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Binary accreting neutron star as a source of x-ray transients – Aql X-1, Cen X-4, 1608-522

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Abstract. A thermonuclear model for x-ray transients has been considered to explain the observed characteristics of x-ray transient outbursts in Aql X-1, Cen X-4, 1608-522. The model is of a compact primary neutron star (NS) in a close binary system. When the secondary companion fills up the Roche-lobe, sometimes sudden rise of mass accretion is there onto the NS. When the accretion rate is quite high ($\sim 10^{-10}$ $M_\odot$ yr^{-1}), temperature and density increases up to $\sim 10^8$ K and $\sim 10^6$ g cm^{-3} respectively leading to thermonuclear flash. Using most recent proton capturing nuclear reaction rates and beta-decay rates, hydrogen burning cyclic reactions proceeding with seed nuclei C, O, Ne, Mg, have been studied and examined about energy generation during transient x-ray outburst time scale. Presently calculated values of energy production, luminosity etc. are found to tally well with the observed parameters. During x-ray outbursts, mass is ejected from the source. Abundances of the nuclei ($Z = 6 - 13$) in the ejected mass have been calculated and compared with the recently observed cosmic ray source composition. Moreover, probable gamma-ray (γ) line spectra radiated by the excited product nuclei have been studied.

Key Words : x-ray transient, H-burning, luminosity, abundances, gamma lines

1. Introduction

For more than two decades x-ray sky has been explored with the help of some ingenious devices such as Vella satellite, ROSAT, Ginga, Einstein, CGRO and most recently with the world's most powerful x-ray telescope Chandra. One of the different types of astronomical x-ray sources is x-ray transient. Some transients exhibit outbursts with soft x-ray spectrum, which are called "Soft X-ray Transients (SXT)". Though the cause of SXT outbursts is yet to be confirmed, it is suggested that in a close binary system, when companion dwarf stars fill up the Roche-lobe an accretion disk is formed. A sudden increase of mass accretion onto the compact object is the main cause for SXT outburst to occur (White et al. 1984; Tanaka and Shibazaki 1996; Rutledge et al. 1999). In our present work, thermonuclear model parameters for x-ray transients have been considered from dashed line curves in Figure 11b of Wallace, Woosley and Weaver, 1982 (hereinafter WWW, 1982). According to WWW's model, where they used KEPLER computer code, incorporating hydrodynamics and radiation transport, a 1.41 $M_\odot$ NS with radius 14.3 km has been considered as a source of SXT. The accreting matter from the companion dwarf consists of H (with mass fraction $X_H = 0.7$), He and a small fraction of heavy nuclei (with mass fraction $X_Z = 4 \times 10^{-5}$). One set of temperatures and densities prevailing in the hydrogen shell of the accreting NS is 1.4×10^8 K and 2.85×10^6 g cm^{-3} respectively with mass accretion rate $\dot{M} \sim 8.52 \times 10^{-11} M_\odot$ yr^{-1}. Under these conditions H burns stably and accumulated mass on the compact NS surface undergoes thermonuclear flash with soft x-ray spectrum emission. During an outburst x-ray intensity increases to $> 10^{37}$ ergs s^{-1} in the range 1-10 keV within several days and then declines to the quiescent level within several tens of days. The recurrent period generally ranges from less than a year to tens of years (WWW 1982; Walter H.G., Lewin et al. 1993; Tanaka and Shibazaki 1996).

In WWW, 1982, they calculated nuclear energy generation using a 19-isotope nuclear reaction network, considering also CNO cycle to explain a generalized x-ray transient event. In our present work, WWW's model parameters have been used with ofcourse recent modified reaction rates and considering all the three H-burning - extended CNOF, NeNa and MgAlSi cycles to interpret the SXT outburst parameters like luminosity, total energy, effective temperature etc. observed in Cen X-4, Aql X-1, 1608-522.

In sections 2 and 3 nuclear energy production under the considered scenario has been found out and compared with the observed parameters. In section 4 abundances of the product nuclei in the CNOF, NeNa, MaAlSi cycle reactions have been calculated out during outburst time. Section 6 gives the conclusion of the present study.

