A chemical abundance analysis of P-rich star candidates

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Abstract

In this memory will be analysed the work done on the spectra of 39 stars to determine if they can be included in the group of the P-rich stars, stars whose abundance of phosphorus is higher than average.

These stars are very important in order to explain the origin of the phosphorus found in our galaxy, currently underpredicted by chemical evolution models. On the other hand, last year were released an article that, analysing data from the APOGEE survey, presents the discovery of the existence of stars with an abundance of P higher than normal, called P-rich [1]. In a second work, were shown 39 stars with anomalies in their composition.[2] This project had as objective to determine if these 39 stars were P-rich and if they presented a correlation between P and other elements (O,Mg, Al,Si and Ce). To do this we used the data, provided by the APOGEE database, of the stars studied (H-band spectra, effective temperature, surface gravity and abundance of carbon, nitrogen and alpha elements, among others) as initial data of the spectral synthesis code BACCHUS, which provided the abundance of phosphorus and cerium of these stars. We found that 37 stars (∼90%) are very rich in P ([P/Fe]>=1 dex) and rich in Ce ([Ce/Fe]>0 dex). Then, we compared the P and Ce abundances with those from other elements as well as with those observed in other stars with similar atmospheric parameters. We found that there is indeed the possibility of a correlation between phosphorous and oxyge, as well between O and Si and between Al and Mg.

Keywords: phosphorus - abundance - stellar spectrum - cerium

Resumen

En esta memoria se analizará el trabajo realizado sobre los espectros de 39 estrellas para determinar si pueden incluirse en el grupo de estrellas P-rich, estrellas cuya abundancia de fósforo es superior a la media.

Estas estrellas son muy importantes para explicar el origen del fósforo que se encuentra en nuestra galaxia, actualmente infraprevisto por los modelos de evolución química. Por el otro lado, el año pasado se publicó un artículo que, analizando datos de la encuesta APOGEE, presenta el descubrimiento la existencia de estrellas con una abundancia de P más alta de lo normal, llamada P-rica [1]. En un segundo trabajo, fueron mostradas 39 estrellas con anomalías en su composición. [2] Este proyecto tuvo como objetivo determinar si estas 39 estrellas eran ricas en P y si presentaban una correlación entre P y otros elementos (O,Mg, Al,Si y Ce). Para ello se utilizaron los datos, proporcionados por la base de datos APOGEE, de las estrellas estudiadas (espectros de banda H, temperatura efectiva, gravedad superficial y abundancia de carbono, nitrógeno y elementos alfa, entre otros) como datos iniciales del código de síntesis espectral BACCHUS, que proporcionó la abundancia de fósforo y cerio de estas estrellas. Encontramos que 37 estrellas (∼90%) son muy ricas en P ([P/Fe]>=1 dex) y ricas en Ce ([Ce/Fe]>0 dex). Luego, comparamos las abundancias P y Ce con las de otros elementos, así como con las observadas en otras estrellas con parámetros atmosféricos similares. Encontramos que efectivamente existe la posibilidad de una correlación entre fósforo y oxigeno, así como entre O y Si y entre Al y Mg.

Palabras claves: estrellas - fósforo - abundancia - espectro estelar - cerio

Contents

1 Introduction

The atoms of the elements that make up matter are created in the nucleus of stars thanks to the nuclear fusion that takes place inside them, and then are released into outer space when the stars reach the end of their lives. This creation of these atoms is called stellar nucleosynthesis.

There are different types of nucleosynthesis process, but two of the most important to this research are the s-process and the r-process.

The slow neutron-capture process, or s-process, where a nucleus undergoes a series of neutron capture to form an isotope of the atom with the successive atomic number. If the isotope is stable, other neutron captures can occur. If is unstable, a beta decay will occur and the atomic number will increase a second time. The process is called slow because there is enough time between two neutron capture to allow a nucleus to undergo beta decay. This is due to the fact that the s-process occurs in stars with a low number of neutrons. The s-process, that occurs during thousands of years, creates half of the atoms heavier than iron.

The rapid neutron-capture process, or r-process, creates the other half. This process is called rapid because the time between neutron captures have to be so short to don't allow the nuclei undergo beta decay. To make this possible, the r-process only can occur in stars with an high density of neutron. The oxygen-burning phase creates energy combining two atoms of oxygen. As result, this process creates some atoms lighter than iron (Si, P, Mg)

However, although the models underlying the theory of these processes have been proved right several times, all of them underestimate the amount of one atom observed in our Galaxy: phosphorous, one of the elements indispensables to life, mainly because is the major component of DNA. Phosphorous is also the ingredient of life with the lowest abundances, but not as low as the actual chemical evolution models predict. In fact, Galactic chemical evolution models predict lower quantities of P than observed, highlighting that the stellar source of P is underestimated by the models or even possibly unknown. Until recent times, searching for this source of P was nearly impossible because P lines are inherently weak and located in near-IR and UV spectral range, two optical range where the observation is osculated by the Earth atmosphere.

On the other hand, 16 low mass red giant stars ($\sim$ 1 solar mass) have recently been identified by Masseron et al. (2020) to have an abnormally high amount of phosphorus (so-called P-rich stars), as well as other light and heavy elements, like O, Si, Mg, Al and Ce, and whose chemical abundance pattern cannot be explained by the current models of stellar nucleosynthesis [1][3]. These stars can be the source of phosphorus that the models are lacking. The abundances of these P-rich stars are more like those in which nucleosynthesis occurs through the s-process, but with some glaring differences such as a higher Ba/La ratio and a lower amount of Eu and Pb [1][3]. In this TFG, we consider the stars to be P-rich when they show a relative abundance [P/Fe] equal or greater than 1 dex.

Several hypothesis were made to explain this anomaly.

It was supposed that the anomaly quantity of phosphorous was due to the action of an invisible companion star, from which the P-rich accreted its materials. However this process is associated with a change in radial velocity to maintain constant the angular momentum, but such change were never seen. For this reason the idea of a binary system was ruled out.

Other possibility is that the P-rich could be the product of the merging process of two stars which doesn't result in a change in velocity, but due to the nature of the elements found in the P-rich, the stars should be brighter than the ones observed or extinct.

It was supposed that this stars could be post-AGB stars and the phosphorous could seems enhanced because others elements have condensed into dust, but P-rich are not bright as post-AGB and some of the elements that normally form the dust and should be depleted (Si, Al, Ni and Ca) can be find in the P-rich.

Finally, as said before, the s-process can't explain the high abundance of Barium and the low abundance of Europium, but it can't explained neither with the r-process [Nature].

So, these stars produce more P than they should do in a way that we don't understand but they are, possibly, also the only explanation to the fact that in our Galaxy there is three times the phosphorous predicted by the models.

In this work we analysed the spectra of 39 P-rich star candidates, listed in the article "Jurassic: A Chemically Anomalous Structure in the Galactic Halo" by José G. Fernández-Trincado, Timothy C. Beers and Dante Minniti [2], that shows an anomalous chemical composition, in order to derive their P and Ce abundances to confirm if they are part of this group. Their chemical composition is studied in detail by looking for correlations between P/Ce and other chemical elements and is compared with the one observed in stars with similar atmospheric parameters, but P abundances correctly predict by models, called P-normal. In short, the objective of this TFG is to determine which of the candidates are P-rich and to uncover possible function behind the abundances of the elements.

The analysis was done thanks to the data obtained from the APOGEE survey, that give us atmospheric data and abundances of elements studied a part for P and Ce, obtained studying the spectra of the stars, and the spectral synthesis code BACCHUS, that gave us the abundance of P and Ce analysing the spectra obtained from APOGEE and fitting synthetic spectra until it fitted with the experimental ones changing the abundance.

2 Theory

En este capítulo se explicarán los términos utilizados en este texto que me parecen los más importantes. En primer lugar, explicaré la teoría sobre la espectroscopia estelar , introduciré brevemente la transferencia radiativa, el fenómeno físico que permite la formación de las líneas de absorción y por lo tanto todo este TFG y la colegaré al calculo del abundancia. Despues presentaré el survey APOGEE. el cual nos ha fornido los datos necesarios para medir las abundancias.

2.1 Stellar spectroscopy

Stellar spectroscopy is a branch of astrophysics that uses spectroscopy to study stars and determine their properties.

The observation, in this field of studies, is done in the frequencies of radio waves, infrared, visible light, ultraviolet and X-rays.

If the observation of radio waves and visible light from the Earth's surface does not present problems, the same cannot be said of the observations with infrared or X-rays, whose frequencies are absorbed by the atmosphere. For this reason, the studies carried out in these frequency ranges require telescopes mounted either on satellites in Earth orbit (in the case of X-rays and UV) or in meteorological balloons (in the case of infrared).

Thanks to this discipline, it is possible to study the absorption and emission spectra of the studied stars and, based on these, determine their chemical composition.

The reason why we are able to understand which elements are present in the atmosphere is due to the quantum nature of the energy levels of the atomic electrons: in fact, to pass to the next energy level, electrons must absorb the same energy as the gap. In the stellar atmosphere, this energy is provided by photons, which possess energy $E=h\nu$, where h is the Planck constant and ν is the frequency. Each atom has different energy jumps, and therefore will absorb different frequencies. In fact, the absorbed frequencies are unique to each atom and form its absorption spectrum.

By analyzing the light coming from the star and seeing which frequencies are obscured, a sign that the photons with that particular energy have been absorbed, we understand what elements are present.

At this point we can form the spectrum of the star, representing the intensity or the flow as a function of the wavelength or frequency.

2.2 Radiative transfer

Radiative transfer is the phenomenon of energy transfer in the form of electromagnetic radiation through absorption, scattering and emission of light. Without introducing it and the concepts behind it, we can't explain how the spectrum can give us the abundance of the studied elements. This transfer is governed by the transport equation. Before introducing it, we must define some concepts:

Specific intensity: Suppose we're analysing the surface of a star. To do this, we consider an element of the surface so small that it can be considered flat, with an infinitesimal area dA and located at a θ angle from one of the poles. The specific intensity is defined as

$$I_\nu = \frac{dE_\nu}{cos\theta \ dA \ dt \ d\nu \ d\Omega}$$

where dE_ν is the energy that is distributed in the $d\Omega$ solid angle and that passes through the area dA in the time interval dt and in the frequency band $(\nu, \ \nu + d\nu)$.

Emission: Consider a beam of light passing through an infinitesimal volume dV in a time interval dt in the direction of $d\Omega$. While passing through the volume, other light, included in the frequency band $d\nu$ and with energy dE_ν, is added to this beam. The monochrome emissivity coefficient j_ν per cm^3 is defined as

$$j_\nu = \frac{dE_\nu}{dV \ dt \ d\Omega d\nu}$$

Now we can express the intensity of the contribution to the local emission as

$$dI_\nu(x) = j_\nu(x)dx$$

where x is the optical path (in cm) measured along the beam.

Extinction: If we talked earlier about the energy added to the beam, now we need to talk about the energy removed from it. The monochromatic extinction coefficient indicates the energy lost from the radius per unit area and is equal to

$$\alpha_\nu = -\frac{dI_\nu}{I_\nu dx}$$

where the sign - indicates that the energy is lost

Source function: The source function S_ν is defined as the ratio between emission and extinction coefficients

$$S_\nu = \frac{j_\nu}{\alpha_\nu}$$

Now we have all the "ingredients" to discuss the transport equation.

Transport equation: The transport equation can be written in three different ways

$$dI_\nu(x) = I_\nu(x+dx) - I_\nu(x) = j_\nu(x)dx - \alpha_\nu(x)I_\nu(x)dx$$

$$\frac{dI_\nu}{dx} = j_\nu - \alpha_\nu I_\nu$$

$$\frac{dI_\nu}{\alpha_\nu dx} = S_\nu - I_\nu$$

What the three versions of the equation indicate is that photons do not decay or originate spontaneously, so any change in intensity is due to external sources that add or remove light. Thanks to these formulas, when we are analysing a star, we can know which elements are present in the atmosphere analysing how much the intensity in a certain frequency is diminished regarding the others. To solve the equation, however, we must first introduce a new magnitude.

Optical length and thickness: We define the optical length and optical thickness of an object of thickness X respectively as

$$d\tau_\nu(x) = \alpha_\nu(x)dx$$

and

$$\tau_\nu(X) = \int_0^X \alpha_\nu(x)dx$$

In our case, once the light has left the star there will be no other photon additions, so $j_\nu = 0$. With these conditions, using the second version of the transport equation, we can obtain

$$I_\nu(X) = I_\nu(0)e^{-\tau_\nu(X)}$$

A volume crossed by light is defined as thick if $\tau_\nu(X) > 1$ and as thin if $\tau_\nu(X) < 1$.

