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The ionization and abundance of C and Si in QSO absorbers

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Abstract

We have analyzed high resolution data of absorption lines of Si and C in the absorption systems observed in the spectra of QSOs, in order to study the ionization state and the overabundance of Si with respect to C in the absorbers and also to study the change in these properties with redshift. No correlation is found between column density ratios of Si IV to C IV of intervening systems and redshift. The data do not provide any evidence for an abrupt change in the values of the ratio at any particular redshift unlike that for Lyman alpha forest clouds. We have compared the observed ratios of column densities of Si II and Si IV and of Si IV and C IV in different classes of absorption systems with predictions of photo ionization models for different shapes of the background radiation field. Overabundance of Si over C can be ruled out in several of the intervening systems for any shape of the background radiation. For these systems we can also rule out any contribution from the stellar sources to the background, which is then entirely from the AGNs. No overabundance is needed in other intervening systems if the radiation field from stellar sources contributes significantly to the UV background. Overabundance is, however, present in Lyman alpha forest clouds at redshifts larger than 3 and in systems associated with the QSOs. For all the intervening systems a minimum of 10 % of the background is contributed by the AGNs.

Key words: Galaxies: Quasars: absorption lines — Galaxies: Abundances — Galaxies: intergalactic medium

1. Introduction

Quasar absorption lines have proved to be extremely useful probes of the high redshift Universe. In recent years important information has been obtained, among other things, about the chemical abundances in galaxies at high redshifts. Evidence for evolution in chemical abundances in these galaxies, the abundance increasing with decreasing redshift, has been obtained (i) directly, through abundance determination in damped Lyman alpha systems (DLAS) at different redshifts (Pettini etal 1995; Lu etal 1996), and (ii) indirectly, from the variation of the number of C IV systems and Lyman limit systems (LLS) per unit redshift interval, per line of sight as a function of redshift (Steidel, Sargent & Boksenberg, 1988; Khare & Rana, 1993). The absorption line studies have also given clues for understanding the history of stellar nucleosynthesis (Lauroesch etal 1996). Lu etal (1996), through an analysis of the observed abundances of 23 DLAS, have shown that the relative abundance patterns of several elements are consistent with their formation in Type II supernovae. In particular, they find evidence for [Si/Fe] $\simeq 0.4$, which is very similar to the overabundance of Si found in the Galactic halo stars. Evidence for overabundance of Si with respect to C, by a factor of three, has also been found in Lyman alpha forest clouds (LAFCs) (Songaila & Cowie, 1996; hereafter SC96) as well as in some intervening and associated systems (Petitjean, Rauch & Carswell 1994, Savaglio etal 1996).

The shape of the UV background radiation is important in deciding the ionization balance of various elements in QSO absorbers. This radiation most likely originates in AGNs, however, a significant contribution from young star forming galaxies can not be ruled out (Bechtold etal 1987; Bajtlik, Duncan & Ostriker, 1988, Madau & Shull, 1996). The shape of the background radiation not only depends on the relative contribution from these two sources but is also decided by the absorption by the material giving rise to QSO absorption lines. Recent observation of a significant Gunn-Peterson optical depth ($\tau \geq 1.7$ for redshift > 3.0) at the wavelength of the Lyman alpha line of He II towards a QSO (Jackobsen etal 1994) indicates the presence of a large break by factors > 25 (Madau & Meiksin, 1994) at the He II ionization edge. Similar break was also found necessary in order to explain the observations of column density of C and Si ions in the Lyman alpha forest lines (SC96) as well as in some heavy element systems (Savaglio etal 1996).

The shape of the background UV field due to AGNs, at various redshifts, taking into account the absorption and reemission from the QSO absorbers has been recently determined by Haardt & Madau (1996).

A lower He II optical depth ($\tau \simeq$1.0) at somewhat lower redshift (z $\simeq$ 2.5) has been observed by Davidsen etal (1996) towards HS1700+64, indicating a higher degree of ionization of He below z=3.0. Evidence for the lowering of the optical depth of the Universe to the He II ionizing photons below z=3.1 has also been obtained by SC96, from the observations of the column density ratios of Si IV and C IV in the LAFCs. They find an abrupt change in the values of this ratio at z = 3.1, the ratio being higher at higher redshifts. As the absorbers producing heavy element systems in the QSO spectra are also most likely ionized by the intergalactic UV background (Srianand & Khare, 1995), it may be of interest to look for signatures of a change in opacity of the Universe in the absorption line data of heavy element systems.

