Contribution of Proton Capture Reactions to the Abundances of Phosphorus and Sulfur in FGK Stars

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Abstract

Elemental abundance pattern is one of the key components which gives clues for understanding not only the cluster formation but also the chemical evolution. But the origin of the abundance pattern is yet to be completely perceived. In this study, we carried out the impact of p-capture reaction cycles on the abundances of Phosphorus (P) and Sulfur (S) considering nuclear burning cycles of PCl in stars of temperature range 0.1×10^9 to 0.7×10^9 K and density of 10^2 $gmcc^{-1}$. Such kind temperature density situations are going to be dominant within the H-burning shell of evolved stars. We have estimated abundances of P and S in 22 FGK dwarfs and giants that span $-0.55 < [Fe/H] < 0.2$. We observe an excellent agreement of [P/Fe] and [S/Fe] between the estimated and observed abundance values with a correlation coefficient above 0.7 and above 0.8 respectively for all 22 FGK stars.

Introduction

- Stars evolve because of changes in their composition (the abundance of their constituent elements) over their lifespans, first by burning hydrogen (main-sequence star), then helium (horizontal branch star), and progressively burning higher elements. However, this does not by itself significantly alter the abundance of elements in the observable universe as the elements are contained within the star (Faulkner 2014).
- A low-mass star will slowly eject its atmosphere via stellar wind, forming a planetary nebula, while a higher–mass star will eject mass via a sudden catastrophic event called a supernova.
- The principle of astrophysics tells us that the universe had a beginning, hence whatever the present abundance that we observe, the condition for that must be present in the early universe as well as in the stars.

Introduction Contd.

- For the study of galactic chemical evolution and nucleosynthesis, the study of light elements abundances (Carbon to Argon) is important. It has been used to learn the differences of the Galactic structure, populations in stellar clusters. Nomoto et al. 2013 have been studied in detail the nucleosynthesis in massive stars including elements O, Mg, Si, S, and Ca.
- The O, Na, Al abundances in the fast-rotating massive star at high temperature and low density have been studied for sample stars of Globular Cluster (GC) M3, M4, M13 and NGC6752 with a correlation coefficient above 0.7 (Mahanta et al. 2017).
- In the context of hydrostatic burning of events, even elements are well understood along with chemical evolution models, successfully predicting observed abundance trends (Nomoto et al. 2013). However, the odd elements are thought to be produced via other mechanism and there are few abundances exist for elements such as P and Cl (Nomoto et al. 2013). Maas et al. 2017 presented the spectroscopic analysis of odd elements such as P and Cl abundances distributions

Introduction Contd.

- Phosphorus has only one stable isotope, ^{31}P, and is reported to be produced mostly in stars through proton capture on Si isotopes, in hydrostatic carbon and neon burning shells (Ross., J. G. et al. 1995).

- Phosphorus & Chlorine abundances have been observed using PCl cycle reaction sequences of (p,γ) reactions and β decays are then closed by a (p,α) reaction for the temperature range $T = 0.1\ to\ 0.7$ GK for 22 FGK dwarfs and giants stars that span $-0.55 <$ $[Fe/H] < 0.2$.

Basic Physical Situation

- Stars are consider to be isolated.
- Equilibrium in abundance is attained.
- The canonical model of stellar evolution focuses on the dominant role of various levels of nuclear burning in the stellar core. Not only is the temperature but density also plays a crucial role in any stellar scenario. Even though the density ranges over many orders of magnitude, its response to the burning rates is only linear and hence its importance is much less significant as far as elemental synthesis is concerned until a low temperature and high-density scenario are dominant. By some physical mechanisms like convection or by dredging up, the materials are synthesized within the inner regions close to the core and are brought to the surface. In this model, the stars are assumed to be spherically symmetrical with no magnetic field, no rotation and no mass loss from the surface. The method of convection is the only mixing mechanism working in the convective areas, which are continually fully mixed (Salaris et al. 2002).