Using the third version and τ_ν we get the equation in non-homogeneous materials

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} S_\nu(\tau_\nu)e^{-(\tau_\nu - t_\nu)}dt_\nu$$

which, in the case of homogeneous objects, i.e. when S_ν does not change in space, becomes

$$I_\nu(X) = I_\nu(0)e^{-\tau_\nu(X)} + S_\nu\left(1 - e^{-\tau_\nu(X)}\right)$$

This equation gives us the intensity of a line associated to a frequency. Thanks to it, we can obtain the abundance, as explained at the end of this section

2.3 Abundance

Is defined as the quantity of a certain element contained in a star. Usually, relative abundances are used instead of absolute ones. Relative abundance compares the amount of two elements in the studied star and the Sun. For example, the [Fe/H] abundance, which compares the amount of iron and hydrogen, is calculated as follows:

$$[Fe/H] = \log_{10}\left(\frac{N_{Fe}}{N_H}\right)_{star} - \log_{10}\left(\frac{N_{Fe}}{N_H}\right)_{Sun}$$

, where the letter N indicates the number of ions of the element inside the star. Relative abundance can be positive or negative: a value of 1 indicates that the star contains 10 times the amount of iron in the Sun, while a value of -1 indicates that it contains a tenth of it.

Obviously, more atoms of an element are present, more photons of a certain frequency will be absorbed, the intensity will decreased and the lines in the spectrum become deeper. So we can use the intensity to obtain the abundance. In our case, we used a synthetic spectral code, BACCHUS, which creates a synthetic spectrum and compares it with the experimental one, changing the value of the abundances of P and Ce until the theoretical spectrum fits with the experimental one. In this way we obtained the values used in our research.

The intensity is influenced also by the temperature and the gravity of the star.

2.4 APOGEE spectroscopic survey

The creation of an astronomical survey arises from the need to make statistical studies and catalogue the stars avoiding long sessions of observations of a single star or a sky region. These surveys make it possible to choose targets for future studies.

The survey used in this project is the **APO Galactic Evolution Experiment**, abbreviated as **APOGEE**, part of the larger **Sloan Digital Sky Survey** (SDSS), an astronomical survey that uses a 2,5 m diameter telescope located at the Apache Point Observatory in Nex Mexico, USA, started in 2000.

APOGEE uses infrared observations to penetrate the dust cloud at the center of the galaxy, which obscures much of the sky to normal optical telescopes, and survey over 10^5 stars to determine, for each stars, accurate abundance pattern for numerous chemical species, studying their absorption spectra. In this way APOGEE obtains high-resolution (R $\sim$ 22,500) near-infrared spectroscopy and high signal/noise ratio (S/N $\sim$ 100) spectra and H $\sim$ 13.5 [3][4]. To carry out this task, the telescope is flanked by a multi-object spectroscope operating in the near-infrared H-band ($\sim$ 1.5-1.7 microns) [3]. Because at 1,6 μm the thermal radiation of the spectrograph isn't negligible, the spectrograph is held in a cryostat and maintained at a temperature of T $<$ 210 K [3]. The data obtained by this survey are the radial velocity, atmospheric parameters and chemical abundance of the stars studied [3]. Radial velocity is obtained by analysing the redshift, while abundances are obtained by studying the spectrum.

The goals of both the first phase (APOGEE 1) and the second phase (APOGEE 2), the extension of APOGEE plus the use of the twin spectrograph 2.5-meter du Pont Telescope at Las Campanas Observatory in Chile, is to penetrate the cloud of dust that obscures part of the center of the galaxy to understand the chemical evolution and the relationship between the different structures of the Milky Way and to understand the history of the formation of the Milky Way by studying its stars and their composition.

3 Methodology followed

En este capítulo hablaremos del trabajo realizado para analizar los espectros de las estrellas. El proceso ha empezado obteniendo los espectros y parámetros estelares que necesita el código BACCHUS para calcular los espectros sintéticos y derivar abundancias químicas. Más tarde, he recogido y organizado los datos obtenidos de la analisis de los espectros para una lectura más rápida y finalmente he creado gráficos para buscar posibles correlaciones entre las abundancias de P/Ce y otros elementos químicos.

3.1 Obtaining stellar data

The stars we analysed are those listed in the article "Jurassic: A Chemically Anomalous Structure in the Galactic Halo" by José G. Fernández-Trincado, Timothy C. Beers and Dante Minniti [2].

We planned to study all the 55 stars cited in [Jurassic], but 16 of these could not be found in the APOGEE public data release 16. To begin analysing the remaining 39 stars (4 of which were analysed in Masseron et al. (2020a) [1] and one in Masseron et al. (2020b) [3]) we downloaded the spectra in FITS format from the APOGEE database and wrote a code in Python language to open each file and extract the fluxes (and their uncertainties).

Our observation range corresponds to the H-band region from 1,5 to 1,7 μm with two small gaps. Once the flux are obtained, we derived the associate wavelengths knowing that are elements of the logarithmic series $\ln(\lambda_{i+1}) - \ln(\lambda_i) = 6 \times 10^{-6}$ with $\lambda_0 = 15100.802$ Å equal for all stars [5].

Once these data are obtained, the program then creates for each star an ASCII file containing for all measured fluxes the uncertainty in the measurement and its wavelength.

As a final step of this preparatory phase, starting this time from the file APOGEE DR16, containing the atmospheric parameters (effective temperature, surface gravity, metallicity, etc.) of all the stars in the database, we also created a table with the effective temperature, the surface gravity, the metallicity and the abundance of carbon, nitrogen and alpha elements of all stars studied, discarding stars that are not part of this study. All collected data are necessary for the operation of the BACCHUS code.

3.2 Spectral synthesis analysis

The **Brussels Automatic Code for Characterizing High accuracy Spectra** (BACCHUS) is a spectral synthesis code that is intended to automatically perform stellar spectroscopy

[6] and were used in this TFG to obtain P and Ce abundances, as said before: the code creates a synthetic spectrum and adjust the abundance values of P and Ce until it fits with the experimental one. We used BACCHUS instead of ASPCAP, the pipeline that APOGEE uses by default to determine the abundances, due that P and Ce lines are too weak for ASPCAP. A comparison of the two code can be found in the next section.

The information about the flux and the wavelength allows BACCHUS to plot the real spectrum, while thanks to the atmospheric information it can plot the synthetic spectrum. The calculation of the synthetic spectrum was too heavy for my local computer, for this it was done remotely using a 'divan' computer of IAC.

BACCHUS plots the normalized flux as a function of the wavelength, measured in angstrom, near the wavelength of the absorption lines, i.e. near $1,57155 \times 10^4$ Å and $1,6483 \times 10^4$ Å in the case of phosphorous and close to $1,57845 \times 10^4$ Å; $1,63765 \times 10^4$ Å; $1,65955 \times 10^4$ Å and 1.67225×10^4 Å for cerium. Sometimes is possible that for a star a line of one or both elements is too weak to be measured. In the case of phosphorus it's $1,6483 \times 10^4$ Å, while for cerium is 1.67225×10^4 Å . For each line, BACCHUS plots the experimental data and the model, the last one calculated five times each time with a different synthetic abundance, then we choose the synthetic abundance whose model was the closest to the experimental data and better approximated it and used it to give an estimate of the real value.

For the some stars, however, some factors, as such the pollution of the line due to other elements, high background noise or a weak line, prevented us to obtain an accurate value. In this scenario, we have chosen for each line in this situation an upper limit for the abundance. To choose the upper limit for each line that needed it, we searched a value strong enough not to be obscured by the background noise, not so strong to predict that the lines should have an abundance that can be determined with a more accurate value, and that can approximate to the experimental observation. The stars with upper limit are indicated in table in the annex B.

In some cases, a line could be to weak or polluted or the noise be to strong to allow us to obtain a precise value or an upper limit, also in the case BACCHUS could plot the line, so the entire line had to be discarded.

At this point, to obtain an abundance value for the stars we calculated the average between the abundances of each lines, discarding the one with an upper limit. If every line had an upper limit, we choose the one that better fits its line. Then, to have a more fair comparison and eliminating effects due to factors such age or distance, we subtracted from each abundance the metallicity of the star and the solar value (5,36 por el P, 1,58 por el Ce).

3.3 Abundance analysis: looking for correlations

Once we got all the data, we started by studying the abundance of phosphorus and cerium in relation to the abundance of iron. Once plots were prepared, they were used to compare the abundance of phosphorus in the stars studied with the abundance of the same element in the stars studied in the article [1] in order to decide whether the stars analysed should be considered P-rich or not.

In the case of the other elements, was possible to use of the APOGEE data. With these data, was possible to compare the abundances of these elements with those of stars with similar atmospheric characteristics (T=[4000,5000] K, log g=[0.20016667, 3.1999478], [M/H]=[-1.5999615, -0.6000115], S/N $>$ 100) but that are not candidates for P-rich to see if any abnormal behaviour could be observed.

At this point we decided to study the abundance of the other elements as a function of that of phosphorus and cerium to see if there is any correlation, that could inform stellar nucleosynthesis modelers about the still unknown progenitors of P-rich stars. We studied the correlation between each element provided by the APOGEE database (mainly O, Mg, Al and Si) and the two elements at the center of the study, phosphorus and cerium. We also studied the correlation between these two elements. When calculating correlations, stars with upper limit were discarded. Those links that we thought are strong enough are presented in a dedicated section of the next chapter, while the weaker and less relevant links are presented in graphs in annex A.

4 Results and discussion

En esta última parte discutiré los resultados obtenidos y sacaré, cuando sea posible, conclusiones utilizando los datos y gráficos obtenidos. Presentaré mis resultados comparando la abundancia de fósforo y cerio con la metalicidad y la abundancia de otros elementos. También dedicaré una parte a la comparación entre el código de síntesis espectral BACCHUS y la " pipeline " automática de APOGEE para la extracción de abundancias ASPCAP [7]. Las estrellas que no son P-rich se excluyen cuando es el momento de calcular la correlación.

4.1 Comparison between BACCHUS and ASPCAP

To obtain the phosphorus abundances used in this survey we used the BACCHUS code and not the pipeline ASPCAP. To test the reliability of BACCHUS, we decided to compare the data obtained for **Cerium** with this software with those obtained by ASPCAP.

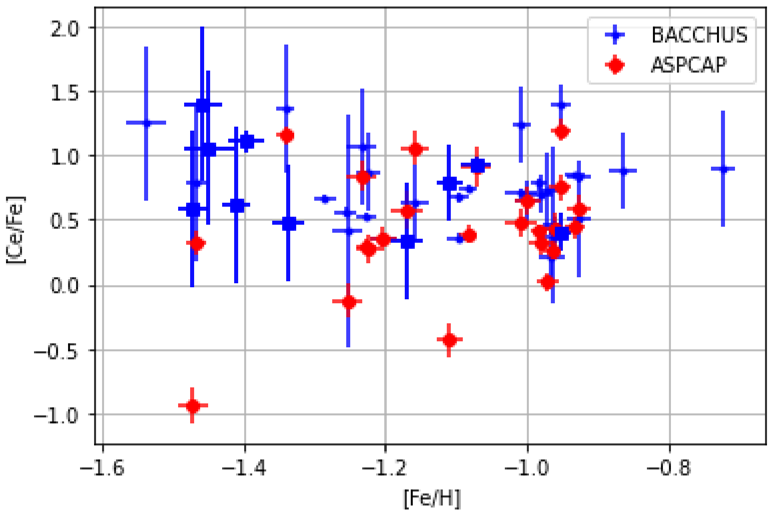
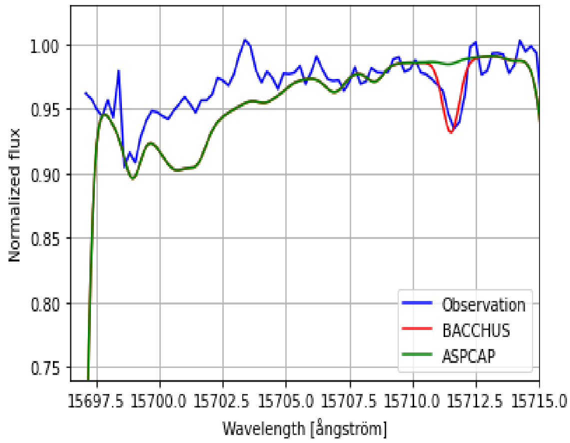


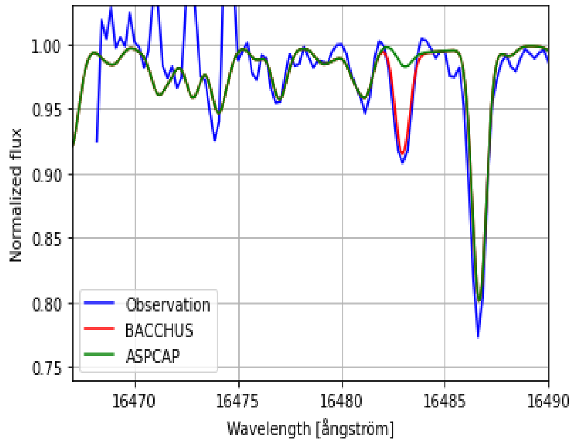
Figure 1: Comparison between Cerium abundance from two different sources. The BACCHUS abundances with an upper limit are represented with a square instead than a dot.

Once we eliminate stars with an abundance of -9999.99 (a placeholder value that indicates that the ASPCAP can't determines the abundance because the line is too weak), we can see in the plot above (figure 1) that the APOGEE ASPCAP code predicts lower **cerium** values than BACCHUS. The difference is bigger for lower metallicity values (that is linked to weaker lines, more difficult to measure). In brief, we can see that BACCHUS seems to not be influenced by metallicity as ASPCAP.

