FIRST COSMOLOGICAL CONSTRAINTS ON THE PROTON-TO-ELECTRON MASS RATIO FROM OBSERVATIONS OF ROTATIONAL TRANSITIONS OF METHANOL

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ABSTRACT

We have used the Australia Telescope Compact Array to measure the absorption from the 2$_0$ $→$ 3$_{-1}$E 12.2 GHz transition of methanol toward the $z = 0.89$ lensing galaxy in the PKS B1830–211 gravitational lens system. Comparison of the velocity of the main absorption feature with the published absorption spectrum from the 1$_0$ $→$ 2$_{-1}$E transition of methanol shows that they differ by $-0.6 \pm 1.6$ km s$^{-1}$. We can use these observations to constrain the changes in the proton-to-electron mass ratio $\mu$ from $z = 0.89$ to the present to $0.8 \pm 2.1 \times 10^{-7}$. This result is consistent, and of similar precision to recent observations at $z = 0.68$ achieved through comparison of a variety of rotational and inversion transitions, and approximately a factor of two better than previous constraints obtained in this source. Future more sensitive observations that incorporate additional rotational methanol transitions offer the prospect of improving current results by a factor of 5–10.

Key words: galaxies: ISM – ISM: molecules – quasars: absorption lines – quasars: individual (PKS 1830-211)

1. INTRODUCTION

Astrophysical observations provide one of the most sensitive methods for searching for possible temporal or spatial changes in the fundamental constants (Uzan 2011). Under the standard model of particle physics these constants are not expected to change: however, the detection of variations would be consistent with some anthropic models, as well as indicating the need for new physics beyond general relativity and the standard model. A large number of observations have been undertaken to attempt to measure, or constrain changes in the fine-structure constant $\alpha = e^2/\hbar c$ (e.g., Webb et al. 1999; Levshakov et al. 2006) and the proton-to-electron mass ratio $\mu = m_p/m_e$ (e.g., King et al. 2008; Henkel et al. 2009; Kanekar 2011; Muller et al. 2011), or combinations of $\alpha$, $\mu$, and the nuclear $g$-factor $g_n$ (e.g., Kanekar et al. 2005, 2010). Although some studies have claimed marginal detections of changes in either $\alpha$, $\mu$, or the combinations, none have yet been confirmed through additional independent observation. Changes in the constants are measured through comparison of the frequency ($\nu$) of two transitions which have different sensitivities to variations in one or more of $\alpha$, $\mu$, or $g_n$:

$$\Delta \nu / \nu = K_\alpha \Delta \alpha / \alpha + K_\mu \Delta \mu / \mu + K_g \Delta g_n / g_n,$$

(1)

where the coefficients $K_\alpha$, $K_\mu$, and $K_g$ represent the sensitivity of the particular transition to changes in that constant.

The proton-to-electron mass ratio will change if there are differences in the spatial or temporal scale of variations in the strong nuclear force compared to the electromagnetic force, and recent observational studies have focused on using molecular observations at radio wavelengths to search for changes in $\mu$. Rotational transitions of molecules are generally more sensitive to changes in $\mu$ than rovibrational transitions of H$_2$, and recent studies have focused on comparison of absorption in NH$_3$ inversion transitions with rotational transitions from molecules such as CS and HCO$^+$ (Henkel et al. 2009; Kanekar 2011). This is because ammonia inversion transitions are more sensitive to changes in $\mu$ than the rotational transitions of most molecules, with $K_\mu = -4.46$ (Flambaum & Kozlov 2007). However, recent investigations have revealed that the different rotational transitions of the methanol molecule have a larger and more varied sensitivity to changes in $\mu$ than any other molecule identified to date (Jansen et al. 2011; Levshakov et al. 2011), with some transitions having approximately an order of magnitude greater sensitivity than the ammonia inversion transitions. Furthermore, in the local universe methanol emission is commonly observed from high-mass star formation regions in the form of masers and thermal emission from hot cores, and absorption is detected toward cold clouds in the foreground of continuum sources (e.g., Menten 1991; van der Tak et al. 2000; Peng & Whiteoak 1992).