A correlation with redshift of the ratio, of equivalent widths of lines of Si IV (λ1393) and C IV (λ1548) in the heavy element systems, observed at intermediate resolution, the ratio increasing with increasing redshift, was found by Bergeron & Ikeuchi (1990). High resolution data (FWHM $\leq$ 23 km s^{-1}) for the column densities of C IV and Si IV are now available for a number of QSOs. In this paper we present the analysis of these data in order to understand the ionization of these elements at different redshifts as well as to study the overabundance of Si with respect to C in these systems. In section 2 we investigate the presence of a correlation between ratios of column densities of Si IV and C IV and redshift. In section 3 we present the results of photoionization models and compare these with the observations. Conclusions are presented in section 4.

2. Correlation Analysis

We have collected from the literature (Cristiani etal 1995, Savaglio etal 1996, Petitjean, Rauch & Carswell 1994, Petitjean & Bergeron 1994, Giallongo etal 1993, Fan & Tytler 1994, Tripp, Lu & Savage 1996, Prochaska & Wolfe 1996, Wampler 1991, Wampler, Petitjean & Bergeron 1993) the column densities of C IV and Si IV observed in the heavy element systems towards several QSOs observed with FWHM between 8 to 23 km s^{-1}. The total sample consists of 30 non-DLA intervening systems including 10 for which only upper limits on the Si IV column density are available. In addition we have 23 components of intervening DLAS.

We note that the data are rather inhomogeneous in the sense that the observations have been made at somewhat different resolutions and with different S/N values. This in principle can introduce an incompleteness in the sample as the lower limit for detection of lines for different QSOs may be different. This could affect the correlation analysis if the incompleteness introduces a redshift dependence of the minimum detectable column density, as a result, introducing an artificial redshift dependence of the column densities in the sample. In order to check this we performed Spearman rank correlation tests for redshift dependence of column densities of C IV for the non-DLA and DLA intervening systems separately. No such correlation was found, the chance probabilities being 0.53 and 0.38 respectively. Similar exercise for column densities of Si IV also rules out any correlation with redshift, the chance probabilities being 0.84 and 0.74 respectively. We thus believe that our data, though inhomogeneous, are not biased and can be used for the correlation analysis.

In Fig.1, we have plotted the ratios of column densities of Si IV and C IV, R, and the upper limits on R as a function of redshift for both categories of intervening absorption lines mentioned above. The non-DLA intervening systems are believed to be produced by the gas in the halos of absorbing galaxies and are most likely irradiated by intergalactic UV background radiation (Srianand & Khare, 1995). Most DLAS have components with high as well as low ionization states. These presumably arise in the halo and disk components of the absorbing galaxy (Wolf etal 1996). Lu etal (1996) have pointed out that the Si IV and C IV absorption profiles of DLAS always resemble each other and have a different appearance from the low-ion absorption lines. They suggest that the bulk of the high-ions could arise from the halo clouds. The DLA components showing high-ions thus, very likely, belong to the same population as that of the non-DLA intervening systems. We can therefore combine the non-DLA intervening systems and the DLA components showing high-ions together, while looking for the redshift dependence of column density ratios of high-ions.

Spearman rank correlation tests for both categories of intervening systems taken together as well as taken separately rule out any correlation between R and z, the values of chance probability being 0.61, 0.229 and 0.213 for all intervening systems, non-DLA intervening systems and DLA intervening systems respectively. Generalized Kendall test (Isobe, Feigelson & Nelson, 1986) applied to the 53 values, including upper limits, for all intervening systems and separately to the 30 values, including upper limits, for the non-DLA intervening systems gives probability of 0.684 and 0.174 respectively, which again indicate the absence of any correlation. We also tried to study the correlation for systems restricted to smaller redshift ranges. No correlation was however seen. KS tests rule out any abrupt change in R values at any particular redshift. Note that Spearman rank correlation test applied to the values of R observed in LAFCs by SC96 gives chance probability equal to 4.27$\times$10^{-3}, showing a good correlation.