To figure out which software was better, we compared the synthetic spectra (BACCHUS versus ASPCAP) with the spectrum observed in one of the P-rich stars in our sample, 2M17255079-2029099. For this particular star, once summed the metallicity and the solar value, BACCHUS predicts a value of 5,71 for the first line and 5,83, while ASPCAP a value of 4,15. We did this analysis with the phosphorus data, because the difference is more marked. In the next two figures will be show the two models and the observation near the two absorption lines. Figure 2a shows the trend around the wavelength $\lambda = 1,57155 \times 10^4$ Å. It can be seen that both models follow the same theoretical trend and doesn't predict the noise. However, when the two models reach the wavelength of the absorption line, the BACCHUS model predicts a decrease in the normalised flux around 1.5711 nm (i.e. where the absorption line is located) that the ASPCAP model ignores. For this reason, we can assume that ASPCAP tends to ignore or minimise the strength of the P absorption lines.



(a) Comparison between Phosphorous abundances from two different sources near $\lambda = 1,57155 \times 10^4$ Å



(b) Comparison between Phosphorous abundances from two different sources near $\lambda = 1,6483 \times 10^4$ Å

Figure 2b shows a similar case to the figure 2a: both models follow the same theoretical trend, ignoring the noise, but when it's time to predict the strength of the absorption line, BACCHUS predicts effectively the strength, while ASPCAP give a value much more lower. For this reason we can say that BACCHUS do a better job in analysing the lines of both P and Ce respect ASPCAP, that under-predict the quantity of said elements. Since ASPCAP shows for some elements the same problem that it showed for phosphorus and cerium and for some stars can not predict a value, showing the placeholder values of -999.99 and -9999.99, we can suppose that the values used for the analysis of Al, O, Mg and Si are lower than the real ones.

4.2 Abundance analysis

Phosphorus

Figure 3 shows the abundance of phosphorus as a function of the abundance of iron. As you can see, of the 39 stars only 6 are out of the range between 1 and 2 dex, range where were the stars of the study [1]. These six stars have an abundance less than 1 dex, an empirical value used also in the original study to separate P-rich from P-normal [1]. Four of them, 2M18091354-2810087, 2M19193412-2931210, 2M16241820-2145485 and 2M17171046-3007398, have such a low value (less than 0.9 dex) that they can be clearly excluded from P-rich. The other two falls in the original interval thanks to the uncertainty, for this reason they won't be discarded. All stars have a higher relative abundance than the Sun, including the four P-normal.

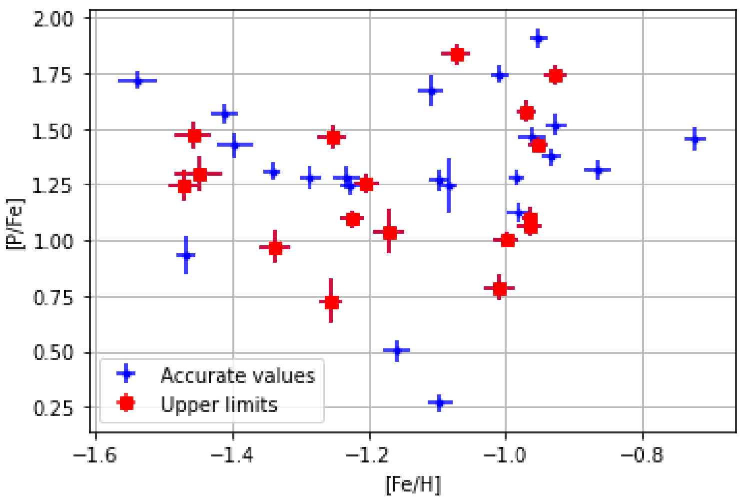


Figure 3: Phosphorus abundances as a function of metallicity. The four stars in the lower part of the graph are P-normal. Red dots indicates upper limit

The four P-normal were excluded from the correlation calculation, as in that case we are interested in the behaviour of P-rich stars only.

Cerium

Even in the case of cerium (figure 4), all stars have a relative greater abundance than that of the Sun. All of them falls in the interval between 0 and 1.5 dex.

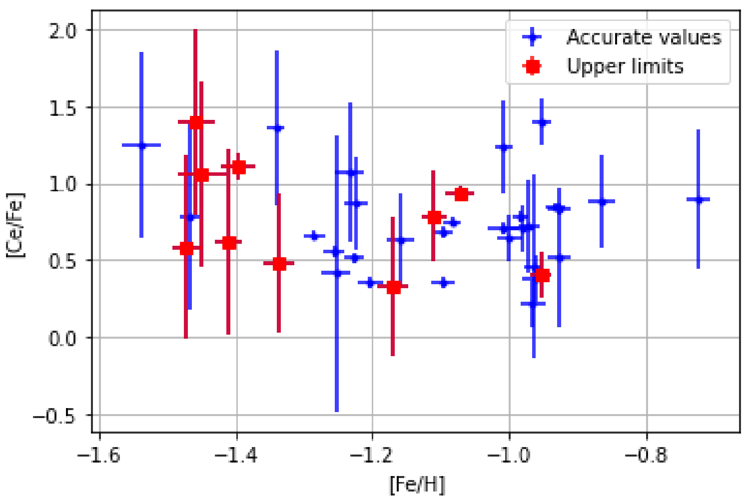


Figure 4: Cerium abundances as a function of metallicity. Red dots indicates upper limit

4.3 Analysis of the difference between P-normal and P-rich abundances

In this section will be discussed the abundance of different elements as a function of M/H in P-rich stars and compare it with that of P-normal stars, to find abnormal abundances in P-rich stars that could deserve special attention. The section will be divided between alpha elements and no alpha elements.

Alpha elements

The first analysed is the abundance of alpha elements (O, Mg, Si, S, Ca) (figure 5). We can see how the majority of P-rich stars (represented in red) have an higher value of [alpha/M] than that of the P-normal ones (in green). The [alpha/M] value represents the average between the abundances of alpha elements. Indeed, we can see that P-rich have higher quantities of Oxygen (figure 6), Magnesium (figure 7) and Silicon (figure 8) than P-normal, while they have similar abundances of Sulphur (figure 9) and Calcium (figure 10). As stated before, Ti is not show because is one of the elements for which ASPCAP performs poorly.

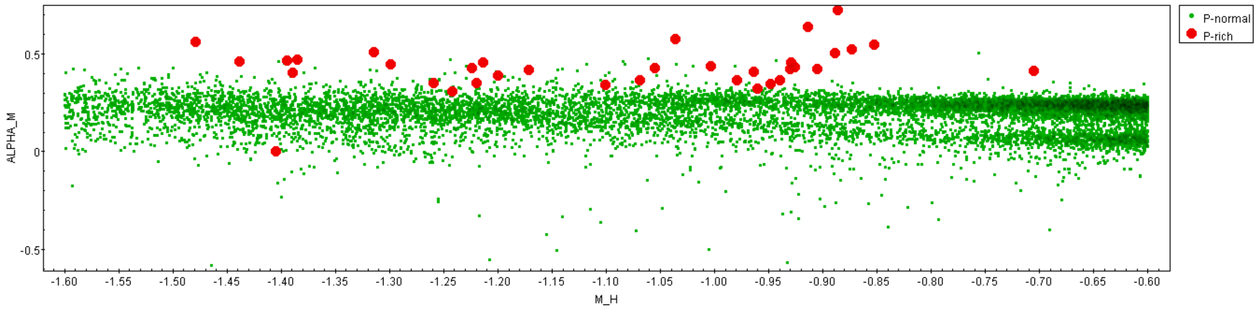


Figure 5: Alpha elements abundance as a function of [M/H]

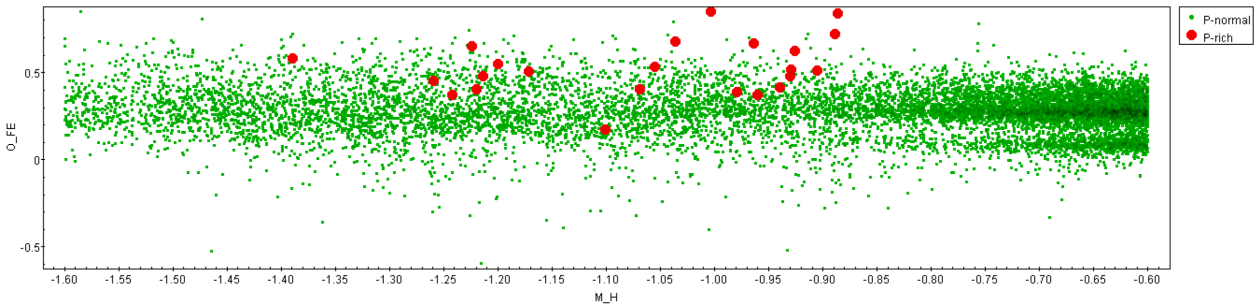


Figure 6: Oxygen abundance as a function of [M/H]

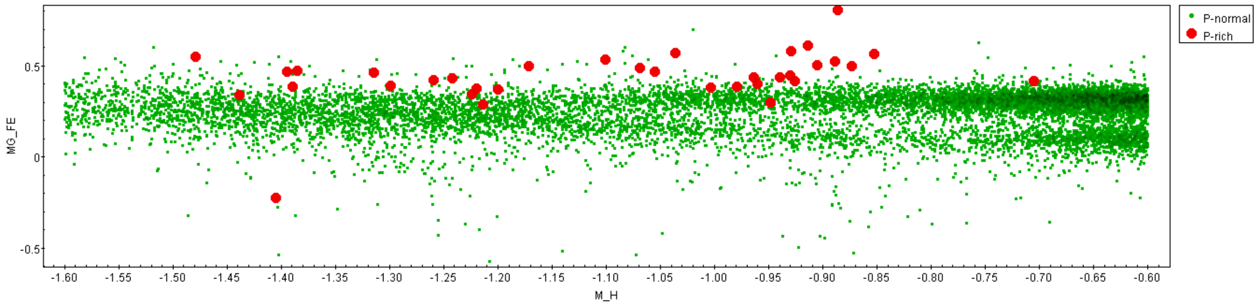


Figure 7: Magnesium abundance as a function of [M/H]

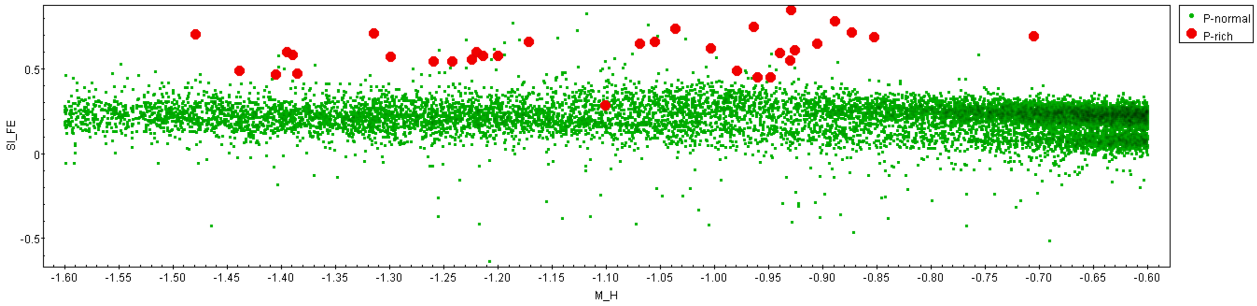


Figure 8: Silicon abundance as a function of [M/H]

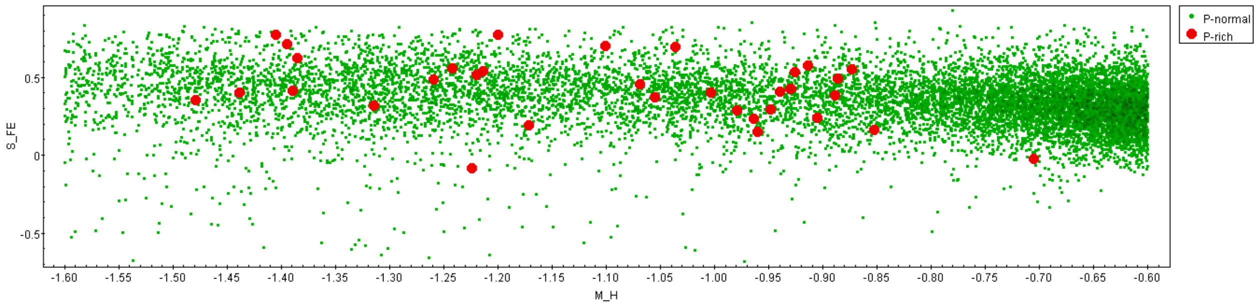


Figure 9: Sulphur abundance as a function of [M/H]

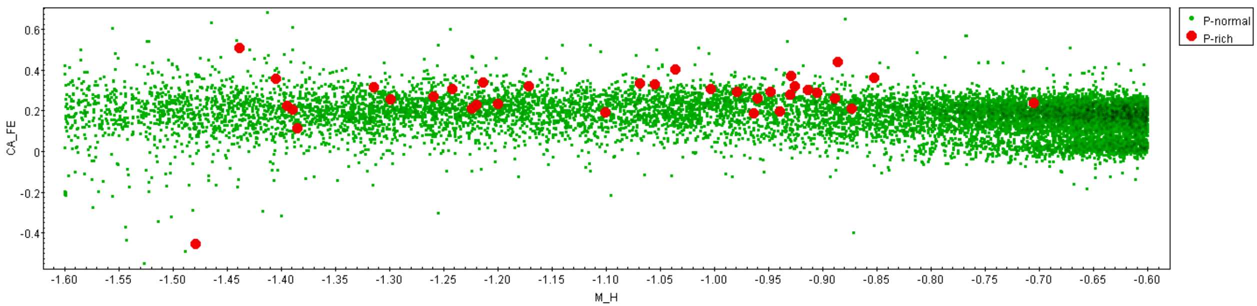


Figure 10: Calcium abundance as a function of [M/H]

Not Alpha elements

Other not alpha elements with an high abundance in P-rich stars Nitrogen (figure 11), Aluminium (figure 12) and Nickel (figure 13). For the other elements, the two types of the stars have similar abundances. As example of this category will be shown the analysis of Carbon abundance (figure 14).