Variations in $\mu$ with density are a prediction of chameleonic-like scalar fields, which are one of the mechanisms which can produce dark energy, and the densities in interstellar molecular clouds are many orders of magnitude lower than can be achieved in the laboratory. Observations of methanol masers within the Milky Way have recently been used to constrain spatial variations in the proton-to-electron mass ratio to $\Delta \mu / \mu < 8.1 \times 10^{-8}$ (3$\sigma$; Levshakov et al. 2011; Ellingsen et al. 2011).

Until very recently methanol emission and absorption had only been detected in nearby galaxies; however, a spectral scan from 30 to 50 GHz in the molecular absorption system toward the gravitationally lensed quasar PKS B1830–211 yielded the first detection of methanol at cosmological distances (Muller et al. 2011). These observations detected methanol absorption from a single transition, the 1$_0$ $→$ 2$_{-1}$E which has a rest frequency of approximately 60.5 GHz, which for a redshift of $z = 0.89$ is observed at a frequency of approximately 32.1 GHz. For sources in the local universe the emission/absorption from this transition is within a region of the electromagnetic spectrum which cannot be studied from Earth’s surface due to absorption by atmospheric O$_2$. Because of this there are no previous studies of this transition.

PKS B1830–211 is a very well studied gravitational lens system, with a quasar at a redshift of $z = 2.507$ (Lidman et al. 1999) and the primary lensing galaxy at a redshift of 0.88582 (Wiklind & Combes 1996). There is also evidence
for a second galaxy along the line of sight at a redshift of 0.19 (Lovell et al. 1996). The two main components of the gravitationally lensed quasar are separated by nearly 1" on the sky, and at frequencies $\lesssim 10$ GHz part of the quasar jet forms an Einstein ring (Jauncey et al. 1991). The quasar has a steep spectrum jet and an optically thick core component. The southwestern core component has an angular size that varies as the wavelength squared, consistent with interstellar scattering in the lensing galaxy (Jones et al. 1996). The majority of the radio continuum emission is contained in the two compact components which lie to the northeast and southwest of the center of the Einstein ring, with the northeastern component being the stronger of the two. The lensing galaxy at $z = 0.89$ is an Sb or Sc spiral seen nearly face-on (Winn et al. 2002), with the line of sight of the southwestern component intersecting the galaxy at a galactocentric radius of approximately 2 kpc, and the northeastern at a radius of $\sim 4$ kpc. The strongest molecular absorption is seen toward the southwestern component, while the strongest H i absorption is seen toward the northeastern component (Carilli et al. 1998; Chengalur et al. 1999). The velocity offset between the absorption from the southwest and northeast components is approximately 150 km s$^{-1}$. The molecular absorption in PKS B1830–211 has been the subject of numerous studies with more than 30 different molecular species detected and multiple complexes spanning a velocity range of nearly 500 km s$^{-1}$ (see Muller et al. 2011 and references therein). To date, no molecular absorption has been detected toward the second line-of-sight galaxy at $z = 0.19$.

The 12.2 GHz ($2_0 \rightarrow 3_1 E$) transition of methanol lies in the same series as the 60.5 GHz and this transition is well studied as it shows both strong maser emission in Galactic high-mass star formation regions (e.g., Breceen et al. 2012) and absorption in cold clouds (Peng & Whiteoak 1992). Ellingsen et al. (2011) suggested that absorption from the 12.2 GHz transition was likely to be detectable in this source and noted that the redshifted frequency of approximately 6.45 GHz lay within the frequency range of both the Australia Telescope Compact Array (ATCA) and the Expanded Very Large Array (EVLA). Observations of this transition, combined with the published spectra for the 60.5 GHz transition present a unique opportunity to utilize the high sensitivity of rotational transitions of methanol to search for possible variations in $\mu$ at cosmological distances. Here we present the first observations of the $2_0 \rightarrow 3_1 E$ 12.2 GHz transition of methanol toward the $z = 0.89$ molecular absorption system in PKS B1830–211.

