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Enhanced heavy magnesium isotopes in quasar absorption systems and varying alpha

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Abstract. We recently reported the analysis of a large sample of quasar absorption systems for varying α. The whole sample comprises data from UVES/VLT and HIRES/Keck in equal proportions, totalling some 300 measurements. Neither sample alone favours a non-varying α and both exhibit opposite trends. Since both samples are of comparable size, taken as a whole, the sample shows no clear, simple redshift evolution, thus could suggest 2 different systematic effects, one from each instrument/telescope, which approximately cancel. An alternative possibility is that α varies spatially over cosmological scales. The angular dependence of the data is well-fitted by a simple spatial dipole, with amplitude that increases with redshift. The data also favour a low-redshift monopole term, which had long-been suspected as being a systematic associated with the assumption of terrestrial magnesium isotopic abundances. In this paper we show the data in fact do require enhanced ^{25,26}Mg relative to terrestrial, and that when the isotopic ratios are included as free parameters, the α-monopole term vanishes, leaving only a spatial dipole.

Key words. Cosmology: observations – Cosmology: first stars – Quasars: absorption lines – Galaxies: abundances

1. Introduction

Detailed spectroscopic modelling to determine the value of the fine structure constant, α, at high redshift, requires the isotopic abundances of the heavy elements transitions used. Recent statistical analyses of $\Delta\alpha/\alpha$ have used high-precision laboratory measurements of the isotope and hyperfine splittings, but since we have little knowledge of the relative isotopic abundances at high redshift, terrestrial values have previously been assumed. However, significant departures from terrestrial values could emulate a varying-α alpha signal (Webb et al. 1999). Magnesium is particularly important in this respect since it is commonly used and because the isotopic and hyperfine spacings are comparable to wavelength shifts caused by an α-variation at existing sensitivity limits on $\Delta\alpha/\alpha = (\alpha_z - \alpha_0)/\alpha_0 \sim 10^{-6}$.

Here we report the preliminary results from a large analysis of Mg isotopes in quasar absorption systems over the redshift range $0.4 \lesssim$

$z_{abs} \lesssim 2$. Our sample is a subset of that used in (King et al. 2012).

2. Fitting the magnesium isotopes

The fitting procedure used to derive the magnesium relative isotopic abundances is an extension of the methods most recently described in detail in King et al. (2012). The present article may be read in conjunction with that paper.

The isotope and hyperfine structures of the MgI 2853 and MgII 2796/2803 transitions have been well-resolved in laboratory experiments (Drullinger et al. 1980; Pickering et al. 1998; Batteiger et al. 2009). Table B1 of King et al. (2012) lists the atomic data used here.

The sample of MgII quasar absorption systems used here is a subset of the King et al. (2012) sample. The spectral data was obtained using HIRES on the Keck telescope and UVES on the VLT. The spectral resolution in FWHM is ~8 times larger than the largest isotope splitting. Intrinsic line widths are comparable to the instrumental resolution. There is thus no prospect of resolving individual isotopes in quasar absorption spectra. Any individual absorption system is unlikely to yield a significant detection of non-terrestrial isotopic abundances unless the spectral signal-to-noise is exceptionally high.

The closeness of the magnesium isotopic lines implies that attempts to fit the 3 stable isotopes independently would suffer from severe degeneracy. We therefore did not fit all 3 isotopes independently, and instead made the approximation that the high redshift stellar enrichment processes scale ^{25}Mg and ^{26}Mg by the same factor relative to ^{24}Mg. Terrestrial abundances are $([^{24}\text{Mg}]:[^{25}\text{Mg}]:[^{26}\text{Mg}])_{\odot}$ = (0.79:0.10:0.11). Two analysis methods have been used, both using VPFIT (Carswell & Webb 2013). An assumption common to both methods is that the parameters [^{24}Mg], [^{25}Mg] and [^{26}Mg] are varied, subject to the scaling constraint above (i.e. we reduce the number of free parameters from 3 to 2), maintaining a fixed ratio for [^{25}Mg]/[^{26}Mg]=10/11. An additional consideration is the hyperfine splitting of [^{25}Mg], requiring the further constraint that the two hyperfine lines maintain a constant line strength ratio [^{25a}Mg]/[^{25b}Mg]=4.2/5.8.