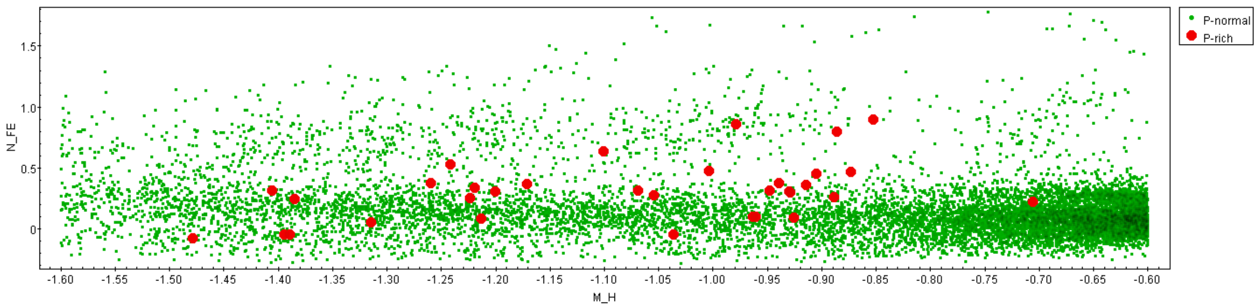


Figure 11: Nitrogen abundance as a function of [M/H]

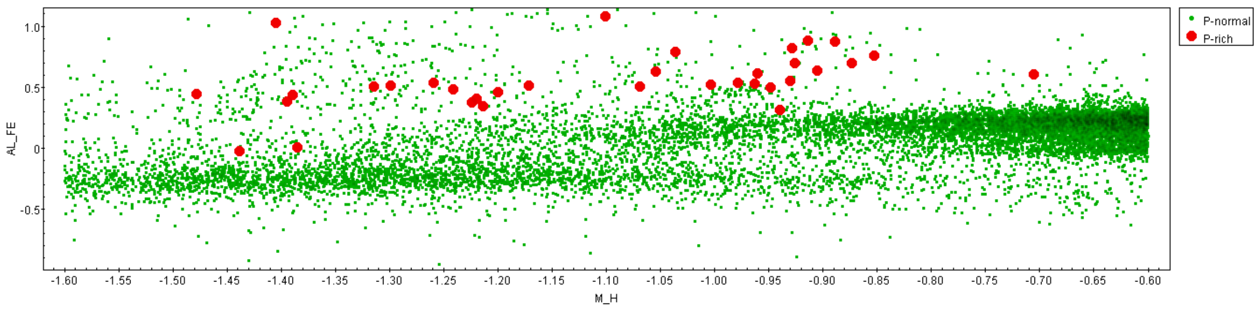


Figure 12: Aluminium abundance as a function of [M/H]

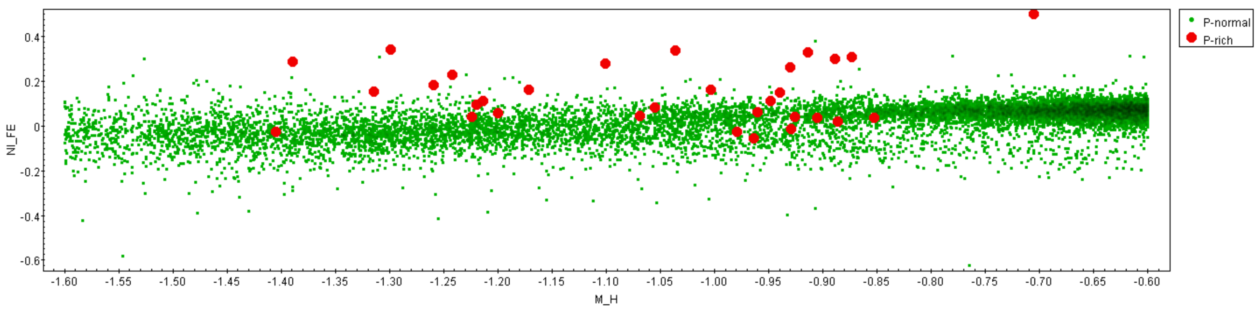


Figure 13: Nickel abundance as a function of [M/H]

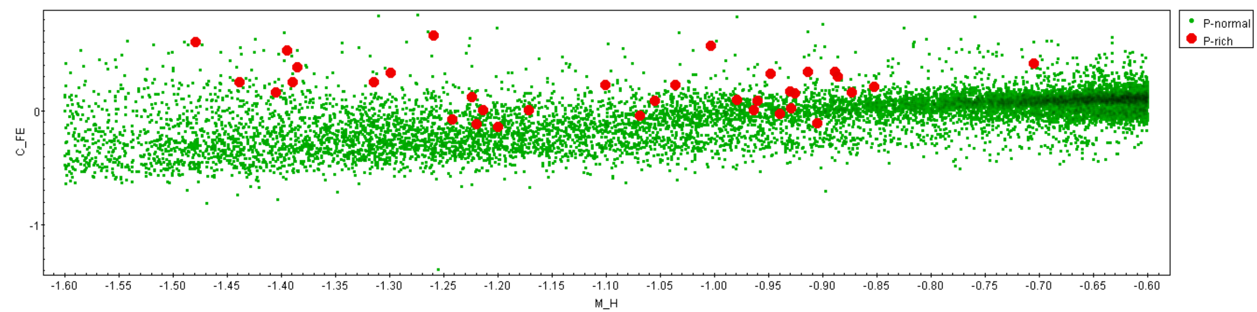


Figure 14: Carbon abundance as a function of [M/H]

4.4 Analysis of possible relationships

We studied the relationship between the amount of phosphorus and cerium and that of the other elements. In this part we will present the results related to the relationship between Phosphorus and Cerium with the elements considered in the article [1], namely O, Mg, Al, and Si. The rest will be found in annex A. In the analysis of each element were discarded the stars for which the ASPCAP code could not get the abundance and therefore had entered the placeholder value of -999,99 or -9999,99. The upper limit will be represented in blue, while the the accurate ones in green. Every correlation is plagued by an high number of stars with an uncertain value, due probably to the fact that P and Ce lines are weak. This effect is more visible in the case of P than in the case of cerium.

To have an objective criterion to identify when two elements are correlated, we used the **Pearson correlation coefficient**, defined as

$$r = \frac{\sigma_{XY}}{\sigma_X \sigma_Y}$$

where σ_{XY} is the **covariance** and σ_X and σ_Y are the **standard deviation** of the two data sets whose correlation we want to calculate. The criterion by which we divide the correlations between weak, moderate and strong is based on the absolute value of the coefficient: when is between 0 and 0.30 the correlation is weak, i.e. the probability that there is a correlation is low; when is between 0.30 and 0.70 is moderate; when is between 0.70 and 1 is strong.

Correlation between phosphorus and cerium

First of all, we analysed the correlation between the two elements at the center of this research, phosphorus and cerium.

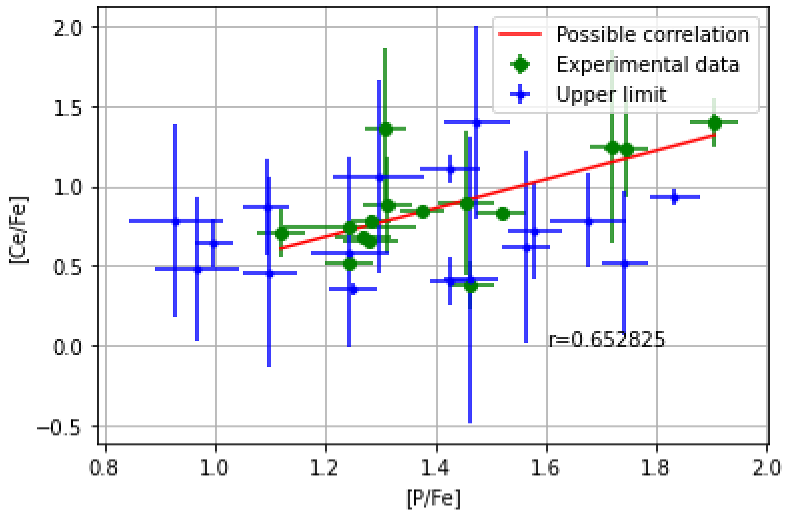
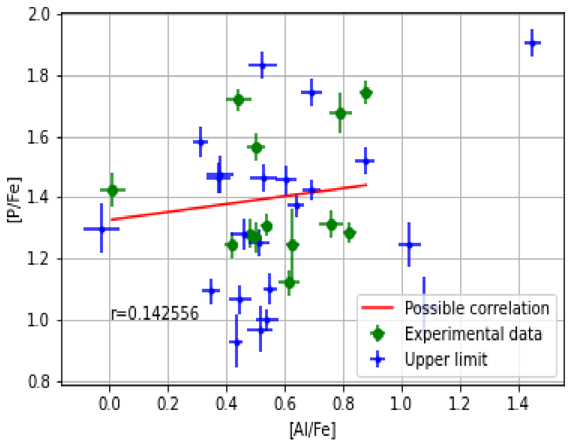


Figure 15: Correlation between Phosphorous and Cerium

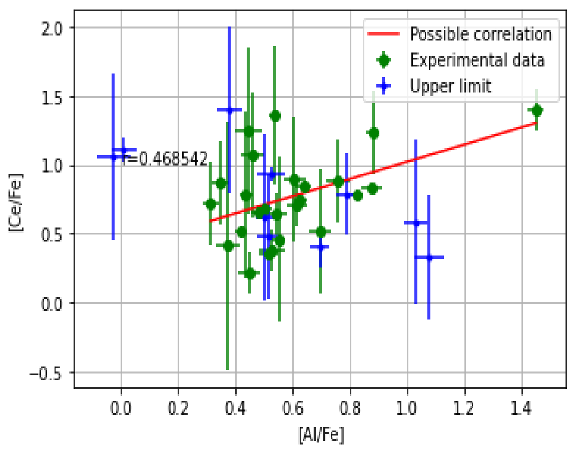
As you can see in the plot (figure 15), the two elements have a correlation of ∼ 0.67, therefore moderate. So, there is the possibility that the two elements are connected. However, the fact that the stars with an upper limit (blue dots) could be find under the correlation line can also mean that the correlation could also not trustworthy. We need more stars to confirm or deny this hypothesis.

Aluminium

In the plots we can see that two stars, 2M15170852+4033475 and 2M09133506+2248579, have very low abundance of aluminium (-0,03 and 0,01, respectively). Both stars have low metallicity (-1,44 and -1,39, respectively. -1,44 is also the second lowest metallicity of all the studied stars) and high temperature (5687,61 K and 5469,402 K, the highest temperature and the third highest temperature among the stars studied respectively). We can also see that one star, 2M17265466-1331522, have a high abundance of Al, 1,45. This star has the four highest metallicity of all the stars (-0,89) and the highest average abundance of alpha elements ([alpha/M] = 0,73).