2. OBSERVATIONS

The observations were made using the ATCA in Director’s time allocations on 2011 November 4, November 18, and December 7 (project code CX223). The Compact Array Broadband Backend (CABB; Wilson et al. 2011) was configured with a $2 \times 2$ GHz bands covering the frequency ranges 4.876–6.924 GHz and 8.667–10.715 GHz. Spectral zoom bands were centered on frequencies of 6.547 GHz and 10.587 GHz, corresponding to the approximate observing frequencies of the $2_0 \rightarrow 3_1 E$ (12.2 GHz) and $2_1 \rightarrow 3_0 E$ (19.9 GHz) transitions of methanol at a redshift $z = 0.89$. The rest frequencies assumed throughout this work were 12.178597 and 19.9673961 GHz (Muller et al. 2004). For the November 4 observations $16 \times 1$ MHz spectral zooms were concatenated with overlaps (for each of the two transitions), to produce spectra with 17408 spectral channels across a bandwidth of 8.5 MHz, corresponding to a spectral resolution of 488 Hz. For the November 18 and December 7 observations a single 64 MHz spectral zoom with 2048 channels was used for each transition, corresponding to a spectral resolution of 31.25 kHz (i.e., a factor of 64 coarser than the November 4 observations). The details of the observations are summarized in Table 1.

The primary target for the observations was the gravitationally lensed quasar PKS B1830–211, which has previously been observed to exhibit molecular absorption from a wide range of molecules from the lensing galaxy at $z = 0.89$. The pointing center for the observations was $\alpha = 18^h 33^m 39.9^s; \delta = -21^o 03' 40"$ (J2000). The observations were constructed as a series of 15 minute scans on PKS B1830–211, interleaved with 2 minute observations of PKS B1908–201 which were used for phase calibration. For each session observations of PKS B1921–293 were undertaken for bandpass calibration and of PKS B1934–638 for primary flux density calibration. The data were reduced using the MIRIAD software package (Sault et al. 1995), applying the standard techniques for spectral line observations, except for the bandpass calibration for the second and third observing sessions. For the observations with a 64 MHz spectral zoom the bandpass calibration was achieved using continuum data for PKS B1830–211 extracted using the task uvlin. This effectively fits a polynomial to the PKS B1830–211 continuum and resulted in a flatter and lower-noise bandpass solution than using PKS B1921–293.

For each of the three observing sessions we extracted a spectrum from the $uv$ data by vector averaging at the position of the southwest component of the PKS B1830–211 gravitational lens ({$\alpha = 18^h 33^m 39.8^s; \delta = -21^o 03' 40.45"$} J2000) Subrahmanyan et al. 1990). This is an offset on the sky of $-0.196$ in right ascension and $-0.450$ in declination from the pointing center of the observations. To enable the data collected on different days to be averaged, and for comparison with molecular absorption observed in other transitions, the observed sky frequency was corrected for the Doppler shift of PKS B1830–211 in the barycentric frame (on a per-visibility basis within MIRIAD). The velocity of the array toward PKS B1830–211 in the barycentric frame is listed in Table 1 for each observing session. The spectra

| Date       | Time (UT) | Array Config. | Correlator Config. | Time On-source (min) | Continuum Flux (Jy) | Barycentric Velocity (km s$^{-1}$) |
|------------|-----------|---------------|--------------------|----------------------|---------------------|-----------------------------------|
| November 4 | 08:00–11:15 | 750C          | CFB 1M-0.5k        | 135                  | 9.640               | 24.98, 25.10                      |
| November 18| 03:00–04:30 | 1.5D          | CFB 64M-32k        | 49                   | 7.785               | 19.96, 20.04                      |
| December 7 | 05:40–06:40 | 6.0A          | CFB 64M-32k        | 60                   | 9.740               | 11.87, 11.95                      |

Notes. Column 5 gives the time on-source for PKS B1830–211. Column 7 gives the barycentric velocity of the observatory toward PKS B1830–211 at the time of the start and end of the observation.
absorption is seen in previous molecular absorption studies toward PKS B1830–211 (e.g., Wiklind & Combes 1996; Muller et al. 2006; Henkel et al. 2008; Muller et al. 2011), with additional, slightly weaker absorption observed at approximately $-130$ km s$^{-1}$. Previous interferometric studies have shown that the absorption close to 0 km s$^{-1}$ arises from the southwestern component of the gravitational lens, while that at around $-150$ km s$^{-1}$ arises from the northeastern component (Muller et al. 2006).