2. Hydrogen burning nucleosynthesis and energy production

Considering accreted heavy seed nuclei as C, O, Ne, Mg sharing heavy nuclei mass fraction ($X_z = 4 \times 10^{-5}$) equally, i.e $X_C = X_0 = X_{Ne} = X_{Mg} = 1 \times 10^{-5}$, any seed nuclei will capture proton at high temperature and density conditions and thermonuclear CNOF, NeNa, MgAlSi cyclic reactions (Figs 1-3) will occur. Updated rates collected through Internet (wherein some References are: Champagne, A. E. et al. 1992; Smith, M.S. et al. 1993; Wormer et al. 1994; Audi et al. 1997; Herndl et al. 1995) have been discussed.

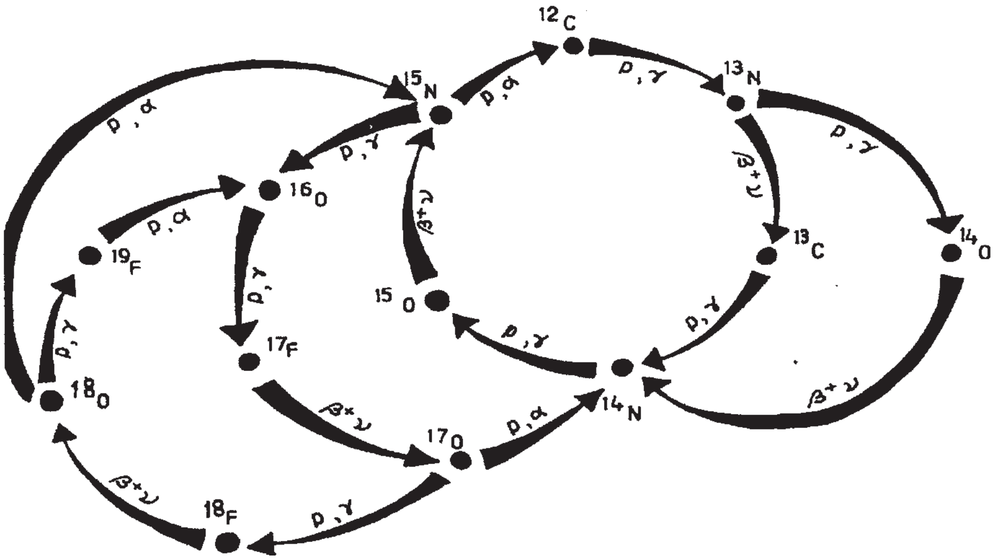

Figure 1. Extended CNOF cyclic reactions (original CN Cycle with cyclic reactions $^{12}C(p,\gamma)$ $^{13}N(\beta^+,\nu)$ $^{13}C(p,\gamma)$ $^{14}N(p,\gamma)$ $^{15}O(\beta^+,\nu)$ $^{15}N(p,\alpha)$ ^{12}C has some bifuractes through

(i) ^{13}N (p,γ) $^{14}O(\beta^+,\nu)$ ^{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

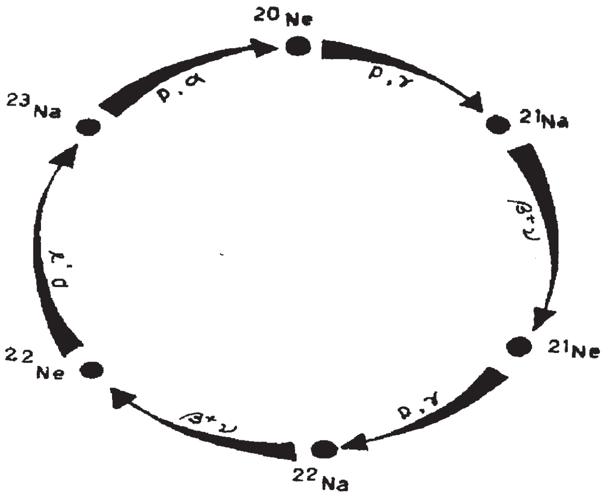

Figure2. NeNa Cycle with cyclic reactions $^{20}Ne(p,\gamma)^{21}Na(\beta^+,\nu)^{21}Ne(p,\gamma)^{22}Na(\beta^+,\nu)$ $^{22}Ne(p,\gamma)^{23}Na(p,\alpha)^{20}Ne$