(a) Correlation between Phosphorus and Aluminium

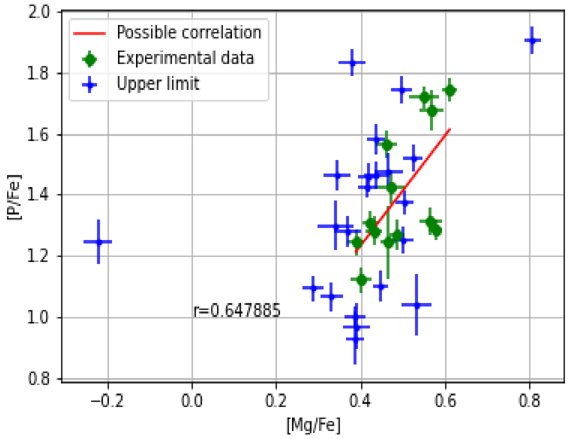


(b) Correlation between Cerium and Aluminium

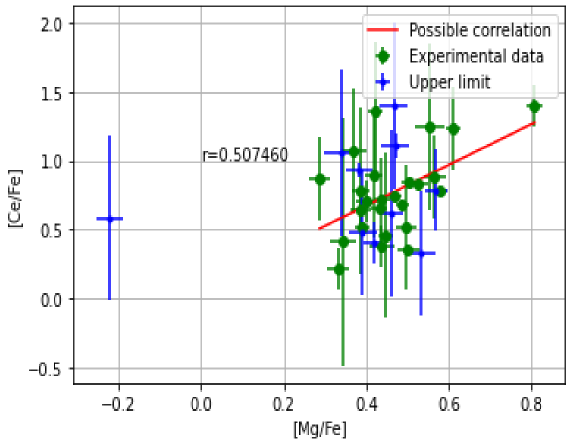
As we can see in figures 16a and 16b, the correlation between P and Aluminum is weak, while the one between Ce and Al is moderate. The high number of stars without an exact value of the abundance, however, tell us that we need more data. With the study of aluminium we can also see that the measure of the abundance of cerium gives us more accurate values than we get by measuring phosphorus, probably because Ce lines are stronger than P ones, or because there are more cerium lines than phosphorous ones, so the probability than at least one line can be measured accurately is higher . So we can suppose that the correlation with cerium are more close to the real value than the one with phosphorous.

Magnesium

In this case, the stars that diverge from the others because their abundance are two. 2M14513934-0602148 has a very low abundance of Mg, -0,22. This star has the third lowest metallicity (-1,41) and the lowest abundance of alpha elements (0,003). Its signal to noise ratio is less than 100 (95,04). The other is 2M17265466-1331522, the one that before we shows is also the star with the highest abundance of aluminium. The correlation between P and Mg is moderate (figure 17a), like the one between Ce and Mg (figure 17b).



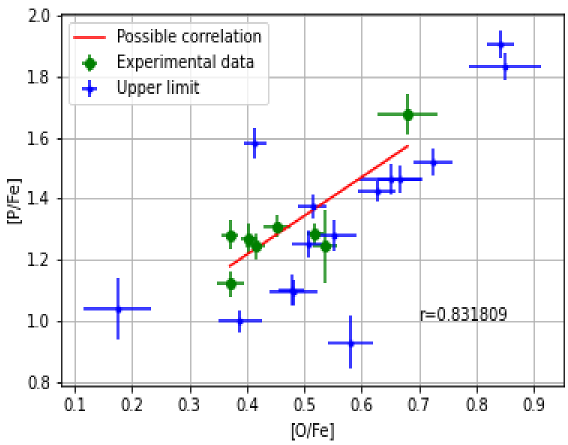
(a) Correlation between Phosphorus and Magnesium



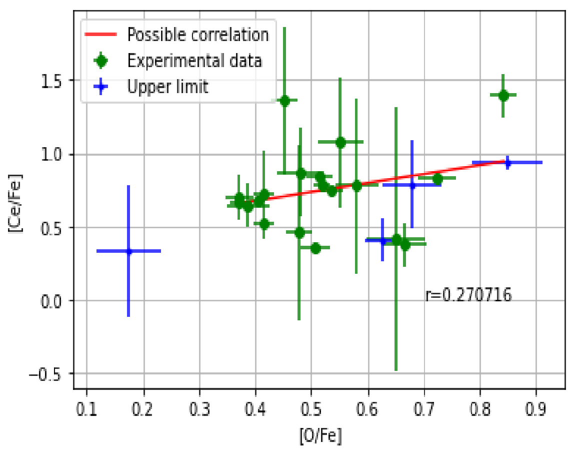
(b) Correlation between Cerium and Magnesium

Oxygen

In this case we have with a weak correlation between Ce and O (figure 18b) and a strong one between P and O (figure 18a). The star with the lowest abundance (0,17), 2M16544476-3939140, is also the star with lowest signal to noise ratio (35,67).



(a) Correlation between Phosphorus and Oxygen

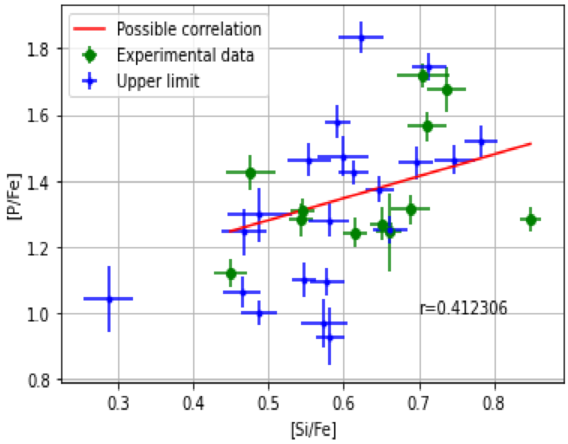


(b) Correlation between Cerium and Oxygen

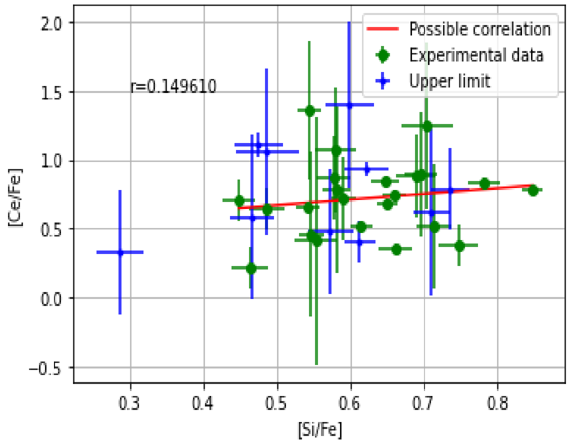
We can see that the correlation between phosphorous and oxygen is strong. If we could measured better the lines with a high error, we could demonstrate that P and O are related. This should be expected, because phosphorous is created during the oxygen-burning phase, a phase during which stars uses nucleus of oxygen to create energy, obtaining also Mg, Si, P and S.

Silicon

In the case of silicon, the star 2M16544476-3939140 , that is also the star with the lowest abundance of oxygen, is also the one with the lowest silicon abundance (abundance = 0,29). we can see that the correlation between P and Si is moderate (figure 19a), while the one with Ce is weak (figure 19a).



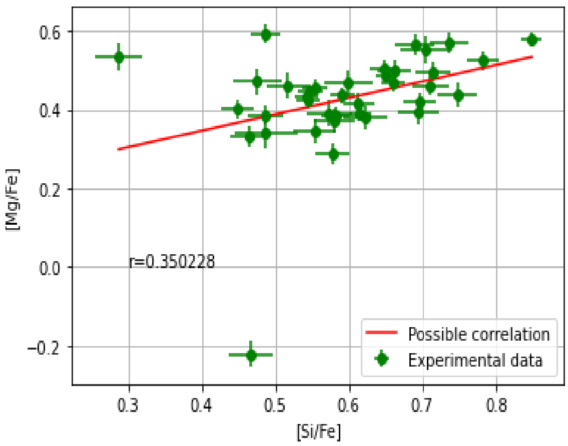
(a) Correlation between Phosphorus and Silicon



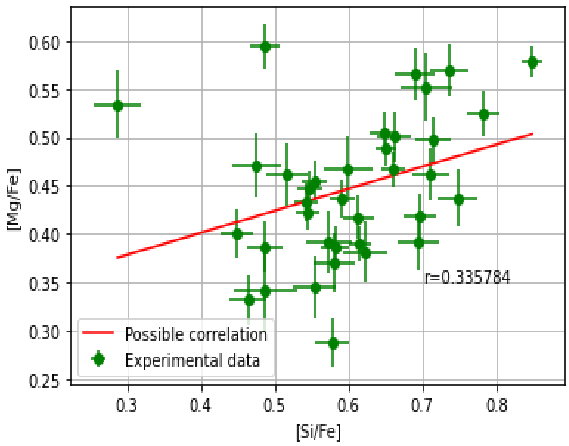
(b) Correlation between Cerium and Silicon

At this point we studied the correlation between the other elements cited (O, Mg, Al and Si) to see if there is any correlation between them. As said before, thanks to the oxygen-burning phase, stars convert oxygen in magnesium, silicon and phosphorous, and we have show that can exist a correlation between O and P (that, however, needs better measurement of some stars to be demonstrated). A correlation between O, Si and Mg, so, should be expected. In this case, the data come from ASPCAP, so we can consider that each abundances has the same accuracy.

In figure 20a and 20b we can see the correlation between Si and Mg with and without the star 2M14513934-0602148, that has been showed before having an anomalously low abundance of magnesium. In both cases, the correlation is moderate.

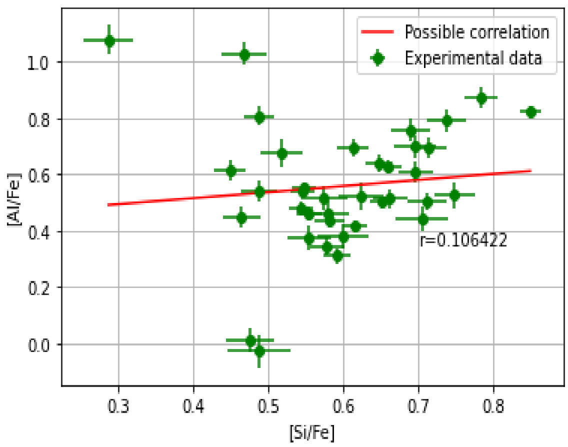


(a) Correlation between Silicon and Magnesium with 2M14513934-0602148

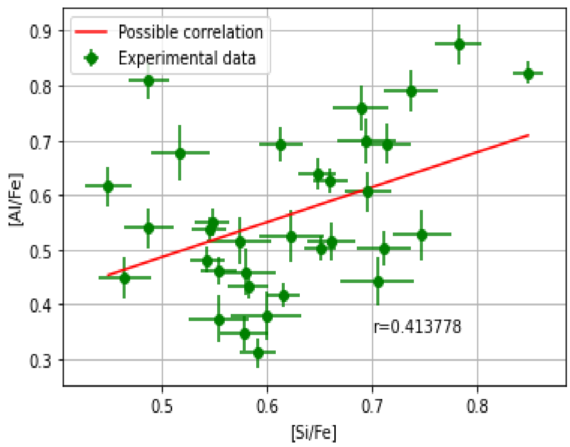


(b) Correlation between Silicon and Magnesium without 2M14513934-0602148

Speaking about the correlation between Si and Al, we can see in figures 21a and 21b that, in order to obtain a moderate value for the correlation, we need to discard the two stars with the lowest aluminium abundance (2M15170852+4033475 and 2M09133506+2248579) as the one with highest (2M16544476-3939140 and 2M17265466-1331522). So, is possible that there is some sort of correlation between the two elements. However, we need before to understand why the four stars mentioned have some anomalous abundances: it could be related to temperature, because the two stars with lowest Al abundance are also the one with the highest temperature.

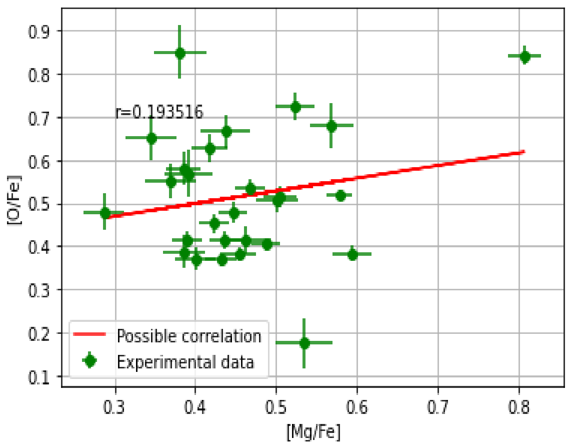


(a) Correlation between Silicon and Aluminium with the four star mentioned

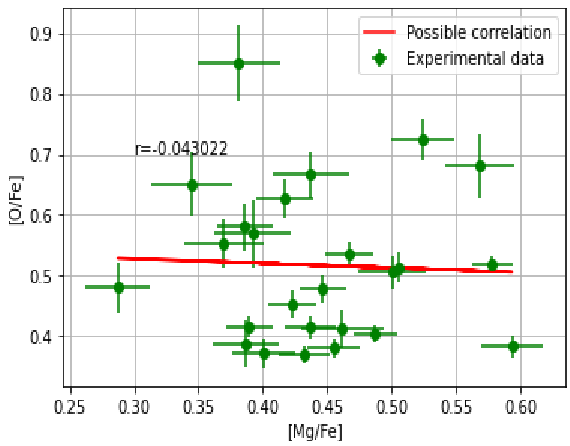


(b) Correlation between Silicon and Aluminium without the four stars

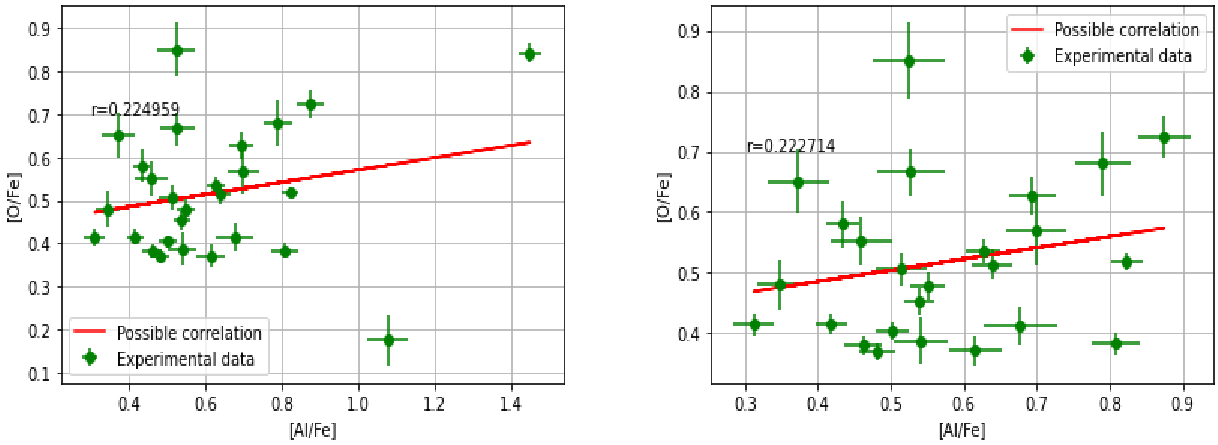
In the case of Magnesium and Oxygen (figures 21a and 21b), as in the case of Aluminium and Silicon (figures 22a and 22b), the correlation is weak with and without the stars that we have removed in the precedent cases. So we can assume that there isn't any correlation.