No absorption was detected from the 19.9 GHz transition, with a $3\sigma$ limit on the level of absorption in the normalized flux density of 0.019. The large rms compared to the observation of the 12.2 GHz transition is because 10.5 GHz lies well beyond the nominal bounds of the current ATCA X-band system and the system performance is very poor compared to that below 9 GHz.

### 4. DISCUSSION

The primary purpose of these observations was to use the sensitivity of different rotational transitions of the methanol molecule to investigate if there is any evidence that the proton-to-electron mass ratio was different at a redshift of 0.89 to that observed at the current epoch. We have fitted a single Gaussian profile to each of the two 12.2 GHz methanol absorption features. The spectral profiles of each of these may be more complex, however, with the signal to noise ratio of the current observations we are only justified in fitting a single component. The parameters of the fitted Gaussians are given in Table 2. We have also fitted Gaussian profiles to the spectrum of the 60.5 GHz methanol transition observed by Muller et al. (2011).4 The 60.5 GHz transition (see Figure 1) also shows its strongest absorption near $-5$ km s$^{-1}$; however, there is a secondary component with about half the optical depth at $-40$ km s$^{-1}$. There is a hint of this component in the 12.2 GHz spectrum, but significantly better signal to noise would be required to reliably establish if this component is present. The HCO$^+$ and HCN spectra show weaker absorption covering this velocity range (Muller & Guélin 2008; Muller et al. 2011). Unlike the 12.2 GHz spectrum, there is no component in the 60.5 GHz spectrum associated with the northeastern component of the gravitational lens. This likely reflects differences in the morphology of the background continuum source at the two frequencies, as the expectation is that the source size is greater at lower frequencies (due to the steep spectrum of the jet). Examination of the 60.5 GHz spectrum shows that the channels appear paired, with every second channel very similar to its predecessor. The observations of Muller et al. (2011) had a spectral resolution of 1 MHz, but the spectra are displayed with a channel separation of 0.5 MHz and this appears to be the underlying reason behind the close correlation between consecutive channels (this can

#### Table 2

| Transition | Velocity (km s$^{-1}$) | $\tau$ | FWHM (km s$^{-1}$) |
|------------|------------------------|------|---------------|
| 12.2 GHz   | $-5.0 \pm 1.3$         | 0.0047 | 17.0 $\pm$ 2.9 |
|            | $-125.1 \pm 2.1$       | 0.0037 | 13.2 $\pm$ 3.3 |
| 60.5 GHz   | $-4.4 \pm 0.9$         | 0.0196 | 17.2 $\pm$ 2.0 |
|            | $-42.4 \pm 3.4$        | 0.0079 | 40 $\pm$ 9    |

4 The 60.5 GHz spectrum was extracted from the ascii format spectrum obtained from http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/535/A103.

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**Figure 1.** Top: the absorption from the 12.2 GHz $2_0 \rightarrow 3_1 J$ transition of methanol toward PKS B1830–211. Bottom: the absorption from the 60.5 GHz $1_0 \rightarrow 2_1 J$ transition over the same velocity range as the 12.2 GHz transition (Muller et al. 2011).

for each session were produced with the same spectral resolution (62.5 kHz) and aligned in frequency. An average spectrum was constructed from the weighted mean of the three days, with the weighting proportional to the time on-source for each day. Prior to averaging, the flux density scale of the spectra were normalized to the continuum level observed at the position of the southwest component. The continuum level varied between the southwest component. The continuum level varied between sessions (see Table 1), due to both the differing angular resolution of the observations and the strong intrinsic variability well known in this source (Lovell et al. 1998). We then transformed the average spectrum to the velocity relative to a redshift of $z = 0.88582$, the redshift of the absorption toward the southwestern component of the lens (Muller et al. 2006). The velocity resolution of the 12.2 GHz spectrum in the rest frame of the absorbing system is 2.9 km s$^{-1}$.

