Astro2020 Science White Paper

Quasar absorption lines as astrophysical probes of fundamental physics and cosmology

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Emphasised Project:

The UV spectropolarimeter POLLUX for LUVOIR

1 Constraining fundamental physics and cosmology

Modern physics and cosmology have been remarkably successful in reproducing the broad observational properties of cosmological evolution with only a small number of parameters. However, this requires that 96% of the mass-energy content of the Universe is in mysterious forms (dark energy and dark matter) that have never been seen in the laboratory. This shows that our canonical theories of gravitation and particle physics are incomplete, if not incorrect.

Improving the sensitivity of current observational constraints is therefore of utmost importance, irrespective of whether these are consistent with the current paradigm—in which case many alternative scenarios will be rejected—or whether they instead favour new physics. A crucial part of this endeavour is characterising the onset of the acceleration of the universe, which entails mapping its properties all the way from low redshifts to the deep matter era; ideally this requires a combination of ground-based and space observations.

Precision spectroscopy is responsible for key developments in fundamental physics, motivating the discovery of quantum mechanics (via the discrete nature of spectral lines and the photoelectric effect), enabling confirmation of QED (via the Lamb shift), and leading to several recent Nobel Prizes in laser physics. The improvements in precision and stability of high-resolution spectrographs, together with theoretical and data analysis developments, provide a unique opportunity to search for new physics. Here we highlight the key opportunities for this field in the coming decade.

2 Absorption line systems as astrophysical probes

Absorption-line systems produced by intervening gas in the spectra of bright background sources located at cosmological distances provide unique laboratories to probe fundamental physics over a wide range of time and space. The most interesting probes identified so far are (1) the measurement of the primordial abundance of light elements, (2) the stability of fundamental constants over time and space and (3) the redshift evolution of the cosmic microwave background (CMB) temperature. Since quasars are intrinsically very bright, distant, and numerous on the sky, they provide background targets of choice. High-resolution spectroscopic observations of quasars then allow one to investigate the absorption lines from the electronic transitions of various atomic and molecular species which encode the fundamental physics to be probed. The abundance of light elements are obtained from their column densities directly measurable from the strength of the absorption lines; constraints on the variation of fundamental constants are obtained from the relative wavelengths of different lines; and finally, the CMB temperature can be derived from the population of atomic and molecular species in different excitation levels.

Importantly, we remark that, while the three probes presented above are observationally independent, they are intimately related by the underlying physics. For example, models involving varying scalar-photon couplings (e.g., Avgoustidis et al. 2014) also affect the temperature-redshift relation so that constraining this relation is complementary to a search for varying fundamental constants. The Big Bang nucleosynthesis calculations of the D/H ratio are also dependent on the fundamental constants and can be altered if new physics is at play (e.g., Olive et al. 2012).

2.1 The abundance of light elements

The relative abundances of the light elements (D, ^{3}He, ^{4}He, ^{7}Li), made just minutes after the Big Bang, currently provide our most reliable probe of the very early Universe, and allow us to address some of the most pressing problems in physics and cosmology. In particular, we know that our current best description of the Universe — the so-called Standard Model (SM) of cosmology

