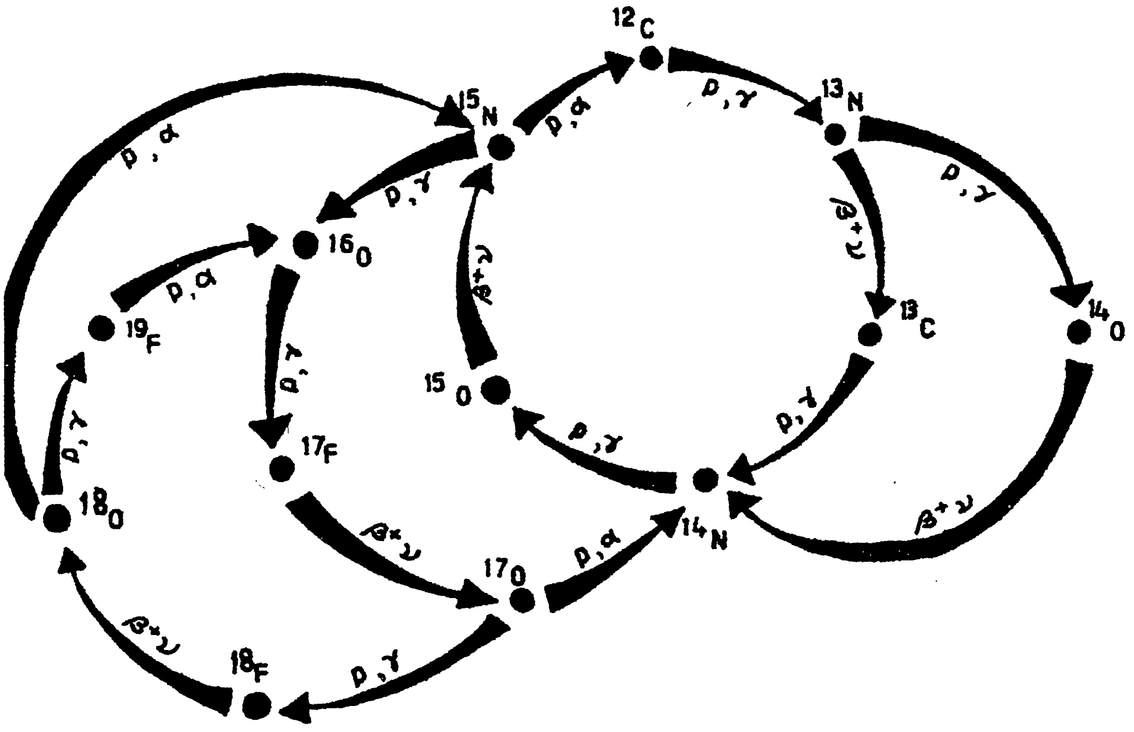


Figure 1. Extended CNOF Cyclic reactions (original CN Cycle with cyclic reactions $^{12}C(p,\gamma)^{13}N(\beta^+,\nu)$ $^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(\beta^+,\nu)^{15}N(p,\alpha)^{12}C$ has some bifurcates through (i) $^{13}N(p,\gamma)^{14}O(\beta^+,\nu)^{14}N$ (ii) $^{15}N(p,\gamma)^{16}O(p,\gamma)$ $^{17}F(\beta^+,\nu)^{17}O(p,\alpha)^{14}N$ (iii) $^{17}O(p,\gamma)^{18}F(\beta^+,\nu)^{18}O(p,\alpha)^{15}N$ and (iv) $^{18}O(p,\gamma)^{19}F(p,\alpha)^{16}O$

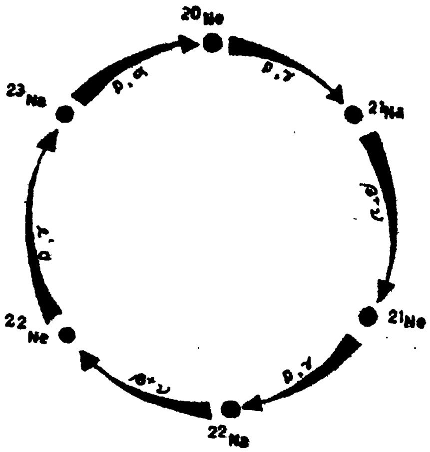


Figure 2. NeNa Cycle with cyclic reactions $^{20}Ne(p,\gamma)^{21}Na(\beta^+,\nu)^{21}Ne(p,\gamma)^{22}Na(\beta^+,\nu)$ $^{22}Ne(p,\gamma)^{23}Na(p,\alpha)^{20}Ne$.