3. Ionization State of the Absorbers and the Background Field

For 14 systems (7 DLA intervening, 5 non-DLA intervening and 2 associated systems) the column density of Si II is also known. We can thus try to investigate the shape of the UV radiation field as well as the Si overabundance with respect to C in these systems. The neutral hydrogen column density is not known for several of these systems. However, as will be seen below, the exact value of this column density is not very important. We have constructed a grid of photoionization models using the code 'cloudy 84' written by Prof. G. Ferland, for three values of neutral hydrogen column density, $N_{\rm H\ I}$, typical of DLAS (10^{20} cm^{-2}), of LLS (3.0×10^{17} cm^{-2}) and of high ionization intervening systems ($\leq 10^{16}$ cm^{-2}), for different shapes of UV radiation field. Heavy element abundance was assumed to be one thirtieth of the solar value, with solar values of relative abundances of different chemical elements. The results, which we present in the form of column density ratios, however, are not sensitive to the heavy element abundances as well as the particle density. The ratios are also independent of $N_{\rm H\ I}$ for $N_{\rm H\ I} \leq 10^{16}$ cm s^{-1}. The ratios for these three values of $N_{\rm H\ I}$ bracket the ion ratios for all the intervening and associated systems considered here.

Heavy element absorbers have complex structures and it has been argued that the lines of different ions may be produced in different regions of the absorbers and also it is possible that a hot collisionally ionized phase may exist in the absorbers (Giroux, Sutherland & Shull, 1994). However, here, we are restricting our analysis to high resolution observations. We can therefore assume that lines produced in individual clouds have been resolved and the the results of 'cloudy' models, which take into account the radiation transfer inside a cloud, can be applied to the column densities seen in individual clouds. Also as we are restricting to the ions of Si II, Si IV, C II and C IV only, the contributions from the collisionally ionized phase may not be very important.

In Fig 2 we have plotted R vs. the column density ratios of Si II to Si IV, S, for the three values of neutral hydrogen column densities mentioned above. Fig 2a, 2b and 2c are for different shapes of the background UV radiation field; these are (a) power law with a slope of -1.5, which corresponds to typical unprocessed AGN spectra, (b) AGN background filtered through the intervening galactic and intergalactic absorbers as given by Haardt & Madau (1996, hereafter HM96) for the redshift of 2.5 and (c) power law with slope of -1.5 and with a cutoff at 4 Ryd, which will be the case if the He II ionization fronts of different QSOs have not yet overlapped at the redshift of the absorbers as suggested by SC96. We have also plotted the observed ratios with their error bars. The observed values have large errors. These are essentially a result of the fact that the lines are often saturated and profile fitting analysis can yield acceptable fits to the observed profiles over a range of column density values. However, as will be seen below, definite conclusions regarding the overabundance and the background can be drawn from the comparison of the observed values with the results of the photoionization models. As seen from the figure the shape of the spectrum makes significant difference to the lower values of the ratios. Pure power law produces very low values of R for S <0.1. Values of R for S <0.1 increase with increase in the magnitude of the break at the He II ionization edge, however, the maximum value of R is around 0.1 for infinite break. For larger values of S, spectra of HM96 gives higher values of R compared to all other spectral shapes. This is due to the decrement in spectra of HM96 short wards of hydrogen ionization edge.

As the heavy element absorption systems are associated with galaxies, it is possible that the radiation field incident on the absorbers may get a significant contribution from the stellar sources. As the stellar radiation field has very few photons beyond 3 Ryd, high values of R are possible if the UV field is dominated by galactic contribution. We have constructed photoionization models for clouds irradiated by different proportions of galactic and UV background (HM96) fields. Steidel (1995), from his study of a large sample of galaxies associated with QSO absorption lines, finds these galaxies to be normal in the sense of their star formation rates. We have therefore taken the shape of the galactic field to be that given by Bruzal (1983). Pure galactic background can not reproduce the observed ratios as it produces much higher values of R, compared to the observed values. A contribution to the radiation field from the intergalactic AGN background is necessary. In Figure 2d we have plotted the column density ratios calculated for the case when the ratio of the flux due to galactic radiation is 90% of the total flux at 1 Ryd, the rest 10% being contributed by the AGN background (HM96). The observed values of R for all the intervening systems are lower than the results of this model. We can thus conclude that a minimum of 10 % (and possibly a much larger fraction, as will be seen below) of the background radiation incident on the intervening absorbers is contributed by the AGNs.