The two VPFIT methods used were as follows. The first used VPFIT recursively, externally fixing the relative isotopic abundances at each call of VPFIT. In practice this meant changing the input atomic data file (atom.dat) at each external VPFIT call. We then minimised χ^2, fitting the appropriate number of blended Voigt profiles to the absorption complex, solving for [^{24}Mg], requiring [^{24}Mg] + [^{25}Mg] + [^{26}Mg] = 1 for 0 <[^{24}Mg]< 1. VPFIT was called recursively, to externally produce a parabolic $\chi^2([^{24}\text{Mg}])$, the minimum of that function defining the relative abundances.

The second method was more direct, required a single run of VPFIT, and solved independently for 2 column densities N(^{24}Mg) and N(^{25}Mg), the third isotope, N(^{26}Mg), being constrained to scale with N(^{25}Mg), as described above. All other free parameters in the fit were varied as usual, in both methods.

Both methods yield consistent results overall. Both methods were used with and without a varying fine-structure constant, α. Full results will be published elsewhere and here we quote only the result from the second method. When fitted assuming no α variation, we find a mean abundance [^{24}Mg]= 60 ± 2% (compared to a terrestrial value of 79%). When fitted allowing α to vary simultaneously, we find [^{24}Mg]= 55 ± 2%. These numbers are averages taken over 133 and 143 absorption systems respectively.

The modified Mg abundances alter the parameters of the possible spatial variation model $\Delta\alpha/\alpha = A\cos\theta + m$ (Webb et al. 2011; King et al. 2012). Previously, $A(10^{-5}) = 0.97^{1.19}_{0.77}$, $m(10^{-5}) = -0.178 \pm 0.084$, 4.06σ significance, (model 7, Table 7, King et al. 2012). With the revised isotopic abundances presented here, $A(10^{-5}) = 1.28^{1.53}_{1.05}$, $m = -0.025 \pm 0.093$, 4.42σ significance (Figure 2).

The conclusions of the computations described above, subject to the validity of the assumption of constant [^{25}Mg]/[^{26}Mg], are (1) the quasar data, on average, require a lower relative abundance of ^{24}Mg and (2) that the previous non-zero monopole term in the spatial dipole+monopole fit to α (Webb et al. 2011;

King et al. 2012) may be emulated by the assumption of terrestrial magnesium isotopic abundances.

3. Discussion

3.1. Sample consistency

It was noted in Webb et al. (1999) that a significant change in the magnesium isotopic abundances could emulate a non-zero $\Delta\alpha/\alpha$. It cannot, of course, emulate a *spatial* variation. The suggestion was discussed further in Murphy et al. (2003). Table 2 in King et al. (2012) provides separate dipole+monopole parameters for the quasar absorption line samples obtained using the Keck telescope and the VLT: $m(10^{-5}) = -0.465 \pm 0.145$ (Keck) and $m(10^{-5}) = -0.109 \pm 0.180$ (VLT). Why does the Keck sample require a statistically significant monopole term, whilst the VLT sample does not? How could this be consistent with a monopole explained by non-terrestrial magnesium isotopes?

The answer to this lies in the significant differences between the 2 samples. The substantially larger wavelength coverage of the VLT/UVES spectra mean that more transitions were generally used in modelling each absorption system, thus reducing the impact of magnesium on $\Delta\alpha/\alpha$. In contrast, the older Keck/HIRES spectra had smaller wavelength coverage. In fact the initial sample selection of a significant fraction of the Keck data specifically targeted MgII absorption systems, and the the smaller wavelength coverage meant MgII lines provided the only "anchor" transitions. One would thus expect *a priori* that the Keck sample would be more prone to the impact of non-terrestrial magnesium isotopes, as is observed.

3.2. Nitrogen, magnesium isotopes and other elements

Fenner et al (2005) argue that if chemical evolution is dominated by 4-8$M_\odot$ AGB stars, (following Ashenfelter et al. (2004), who explored enhanced heavy magnesium isotopes as an explanation for non-zero $\Delta\alpha/\alpha$), then N is over-produced, and this conflicts with the observations. We note that this argument would require an empirical correlation between ^{25,26}Mg and N.