### 3. RESULTS

The normalized absorption spectrum for the 12.2 GHz transition of methanol toward the southwestern component of PKS B1830–211 is shown in Figure 1. The maximum absorption is only about five times the rms noise in the average spectrum, but is spectrally well resolved, and was detected in each of the individual observing sessions. The maximum absorption is very close to the velocity at which the strongest
also be seen in many of the spectra displayed in Muller et al. 2011; see, e.g., their Figure 7). The effective velocity resolution (i.e., spectral resolution of 1 MHz) of the 60.5 GHz spectrum in the rest frame of the absorbing system is 9.4 km s\(^{-1}\).

We have calculated the optical depth of the absorption for each transition (see Table 2) using Equation (1) of Muller et al. (2011), assuming 38% of the total flux density from the source originates from the southwestern component. We are not able to measure this fraction through our observations, but rather use the value derived from earlier observations of saturated lines by Muller et al. (2006, 2011). This value is also consistent with imaging studies that directly measure the flux density in the two components (e.g., Nair et al. 1993; Lovell et al. 1998).

Temporal and spectral variations in the source mean that this factor is somewhat uncertain for individual epochs, but it is the best estimate available. The difference in the central velocity of the main absorption components from the two transitions is \(-0.6 \pm 1.6\) km s\(^{-1}\), with the uncertainty calculated by adding the formal error from the two Gaussian fits, and other sources of error in the relative velocity scales in quadrature. The uncertainties in the rest frequency of the two methanol transitions and in the barycentric velocity corrections for both the current observations and the Muller et al. spectrum added in quadrature contribute approximately 0.13 km s\(^{-1}\) to the total error budget.

The sensitivity coefficients for calculating changes in the proton-to-electron mass ratio for the 12.2 and 60.5 GHz methanol transitions are \(K_\mu = -33\) and \(-7.4\), respectively (Jansen et al. 2011; Levshakov et al. 2011). Using the observed difference between the velocity of the absorption in these two transitions we can constrain the proton-to-electron mass ratio \(\Delta \mu/\mu = 0.8 \pm 2.1 \times 10^{-7}\), corresponding to a 3\(\sigma\) limit of \(\Delta \mu/\mu < 6.3 \times 10^{-7}\). This is a factor of two better than previous constraints obtained from ammonia observations in the same source (Henkel et al. 2009), and comparable to the 3\(\sigma\) limit of 3.6 \(\times 10^{-7}\) derived from simultaneous fitting of multiple molecular transitions in B0218+357 at \(z = 0.685\) (Kanekar 2011). We note that our observations are not consistent with the \(4\sigma\) detection of a variation in \(\mu\) by Muller et al. (2011) of \(\Delta \mu/\mu = -1.95 \pm 0.47 \times 10^{-6}\) obtained by comparing a large number of different molecular transitions with absorption near 0 km s\(^{-1}\). The look-back time for the \(z = 0.89\) absorbing system is 7.24 Gyr (using standard LCDM with \(H_0 = 71\) km s\(^{-1}\) Mpc\(^{-1}\); \(\Omega_m = 0.27\); \(\Omega_\Lambda = 0.73\)), this translates to an upper limit on the time variation in the proton-to-electron mass ratio of \(\Delta [\mu/\mu] = 8.7 \times 10^{-17}\) yr\(^{-1}\).