3.1. Non-DLA intervening systems

Assuming the shape of the radiation field incident on the absorbers producing these lines to be that given by HM96, the observed ion ratios for two of the systems, with redshifts 2.1 and 2.77, are consistent with the results of the photoionization models. For other three systems, one with redshifts 2.1 and two with redshifts 2.7, the observed values of R, even after allowing for the errors are considerably smaller than the model predictions. Adding galactic radiation field to that of HM96 can only increase R, thereby increasing the discrepancy. For other shapes of the background radiation the observed ratios for four of the five systems are either consistent with or are lower than the model values. For three of these systems we can definitely rule out overabundance of Si w.r.t. C for any shape and intensity of the background radiation. For these systems we can also rule out any contribution of the galactic field to the radiation field. This also holds for the remaining two systems if the shape of the background is that given by HM96. Overabundance of Si by factors > 1.5 is necessary only for one system for other shapes of the background. Alternatively a small contribution from the stellar sources is required.

3.2. DLA intervening systems

For two of the systems, with redshifts 3.08 and 3.39, we can rule out the overabundance of Si for any shape of the background. Between the three shapes of the background radiation, the observed ion ratios for other 3 sytems with redshifts between 1.7 and 3.38, are consistent with the results of the photoionization models, without requiring any overabundance of Si or any contribution from the galactic sources. For the remaining two systems, with redshifts 2.84 and 3.39, the observed values of R are higher than model results for all the three shapes of the background. An overabundance of Si by factors > 1.5 or a significant contribution (Fig.2d) from the galactic sources is needed.

3.3. Associated systems

For the two associated systems with redshifts around 3.0, S is smaller than 0.1 and R is larger than 0.3. Associated systems being close to the QSO are expected to be ionized by pure power law radiation field. Such a field, produces (Fig. 2a) smaller values of R. The errors in the observed ratios are, however, too large and within those error bars the ratios may be consistent with the model results. However, though no overabundance is warranted by the observations due to the large uncertainty in the observed values, one can not rule out the possibility of Si being overabundant w.r.t. C by a large (>10) factor in these systems.

3.4. Lyman alpha forest clouds

In Fig 3 we have plotted the observed ratios, R, vs. the ratio of column densities of C II to C IV in Lyman alpha forest lines observed by SC96. The theoretical results, assuming the UV background near the Lyman alpha absorbers is purely from AGNs, for four spectral shapes (i) power law with a slope of -1.0 (ii) power law with a slope of -1.5 (iii) power law with a slope of -1.5 with a cutoff at 4 Ryd and (iv) field of HM96, are also plotted for $N_{\rm H\,I} = 10^{16}$ km s^{-1}. These results are independent of $N_{\rm H\,I}$ for $N_{\rm H\,I} \leq 10^{16}$ km s^{-1}. No overabundance of Si is required for half of the LAFCs which are mostly at redshifts smaller than 3.1 (SC96). The column densities for these systems are consistent with radiation field without any break at 4 Ryd. The amount of overabundance of Si needed for the other systems (mostly at redshifts lager than 3.1) does depend on the shape of the background and is smaller than a factor of 2 if a complete cutoff beyond 4 Ryd is assumed. We thus agree with the conclusion of SC(96) that the data do indicate a break in the background at 4 Ryd at high redshifts indicating a higher He II opacity at these redshifts.

4. Summary

We have analyzed high resolution observations of Si and C absorption lines in the QSO spectra in order to study the ionization state of absorbers and its change with redshift as well as to understand the overabundance of Si w.r.t. C.