(a) Correlation between Magnesium and Oxygen

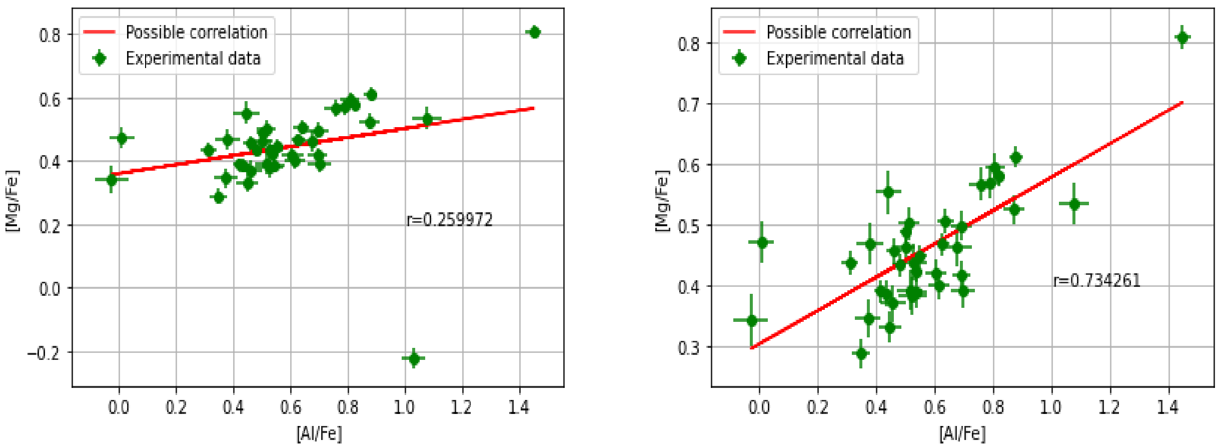


(b) Correlation between Magnesium and Oxygen



(a) Correlation between Aluminium and Oxygen (b) Correlation between Aluminium and Oxygen

In figures 23a and 23b, we can see that once removed the star 2M14513934-0602148, i.e. the one with the lowest abundance of magnesium, there is a strong correlation between Mg and Al, so we can suppose that there is a link between the two elements.



(a) Correlation between Aluminium and Magnesium (b) Correlation between Aluminium and Magnesium

Finally, in figure 25 we can see that there is a moderate correlation between Silicon and Oxygen. So there can be also a link between these two elements.

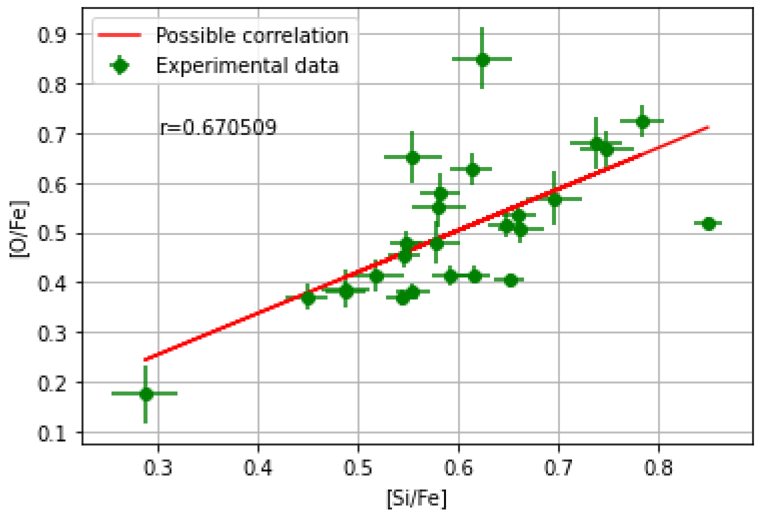


Figure 25: Correlation between Silicon and Oxygen

4.5 Conclusions

In this work, we analysed the spectra of 39 stars suspected to be part of the new discovered category of P-rich stars, i.e. stars with an abundance of phosphorous that is higher than average and can't be explained with actual nucleosyntesis models. We used the code BACCHUS to obtain the abundance value of P and Ce and compared the results with the ones proportioned by the pipeline ASPCAP, used by default by the database APOGEE, to prove that BACCHUS can do a better job at obtain the abundance of phosphorous. Finally, we used the data obtained to search correlation with other elements, correlations that can help us understand how this abnormal quantity of P came from.

At the end of this work, we obtained that:

- Apart for 2M18091354-2810087, 2M19193412-2931210, 2M16241820-2145485 and 2M17171046-3007398, the stars analysed are part of the P-Rich group, as they have high levels of phosphorus. After this analysis the number of P-rich discovered increased from 16 to 48, allowing a better statistical study;

- While some stars have a high abundance of cerium, others have a quantity that doesn't differ too much from that the abundance of the Sun. So is possible that the quantity of cerium isn't linked to the abundance of phosphorous, as hinted by their moderate correlation coefficient;

- With the same metallicity, the P-rich stars analysed have higher levels of some alpha elements (O, Mg, Si) and average levels of S and Ca. This can mean that phosphorous in these stars is created with the action of alpha elements. They presents also an high quantity of N, Al and Ni;

- There seems to be a strong relationship between Phosphorous and Oxygen and there is a moderate one between Si and O. It's interesting to note that both Si and P are created utilising Oxygen. Also is worth nothing that magnesium, that can be created consuming oxygen or silicon, has weak correlation with both.

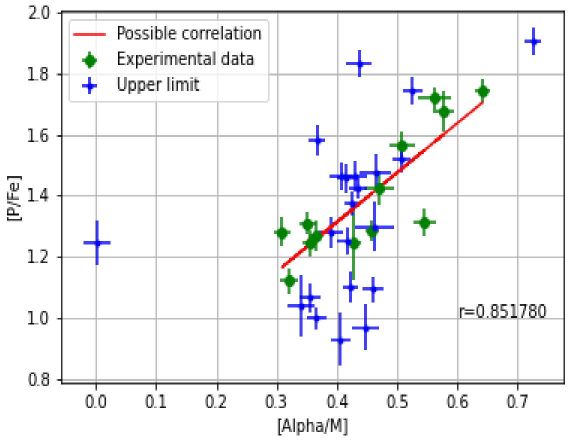
This project aided to discover new P-rich stars. This type stars could aid to uncover the origin of one of the most important ingredients of life. These stars can also aid future astrophysics to understand more about the nuclear process that happens in the nucleus of stars.

To continue this project, the new discovered stars shall be analysed with the old ones, and other P-rich shall be discovered, because the actual number of P-rich (48) makes statistical studies plagued liked the ones did in this project by error and approximations, as can be see in the final parts.

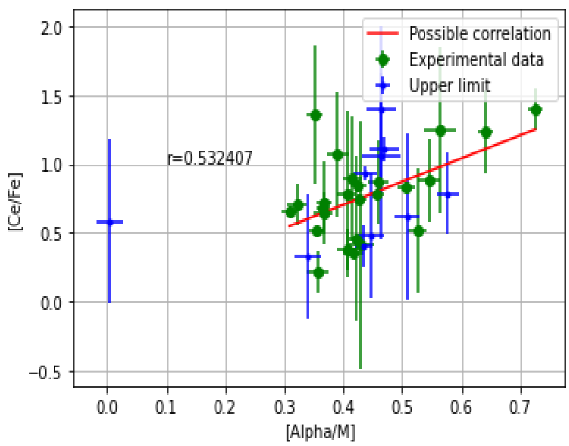
5 Appendixes

5.1 Appendix A: Correlation plots

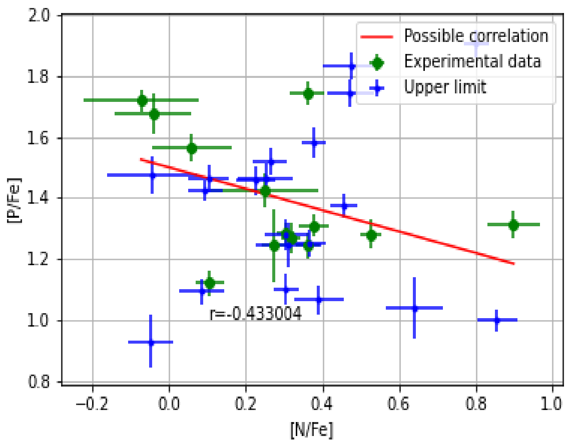
As said before, we analysed the correlation between P/Ce and other abundances. Here we presents this additional results. It's important to remember that also these measurements were plagued by upper limit (plotted in blue)



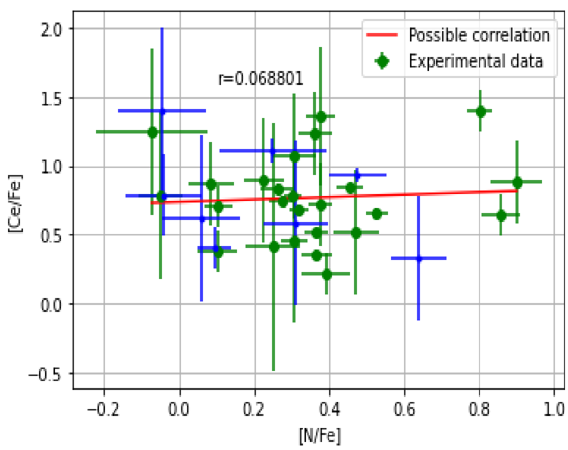
(a) Correlation between Phosphorous and Alpha elements



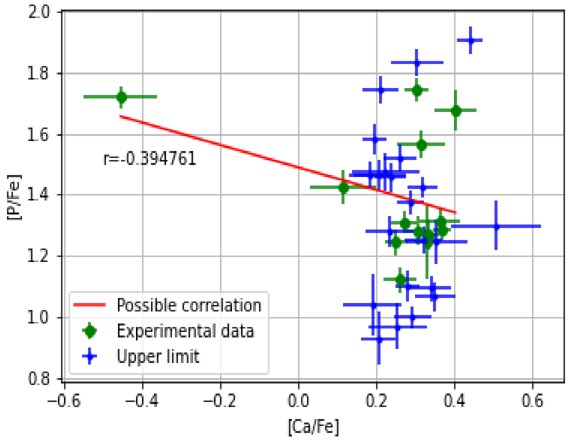
(b) Correlation between Cerium and Alpha elements



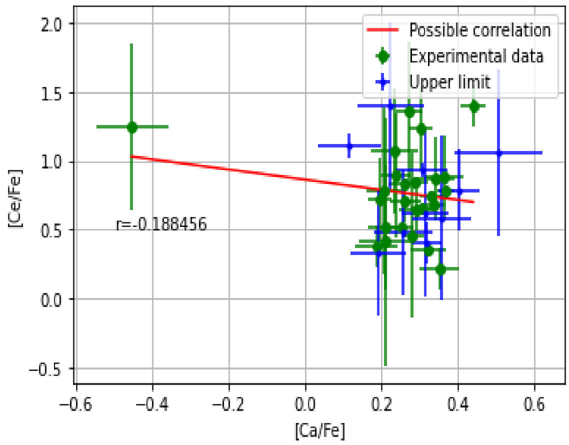
(a) Correlation between Phosphorous and Nitrogen



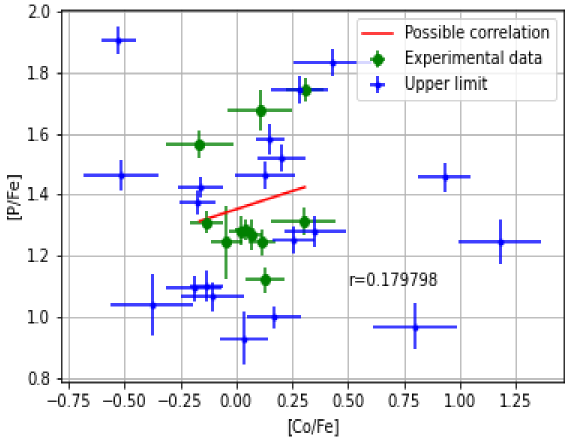
(b) Correlation between Cerium and Nitrogen