Methodology

- At temperature, 0.1 to 0.7 GK and density, 100 gm/cc, the $^{31}P(p,\gamma)\,^{32}S$ can compete with p-p reaction and can initiate the Phosphorus Chlorine (PCl) burning mechanism (Iliadis et al. 1994).
- The PCl cycle –

Temperature Range 0.1 to 0.3 GK

$$^{31}P + p \rightarrow ^{32}S + \gamma$$
$$^{32}S + p \rightarrow ^{33}Cl + \gamma$$
$$^{33}Cl + p \rightarrow ^{34}Ar + \gamma$$
$$^{34}Ar \rightarrow ^{34}Cl + \beta^+ + \nu_e$$
$$\underline{^{34}Cl \rightarrow ^{34}S + \beta^+ + \nu_e}$$
$$^{34}S + p \rightarrow ^{35}Cl + \gamma$$
$$^{35}Cl + p \rightarrow ^{32}S + \alpha$$

Temperature range 0.35 to 0.65 GK

$$^{31}P + p \rightarrow ^{32}S + \gamma$$
$$^{32}S + p \rightarrow ^{33}Cl + \gamma$$
$$^{33}Cl + p \rightarrow ^{34}Ar + \gamma$$
$$^{34}Ar \rightarrow ^{34}Cl + \beta^+ + \nu_e$$
$$\underline{^{34}Cl + p \rightarrow ^{35}Ar + \gamma}$$
$$^{35}Ar \rightarrow ^{35}Cl + \beta^+ + \nu_e$$
$$^{35}Cl + p \rightarrow ^{32}S + \alpha$$

Methodology Contd.

- The generalized equation that governs the evolution of elements via a proton capture reaction or beta decay is given by Clayton 1983 –

$$\frac{dN_i}{dt} = -N_i N_H < \sigma\nu >_{p,i} + N_j N_H < \sigma\nu >_{H,j} \pm \lambda_k N_k \quad (1)$$

Where, N is the number density, $< \sigma\nu >$ is the reaction rate constant & λ_k is the decay constant of an unstable nucleus with number density N_k.

Methodology Contd.

- In terms of mass fraction, the time evolution of any element present in the cycle is given by the following equation:

$$\dot{X}_i = \left[-R_{p,i} X_i X_p \rho + \frac{A_i}{A_j} R_{p,j} X_j X_p \rho \right] \tag{2}$$

R_ps are $[N_A < \rho\nu >]$ terms for respective proton capture reactions of i-th and j-th element and A_i and A_j stands or the mass number of the same two nuclei involved in the cycle.

- Now the above equation can be expressed as a function of the hydrogen mass fraction to get a series of first order simultaneous linear differential equations for each cycle as –

$$\frac{dX_i}{dX_{\mathrm{H}}} = \frac{\left(-R_{p,i} X_i + \frac{A_i}{A_j} R_{p,j} X_j \right)}{\left[-\sum_{A_i}^{A_j} \left(\frac{1}{A_i} R_{p,i} X_i \right) \right]} \tag{3}$$

Methodology Contd.

- The Abundance by a mass fraction can be obtained for any stable element (x) with respect to Fe using the following expression –

$$\left[\frac{x}{Fe}\right] = \left[\frac{x}{H}\right] - \left[\frac{Fe}{H}\right] \tag{4}$$

Here, $\left[\frac{x}{H}\right] = \log\left[\frac{N_x}{N_H}\right]_{Star} - \log\left[\frac{N_x}{N_H}\right]_{Sun}$

And, $\left[\frac{Fe}{H}\right] = \log\left[\frac{N_{Fe}}{N_H}\right]_{Star} - \log\left[\frac{N_{Fe}}{N_H}\right]_{Sun}$

Now, the abundance will be calculated using the following equation -

$$\varepsilon(x) = \left[\frac{x}{Fe}\right] + \left[\frac{Fe}{H}\right] + 6.17 \tag{5}$$