The two transitions observed here are from the same family, so we would expect the intrinsic absorption profiles of the two lines to be similar, with differences likely reflecting differences in the morphology of the background continuum source at the two frequencies. The absorption in the 12.2 GHz methanol transition is approximately a factor of four lower in optical depth than that seen in the 60.5 GHz transition. This is likely because the energy of the lower state for the 60.5 GHz transition is 12.5 K above the ground state, compared to 19.5 K for the 12.2 GHz transition. This is consistent with earlier observations of molecular absorption in PKS B1830–211 which find that the detections are primarily from transitions to the ground state, or those with low energy levels (Muller et al. 2011). Observations covering the frequency of three other methanol transitions are also available, the 19.9 GHz (\(2_1 \rightarrow 3_0 E\)) transition was observed as part of the current project, but not detected, with a 3\(\sigma\) limit on the optical depth of <0.05, and the 68.3 GHz (\(1_1 \rightarrow 2_0 E\)) and 84.5 GHz (\(5_1 \rightarrow 4_0 E\)) transitions were within frequency coverage of the spectral scan of Muller et al. (2011), for which the 3\(\sigma\) limits on the optical depth are <0.004 and <0.006, respectively. These three transitions have lower states 27, 20, and 36 K above the ground state for 19.9, 68.3, and the 84.5 GHz, respectively, but also have weaker line strengths than either the 12.2 or 60.5 GHz transitions, so their non-detection is perhaps not surprising. The FWHM of the main component of absorption is 17 km s\(^{-1}\) for both the 12.2 and 60.5 GHz transitions. This is significantly larger than the typical values observed in 12.2 GHz absorption seen toward individual cold clouds in the Galaxy, which have a median of 4.2 km s\(^{-1}\) (Peng & Whiteoak 1992). Within the Milky Way, only clouds near the Galactic center have widths that approach or exceed 17 km s\(^{-1}\), which suggests that the main absorption component may be a blend of two or more clouds along the line of sight from the southwestern component.

Formally, the strongest constraints on variations in the proton-to-electron mass ratio that have been reported to date are those from Kanekar (2011), obtained through simultaneous multi-component Voigt fitting of three blended absorption systems from high signal-to-noise ratio spectra from three different molecular species (NH3, CS, and H2CO), which yielded \(\Delta [\mu/\mu] = -3.5 \pm 1.2 \times 10^{-7}\). That the measurement is approximately three times the quoted uncertainty may be statistical chance, or it may indicate that the quoted uncertainty is an underestimate (for example, that the degree to which the absorption from different molecules is co-spatial is very difficult to accurately quantify).

5. CONCLUSIONS

We have undertaken observations of the 12.2 GHz transition of methanol toward the \(z = 0.89\) absorption system in PKS B1830–211. Combining our results with the only other published methanol absorption spectrum in this source we have been able to constrain changes in the proton-to-electron mass ratio over the last 7.24 Gyr to be <6.3 \(\times 10^{-7}\) (3\(\sigma\)). We have achieved a similar accuracy to the most precise previous cosmological measurements of \(\Delta \mu/\mu\), but through much more direct and simpler means (fitting only a single component to two transitions of the same molecule). Future higher sensitivity observations of the methanol absorption are likely to reveal additional components; however, within Galactic clouds methanol is less widely distributed than molecules such as HCO\(^+\) or HCN. Hence, the relative simplicity of the methanol absorption spectra in PKS B1830–211 compared to that observed in other molecules, combined with the unique sensitivity of rotational transitions of methanol to changes in the proton-to-electron mass ratio, identified by Jansen et al. (2011) and Levshakov et al. (2011), suggest that future observations with better signal to noise and/or including additional transitions should be able to either measure changes in \(\mu\), or constrain it to levels better than 1 part in 10 million (i.e., a factor of five or more better than the observations presented here). In particular the \(1_0 \rightarrow 0_0 E^*\) transition, which has a rest frequency of 48.4 GHz should be readily detectable (redshifted to 25.7 GHz) using either the ATCA or EVLA, although possible blending with the \(1_0 \rightarrow 0_0 E\) transition (separated by 4.4 MHz or \(\sim 28\) km s\(^{-1}\)) may cause additional complexity.

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