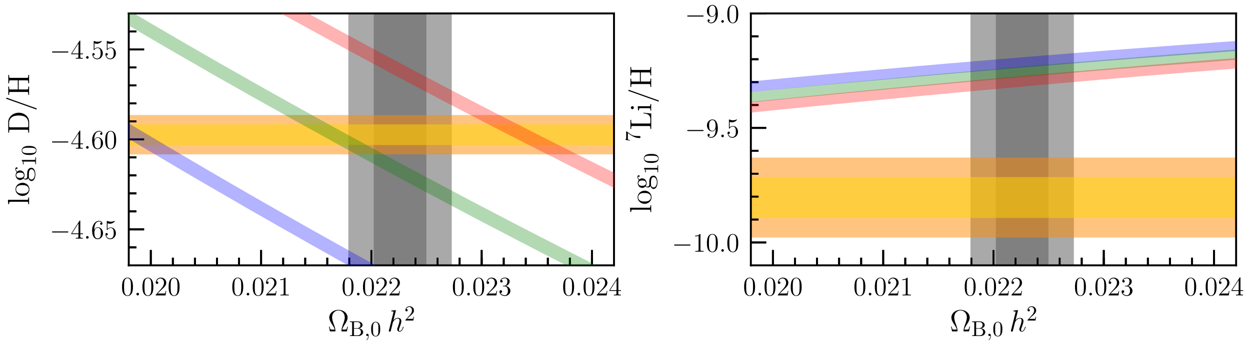

Figure 1: Measurements of (D/H)$_{\rm P}$ and (^{7}Li/H)$_{\rm P}$ (gold bands, left and right panels, respectively) compared to BBN calculations (coloured bands). The blue/green/red curves correspond to an effective number of neutrino species, $N_{\rm eff} = 2, 3, 4$, where the height of each band represents the uncertainty in the calculation. The Planck (2018) value of $\Omega_{\rm B,0}\,h^2$ is shown by the gray band.

and particle physics — is incomplete. In principle, some of the missing components of the SM can be studied by measuring the abundances of the light elements that were made just after the Big Bang, a period known as Big Bang Nucleosynthesis (BBN; e.g. Cyburt et al. 2016). Here, we focus on the primordial abundances of deuterium and lithium (see Fig. 1).

Deuterium — The primordial deuterium abundance, (D/H)$_{\rm P}$, is the most well-determined primordial abundance, and is a sensitive probe of the Universal baryon density and the expansion rate. The most precise measure of (D/H)$_{\rm P}$ (Cooke et al. 2018) translates to a baryon density with a precision of ~ 0.7 per cent, which is similar to that reached by the Planck satellite observations of the Cosmic Microwave Background (CMB) temperature fluctuations ($\sim$1 per cent). *Nonetheless, after two decades of research, this determination of (D/H)$_{\rm P}$ is based on only seven systems.* This meagre statistic is partly due to the difficulty of finding gas clouds at high redshift where this measurement is possible from ground-based facilities.

Both accurate and precise measurements of (D/H)$_{\rm P}$ are possible by observing quasars whose spectra are imprinted with the Lyman series absorption lines of D I and H I, which have rest-frame wavelengths in the range [911–1215]Å. The accuracy on D/H depends on the density of the Lyα forest (see Cooke et al. 2018); for a given system, however, it correlates linearly with S/N. Recent measures reach a precision of about 0.01 dex on D/H at high-redshift using spectra with $S/N \sim 40$ and $R \sim 50,000$. Since the Lyα forest is less dense at lower redshift, such an accuracy can be reached with POLLUX in a few hours of observing time for $0.3 < z < 2.3$ systems towards known $m \sim 18$ quasars. By extending D/H measures to low redshift, it will be possible to increase the sample size and search for relatively higher metallicity clouds where D/H can be measured. Such a sample will provide new insight to the chemical evolution of D/H, and the long sought after 'primordial D/H plateau', which would secure the primordial abundance.

Lithium-7 — Current observations show that the (^{7}Li/H)$_{\rm P}$ ratio of metal-poor stars in the halo of the Milky Way is constant, independent of temperature, and has very little scatter. This plateau – known as the 'Spite Plateau' – has been adopted as the best observational value of the primordial ^{7}Li abundance (e.g. Spite et al. 2015). However, the Spite Plateau is a factor of 3–4 below the SM prediction, constituting a significant ($\sim 6\sigma$) discrepancy. This disagreement represents one of the most pressing problems in cosmology and is widely known as the 'Cosmic Lithium Problem'.

Obtaining a new determination of the ^{7}Li/H abundance — independent of stars — is the key to solving this problem. Perhaps the most promising opportunity is to measure the ^{7}Li/H abundance of the interstellar medium of external galaxies: A cold foreground gas cloud imprints a weak ^{7}Li I absorption line on the spectrum of an unrelated background source. Recent extragalactic detections of ^{7}Li I demonstrate the future utility of this approach (Howk et al. 2012; Ritchey et al. 2015).