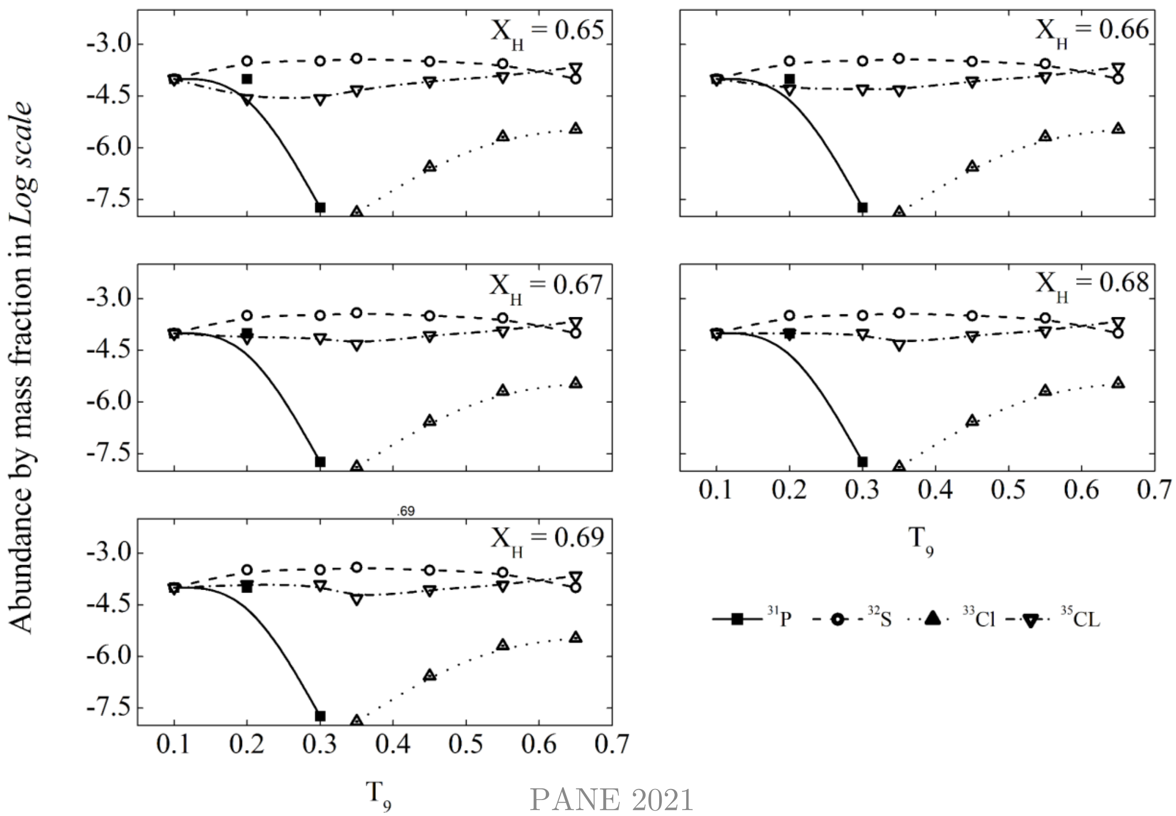
Calculation & Results

- From equation (2) after converting into the format of equation (3) which are basically nothing but five simultaneous linear first order differential equations, then solved numerically using computer software for the cycle varying the hydrogen mass fraction to $X_H = 0.65$ to get the equilibrium mass fraction abundances. We assume that the heavy elements mass fraction has been shared equally. Thus starting with the initial condition to be as the universal one, i.e. $X_H = 0.70, X_{He} = 0.2995, X_{he} = 0.0005$ such that

$$X_H + X_{He} + X_{he} = 1$$

Calculation & Results Contd.

- The abundance shown as a function of temperature (T_9) at different hydrogen mass fractions



Calculation & Results Contd.

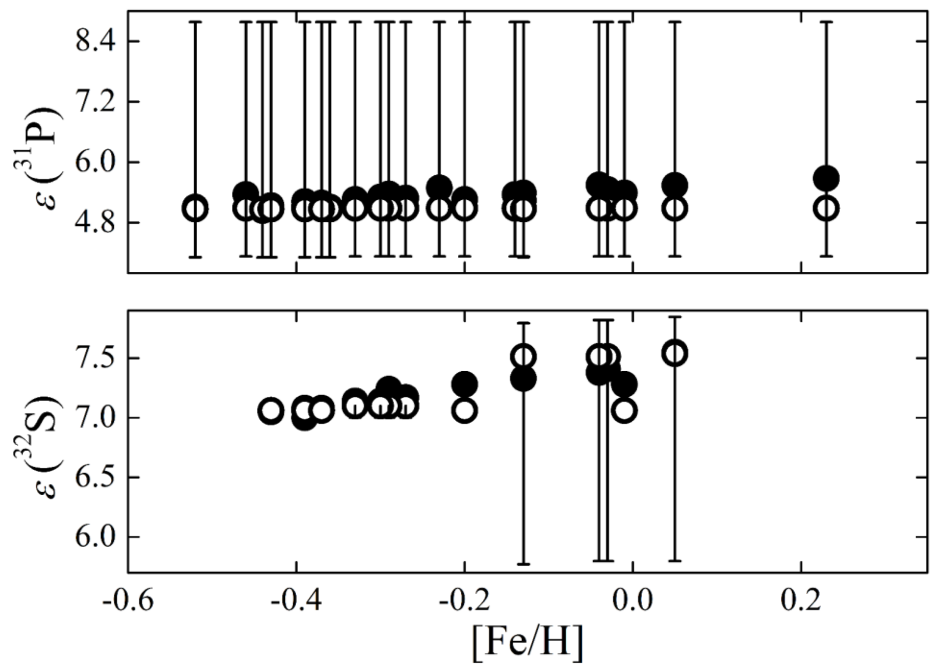
- **Table 1** The Estimated Abundance Ratios of [P/Fe] and [S/Fe]