The column density ratios of Si IV to C IV in LAFCs, show a correlation with redshift, as already noted by SC96. The observations of this ratio in 30 non-DLA intervening absorbers, as well as in 23 intervening DLAS, however, fail to show any correlation with redshift. The data do not show any abrupt change in the ionic ratios at any particular redshift, unlike the case of LAFCs noted by SC96. Thus there is no evidence for the change in the opacity of the Universe beyond 4 Ryd from the column density ratios of the heavy element line systems in the QSO spectra. It may be argued that the radiation field incident on the heavy element absorbers gets a significant contribution from local stellar sources, thereby diluting the effect which is seen in the LAFCs. Our analysis of ion ratios, presented in the previous section, argues against such a possibility. Srianand and Khare (1995) have also presented several arguments against such a possibility.

Observed column density ratios of Si IV to C IV and of Si II to Si IV in several intervening and associated systems have been compared with the results of photoionization models with different shapes of the incident radiation. In spite of a large uncertainty in the observed values, definite conclusions can be drawn about the overabundance. We find that for all the non-DLA intervening systems the overabundance of Si can be ruled out if the shape of the background is as given by HM96. For other shapes of the background also, the overabundance can be ruled out for three of the five systems. The other two systems may allow an overabundance by factors > 1.5 if no contribution from galactic sources to the background is assumed to be present. For two of the DLA systems also, overabundance can be ruled out for any shape of the background. Three other DLA systems are consistent with the observations for shape of the background given by HM96. The remaining two DLA systems, however, either require an overabundance by factors > 1.5 or a significant contribution from the galactic radiation to the background. The possibility of overabundance by factors > 10 can not be ruled out for the associated systems. Lyman alpha forest clouds at high (>3) redshifts do indicate an overabundance of Si over C as well as higher opacity of the Universe to radiation beyond He II ionization edge at these redshifts.

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Figure Captions

Fig 1: Plot of the ratio of column densities of Si IV and C IV with redshift. Triangles and circles represent non-DLA and DLA intervening systems respectively. Upper limits are indicated by T.

Fig. 2: Theoretical and observed column density ratios of Si IV and C IV vs that of Si II and Si IV. The dotted line is for $N_{\rm H\ I} \leq 10^{16}$ cm^{-2}, solid line is for $N_{\rm H\ I} = 3.0 \times 10^{17}$ cm^{-2} and the dash-dotted line is for $N_{\rm H\ I} = 10^{20}$ cm^{-2}. Circles correspond to the DLAS, squares correspond to the associated systems and triangles correspond to the non-DLA intervening systems. The shape of the UV continuum for Fig 2a, 2b and 2c is power law with slope =-1.5, Haardt & Madau (96) spectra for redshift of 2.5 and power law with slope =-1.5, with a cutoff at 4 Ryd, respectively. Fig 2d shows the results for a combined background field due to galaxies (90% at 1 Ryd) and that given by Haardt & Madau (96) at the redshift of 2.5 (10% at 1 Ryd). Horizontal dashed lines indicate the range of observed values.

Fig. 3: Theoretical and observed (SC96) column density ratios of Si IV and C IV vs that of C II and C IV for Lyman alpha forest lines for different shapes of UV background for $N_{\rm H\ I} \leq 10^{16}$ cm^{-2}. Solid line is for Haardt & Madau (96) spectra for redshift of 2.5; dashed line is for power law with slope of -1.0; dotted line is for power law with slope of -1.5 and dash-dotted line is for power law with slope of -1.5 with a cutoff at 4 Ryd.

