VU Research Portal

A stringent limit on a drifting proton-to-electron mass ratio from alcohol in the early Universe

Bagdonaite, J.; Jansen, P.; Henkel, C.; Bethlem, H.L.; Menten, K.; Ubachs, W.M.G.

published in

Science

2013

DOI (link to publisher)

[10.1126/science.1224898](https://doi.org/10.1126/science.1224898)

document version

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Bagdonaite, J., Jansen, P., Henkel, C., Bethlem, H. L., Menten, K., & Ubachs, W. M. G. (2013). A stringent limit on a drifting proton-to-electron mass ratio from alcohol in the early Universe. *Science*, 339(6115), 46-48.
<https://doi.org/10.1126/science.1224898>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

the methyl and hydroxyl groups and have a sensitivity coefficient of -2.5 . The sensitivity of mixed transitions—i.e., transitions in which both the internal and overall rotation state is

changed—is strongly enhanced. The sensitivity coefficients for different transitions in methanol range from -42 to $+53$. These enhancements occur generally in every internal rotor molecule,

but because of a number of favorable properties, the effect is exceptionally large in methanol (17).

Methanol is abundantly present in the universe, and more than a 1000 lines have been recorded in our galaxy (18). So far, searches for methanol absorption in far-distant galaxies have yielded detection only in the gravitational lens system PKS1830-211 (19). A limit on $\Delta\mu/\mu$ (20) has been previously derived on the basis of two methanol lines. We present a comprehensive study of radio astronomical observations of four methanol lines in PKS1830-211, including the two previously observed, with improved signal-to-noise ratio.

The background source of this system, PKS1830-211, is a high redshift ($z = 2.507$) blazar, which is radio loud and time variable and is viewed as two spotlike features and an Einstein ring, which result from gravitational lensing by the intervening face-on spiral galaxy (21, 22). The redshift of the main molecular absorptions from the galaxy is $z = 0.88582$ (19, 23), corresponding to a look-back time of 7.0 billion years, or half the age of the universe (24). More than 30 different molecular species were detected in the lensing galaxy of PKS1830-211 (19). Molecular absorption is mostly detected toward one of the two blazar images (the southwestern), whereas the other image (the northeastern) shows weaker and fewer molecular lines at a slightly different redshift but stronger neutral hydrogen absorption [e.g., (19, 25)].

The CH_3OH lines were recorded with the 100-m single-dish Effelsberg radio telescope, using the 5-, 1.3-, and 1-cm receivers. Preliminary detections were performed during the course of 2011, and subsequently systematic observations were performed in a narrow time slot. The data were registered onto a local standard of rest velocity scale, which was centered at $z = 0.88582$. The two blazar images and the Einstein ring are unresolved and PKS1830-211 is effectively treated as a point source, which is an assumption underlying the present study.

The recorded spectra are shown in Fig. 2. For a single transition, the spectra taken on various days were averaged together, weighting the individual scans by their integration time. The lines were calibrated by the total continuum so that their strength is expressed as line-to-continuum flux density ratio. The profiles, devoid of underlying structure, were fitted as a single Gaussian (Table 1). The accuracy of the position measurements is at the level of 1 to 4% of the line width. The velocities between different transitions are interrelated via

$$V/c = -K_\mu \Delta\mu/\mu$$

where c is the speed of light, and $\Delta\mu/\mu$ represents the deviation from the current laboratory value of μ , defined so that a positive sign indicates a larger μ in the high-redshift-absorbing

Table 1. A summary of the relevant parameters and results. Laboratory data: lower and upper energy level quantum numbers; laboratory frequencies, ν , of the four relevant methanol absorption lines; and their uncertainties, fractional uncertainties, and uncertainties in terms of Doppler shift, $\Delta\nu_D$, in km/s. Calculations: the sensitivity coefficients, K_μ . Observations: the measured local standard of rest velocities of the lines (relative to $z = 0.88582$) and the line widths with their 1σ uncertainties. Assuming a molecular hydrogen density of $2 \times 10^3 \text{ cm}^{-3}$ and a kinetic temperature of 80 K (12, 29), full width at half maximum linewidths as fitted to observations and a $T_{\text{CMB}} = 2.728(1+z) = 5.145 \text{ K}$ for the temperature of the cosmic microwave background (CMB) radiation at $z = 0.88582$, the optical depths τ yield a total column density of $2.0 \times 10^{14} \text{ cm}^{-2}$ from a large velocity gradient radiative transfer model (30).