Star	**[Fe/H]**	$\epsilon(^{31}P)^a$	$\epsilon(^{32}S)^a$	$\epsilon(^{31}P)^o$	$\epsilon(^{32}S)^o$
HD 20794	-0.46	5.36	...	5.08	...
HD 46114	-0.44	5.04	...	5.06	...
HD 107950	-0.13	5.39	...	5.08	...
HD 120136	0.23	5.68	...	5.08	...
HD 121560	-0.39	5.14	7.00	5.07	7.06
HD 124819	-0.27	5.29	7.17	5.08	7.09
HD 124897	-0.52	5.11	...	5.07	...
HD 126053	-0.36	5.11	...	5.07	...
HD 136925	-0.29	5.37	7.24	5.08	7.09
HD 140324	-0.30	5.31	7.14	5.08	7.09
HD 148049	-0.33	5.26	7.14	5.08	7.09
HD 151101	-0.14	5.36	...	5.08	...
HD 152449	-0.03	5.46	7.41	5.08	7.51
HD 160507	-0.23	5.49	...	5.08	...
HD 163363	-0.04	5.55	7.38	5.08	7.51
HD 167588	-0.39	5.22	7.08	5.07	7.06
HD 174160	-0.01	5.39	7.28	5.08	7.06
HD 186379	-0.37	5.19	7.08	5.07	7.06
HD 186408	0.05	5.54	7.55	5.08	7.53
HD 191649	-0.20	5.26	7.28	5.08	7.06
HD 193664	-0.13	5.24	7.33	5.07	7.51
HD 194497	-0.43	5.14	7.05	5.07	7.06

[a] Maas, Z. G. et al. 2017
[o] This work

Calculation & Results Contd.

- A comparison between the calculated and observed abundance ratios of [P/Fe] and [S/Fe]. The data points are taken from Table 1.



Here open circles mean "this work" and solid circles mean Maas, Z. G. et al. 2017

Discussion

- Hydrogen (H) & some amount of Helium (He) is only the abundant elements that were present at the beginning of the universe. In the early '90s, the uneven distribution of elements was confirmed by the COBE satellite that under the influence of gravity they began to "clump" to form more concentrated volumes. These clumps would eventually form galaxies and stars. Studies on metal-poor stars have advanced significantly over the past decades. Despite several efforts to understand their formation mechanisms, numerous questions remain as to the nucleosynthetic histories and astrophysical sites related to the production of those classes of objects. In this work, we studied the distribution and production mechanisms of light and heavy elements in metal-poor stars.

Discussion Contd.

- We tend to propose a reaction network of a nuclear cycle at evolved stellar circumstances because Phosphorus (^{31}P) & Sulfur (^{32}S) are such elements that get plagued by proton capture reactions. The stellar temperature thought about here ranges from 0.1 to 0.7 GK and there has been an accretion going on, with material density being 100 gm/cc.

- Such type of temperature density conditions is likely going to be prevailing inside the H-burning shell of evolved stars.

- We have taken the PCl cycle to explain the abundance of Phosphorus & Sulfur which are observed in metal-poor FGK stars. Here we find a strong correlation between the observed & estimated Phosphorus & Sulfur abundance within the framework of the evolutionary scenario.

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