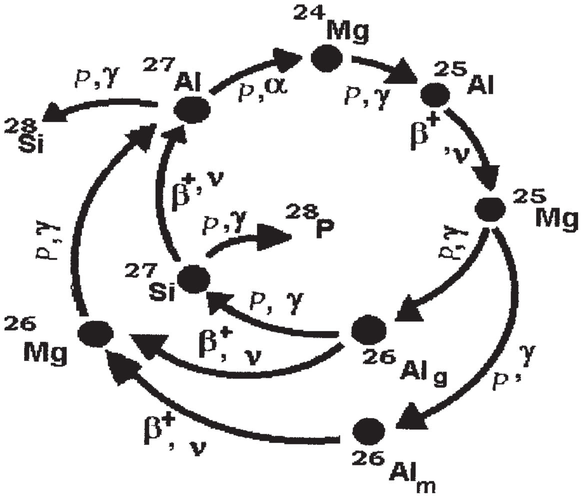

Figure 3. Extended MgAlSi cycle with reactions ^{24}Mg(p, γ)^{25}Al(β$^+$,ν)^{25}Mg(p, γ)^{26}Alg(p, γ)^{27}Si(β$^+$,ν) ^{27}Al(p, α)^{24}Mg with additional reactions
(i) ^{25}Mg(p, γ) ^{26}Alm(β$^+$,ν)^{26}Mg(p, γ)^{27}Al
(ii) ^{26}Alg(β$^+$,ν)^{26}Mg
(iii) ^{27}Si(p, γ)^{28}P (iv) ^{27}Al(p, γ)^{28}Si.

When two nuclei interact with each other, lifetime of the reaction between these two nuclei depends on temperature and density condition (Wiescher, 1998). Lifetimes for proton capturing reactions have been calculated out which is given by,

$$\text{Lifetime} = [\rho X_H\, N_A\langle\sigma v\rangle]^{-1}\ \text{sec.} \tag{1}$$

Where $N_A\langle\sigma v\rangle]$ is the reaction rate. If R_{12} represents the slowest reaction rate in a cycle, then nuclear energy generation rate due to H-burning cyclic reactions is given by,

$$E_{nuc} = \frac{QR_{12}}{\rho}\ \text{erg g}^{-1}\ \text{s}^{-1}$$

$$E_{nuc} = \frac{Q\rho N_A}{A_1A_2}[N_A\langle\sigma v\rangle\ X_H\ X_Z]\ \text{erg g}^{-1}\ \text{s}^{-1} \tag{2}$$

where A_1, A_2 are the mass numbers of the reacting nuclei of the slowest in a chain of reactions, Q is the total disintegration energy in a cycle which is about 26 MeV, since a part of it is carried away by neutrions. It is found that ^{16}O(p,γ) ^{17}F is the slowest among the CNOF reactions with lifetime 0.213s. Contribution of CNOF towards E_{nuc} is 1.38 x 10^{14} erg g^{-1} s^{-1}. In the NeNa [MgAlSi] cycle, ^{20}Ne(p,γ) ^{21}Na [^{27}Si (p,γ) ^{28}P] is the slowest one with lifetime 4.39s [0.77 s]; generating energy 1.39 x 10^{12} erg g^{-1} s^{-1} [1.20 x 10^{13} erg g^{-1} s^{-1}], resulting net $E_{nuc} = (E_{nuc})_{net}$ = 1.51 x 10^{14} erg g^{-1} s^{-1}.