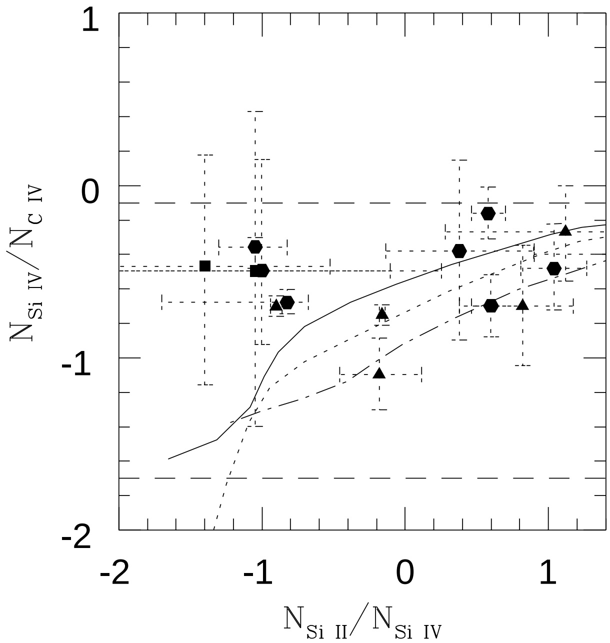
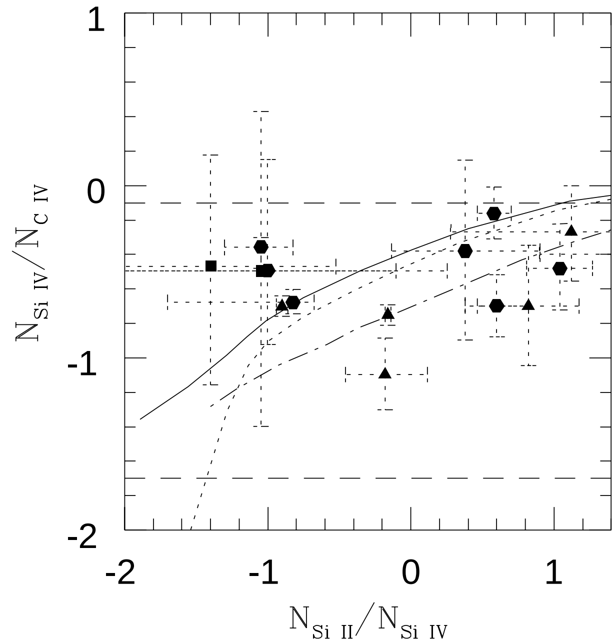


Fig 2a



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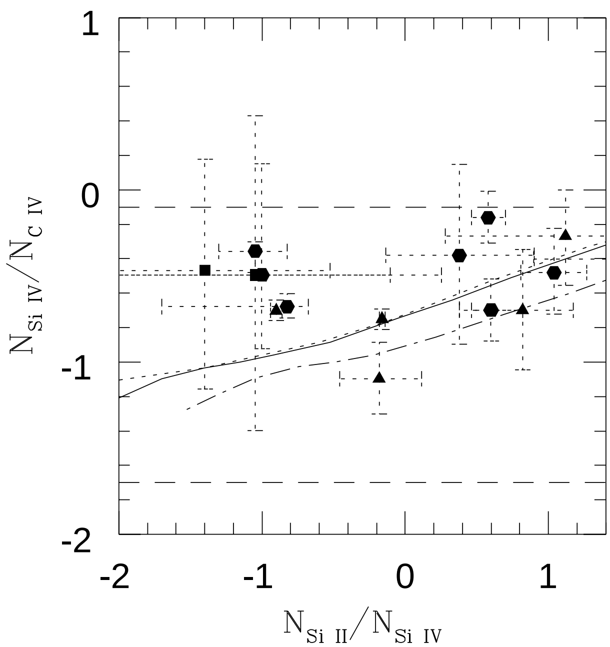

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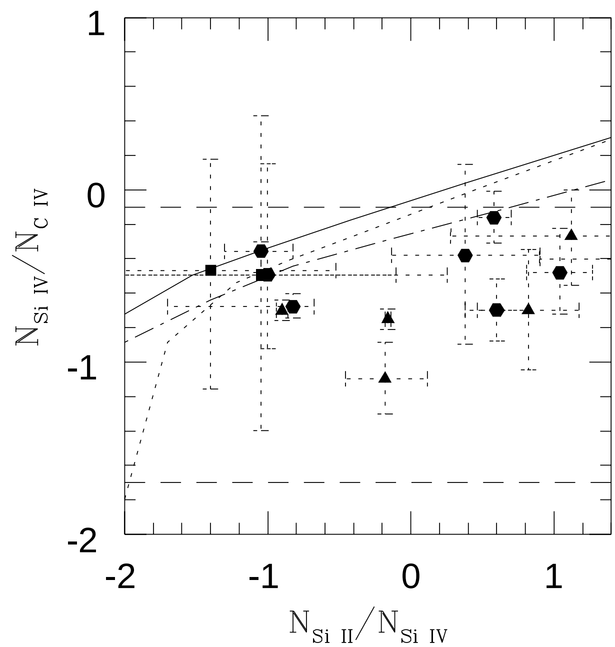