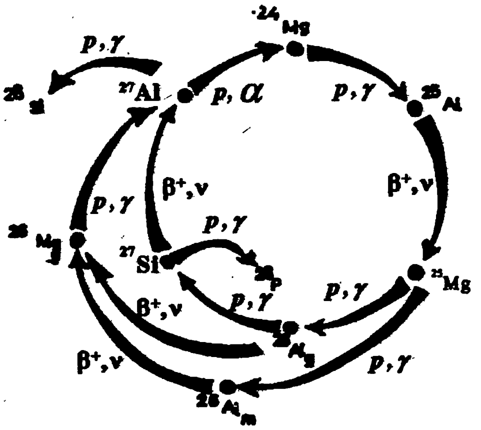


Figure 3. Extended MgAlSi cycle with reactions $^{24}Mg(p,\gamma)^{25}Al(\beta^+,\nu)^{25}Mg(p,\gamma)^{26}Al_g(p,\gamma)^{27}Si(\beta^+,\nu)^{27}Al$ $(p,\alpha)^{24}Mg$ with additional reactions
(i) $^{25}Mg(p,\gamma)$ $^{26}Al_m(\beta^+,\nu)^{26}Mg(p,\gamma)^{27}Al$
(ii) $^{26}Al_g(\beta^+,\nu)^{26}Mg$ (iii) $^{27}Si(p,\gamma)^{28}P$ (iv) $^{27}Al(p,\gamma)^{28}Si$.

During the outbursts, explosive nucleosynthesis processes *CNOF, NeNa, MgAlSi* yield radioactive, excited nuclei which emit γ-photons after β^+ - decay and de-excitation. Probable emission of γ-photons with energy E'_γ from the product nuclei in the above considered ns SXT sources are to be examined due to (i) decay of radioactive isotopes ($^{26}Al_g$, ^{22}Na) and (ii) de-excitation of the excited nuclei.

Due to strong gravity field of the *ns*, γ-photons will be red-shifted. The red-shift correction factor due to a *ns* of mass 1.41 $M_\odot$ and radius R=14.3 km is given by

$$\left(1-\frac{2GM}{Rc^2}\right)^{-\frac{1}{2}} = 1.187 \tag{1}$$

Therefore, the corrected E'_γ is $E_\gamma = 1.187\, E'_\gamma$ *MeV*. Since each excited nuclei is to emit one photon, number density of γ-photon received on earth per cm^2 per sec. i.e. intensity I, is given by–

$$I = \frac{N_j(t) \times M_e}{4\pi D^2} \tag{2}$$

where, $N_j(t)$ = Average no. density of the j th product during burst time 't' in a nuclear chain reaction, M_e=ejected mass per sec. during explosion, D = distance of the SXT sources. $N_j(t)$ for each of the product nuclei have been calculated applying Bateman equation and $M_e = 10^{18} g\, s^{-1}$.