Such a measurement is observationally demanding; Li I is a sub-dominant ionization stage in neutral gas, which means that: (1) the strength of the ^{7}Li I 6707Å is weak ($W_{\rm r} \lesssim 5\,{\rm m\AA}$), so high S/N data (S/N $\gtrsim 500$) are required; and (2) an ionization correction may be required to correct for unseen ion stages of Li (i.e. Li II). In addition, observations of H I Lyman-α and H_2 Lyman-Werner band absorption (rest-frame wavelengths [911–1215]Å) are required to establish the abundance of lithium relative to hydrogen. Finally, assessing the aforementioned ionization corrections requires observations of several ionization states from interstellar metals (e.g. C I–IV, Mg I–II, Si I–IV, S I–IV, Fe I–III; rest-frame wavelengths [911–3000]Å). Thus the requirement of broad wavelength coverage, in combination with the requirement for high S/N given the expected weakness of the target absorption lines, can only be achieved with the combined power of the next generation 30+ m optical/near-infrared telescopes and a sensitive high-resolution ultraviolet spectrograph.

2.2 The variation of fundamental constants

Modern theories that aim to unify the fundamental interactions predict the fundamental constants to vary over cosmological times and scales. Such constants determine the energy level structure of atoms and molecules. Comparing spectra of the same species in different places in the Universe and in the laboratory can therefore set strong constraints on any space-time variation of these constants (e.g. Ubachs et al. 2016). Here we focus on the proton-to-electron mass ratio (μ) and fine-structure constant (α) which can be measured using high resolution spectroscopy.

Proton-to-electron mass ratio, μ — The Lyman and Werner bands of molecular hydrogen ($\sim$[900-1100]A rest-frame) imprinted on the high resolution spectra of background QSOs can be used for precise μ measurements. Similarly, combining the resonance UV metal absorption lines with 21-cm absorption lines, from the same absorber, leads to a stringent constraint on a combination of fundamental constants, $x = g_p\alpha^2/\mu$ (e.g. Rahmani et al. 2012).

Since H_2 lines have Doppler broadening of few km s^{-1} and are located in the Lyα forest, the high resolution of POLLUX will allow not only better precision on single-component wavelength measurements, but also the de-blending of different kinematic components and the identification of hidden components, which otherwise produce systematic errors. *As for the primordial abundance and $T_{\rm CMB}(z)$ cases discussed in this paper, the precision depends almost linearly on the achieved S/N.* For known H_2 systems detected by HST/COS at low-to-intermediate redshifts by Oliveira et al. (2013) and Muzahid et al. (2015), we estimate that, in only 10h, the precision on $\Delta\mu/\mu$ will equal that derived from the best H_2 observations at high redshifts. With a 100 h exposure time, the statistical precision reduces to a few parts-per-million (ppm) in each individual case, close to what has been obtained from radio observations of NH_3 inversion transitions in rare systems (Fig. 2). *We also note that POLLUX will probe lookback times not covered by any other observation.*

The fine structure constant, α — The relative wavelengths of metallic ion absorption lines from intervening systems along QSO sight-lines are a characteristic signature of the α's value at cosmic distances. Well-established techniques now provide limits on α's variability at the 1 ppm precision level at high redshifts, $z \sim 0.5$–3, in the most reliable sample of $\sim$30 systems (Murphy & Cooksey 2017)[Fig. 2, right panel]. More reliable, but similarly precise, measurements will be made by the new ESPRESSO spectrograph on the VLT, with modest (factor of $\sim$2) precision