Fig 2d

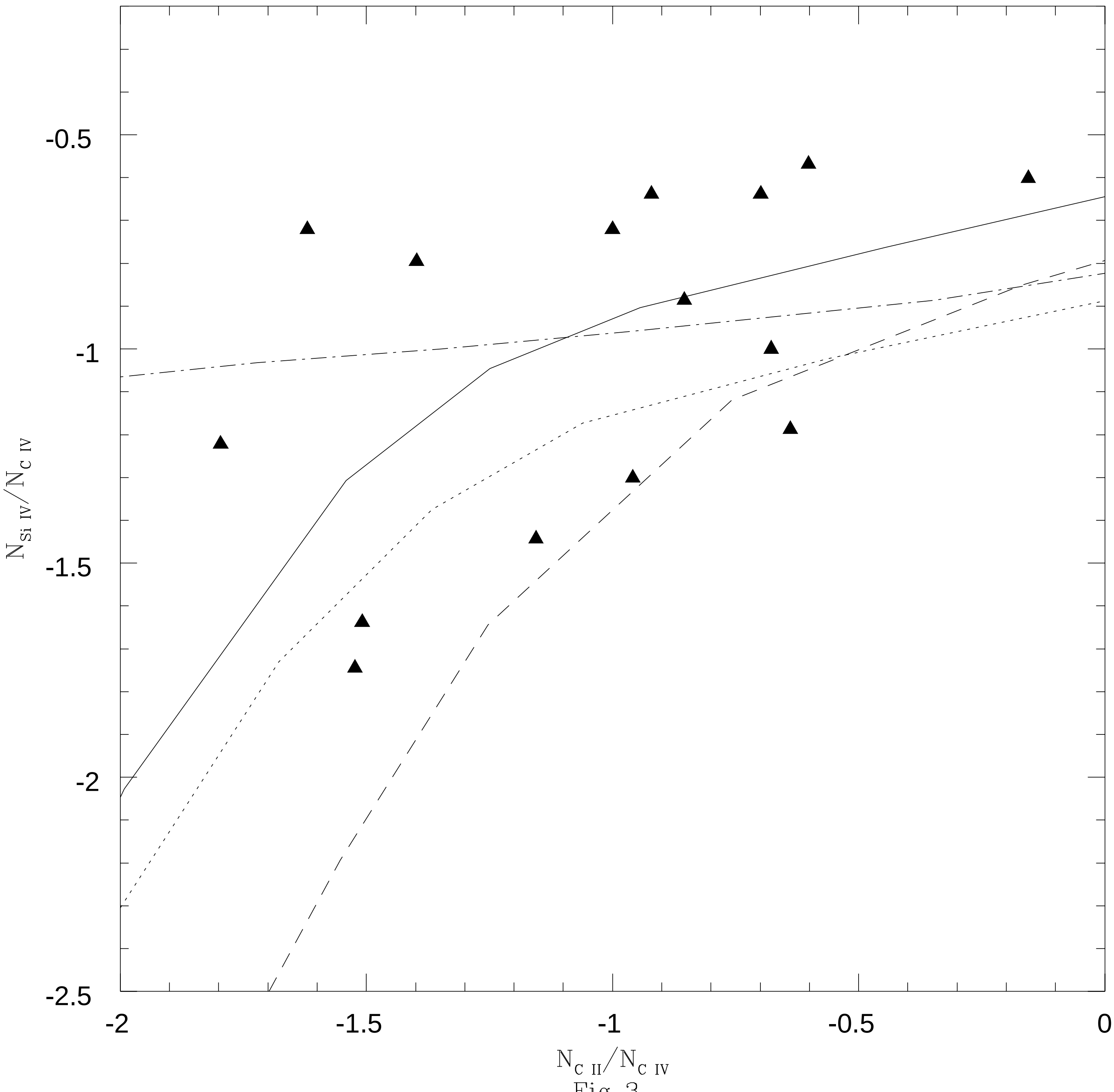