When mass accretion rate is $\dot{M}$(g s^{-1}) and t_i is the time interval between two out bursts total mass of the accreted matter is $\dot{M}(=\dot{M}t_i)$. Energy radiated per second i.e. luminosity L and the total energy generated is given by

$$L = M(E_{nuc})_{net} \text{ erg s}^{-1} \tag{3}$$

$$E_{total} = L\, t_r \text{ erg} \tag{4}$$

where t_r is the rise time of luminosity reaching up to the maximum value. The generated nuclear energy is thermalised as it is transmitted to the neutron star photosphere and the effective temperature, T_{eff} is given by,

$$T_{eff} = \left[\frac{L}{4\pi R^2 \sigma}\right]^{1/4} \tag{5}$$

where R is the radius of the NS and σ is the Stefan-Boltzmann constant.

3. Comparison between the present work and observed parameters of SXT outbursts in Cen X-4, Aql X-1, 1608-522

Some of the observed characteristics of SXT outbursts are luminosity L, effective temperature T_{eff} average luminosity (L_{av}). L_{av} is given by -

$$L_{av} = \frac{E_{total}}{\text{Time interval between two outbursts}} \tag{6}$$

These characteristics have been evaluated for Cen X-4, Aql X-1 and 1608-522 and compared with observed values of these sources collected through Tanaka and Shibazaki 1996. It has been found that considering the observed time interval t_i between two outbursts, calculated L, E_{total}, T_{eff} and L_{av} are found to tally very well with the observed values for all the three sources (Table 1).

Table 1. Comparison between calculated values of L, E_{total}, T_{eff} and L_{av} with that of observed ones of sources Cen X-4, Aql X-1, 1608-522.

1. SOURCE : Cen X-4

Parameters	Time Interval between two outbursts t_i	Luminosity L (erg s^{-1})	Rise time t_r (days)	Total energy E_{total} (erg)	Effective Temperature T_{eff} (keV)	Average Luminosity L_{av} (erg s^{-1})
Observed Values	10 years	~ 10 (38) for a distance of d=1.2kpc	few days	3(44) in 1969 outburst; .3(44) in 1979 outburst	1 to 10	1.4(35) in 1969 outburst; 1.0(35) in 1979 outburst
In present work	10 years (considered)	2.55(38) (calculated)	5 days (considered)	1.09 (44), (considered)	1.76 (calculated)	3.46 (35) (calculated)

Table contd...

2. SOURCE : Aql X-1

Parameters	Time Interval between two outbursts t_i	Luminosity L (erg s^{-1})	Rise time t_r (days)	Total energy E_{total} (erg)	Effective Temperature T_{eff} (keV)	Average Luminosity L_{av} (erg s^{-1})
Observed values	1 year	~2 (37) for d = 2.5 kpc; ~1 (36) in 1997 outburst for d=2.5-2.3 kpc	5 days	1 to 5 (43)	1 to 10	3.0 (35)
In present Work	1 years (considered)	2.55 (37), (calculated)	5 days (Considered)	1.09 (43), (considered)	1.01 (calculated)	3.46 (35) (calculated)
3. SOURCE : 1608-522						
Observed values	~ 6 months	~ 4 (37)	> 10 days	1 (43-44)	1 to 10	2 (36)
In present work	6 months (considered)	1.27 (37) (calculated)	12 days (Considered)	1.33 (43) (considered)	0.83 (calculated)	2.10 (36) (calculated)

Numbers within brackets give powers of 10.

4. Nuclei abundance distribution during mass ejection

Elemental and isotopic abundances of the product nuclei in the network of CNOF, NeNa, MgAlSi cycles have been determined using a Bateman Equation (Duorah 1976) during outburst rise time. Bateman equation gives the abundance by number density of the j^{th} product (j = 1,2,3..................j) in a radioactive chain reactions, which is given by,

$$N_j(t) = N_o[h_{1j}\, e^{-\lambda_1 t} + h_{2j}\, e^{-\lambda_2 t} + ... + h_{ij}\, e^{-\lambda_j t}] = N_o \overset{j}{\underset{i=1}{O}} h_{ij}\, e^{-\lambda_i t} \tag{7}$$

