ON THE VARIATIONS OF FUNDAMENTAL CONSTANTS AND ACTIVE GALACTIC NUCLEUS FEEDBACK IN THE QUASISTELLAR OBJECT HOST GALAXY RXJ0911.4+0551 AT z = 2.79

A. WEIß1, F. WALTER2, D. DOWNES3, C. L. CARRILll4, C. HENKEL1,5, K. M. MENTEN1, and P. COX3
1 Max-Planck Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
2 Max-Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
3 Institut de Radio Astronomie Millimétrique, 300 Rue de la Piscine, Domaine Universitaire, 38406 Saint Martin d’Hères, France
4 National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA
5 Astronomy Department, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia

ABSTRACT

We report on sensitive observations of the CO(J = 7 → 6) and C(3)P2 → 3P1) transitions in the z = 2.79 QSO host galaxy RXJ0911.4+0551 using the IRAM Plateau de Bure interferometer. Our extremely high signal-to-noise spectra combined with the narrow CO line width of this source (FWHM = 120 km s−1) allows us to estimate sensitive limits on the spacetime variations of the fundamental constants using two emission lines. Our observations show that the C1 and CO line shapes are in good agreement with each other but that the C1 line profile is of the order of 10% narrower, presumably due to the lower opacity in the latter line. Both lines show faint wings with velocities up to ±250 km s−1, indicative of a molecular outflow. As such, the data provide direct evidence for negative feedback in the molecular gas phase at high redshift. Our observations allow us to determine the observed frequencies of both transitions with so far unmatched accuracy at high redshift. The redshift difference between the CO and C1 lines is sensitive to variations of ΔF/F with F = α2/μ where α is the fine structure constant and μ is the electron-to-proton mass ratio. We find ΔF/F = (6.9 ± 3.7) × 10−6 at a look-back time of 11.3 Gyr, which, within the uncertainties, is consistent with no variations of the fundamental constants.

Key words: cosmology: observations – galaxies: evolution – galaxies: high-redshift – galaxies: individual (RXJ0911.4+0551) – ISM: molecules

1. INTRODUCTION

Possible time variation of coupling strengths and elementary particle masses is now being discussed with regard to the accelerating, expanding universe. Theoretical models that impose extra dimensions predict that dimensionless quantities like the fine-structure constant α = e2/ℏc or the electron-to-proton mass ratio μ = me/mp depend on the scale length of extra dimensions in Kaluza–Klein, superstring theories or other grand unification theories (see, e.g., reviews by Flambaum 2008; Chiba 2011). This scale factor may vary with cosmic time, which in turn gives rise to variations of fundamental constants in the 4D or extra-D spacetime. Very different time dependencies from linear to slow-rolling to oscillating variations are considered in some theoretical models (e.g., Marciano 1984; Fujii et al. 2000). Such variations are now intensively searched for both in astrophysical observations and in laboratory experiments.

So far, essentially all sensitive astrophysical experiments that probe variations of the fundamental constants at high redshift have used intervening absorbing systems toward QSOs by comparing the redshifts of different lines. This holds for optical but also for millimeter (mm) and centimeter (H1, OH) absorption lines (e.g., Carilli et al. 2000; Murphy et al. 2003; Henkel et al. 2007; Kanekar et al. 2010) which typically give rise to narrow (~10 km s−1 wide) absorption features, which, in principle, allow very precise estimates of the line centroids. A possible systematic frequency shift in these experiments can arise from the different velocity distributions of different species in the absorbing gas (the so-called Doppler noise; see, e.g., Kozlov et al. 2009). This is due to the fact that absorption experiments only probe pencil beams through the interstellar medium (ISM) of intervening galaxies, which makes these experiments sensitive to the physical and chemical small-scale structure of the ISM. This effect can be largely reduced by using multiplets from a single species (e.g., Webb et al. 1999) and large samples of absorbing systems that are now available in the optical/UV (e.g., King et al. 2012). For absorption studies in the radio regime, the analysis can be further complicated by the fact that the continuum source itself may have a frequency and/or time-dependent structure (e.g., synchrotron emission from compact radio jets) and therefore absorption may trace different parts of the absorbing cloud. In addition, such studies until today are limited to a few suitable objects which compromises statistical approaches. On the other hand, radio and mm studies are particularly sensitive probes for variations of the fundamental constants as coupling strength of fine-structure or inversion transitions to variations in α and/or μ is more than an order of magnitude larger than that of electronic transitions in the optical/UV (e.g., Flambaum & Kozlov 2007).