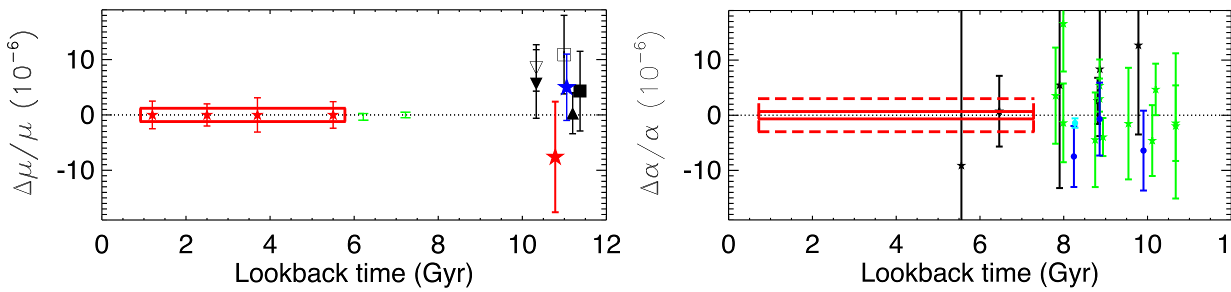

Figure 2: *left:* Existing $\Delta\mu/\mu$ constraints (at high-z from H_2 and at intermediate-z from NH_3 and CH_3OH, green) compared with those expected for POLLUX observations (red points) of low-z H_2 systems. Combined POLLUX constraint, shown as red box, would be about an order of magnitude better than that of high-z H_2 system. *right:* The most precise existing $\Delta\alpha/\alpha$ measurements (Murphy&Cooksey 2017) and the $\Delta\alpha/\alpha$ precision expected from POLLUX shown as red dashed and solid boxes for individual and ensemble measurements, respectively. **Both panels show the large empty gaps in the look-back time that would be covered by POLLUX.**

improvement with G-Clef on the 26-metre GMT.

However, optical spectroscopy is severely limited to redshifts $z \gtrsim 0.5$ because the metal line combinations that are most sensitive to α are all at <2800 Å (e.g. Mg II, Fe II, Zn II, Cr II etc). POLLUX is therefore essential for measuring α at lower redshifts where some models predict strong, late-time α variability (e.g. Martins et al. 2015). The statistical precision achievable is again linearly related to S/N of the spectra. The brighter QSOs available at lower redshift would provide an ensemble precision of 0.5 ppm – the current state-of-the-art – in just 30 h (Fig. 2, right panel). Achieving 0.1 ppm precision in ~750 h, would strongly complement the similar precision of μ measurements at the same redshifts. Note that all spectra of QSOs at $z \lesssim 1$ can contribute to this goal, not just QSOs specifically targetted for this purpose.

2.3 The temperature of the cosmic microwave background radiation

According to the SM, if gravitation is described by general relativity and electromagnetism by Maxwell theory, photons propagate along null geodesics and the CMB black-body temperature, $T_{\rm CMB}$, follows the relation $T_{\rm CMB}(z) = T_{\rm CMB}(z=0) \times (1+z)$. The $T_{\rm CMB}(z=0) = 2.72548 \pm 0.00057$ K is accurately measured directly from the CMB black-body spectrum (Fixsen 2009). Any departure from the above $T_{\rm CMB}$-redshift relation would have strong implications either indicating a violation of the hypothesis of local position invariance (and thus of the equivalence principle) or that the number of photons is not conserved, with the constraint that the energy injection does not induce spectral distortion of the CMB (Uzan et al. 2004). The former should be associated with a variation of the fundamental constants and the latter with decaying dark energy (e.g. Lima et al. 2000; Jetzer et al. 2011), with axion-photon-like coupling process (Jaeckel & Ringwald 2010), or with alternative cosmological scenarios (Maeder 2017). Therefore, direct measurements of the $T_{\rm CMB}$-redshift relation provide an important test of fundamental physics and cosmology.

Atomic carbon has been used in the past to put the first constraints on $T_{\rm CMB}$ at high-redshift (after correction for collisional excitation and UV pumping). More recently, a few, rare CO absorption systems at $1.7 < z < 2.7$ have been used as more precise and more direct CMB thermometers in diffuse gas where collisional excitation is small (i.e., $T_{\rm ex} \approx T_{\rm CMB}$, e.g. Srianand et al. 2008, Noterdaeme et al. 2011). At $z < 1$, $T_{\rm CMB}$ measurements have been obtained from the Sunyaev-Zeldovitch effect in galaxy clusters (Hurrier et al. 2014) while the precision quickly decreases with increasing redshift. The only direct measurement at $z < 1$ is based on interstellar species at $z = 0.9$ from a peculiar sub-mm molecular absorber towards PKS 1830−211 (Muller et al. 2013).