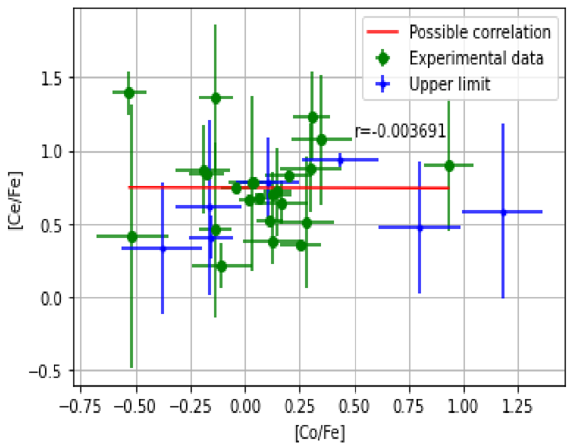
(a) Correlation between Phosphorous and Calcium



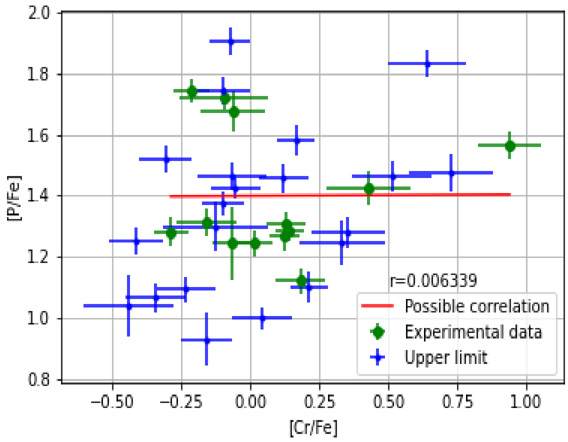
(b) Correlation between Cerium and Calcium



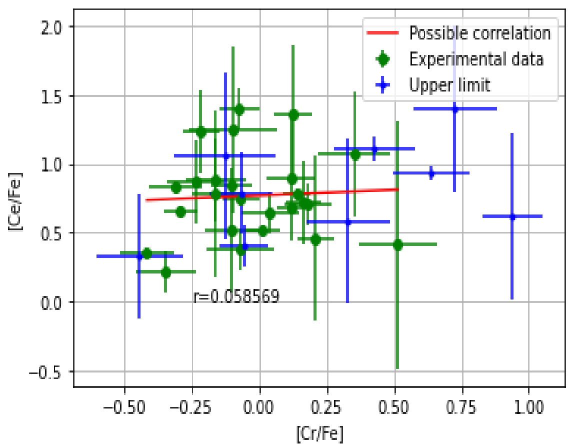
(a) Correlation between Phosphorous and Cobalt



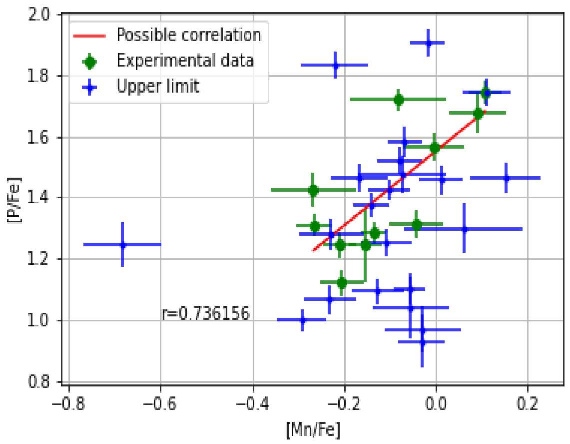
(b) Correlation between Cerium and Cobalt



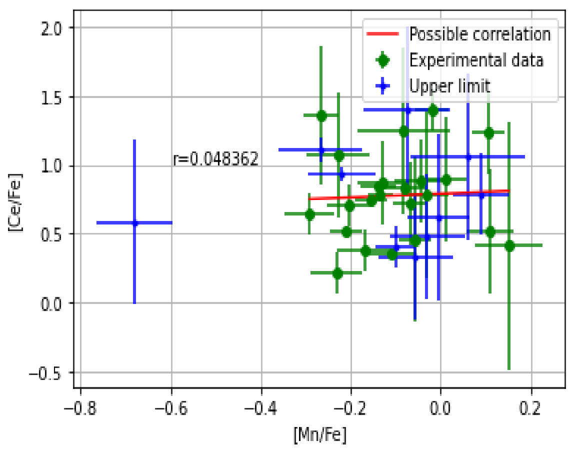
(a) Correlation between Phosphorous and Chrome



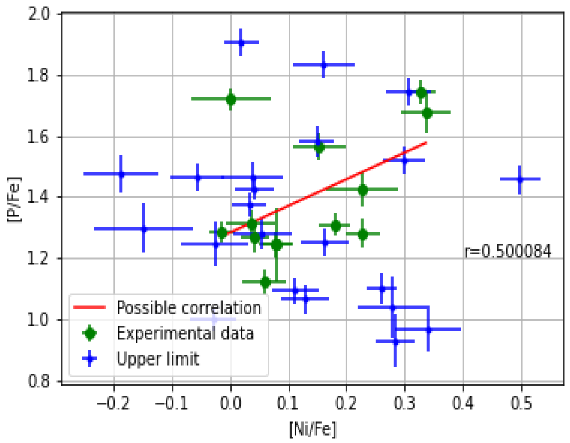
(b) Correlation between Cerium and Chrome



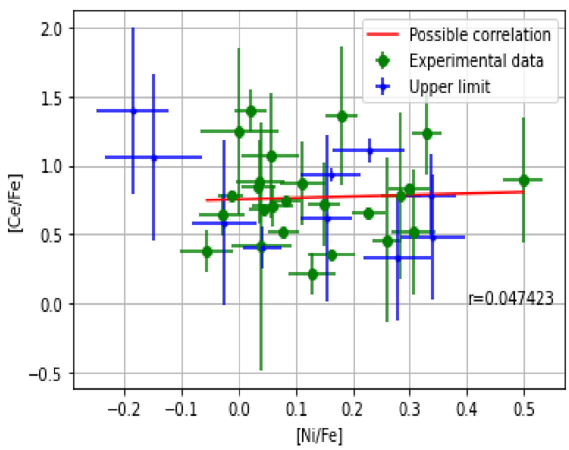
(a) Correlation between Phosphorous and Manganese



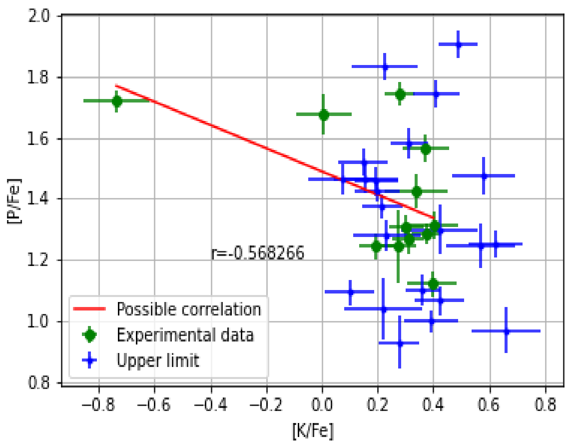
(b) Correlation between Cerium and Manganese



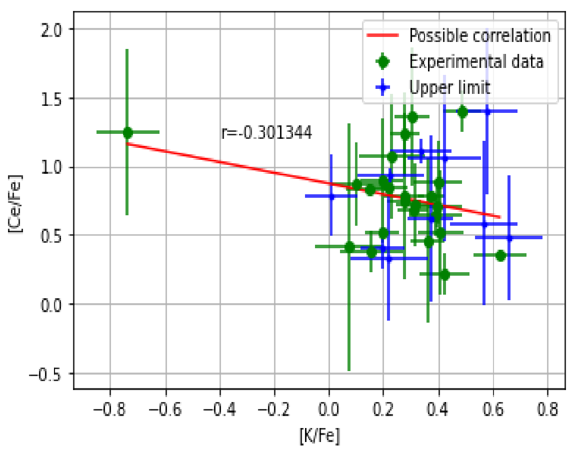
(a) Correlation between Phosphorous and Nickel



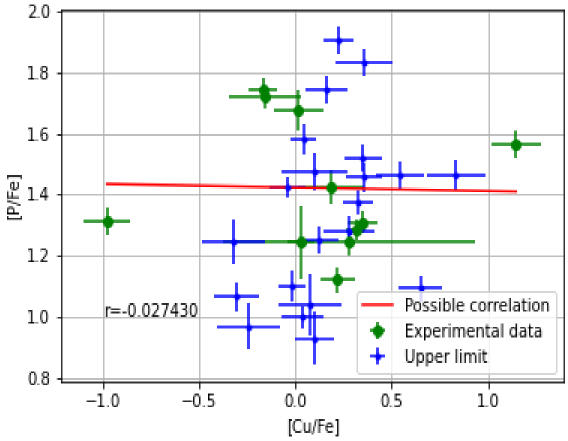
(b) Correlation between Cerium and Nickel



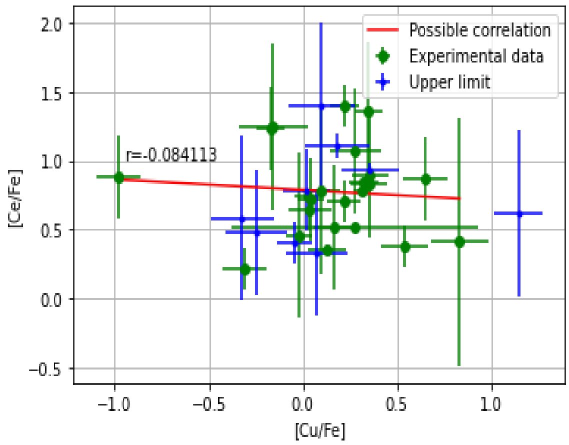
(a) Correlation between Phosphorous and Potassium



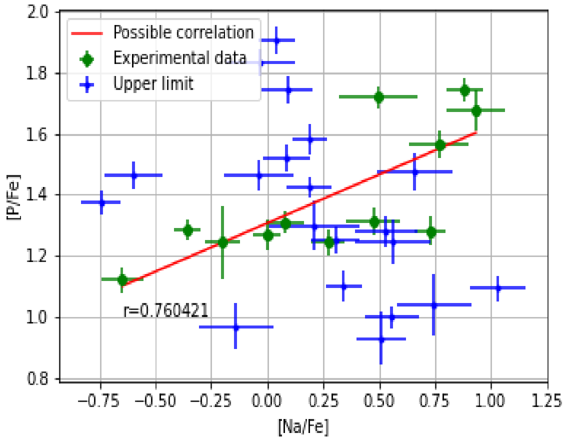
(b) Correlation between Cerium and Potassium



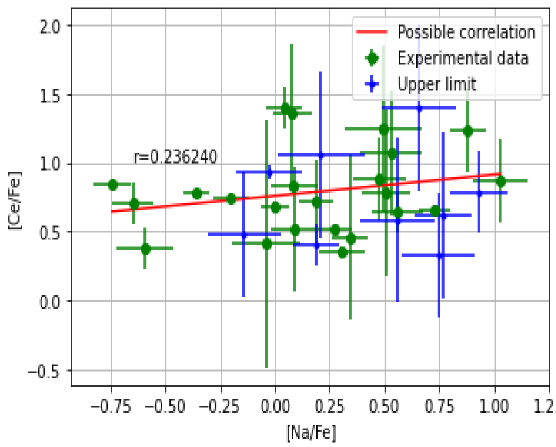
(a) Correlation between Phosphorous and Copper



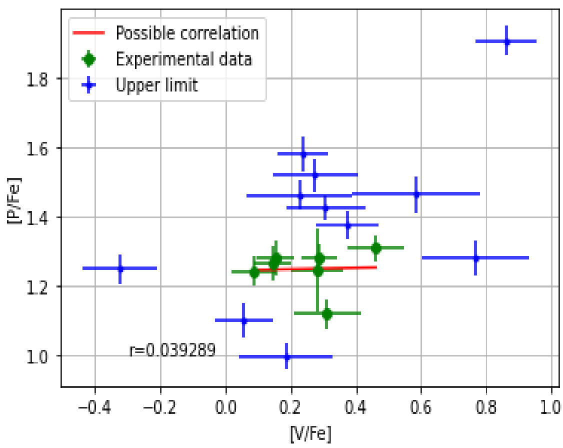
(b) Correlation between Cerium and Copper