In the equation, N_o is the initial abundance of the seed nuclei and is given by,

$$N_o = \frac{\rho X'_Z N_A}{A} \tag{8}$$

Here X'_Z is the mass fraction of the seed nuclei in a chain reaction at time t = 0, N_A is the Avogradro's number, A is the mass number of the nucleus, h_{ij} s are given by,

$$h_{ij} = \overset{j-1}{\underset{k=1}{\mathrm{II}}} \lambda_k \,/\, \overset{j}{\underset{\substack{m=1\\ m\neq i}}{\mathrm{II}}} (\lambda_m - \lambda_i) \tag{9}$$

where λs are the reaction probabilities which are inverse of life times. To explain the calculational method in detail, if there be only three numbers of nuclei in a certain set of chain reaction, then j = 3. So, number density of consecutive nuclei at different times 't' are given by,

$$N_1 = N_o e^{-\lambda_1 t} \tag{10}$$

$$N_2 = N_o(h_{12}e^{-\lambda_1 t} + h_{22}e^{-\lambda_2 t}) \tag{11}$$

$$N_3 = N_o(h_{13}e^{-\lambda_1 t} + h_{23}e^{-\lambda_2 t} + h_{33}e^{-\lambda_3 t} \tag{12}$$

Again using equation (9), h_{ij}'s for j = 3 and i = 1 ....j i.e. i = 1,2,3 are given by,

$$h_{12} = \frac{\lambda_1}{\lambda_2 - \lambda_1} \tag{13}$$

$$h_{22} = \frac{\lambda_1}{\lambda_1 - \lambda_2} \tag{14}$$

$$h_{23} = \frac{\lambda_1\lambda_2}{(\lambda_1 - \lambda_2)\ (\lambda_3 - \lambda_2)} \tag{15}$$

$$h_{33} = \frac{\lambda_1\lambda_2}{(\lambda_1 - \lambda_3)\ (\lambda_2 - \lambda_3)} \qquad 16)$$

Thus putting different values for j, abundance by number density of the jth products in any chain reaction can be determined. As original CNO and MgAl cycles have some additional branching reactions (figs 1-3) and leakages which have important influence on abundance distribution, branching ratios have to be considered. Branching ratio for a pair of reaction is the ratio of life times of those two reactions at a particular temperature and density (table 2) (Bardoloi, 1988). In extended CNOF cycle, though on ^{12}C there is no effect of branching or leakage, but on other nuclei there is much effect. As for example, in case of ^{15}N nucleus, we have considered effects due to bifurcation of ^{13}N through (β^+,ν) and (p,γ) reactions. In case of

Table 2. Branching ratios for pairs of reactions at $\rho = 2.85 \times 10^6$ g cm^{-3} for $T = 1.4 \times 10^8$ K.

Pairs of Reactions	$\frac{^{13}N(p,\gamma)^{14}O}{^{13}N(\beta^+,\nu)^{13}C}$	$\frac{^{15}N(p,\alpha)^{12}C}{^{15}N(p,\gamma)^{16}O}$	$\frac{^{17}O(p,\gamma)^{18}F}{^{17}O(p,\alpha)^{14}N}$	$\frac{^{18}O(p,\alpha)^{15}N}{^{18}O(p,\gamma)^{19}F}$
Branching ratio	1.655 (-5)	6.62 (-4)	8.79 (-1)	6.12 (-3)
Pairs of Reaction	$\frac{^{25}Mg(p,\gamma)^{26}Al_g}{^{25}Mg(\beta^+,\nu)^{26}Al_m}$	$\frac{^{27}Si(p,\gamma)^{28}P}{^{27}Si(\beta^+,\nu)^{27}Al}$	$\frac{^{27}Al(p,\alpha)^{24}Mg}{^{27}Al(p,\gamma)^{28}Si}$	$\frac{^{26}Al_m(\beta^+,\nu)^{26}Mg}{^{26}Al_m(p,\gamma)^{27}Si}$
Branching ratio	2.50 (-1)	1.29 (-1)	2.14 (-1)	1.07 (-2)

Numbers within brackets give powers of 10.