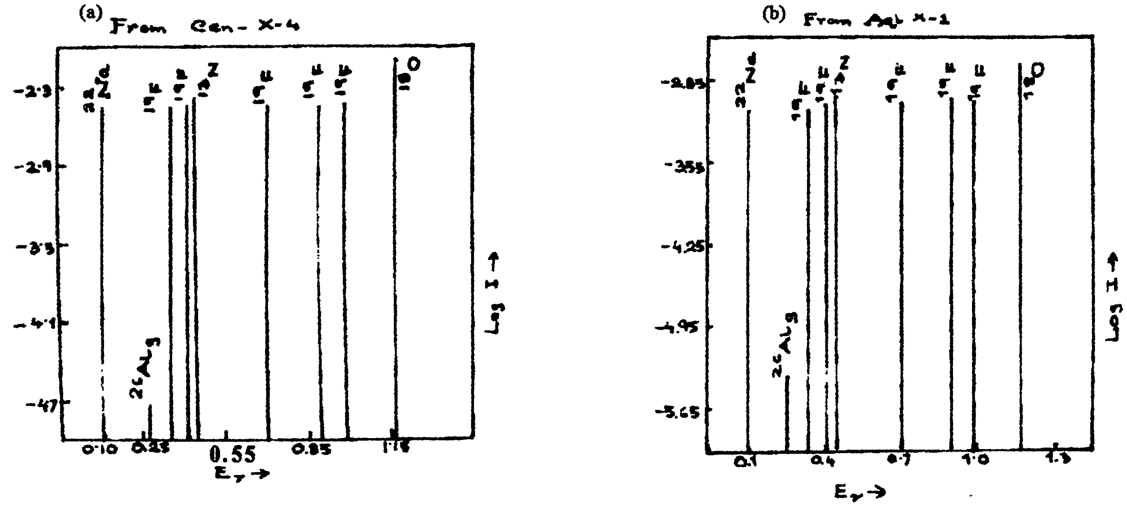
2.1 Gamma-emission due to decay of the radioactive nuclei :

Data obtained by different experiments on board the space probes reveal diffuse galactic γ-lines of energy 1.809 *MeV*, 1.275 *MeV* emitted due to β^+ –decay of $^{26}Al_g$, ^{22}Na respectively.

Flux for 1.809 *MeV* line has been found to be 1.37×10^{-4} photons $cm^{-2}s^{-1}$ from the inner galactic plane as observed by OSSE (Purcell et al 1995) and to be 1.7×10^{-5} $cm^{-2}s^{-1}$ from Orion as observed by COMPTEL on board CGRO observatory (Oberlack et al., 1995). On the other hand, the diffuse galactic 1.275 *MeV* line is measured to have intensity of 4.4×10^{-4} photons $cm^{-2}s^{-1}$ by HEAO-3 (Mahoney et al.1982).

In the present work,considering 96% of $^{26}Al_g$ β^+ - decay to 1.809 MeV level of ^{26}Mg, calculated intensity of 1.809 *MeV* line to receive on earth should be 1.93×10^{-5}, 4.43×10^{-6}, 2.14×10^{-6} photons $cm^{-2}s^{-1}$ from *Cen X*-4 (*D*=1.2 kpc), *Aql X*-1(*D*=2.5 kpc) and 1608-522 (*D*=3.6 kpc) respectively (Fig. 4a, 4b, 4c). Considering 99.938% of ^{22}Na β^+ - decay to1.275 MeV level of ^{22}Ne, probable contribution towards intensity of 1.275 *MeV* line from the above three sources are 3.47×10^{-3}, 7.99×10^{-4}, 3.85×10^{-4} photons $cm^{-2}s^{-1}$, suggesting *Cen X*-4, *Aql X*-1, 1608-522 to be good candidates for observing astronomical γ -lines by INTEGRAL spacecraft.

2.2 Very feeble chance to detect some more γ-lines due to de-excitation of excited nuclides :



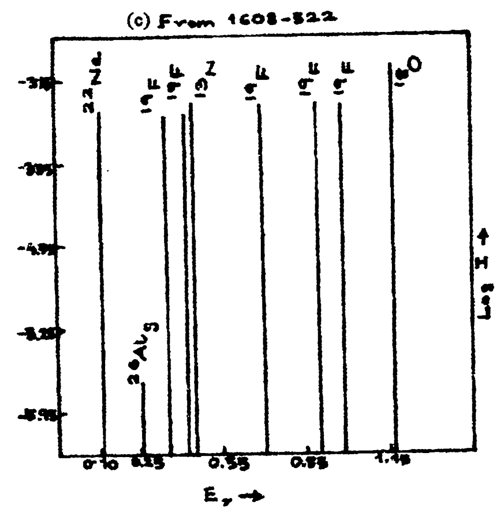


Figure 4. Intensity I(photons cm^{-2} s^{-1})vs. energy E_γ(MeV) of gamma-lines to receive on earth from
(a)Cen X- 4 (b)Aql X-1 (c)1608-522

At high temperature, a nucleus is at an excited state for fractions of a second with energy E'_x, given by –

$$E'_x = 0.12\,(Z_1^2 Z_2^2 A T_9^{\,2}) + q \quad MeV \tag{3}$$

q being the disintegration energy. Different energy levels of each nuclei with spin and parity J^π values and transitions to lower levels have been taken from Endt 1990; Ajzenberg-Selove, 1990, 1991; Tilley et al. 1993, 1995. The considered excited state with energy E_x is taken to be the nearest level to E'_x. When the nuclei at E_x level comes down to a lower level, a γ-photon is emitted. Energy E'_γ of emitted γ-photon is the difference of energy between two transition levels. We consider here mainly $E1$, $M1$ transitions from the excited states which are available in the considered references.