Consequently, it has been suggested to use low- or mid-J rotational CO lines in conjunction with fine structure lines of atomic carbon to search for variations of the fundamental constants (Levshakov et al. 2008). In contrast to the absorption studies, both lines can be seen in emission and therefore their line profiles probe the gas distribution and kinematics on galactic scales rather than random motion along a single line of sight. As such, their line centroids will not depend on the small-scale physical and chemical structure of the ISM, which makes both emission lines promising candidates to complement absorption line studies. This line combination is sensitive to variations of F = α2/μ. Variations of this quantity are related to the observed redshift of both lines via ΔF/F = Δz/(z + 1) where Δz is the redshift difference between the CO and C1 lines. As such, their sensitivity to α-variations is about 30 times higher than any UV line (see Levshakov et al. 2008). The downside of using emission lines is that the intrinsic line widths are large compared to the
absorption lines, which reduces the accuracy to determine the line centroids at the same signal-to-noise ratio.

CO and C\textsc{i} observations of high-\(z\) galaxies are becoming available in increasing number (see Walter et al. 2011 and references therein). These spectra, however, typically have low velocity resolution and low signal-to-noise and therefore cannot be used to analyze the variations of the fundamental constants (Curran et al. 2011). Furthermore, most high-\(z\) galaxies detected in C\textsc{i} so far have large line width (>200 km s\(^{-1}\)) which implies that even with high signal-to-noise observations it would be extremely challenging to study \(\Delta F/\Delta F\) as this would require redshift accuracies below 1 km s\(^{-1}\).

In this paper, we present sensitive observations of the CO(7–6) and C\textsc{i}(2–1) hereafter) in the high-\(z\) QSO host galaxy RXJ0911.4+0551 at redshift \(z = 2.79\). RXJ0911.4+0551 is currently the most suitable candidate for high-precision CO and C\textsc{i} redshift measurements as it exhibits very strong line emission due to gravitational lensing and has the narrowest CO line width (FWHM = 120 km s\(^{-1}\)) of any high-redshift source observed so far. Furthermore, the increased bandwidth of millimeter facilities implies that the redshifted CO(7–6) and C\textsc{i}(2–1) lines can now be measured simultaneously in a single observational setup which eliminates efficiently potential instrumental systematics.

Measuring possible changes in the fundamental constants clearly requires very high signal-to-noise observations of the CO and C\textsc{i} lines. Such high quality observations have also the potential to reveal outflows, i.e., negative feedback from star formation and/or active galactic nucleus (AGN) winds. AGN-driven molecular outflows have been recently observed in nearby active galaxies (Feruglio et al. 2010; Alatalo et al. 2011; Chung et al. 2011; Sturm et al. 2011) and are a crucial ingredient to galaxy evolution models to explain the number density of massive galaxies and their old stellar populations (e.g., Di Matteo et al. 2005).

2. OBSERVATIONS

We observed RXJ0911.4+0551 using the IRAM Plateau de Bure interferometer (PdBI) in 2011 October in the compact D configuration with six antennas. The receivers were tuned to 213.1 GHz and data were recorded using the 3.6 GHz WideX correlator at PdBI. At a redshift of \(z = 2.79\) the observing frequencies for CO(7–6) and C\textsc{i}(2–1) are 212.5 and 213.2 GHz, respectively, and comfortably fall into the bandwidth afforded by the correlator. WideX’s channel separation is 1.95 MHz. The synthesized beam is 2.75 km s\(^{-1}\) at the observed frequency). Observations were done during good observing conditions using CRL618 as primary flux calibrator and the nearby source J0906+015 as phase and secondary amplitude calibrator. RXJ0911.4+0551 was observed for \(\approx 15\) hr on-source resulting in a noise level of 2.2 mJy beam\(^{-1}\) at WideX’s original frequency resolution (1.95 MHz). The synthesized beam is \(20\times 14^\prime\) with a position angle of P.A. = 10\(^\circ\). Data reduction was performed using the \textit{GILDAS} package with standard calibration, flagging, and imaging steps.