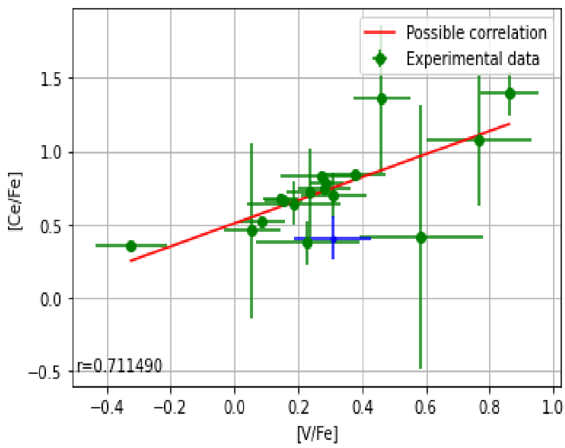
(a) Correlation between Phosphorous and Sodium



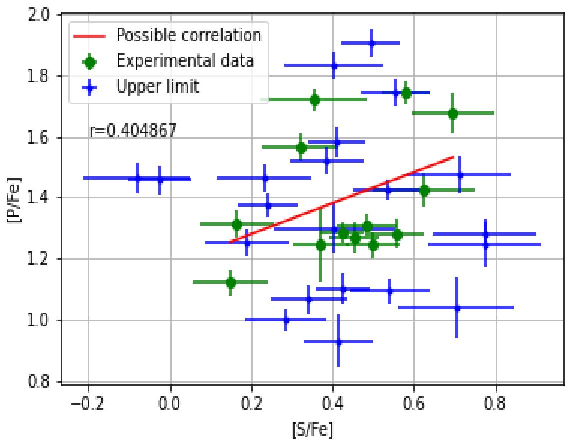
(b) Correlation between Cerium and Sodium



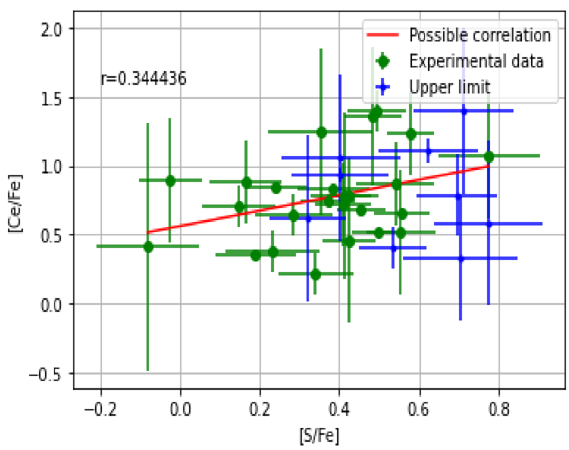
(a) Correlation between Phosphorous and Vanadium



(b) Correlation between Cerium and Vanadium



(a) Correlation between Phosphorous and Sulphur



(b) Correlation between Cerium and Sulphur

5.2 Appendix B: Names, atmospheric data and abundance of Phosphorus and Cerium of the analysed stars

Name	Temperature	log g	M/H	Phosphorous	Cerium
2M02175837-7313144	4.147,1255	1,1603875	-0,92902154	1,28402154	0,78402154
2M09133506+2248579	5.469,402	2,2426965	-1,38536160	1,4253616	<=1,1053616
2M12242950+4408525	5.451,229	3,1737232	-1,4786615	1,7186615	1,2486615
2M12443130-0900220	5.505,2524	3,0894365	-1,3948616	<=1,4748616	<=1,3948616
2M13303961+2719096	5.147,5425	2,8895993	-0,954197	<=1,064197	0,214197
2M13472354+2210562 º	5.418,0127	2,303917	-1,3142616	1,5642616	<=0,6142616
2M13535604+4437076 º	5.150,6763	2,466051	-0,91420156	1,74420156	1,23620156
2M14513934-0602148	5.011,6855	2,3176212	-1,4053615	<=1,2453615	<=0,5853615
2M14533964+4506180	5.104,8887	2,446529	-1,2987616	<= 0,9687616	<= 0,4787616
2M15170852+4033475	5687,61	2,274259	-1,4384615	<= 1,2984615	<= 1,0584615
2M15243300+2819313	4.636,041	2,0698051	-0,93017155	<= 1,10017155	0,46017155
2M15275895+4226412	4.275,604	1,2409714	-1,2033615	1,2433615	0,5158615
2M16013102+0618450	4.910,327	2,3149052	-1,21366	<=1,09366	0,86866
2M16130340-3144580	5.067,175	2,3418634	-1,00376	<= 1,83376	<=0,93376
2M16241820-2145485 *	4.006,5645	0,5136075	-1,20596	<= 0,72596	0,55596
2M16441013-1850478	4.706,766	2,117731	-0,889112	1,519112	0,829112
2M16483594-0150117	4.751,557	2,2370236	-0,925792	<= 1,425792	<=0,405792
2M16543450-0429397	5.171,836	2,407289	-0,873662	<=1,743662	0,513662
2M16544476-3939140	4.855,021	2,258393	-1,10056	<=1,04056	<=0,33056
2M16595910+1127496	5.128,497	2,420613	-0,705532	1,455532	0,895532
2M17161376-2910175	4.280,272	1,5412282	-0,960532	1,120532	0,700532
2M17171046-3007398 *	4.229,5234	1,3378177	-0,996812	<= 0,786812	0,701812
2M17183459+4302520 º	5.068,5557	2,8736806	-1,03606	1,67606	<= 0,78606
2M17255079-2029099	4.529,609	1,6951479	-0,905242	1,375242	0,841909
2M17265466-1331522	4.510,1904	1,8845245	-0,886102	1,906102	1,394852
2M17295157-3737045	4.567,0205	1,484524	-1,20026	<= 1,28026	1,07326
2M17421220-3443594	4.606,099	1,888838	-0,963502	1,463502	0,373502
2M17513049+5801309	4.988,635	2,4623582	-1,38926	<= 0,92926	0,77926
2M17572447-3056414	4.873,992	1,8769562	-1,22386	<= 1,46386	0,41386
2M18013098-3307263	4.268,7754	1,2258036	-0,939542	<= 1,579542	0,718842
2M18024132-2940238	4.763,641	2,174043	-0,978952	<= 0,998952	0,644975
2M18043255-4819138	4.312,481	1,2479963	-1,17126	<= 1,25126	0,353535
2M18091354-2810087 *	3.987,8542	0,7817935	-1,04666	0,26666	0,35666
2M18151248-4403407	4.452,6006	1,6274712	-1,05476	1,2447615	0,7447615

Name	Temperature	log g	M/H	Phosphorous	Cerium
2M18453994-3010465	3.977,1946	0,32883674	-1,24176	1,28176	0,660093
2M19105369+2717150	5.270,833	3,141436	-0,852962	1,312962	0,879662
2M19193412-2931210 *	4.999,254	2,241805	-1,15176	0,50176	0,63176
2M19214936-1232462 º	4.083,6162	0,76423234	-1,06916	1,26916	0,67466
2M22045404-1148287 ºº	4.577,8643	1,6439656	-1,25976	1,3097616	1,3585616

The stars signed with * are P-normal.

The sign '<=' indicates an upper limit.

The stars signed with º have been previously studied in Masseron et al.(2020a) [1]

The star signed with ºº has been previously studied in Masseron et al.(2020b) [3]

Name	Abundance (first line of P)	Abundance (second line of P)
2M02175837-7313144	5,715	Too much error
2M09133506+2248579	Too much error	5,356
2M12242950+4408525	5,6	Too weak
2M12443130-0900220	<=5,44	<=5,44
2M13303961+2719096	<=5,67	5,47
2M13472354+2210562 º	5,56	5,66
2M13535604+4437076 º	6,19	Too weak
2M14513934-0602148	<=5,2	<=5,2
2M14533964+4506180	<= 5,03	Too weak
2M15170852+4033475	<=5,22	Too weak
2M15243300+2819313	<= 5,53	Too weak
2M15275895+4226412	5,4	Too weak
2M16013102+0618450	<=5,24	Too weak
2M16130340-3144580	<= 6,19	<= 6,19
2M16241820-2145485 *	<= 5,05	<= 4,88
2M16441013-1850478	<= 5,39	5,99
2M16483594-0150117	<= 5,86	Too weak
2M16543450-0429397	<= 6,23	Too weak
2M16544476-3939140	<= 4,7	<= 5,3
2M16595910+1127496	<= 6,01	6,11
2M17161376-2910175	Too much error	5,2
2M17171046-3007398 *	<=5,15	Too weak
2M17183459+4302520 º	6	Too much error
2M17255079-2029099	<= 5,71	5,83
2M17265466-1331522	<= 6,08	6,38
2M17295157-3737045	<= 5,44	Too weak

Name	Abundance (first line of P)	Abundance (second line of P)
2M17421220-3443594	<= 5,67	5,86
2M17513049+5801309	<=4,9	Too weak
2M17572447-3056414	<=5,4	<=5,6
2M18013098-3307263	<= 6	Too weak
2M18024132-2940238	<= 5,38	5,58
2M18043255-4819138	<= 5,44	Too weak
2M18091354-2810087 *	<= 5,31	4,58
2M18151248-4403407	5,55	Too much error
2M18453994-3010465	5,4	5,4
2M19105369+2717150	5,82	Too weak
2M19193412-2931210 *	4,71	Too weak
2M19214936-1232462 º	5,56	Too much error
2M22045404-1148287 ºº	Too much error	5,41

The term 'Too weak' indicates a lines so weak that BACCHUS can't plot it at all.

The term 'Too much error' indicates a line that was discarded because its plots shows sign of pollution or because the line was weak and the code ended up creating a model without sense.

Standard deviation for the first line: 0,517428

Standard deviation for the second line: 0,622397

Standard deviation for phosphorous: 0,342642

Name	First line of Ce	Second line of Ce	Third line of Ce	Fourth line of Ce
2M02175837-7313144	Too weak	1,495	1,39	1,42
2M09133506+2248579	Too weak	<=0,94	<=1,4	<=1,3
2M12242950+4408525	<= 1,55	1,35	<= 1,65	<= 1,65
2M12443130-0900220	<= 1,58	<= 1,58	<= 1,78	<= 2,08
2M13303961+2719096	<= 1,06	0,84	<= 1,26	<= 1,56
2M13472354+2210562 º	<= 0,88	<= 1,08	<= 1,08	<= 1,68
2M13535604+4437076 º	<= 1,47	1,902	<=1,47	<= 1,47
2M14513934-0602148	Too weak	<= 0,96	<= 0,76	<= 1,26
2M14533964+4506180	<= 0,76	<= 1,22	<= 1,12	<=1,42
2M15170852+4033475	<= 0,9	<= 1,2	<=1,2	<=1,6
2M15243300+2819313	0,87	1,23	1,23	<= 1,23
2M15275895+4226412	0,77	0,97	0,86	0,97
2M16013102+0618450	<= 0,66	<= 0,76	1,235	<= 1,18
2M16130340-3144580	Too weak	<=1,31	<= 1,51	<=1,71
2M16241820-2145485 *	<= 0,63	0,93	0,93	<= 0,63
2M16441013-1850478	Too weak	1,2	1,62	1,74
2M16483594-0150117	Too weak	<=1,06	<= 1,06	<= 1,26
2M16543450-0429397	Too weak	<=1,22	Too much error	1,82

Name	First line of Ce	Second line of Ce	Third line of Ce	Fourth line of Ce
2M16544476-3939140	<=0,81	<=1,11	<= 1,11	<= 1,49
2M16595910+1127496	1,77	<=1,37	<= 1,37	<= 1,87
2M17161376-2910175	1,16	1,48	<= 0,99	<=1,09
2M17171046-3007398 *	1,13	1,23	1,33	1,45
2M17183459+4302520 º	<= 1,33	<= 1,73	<=1,73	<= 1,93
2M17255079-2029099	Too weak	1,58	1,4	1,57
2M17265466-1331522	1,87	2,095	2,07	2,32
2M17295157-3737045	1,453	<=0,72	<=0,72	<= 0,92
2M17421220-3443594	Too weak	1,51	1,11	<= 0,99
2M17513049+5801309	<=0,88	0,97	<= 0,98	<= 0,98
2M17572447-3056414	Too weak	<=0,77	<= 0,77	<=0,87
2M18013098-3307263	<= 0,62	1,438	1,32	1,32
2M18024132-2940238	1,053	1,332	1,408	1,6
2M18043255-4819138	0,943	1,23	1,137	1,17
2M18091354-2810087 *	Too weak	1,39	1,33	<= 0,89
2M18151248-4403407	1,27	<=0,87	<= 0,97	<=0,97
2M18453994-3010465	Too weak	1,07	0,886	1,039
2M19105369+2717150	1,44	1,64	1,74	2,04
2M19193412-2931210 *	1,06	<=1,16	Too much error	<=1,46
2M19214936-1232462 º	1,01	1,3	1,133	1,299
2M22045404-1148287 ºº	1,465	1,8042	1,706	1,74

Standard deviation for the first line: 0,346135

Standard deviation for the second line: 0,318386

Standard deviation for the third line: 0,334641

Standard deviation for the fourth line: 0,376092

Standard deviation for cerium: 0,306365

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Line lists included in BACCHUS: To work, BACCHUS needs atomic and molecular line list, i.e. a list of allowed and forbidden atomic transitions. The line lists used are liste here below.

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