Laboratory data					Calc.	Observations		
Line $J''_{K''}-J'_{K'} \text{ Ts}$	ν (GHz)	$\Delta\nu/\nu$	$\Delta\nu_D$ (km/s)	Ref.	K_μ	Position (km/s)	Width (km/s)	τ
$3_{-1}-2_0 \text{ E}$	12.178597 (4)	3×10^{-7}	0.1	(31)	-32.8	9.06 ± 0.67	16.4 ± 1.4	0.0024
0_0-1_0 A^+	48.3724558 (7)	2×10^{-8}	0.006	(32)	-1	8.40 ± 0.10	10.8 ± 0.2	0.045
0_0-1_0 E	48.376892 (10)	2×10^{-7}	0.06	(33)	-1	9.12 ± 0.30	14.6 ± 0.6	0.016
$2_{-1}-1_0 \text{ E}$	60.531489 (10)	2×10^{-7}	0.06	(33)	-7.4	9.83 ± 0.43	17.0 ± 0.9	0.028

Fig. 3. The positions of the four observed methanol lines (represented by V/c with respect to $z = 0.88582$) are plotted versus their sensitivity coefficients, K_μ . The bold blue horizontal line represents the fiducial result of a fit to the E-type lines, whereas the dashed line represents a fit to all four lines. A positive slope of the fitted line implies that μ had a smaller value in the early universe than is measured in the laboratory. The blue-shaded surface is a density plot of simulated data points from the blue fitted line and reflects the confidence bands of the fit. Color-coding of the data points is the same as in Figs. 1 and 2.

galaxy (i.e., $\Delta\mu = \mu_z - \mu_{\text{lab}}$). Therefore, to determine the fractional change in μ , the peak positions of the four transitions are plotted (in V/c) versus K_μ , and a (dashed) line is fitted to the data (Fig. 3). Because the A and E levels of methanol can be regarded as belonging to two separate species, the data were analyzed in two different ways: First, only the three transitions from E levels were fitted, then the A transition was added to the sample. The analysis of the E transitions results in $\Delta\mu/\mu = (-0.1 \pm 7.6) \times 10^{-8}$, which is consistent with a nonvarying μ at the level of 1.5×10^{-7} (95% confidence level). The reduced chi-squared, χ_v^2 , which is a measure of the quality of the fit, is ~ 2.0 (26). The fit on all four transitions has a much larger χ_v^2 of 6.4, which might be attributed to segregation issues (see below), and it delivers $\Delta\mu/\mu = (11.0 \pm 6.8) \times 10^{-8}$.

The upper limit derived here is statistically more constraining than that derived in previous tests in the radio-domain (11–13, 19, 20). Moreover, compared to the methods used in previous studies, the methanol method is more robust against systematic effects. In particular, it is much less sensitive to the assumption that all absorbing species reside in the same physical location and hence are at the same redshift. Spatial segregation of different absorbers may mimic or hide a variation of μ . This is the limiting systematic error for tests based on the comparison between different molecular species, such as the comparison of ammonia with various rotational lines in HCO^+ , HCN , CS , and so forth (11–13). The molecular survey in PKS1830-211 suggests that segregation effects are prominent among different species (19). For instance, a single methanol line was found to be displaced from the average absorption velocity by more than 3 km/s (19). Our test is based exclusively on a single molecular species. However, as discussed above, the E and

A type methanol should be considered as different species and thus may undergo spatial segregation effects. In the combined spectrum, the $0_0-1_0 A^+$ and $0_0-1_0 E$ transitions, falling in close proximity in a single scan of the receiver, are separated by 0.72 ± 0.32 km/s. Moreover, the linewidths of the E lines are markedly larger than that of the A line (Table 1). Because this is suggestive of a spatial segregation of the E and A symmetry methanol molecules, we adopt a fiducial limit on $\Delta\mu/\mu$ from the fit of only E transitions.

Another source of systematic error is the known variability of the lensed object PKS1830-211. The absorption strength of radio lines was found to vary strongly, by a factor of >6 in a time span of 3 years, and this was ascribed to the intensity changes in the background continuum source (27). This phenomenon might cause a varying alignment through parts of the absorbing spiral and therewith absorption through varying Doppler components over time. Hence this variability may affect the derivation of a μ -constraint from radio-observations. For this reason we adopted a measurement strategy to explicitly address the source variability issue. Spectra of the anchor lines (the middle panel in Fig. 2) were recorded in December 2011 and April 2012, whereas the two strongly shifting lines have been observed in-between in February and March 2012 (28). The strong ($0_0-1_0 A^+$) line in the combined spectrum from December 2011 is positioned at 8.32 ± 0.10 km/s, and at 8.80 ± 0.24 km/s in the spectrum from April 2012. The difference between them is 0.48 ± 0.26 km/s, possibly indicative of a small systematic shift due to variability. We have assessed this possible systematic effect as caused by time variability in two models (26) and have chosen the one producing the largest uncertainty ($\Delta\mu/\mu$ of 7.0×10^{-8}) to give a conservative estimate.