^{16}O we have considered the initial abundance ($X_o = 1 \times 10^{-5}$) over and above its production in the chain reaction starting from ^{12}C. For the product nuclei after ^{16}O, branching at ^{17}O, ^{18}O, though (p,γ), (p,α) reactions have been considered. Again in case of MgAlSi, network, except for ^{24}Mg and ^{25}Al, abundances of other product nuclei are largely affected due to branching at ^{25}Mg, ^{26}Alg, ^{27}Si, ^{27}Al. Computer assisted solutions of all the above equations for the three cycles give the number density N of different nuclei at different times in Fig. 4 (i–v). During outburst the star loses its mass when L remains near Eddington value (L_{edd}). L_{edd} is given by,

$$L_{edd} = 4\pi GMc \ / \ K_{es} \ \text{erg s}^{-1} = 2.5 \times 10^{38} \ (0.2 \ / \ K_{es}) \ (M \ / \ M_{\odot}) \ \text{erg s}^{-1} \qquad (18)$$

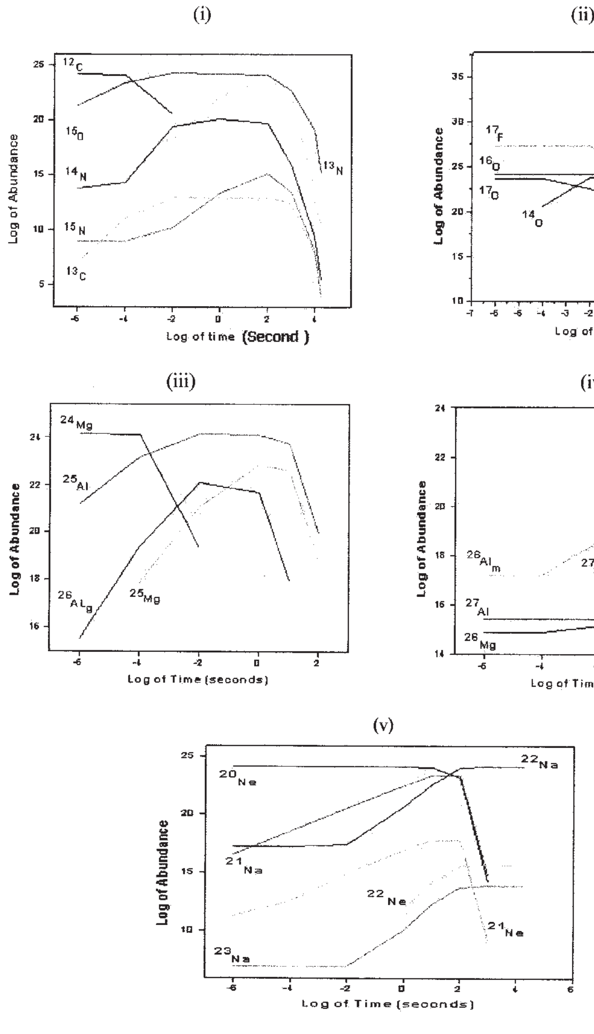

Figure 4. (i–v) Log of abundance of different nuclei vs. log of time.

Considering the electron scattering opacity K_{es} which is equal to 0.33 for $X_H = 0.7$ (Bodenheimer et al., 1965), L_{edd} is 2.12 x 10^{38} ergs s^{-1} for a NS of mass 1.41 $M_{\odot}$. As L_{edd} is approximately equal to L of the three considered sources material will be ejected into inter stellar matter (ISM) at the rate of ~ 10^{18} g s^{-1} with a velocity comparable to escape velocity. If ejected mass is not trapped in the magnetosphere, these can contribute to low energy (~100 MeV) cosmic radiation (WWW, 1982). So, abundances of the product nuclei (Z = 6-13) have been compared to observations by CRRES mission, HET observations on Ulysses Space Craft (Connell and Simpson, 1997; Du vernois et al., 1996; Lukasiak et al. 1994). All isotopic ratios except for $^{17}O/^{16}O$, $^{18}O/^{16}O$ are found to be many orders of magnitude higher than the presently calculated values (Table 3).

Table 3. Isotopic abundance ratios in the NS SXT outburst ejecta and comparison with measured cosmic ray source abundance.