Fig 3

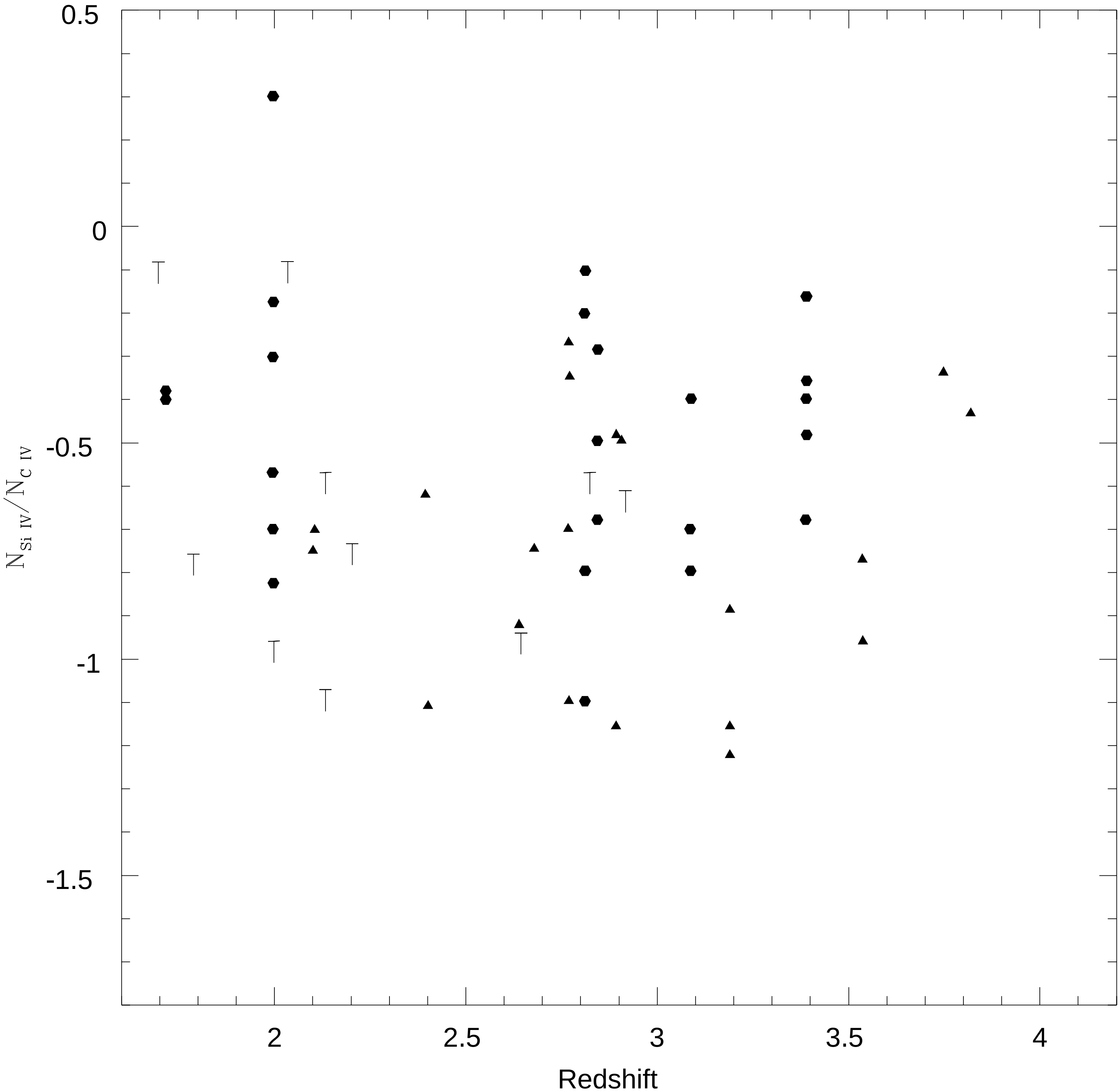

Fig 1