Thus, we obtain a limit on varying μ to be $\Delta\mu/\mu = (-0.1 \pm 7.6_{\text{stat}} \pm 7.0_{\text{sys}}) \times 10^{-8}$ or, if the statistical and systematic uncertainties are added in quadrature, a limit of $\Delta\mu/\mu = (0.0 \pm 1.0) \times 10^{-7}$.

References and Notes

1. L. Smolin, *Physica A* **340**, 705 (2004).
2. J. D. Barrow, J. Magueijo, *Phys. Rev. D Part. Fields Gravit. Cosmol.* **72**, 043521 (2005).
3. J. K. Webb, V. V. Flambaum, C. W. Churchill, M. J. Drinkwater, J. D. Barrow, *Phys. Rev. Lett.* **82**, 884 (1999).
4. M. T. Murphy, J. K. Webb, V. V. Flambaum, *Mon. Not. R. Astron. Soc.* **345**, 609 (2003).
5. J. K. Webb et al., *Phys. Rev. Lett.* **107**, 191101 (2011).
6. J. A. King et al., *Mon. Not. R. Astron. Soc.* **422**, 3370 (2012).
7. E. Reinhold et al., *Phys. Rev. Lett.* **96**, 151101 (2006).
8. A. Malec et al., *Mon. Not. R. Astron. Soc.* **403**, 1541 (2010).
9. F. van Weerdenburg, M. T. Murphy, A. L. Malec, L. Kaper, W. Ubachs, *Phys. Rev. Lett.* **106**, 180802 (2011).
10. J. van Veldhoven et al., *Eur. Phys. J. D* **31**, 337 (2004).
11. M. T. Murphy, V. V. Flambaum, S. Muller, C. Henkel, *Science* **320**, 1611 (2008).
12. C. Henkel et al., *Astron. Astrophys.* **500**, 725 (2009).
13. N. Kanekar, *Astrophys. J. Lett.* **728**, L12 (2011).
14. P. Jansen, L.-H. Xu, I. Kleiner, W. Ubachs, H. L. Bethlem, *Phys. Rev. Lett.* **106**, 100801 (2011).
15. S. A. Levshakov, M. G. Kozlov, D. Reimers, *Astrophys. J.* **738**, 26 (2011).
16. C. C. Lin, J. D. Swalen, *Rev. Mod. Phys.* **31**, 841 (1959).
17. P. Jansen, I. Kleiner, L.-H. Xu, W. Ubachs, H. L. Bethlem, *Phys. Rev. A* **84**, 062505 (2011).
18. F. J. Lovas, *J. Phys. Chem. Ref. Data* **33**, 177 (2004).
19. S. Muller et al., *Astron. Astrophys.* **535**, A103 (2011).
20. S. P. Ellingsen, M. A. Voronkov, S. L. Breen, J. E. J. Lovell, *Astrophys. J. Lett.* **747**, L7 (2012).
21. D. L. Jauncey et al., *Nature* **352**, 132 (1991).
22. C. Lidman et al., *Astrophys. J.* **514**, L57 (1999).
23. T. Wiklind, F. Combes, *Nature* **379**, 139 (1996).
24. Adopting a standard Λ -cosmology with $H_0 = 73$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_m = 0.28$, $\Omega_\Lambda = 0.72$.
25. J. N. Chengalur, A. G. de Bruyn, D. Narasimha, *Astron. Astrophys.* **343**, L79 (1999).
26. See supplementary materials on Science Online.
27. S. Muller, M. Guélin, *Astron. Astrophys.* **491**, 739 (2008).
28. Each line required a change of receiver, for which reason the time intervals could not be shorter.
29. K. M. Menten et al., *Astron. Astrophys.* **492**, 725 (2008).
30. S. Leurini et al., *Astron. Astrophys.* **422**, 573 (2004).
31. S. M. Breckenridge, S. G. Kukolic, *Astrophys. J.* **438**, 504 (1995).
32. J. E. M. Heuvel, A. Dymanus, *J. Mol. Spectrosc.* **45**, 282 (1973).
33. H. S. P. Müller, K. M. Menten, H. Mäder, *Astron. Astrophys.* **428**, 1019 (2004).

Acknowledgments: This work is supported by the Foundation for Fundamental Research on Matter program “Broken Mirrors & Drifting Constants.” H.L.B. acknowledges support from the Netherlands Organization for Scientific Research via a VIDI grant and by the European Research Council via a Starting Grant. We thank the staff of the Effelsberg radio telescope for their hospitality and support. The raw data of the radioastronomical observations are available upon request from the Max Planck Institute for Radio Astronomy at Bonn (kmenten@mpifr-bonn.mpg.de).

Supplementary Materials

www.sciencemag.org/cgi/content/full/science.1224898/DC1
Supplementary Text
Table S1
Reference (34)

18 May 2012; accepted 16 November 2012
Published online 13 December 2012;
10.1126/science.1224898