Determining E_x of all the nucleosynthesis yields of *CNOF, NeNa, MgAlSi* cyclic operations in the considered scenario, it can be suggested that 2.81 *MeV* line (with red shift correction factor) is emitted due to $^{12}C(p,\gamma)^{13}N$ reaction. The product ^{13}N, being at 2.37 $MeV(\frac{1}{2}^+)$ excited level, when de-excited to the level $O\ MeV(\frac{1}{2}^-)$, E1 transition will be there. Flux of this γ-line to receive on earth from the three considered transient sources should be 4.05×10^{-3}, 9.33×10^{-4}, 4.49×10^{-4} photons $cm^{-2}s^{-1}$ respectively. The product nuclei ^{14}N, due to fusion reaction $^{13}C(p,\gamma)\,^{14}N$, are to emit lines with flux $\sim10^{-8}$ photons $cm^{-2}s^{-1}$ which is quite less intense to be detected. On the other hand, a 14.77 *MeV* line [de-excitation of ^{18}O from 12.44 $MeV\,(1^-)$ level to O $MeV\,(O^+)$ level ($E1$ transition)] should reach the earth with a detectable flux of 8.29×10^{-3}, 1.91×10^{-3}, 9.22×10^{-4} photons $cm^{-2}s^{-1}$ from the three considered sources respectively. Moreover, the excited ^{19}F can emit lines with energy 9.66 *MeV* [$M1$ transition from 8.14 *MeV* $(\frac{1}{2}^+)$ level to O $MeV(\frac{1}{2}^+)$ level], 9.53 *MeV* [$E1$ transition from 8.14 $MeV(\frac{1}{2}^+)$ to 0.11 $MeV(\frac{1}{2}^-)$], 7.82 *MeV* [$M1$ transition due to 8.14 $MeV(\frac{1}{2}^+)$ to 1.55 $MeV(\frac{3}{2}^+)$ level], 5.02 *MeV* [$M1$ transition due to 8.14 $MeV(\frac{1}{2}^+)$ to 3.91 $MeV(\frac{3}{2}^+)$], 2.61 *MeV* [M1 transition due to 8.14 $MeV(\frac{1}{2}^+)$ to 5.94 $MeV(\frac{1}{2}^+)$] and 2.23 *MeV* [$M1$ transition due to 8.14 $MeV(\frac{1}{2}^+)$ to 6.26 $MeV(\frac{1}{2}^+)$]. Due to non-availability of gamma-ray branching ratios from 8.14 MeV level of ^{19}F, 1/6th of flux of E1 and M1 transitions has been considered here. Thus the gamma-ray line intensity to reach the earth from the considered three sources through ^{19}F nuclei for each of the above lines are 3.7×10^{-3}, 8.52×10^{-4}, 4.1×10^{-4} photons $cm^{-2}\,s^{-1}$ respectively.

But as the lifetimes of these reactions are very very less (~ fractions of a second), only a very feeble chance is there to observe these lines. They may be observed only if the product nuclei are carried away within fractions of a second to a low density region which is transparent to γ-rays.

