AMMONIA AS A TRACER OF FUNDAMENTAL CONSTANTS

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Observing inversion lines of ammonia (NH₃), complemented by rotational lines of NH₃ and other molecular species, provides stringent constraints on potential variations of the proton-to-electron mass ratio, μ. While a limit of |Δμ/μ| ∼ 10⁻⁶ is derived for a lookback time of 7×10⁹ yr, nearby dark clouds might show a significant variation of order (2–3)×10⁻⁸, possibly being related to chameleon fields. The detection of radio-loud quasars with strong molecular absorption lines at redshifts z > 1 as well as the identification of a larger sample of nearby molecular clouds with exceptionally narrow lines (ΔV < 0.2 km s⁻¹) would be essential to improve present limits and to put the acquired results onto a firmer statistical basis.

Keywords: Fundamental physical constants — proton-to-electron mass ratio — Chameleon effect — ammonia — molecular clouds

1. Introduction

Comparing redshifts of various spectral lines, observed toward the same distant highly redshifted object, has the potential to yield important contraints on tem-
poral variations of fundamental constants of the standard model over timescales of billions of years, even surpassing the age of the solar system. A pre-condition is that the lines in question have different dependencies on the respective constant. Among the most commonly studied fundamental parameters are the dimensionless fine structure constant, \(\alpha\), and the proton-to-electron mass ratio, \(\mu\) (e.g., Uzan 2003; García-Berro et al. 2007; Dent 2008). It may be possible that variations in \(\mu\) are more pronounced than those in \(\alpha\) (e.g., Flambaum 2008). Therefore, studies containing \(\mu\) may be particularly rewarding.

2. The role of ammonia

Making use of the different dependencies of electronic, vibrational, and rotational line frequencies of molecules on the proton-to-electron mass ratio \(\mu\), limits on variations are commonly derived from \(H_2\) spectra of damped Lyman \(\alpha\) systems measured in absorption toward quasars. To date, these observations indicate that \(\mu\) is unchanged to an accuracy of order \(10^{-5}\) over the last 80% of the age of the Universe (e.g., Malec et al. 2010).

Ammonia (\(NH_3\)), having been detected for the first time at significant redshifts by Henkel et al. (2005, 2008), opens up a new avenue to constrain \(\mu\) over large time scales. Its inversion transitions are strongly dependent on \(\mu\) (J. N. Chengalur, priv. comm.; Flambaum & Kozlov 2007), with a fractional change in frequency \(\Delta\nu_{\text{inv}}/\nu_{\text{inv}}\) corresponding to \(-4.46\Delta\mu/\mu\). For rotational lines, \(\Delta\nu_{\text{rot}}/\nu_{\text{rot}} = -\Delta\mu/\mu\). Therefore, comparing \(NH_3\) inversion line redshifts with redshifts of rotational transitions should provide sensitive limits on the variation of \(\mu\).

3. B0218+357 and PKS 1830–211

The two redshifted sources, toward which ammonia has been detected in absorption, are the main gravitational lenses of the quasars B0218+357 and PKS1830-211. Flambaum & Kozlov (2007) combine the three detected \(NH_3\) absorption spectra from B0218+357 with rotational spectra of CO, HCO\(^+\), and HCN to place a limit of \(|\Delta\mu|/\mu = (0.6 \pm 1.9) \times 10^{-6}\) for a lookback time of \(6 \times 10^9\) yr (redshift \(z = 0.68\)). Accounting in detail for the velocity structure of the line profiles, Murphy et al. (2008) reanalyzed the ammonia data in combination with newly obtained high-signal-to-noise rotational spectra of HCO\(^+\) and HCN. This yields \(|\Delta\mu|/\mu < 1.8 \times 10^{-6}\) at a 95% confidence level.

While B0218+357 provided first useful limits, PKS1830-211 is by far more suitable when trying to constrain \(\mu\). With ten (instead of three) detected \(NH_3\) inversion lines and a forest of rotational transitions at nearby frequencies, a higher accuracy can be achieved. From a comparison of the ammonia inversion lines with the \(NH_3\) \((J,K) = (1,0) \leftarrow (0,0)\) rotational transition, Menten et al. (2008) find consistency within \(3.8 \times 10^{-6}\) at a 95% confidence level. The strength of this study is its focus on lines arising entirely from one molecular species. However, the frequencies of the inversion lines are much lower than that of the rotational line by a factor of \(\sim 25,\)
which might cause differences in the absorbed background radio continuum.

Analyzing the ten NH$_3$ inversion lines and a similar number of rotational transitions from other molecules, Henkel et al. (2009) obtain a 3σ limit of $\Delta \mu/\mu = 1.2 \times 10^{-6}$ for a lookback time of $7 \times 10^9$ yr ($z=0.89$). This study is based exclusively on optically thin absorption features located within a limited frequency band that were observed within a limited time interval, thus minimizing effects caused by a time variable and frequency dependent continuum background morphology. Also, no frequency shift as a function of excitation is found. Nevertheless, a detailed velocity component analysis like that presented by Murphy et al. (2008) for the much smaller data set from B0218+357 has not yet been performed.

4. Nearby dark clouds

We can probe the values of fundamental constants at a considerably more accurate level in quiescent dark clouds of the Milky Way, where line widths $\Delta V \ll 1$ km s$^{-1}$ are encountered. $\mu$, measured in the drastically different environments of high terrestrial and low interstellar densities of baryonic matter, is supposed to vary in Chameleon-like scalar field models, which predict a strong dependence of masses and coupling constants on the ambient density (Olive & Pospelov 2008; Upadhye et al. 2010). High spectral resolution data of NH$_3$, HC$_3$N, and N$_2$H$^+$ provide a variation of $\Delta \mu/\mu = (–2.2 \pm 0.4_{\text{stat}} \pm 0.3_{\text{sys}}) \times 10^{-8}$ (Levshakov et al. 2010).

5. Conclusions

Measurements of ro-vibrational H$_2$ quasar absorption spectra yield $|\Delta \mu/\mu| < 10^{-5}$ over the last 80% of the age of the Universe. Radio data including NH$_3$ inversion lines result in $|\Delta \mu/\mu| \lesssim 10^{-6}$ over the last 50% of the age of the Universe. Similar data obtained from local dark clouds suggest a potential variation of order $(2–3) \times 10^{-8}$.

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