Isotopic Ratios of	In the Ejected Mass (Calculated value)	Measured in the space Missions
^{12}C / ^{12}C	3.53 (-12)	3.1 (-3) (Lukasiak, 1993)
^{15}N / ^{14}N	5.71 (-6)	4.98 (-1) (Connell & Simpson, 1997)
^{14}N / ^{16}O	1.76 (-5)	1.23 (-1) (Lukasiak, 1994)
^{15}N / ^{16}O	1.13 (-10)	1.65 (-1) (Lukasiak, 1994)
^{17}O / ^{16}O	1.51 (-1)	1.0 (-1) (Connell & Simpson, 1997)
^{18}O / ^{16}O	3.89 (1)	1.5 (-2) (Lukasiak, 1994; Connel & Simpson, 1997)
^{21}Ne / ^{20}Ne	1.62 (-7)	2.3 (-1) (Connell & Simpson, 1997)
^{22}Ne / ^{20}Ne	2.74 (-8)	5.9 (-1) (Connell & Simpson, 1997)
^{25}Mg / ^{24}Mg	4.0 (-2)	2.0 (-1) (Connell & Simpson, 1997)
^{26}Mg / ^{24}Mg	2.04 (-4)	2.3 (-1) (Connell & Simpson, 1997)

Numbers within brackets give powers of 10.

5. Probable gamma ray line spectrum

Comparison between the predicted and observed emission line spectra from an astronomical object and diffuse galactic γ-ray lines can indicate chemical as well as physical properties of the nucleosynthesis sites where the γ-emitter nuclei are produced (Wiescher, 1998; Mc Connell et al. 1997; Knodlseder et al. 1995; Bardoloi et al., 1996, 2002; Mahoney et al., 1982; Ramaty and Lingenfelter, 1977). These γ-lines with energy 0.5 - 15 MeV have been interpreted as due to positron-electron annihilation and decay or de-excitation of the excited nuclei produced in some explosive sites and then ejected into ISM (Durouchoux and Sap, 1986).

In our already published (Bardoloi and Baruah, 2002) we tried to find out whether the ejected material can emit gamma lines with observable intensites. 2.81 MeV line is expected due to deexcitation of ^{13}N with flux received on earth from the three sources Cen X-4, Aql X-1, 1608-522 to be 4.05×10^{-3}, 9.33×10^{-4}, 4.49×10^{-4} photons cm^{-2} s^{-1} respectively. A 14.77 MeV line due to de-excitation of ^{16}O, 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, calculated 1.809 MeV line intensity due to β^+ - decay of $^{26}Al_g$ to ^{26}Mg is 1.93×10^{-5}, 4.43×10^{-6}, 2.14×10^{-6} photons cm^{-2} s^{-1} from Cen X-4, Aql X-1, 1608-522 respectively. Intensity of 1.275 MeV line due to β^+ -decay of ^{22}Na from the three sources are 3.47×10^{-3}, 7.99×10^{-4}, 3.85×10^{-4} photons cm^{-2} s^{-1}, suggesting the considered SXT sources to be good candidates for observing astronomical γ- lines.

6. Conclusion

From our study and comparing with recently observed data we can conclude that – (i) The three S X T sources Cen X-4, Aql X-1, 1608-522 are accreting NS of mass 1.41 $M_\odot$ and radius 14.3 km, in a close binary system. The accretion is from the accreting disk in a hot state with accretion rate $\dot{M}$ ~5.45×10^{15} g s^{-1}.

(ii) The proton capturing CNOF, NeNa, MgAlSi cyclic reactions can contribute well to energy production in those transients at temperature $T_9 = 0.14$ and density = 2.85×10^6 g cm^{-3} with T_{eff} in the range ~ 1-2 keV.

(iii) Though earlier it was suggested that the ejection from SXT may contribute to cosmic ray isotopic distribution (Wallace, Woosley and Weaver, 1982) but Cen X-4, Aql X-1, 1608-522 are found to be not a good contributor towards cosmic - ray isotopic abundance.

(iv) It can be suggested that Cen X-4, Aql X-1, 1608-522 are emitters of γ-ray lines with intensities in observable range which we hope will be observed with the sophisticated instruments on board the space missions in near future.

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