3. Case II -nova explosion

A model suggested by Starrfield (1978) has been considered to study the *CNOF, NeNa, MgAlSi* cyclic reactions during a nova explosion. These proton capturing reactions will yield $^{26}Al_g$ and ^{22}Na nuclei alongwith other nuclear burning products. According to

Starrfield, during the explosion, temperature of the envelope remains at about 2×10^8 K for 100 S. The model suggests ejected mass to be 2×10^{29} g which lasts for nearly 5 hours. Abundance by number $n_j(t)$ for $^{26}Al_g$ and ^{22}Na nuclei has been calculated out using Bateman equation during the outburst time (figure-5). Abundance calculation of these two nuclei have lead to the possibility that intensities of 1.809 *MeV* and 1.275 *MeV* γ-lines from a novae should be distinctly observed by a sophisticated spectrometer like SPI with high resolving power and high spatial resolution. Intensity I, of the lines to be detected at earth is given by –

$$I = \frac{n_j(t)}{d^2} \times 9.3206 \times 10^{-14} \text{ photons cm}^{-2}\text{s}^{-1} \qquad (4)$$

where, $n_j(t)$ is the no. density of the j^{th} product at time 't' in a nuclear chain reaction and 'd' is the distance in kpc of the novae sources. Calculated I for 1.809 *MeV* line has been found to be 4.27×10^{-4} photons $cm^{-2}s^{-1}$ for d = 5 kpc and for 1.275 *MeV* line to be 9.32×10^{-6} photons $cm^{-2}s^{-1}$ for d = 1 kpc at outburst time $\sim10^{-3}$s.

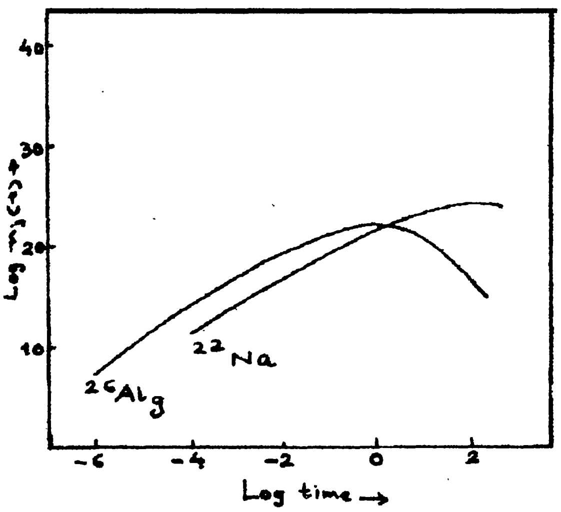


Figure 5. Variation of abundances by number $n_j(t)$ of ^{22}Na and $^{26}Al_g$ with time 't', during a nova outburst.

Consideration of different novae model and detail calculations will certainly result to simulate the actual picture of contribution of novae towards the galactic diffuse γ-lines. Though no γ-lines have been detected directly so far from any classical novae, yet it is hoped that these lines will be observed very soon by the long cherished mission of the scientific community i.e. the INTEGRAL.

References

Ajzenberg-Selove, F. (1990) Nucl. Phy. A. 506 : 1–158

Ajzenberg-Selove, F. (1991) Nucl. Phy. A. 523 : 1–196

Bardoloi, I. et al. (1995) 24th ICRC Papers, Rome, Italy, 2:263

Bardoloi, I. et al. (1996) Bull.Astro. Soc. India, 24 : 749

Bardoloi, I. et al. (1999) 26th ICRC Papers, Utah, USA 4 : 76

Endt, P.M. (1990) Nucl. Phy. A 521 : 1-830

Knodlseder, J. et al. (1995) 24th ICRC Papers, Rome, Italy 2:186

Mahoney, et al. (1982) Ap. J. 262 : 742–748

Mc Connell, M. et al. (1997) 25th ICRC Papers, Durban, 3 : 93

Oberlack, U. et al. (1995) 24th ICRC Papers, 2 : 207

Paul, J. (1999) 26th ICRC Papers, Utah, U.S.A. 5 : 144–147

Purcell, et al. (1995) 24th ICRC Papers, 2 : 211

Ramaty and Lingenfelter, (1977) Ap. J. 213 : L5–L7

Schonfelder, V (1999) ASP Conf. Series, Ed. R. Ramaty, et al. 171 : 217

Tanaka, Y. and N. Shibazaki (1996) Ann. Rev. Astron. Astrophys. 34 : 607.

Tilley, D.R. et al. (1993) Nucl. Phy. A 565 : 1–184

Tilley, D.R. et al. (1995) Nucl. Phy. A 595 : 1–170

Wallace, R.K., Woosley, S.E. and Weaver, T.A. (1982), Ap. J. 258 : 696