The CO-based measurements are derived from the relative column densities of different rotational levels, for which the corresponding lines in a given band are separated by only a few km s^{-1}. The statistical uncertainty, based on S/N$\sim$ 30, R$\sim$ 50,000 data is currently of the order of 1K. This accuracy is expected to linearly correlate with the S/N and the spectral resolution. When reaching a resolution $R \sim 100,000$, the lines from the different rotational levels are fully separated, allowing for high-precision measurement of the excitation temperature. We estimate that, for $S/N \sim 100$ and $R \sim 120,000$, the statistical uncertainty on T_{ex}(CO) becomes less than 0.1 K, i.e. below the excess temperature due to collisional excitation (e.g. Sobolev et al. 2015). As for PKS 1830−211, investigating simultaneously several atomic and molecular species with different sensitivities on collisional and radiative excitation is then necessary to break the remaining degeneracy between excitation processes and obtain an accurate measurement of $T_{\rm CMB}$. Molecular hydrogen, H_2, as well as C I are particularly useful to this end. While C I lines are located close to CO$\sim$AX bands and covered simultaneously, the Lyman-Werner bands of H_2 have short wavelengths (< 110 nm rest-frame), meaning that UV-blue wavelength coverage is crucial, even for high-z targets.

3 Technical requirements

Quasars beyond a redshift $z \gtrsim 3.5$ are significantly impacted by the increasing opacity of the IGM. This hampers the analysis of H I and H_2 lines, and renders these quasars unusable for the present science cases. In fact, most of the known quasars are at $z \sim 2.3$. The analysis of absorption lines at lower redshift is then facilitated by: (1) the higher number of potential targets; (2) the larger quasar fluxes; and (3) the reduced density of the Lyman-α forest at low redshift. However, all the above probes rely on spectroscopic observations of electronic transitions with FUV rest-frame wavelengths. Thus UV-blue coverage is absolutely crucial. In addition, the precision reached increases roughly linearly with the achieved S/N ratio and the spectral resolution.

In the future decade, several high-resolution ($R > 100,000$) UV or optical instruments on large telescopes are forecast. Three of them on ground-based optical/near-infrared telescopes (HIRES on the ELT, G-CLEF on the GMT, and HROS on TMT) and one (POLLUX) on the space telescope LUVOIR. *Hence, POLLUX would be the only direct probe of fundamental physics at low-z.*

Ground-based instruments will naturally have to deal with the atmospheric cutoff (at ~ 320 nm) as well as compromises with the mirror coating. For example, HIRES on the ELT will only cover $\lambda > 400$ nm. This means that the above probe will be reachable only from $z > 3.3$ (for μ, D/H) or $z > 2$ for CO. Since in the latter case, H I and H_2 also have to be covered, complementary data at shorter wavelengths will still be required. POLLUX on LUVOIR will then be a perfect complement, covering the full wavelength range from 90 nm to 390 nm. POLLUX will also allow on its own to perform the three above tests from $0 < z \lesssim 1.5$ ($T_{\rm CMB}$) or up to $z \sim 2.5$ (D/H, μ).

For μ and α variation studies, accuracy in the relative wavelength scale is essential; these are effectively measurements of velocity shifts between different transitions, at different wavelengths, in the same spectrum. To limit systematic uncertainties below the 0.1 ppm precision goal, these velocity shifts must be reliable at the $\sim$2 m s^{-1} level. Accurate wavelength calibration is therefore an important technical requirement. In the optical regime, the required accuracy is now being achieved in highly stablised instruments like ESO 3.6-m/HARPS and VLT/ESPRESSO with thorium–argon lamps, Fabry–Perot cavities and laser frequency combs. Development of similar technologies may be required for POLLUX to reach the statistical precision level available.

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