Levshakov et al. (2009) analysed 11 metal-rich (above solar) absorbers. In general, the abundance patterns are consistent with outflows from intermediate and low mass stars, with the exception of N. Empirically, N is uncorrelated with C/H so N production is irregular. Sometimes it is over-abundant compared to C and sometimes it is under-abundant. Therefore N production is probably complex and has several sources. These authors suggest the Mg lines show evidence for shifting, and attribute that to heavy isotope enhancement. If so, it must be possible to enhance the heavy Mg isotopes without over-producing N. The slower enrichment timescale for N may help increase scatter in N/O measurements (Chiappini et al. 2003).

Centurion et al. (2003) report some DLAs with very low N abundances compared to others. High nitrogen abundances are seen in fast-rotating massive stars as well as intermediate-mass stars. The former have been suggested as one source for abundance anomalies (Mink et al. 2009). Cescutti and Chiappini (2010) suggest a larger scatter in C/O and N/O at low metallicities if massive stars contribute to chemical enrichment via stellar winds.

Melendez and Cohen (2007) look into Mg isotopes in the Galaxy using halo dwarf stars. Empirically they look at ^{26}Mg/^{24}Mg (avoiding ^{25}Mg because its proximity to ^{24}Mg makes it harder to measure). They suggest that AGBs don't contribute to the halo of our own galaxy until metallicities go above [Fe/H] = -1.5. The chemical evolution of our Galactic halo is not dominated by AGB but we lack definitive information as to what type of galaxies quasar absorption systems arise in. For absorption systems arising in dwarf galaxies for example, AGB enrichment could be important.

Henry et al. (2000) study C and N production in Galactic and extragalactic HII regions, concluding C and N are decoupled and originate from separate production sites. Timmes et al. (1995) give a detailed theoretical analysis of Mg isotope production. Type II super-

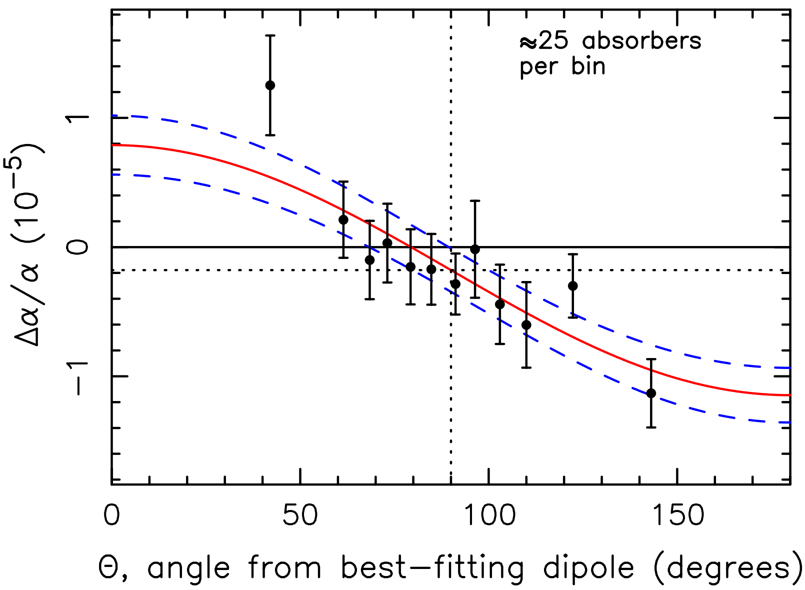

Fig. 1. Before: terrestrial magnesium isotopic abundances assumed.

novae with massive-star progenitors can return plenty of Mg to the ISM and can enhance ^{25}Mg and ^{26}Mg. SN1a cannot return appreciable amounts of Mg to the ISM. However, Timmes et al. (1995) did not consider intermediate-mass stars and their N/Fe predictions had problems reproducing the observations. Gay and Lambert (2000) observe 20 stars and measure ^{24}Mg:^{25}Mg:^{26}Mg noting that 8$M_\odot$ stars can produce copious amounts of ^{25}Mg and ^{26}Mg.

Chiappini et al. (2006) argue that DLA abundance patterns fit with "bursting models" and in a detailed study, Dessauges-Zavadsky et al. (2007) argue that no single star formation history explains the diversity of abundance patterns in DLAs. Our sample is not restricted to DLAs but it is reasonable to presume this applies more broadly.

4. Conclusions

The analysis of a large sample of Keck and VLT quasar absorption systems shows that, on average, the relative abundance of ^{24}Mg is lower than on Earth. Fitting the data, solving simultaneously for magnesium isotopic ratios, and varying-α, we find the previously required monopole term vanishes, leaving only a spatial dipole (Figure 2).

There are at least two caveats. First, we have not yet explored the impact of possible long-range wavelength distortions on our estimates of the magnesium isotopes. Second, we have assumed a constant ratio ^{25}Mg/^{26}Mg and have not quantified the consequences of departures from this assumption, e.g. Kobayashi et al. (2011).

Overall, N production appears complex and not fully understood, we cannot uniquely associate a given absorption system with a particular galaxy type, thus the observed N abundance cannot be used as a meaningful discriminator for magnesium isotope enhancements. Empirically, there are no compelling arguments against enhanced ^{25,26}Mg emulating an α monopole.

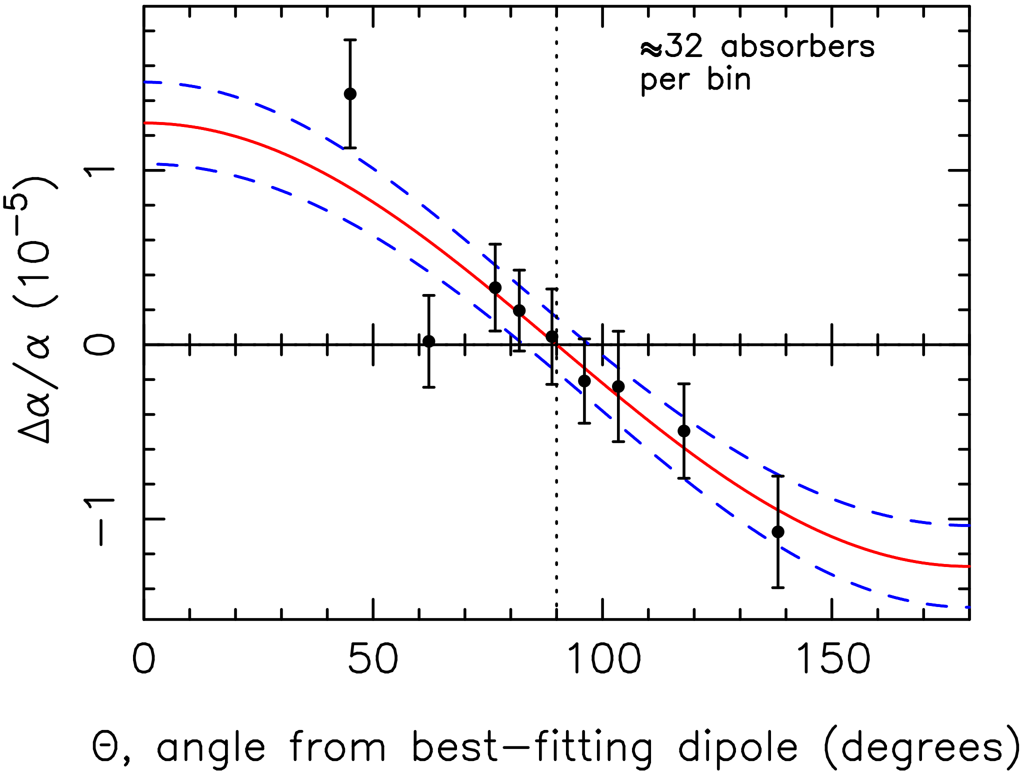

Fig. 2. After: terrestrial isotopic abundances *not* assumed. Binned $\Delta\alpha/\alpha$(279 individual measurements). All absorption systems containing magnesium were fitted simultaneously for relative isotopic abundances, subject to the constraints described in the text. The previously required monopole term has vanished.

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