3. RESULTS

3.1. Line and Continuum Distribution

The line and continuum distribution of our observations is shown in comparison to the near-infrared (NIR; archival \textit{HST}-NICMOS image) in Figure 1 (left). The PdBI image shows two separate sources. The eastern source (A) is a blend of three images (A1, A2, and A3; Burud et al. 1998), the western source is the fourth lens image of the QSO (image B) which is spatially separated from component A by \(\approx 3^\prime\). The NIR and mm emission regions are displaced with respect to each other by about \(\sim 0.25^\prime\). This shift is obvious for image B but can also be established for A if one convolved the \textit{HST}-NICMOS image to the PdBI beam. We interpret the offset as inaccurate astrometry (rather than an indication for differential magnification between the mm and NIR light), presumably in the \textit{HST}-NICMOS image, as the coordinates in the PdBI observations are phase referenced. The PdBI position for image B is R.A.: 09\(^h\)11\(^m\)27\(^s\)430 (±0.01), decl: 05\(^\circ\)50\(^\prime\)54\(^\prime\)7 (±0.015) (J2000).

The line intensity ratio between C\textsc{i} and CO is comparable for both components with \(I_{\text{C-i}(2-1)}/I_{\text{CO}(7-6)} = 0.60 \pm 0.02\) and

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Left: integrated CO(7–6) intensity + continuum distribution (black contours) shown on an archival \textit{HST}-NICMOS NIR image of RXJ0911.4+0551. Contours are shown for 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.7, 1.0, 1.5, and 2.0 Jy beam\(^{-1}\) km s\(^{-1}\). The eastern PdBI image (A) is a blend of three images (A1, A2, and A3; Burud et al. 1998) of the QSO, the western peak (B) is the fourth lens image. Right: 3.6 GHz wide spectrum toward the peak of image A at 10 km s\(^{-1}\) resolution. Other redshifted molecular transitions which fall into the observing band and have been detected toward Orion (Comito et al. 2005) are labeled in the figure.}
\end{figure}
difference spectrum CO–C

The redshift of the CO line \((\alpha \equiv \Delta z_{CO})\) and the redshift difference between CO and C i \((\Delta \alpha \equiv \Delta z_{CO} - \Delta z_{C i})\) are related to the variations of the fundamental constants via \(\Delta z/(1 + z) = \Delta F/F\) with \(F = F \alpha^2/\mu\) where \(F\) is the fine structure constant and \(\mu\) is the electron-to-proton mass ratio (Levshakov et al. 2008). With the numbers in Table 1 we find \(\Delta z = (2.62 \pm 1.39) \times 10^{-5}\) and thus \(\Delta F/F = (6.91 \pm 3.67) \times 10^{-6}\).

### 3.3. Line Centroids and Limits on the Fundamental Constants

To determine the line centroids we fitted the line shape by models with a single Gaussian and two nested Gaussians. The line centroids for both methods agree well within the uncertainties even when all six parameters of the nested Gaussians are kept free. The fitting uncertainties, however, increase by \(\approx50\%\) in the latter case. We therefore used a single component Gaussian fit for each line and omitted the line wings in the fitting process. The fitting was performed on the original resolution data as binning was found to reduce the accuracy of the results. We have compared results from different programs (CLASS, GNUPLLOT) and did not find significant differences in the fitting results. We find uncertainties for the line centroids of only 500 and 600 kHz (corresponding to a velocity uncertainty of 0.7 and 0.9 km s\(^{-1}\)) for the CO and C i line, respectively. The results including the corresponding redshifts are given in Table 1.

| Line     | \(\nu_{\text{obs}}\) (GHz) | \(z_{\text{line}}\) | FWHM (km s\(^{-1}\)) |
|----------|-----------------------------|---------------------|-----------------------|
| CO(7–6)  | 212.4935(5)                 | 2.796125(9)         | 119 ± 1.8             |
| C i(2–1) | 213.2036(6)                 | 2.796099(11)        | 107 ± 2.4             |

Note. Calculated using rest frequencies of 806.6518060(5) and 809.341970(5) GHz CO(7–6) for and C i(2–1), respectively (Müller et al. 2001).

The 3.6 GHz wide spectrum toward image A is shown at a velocity resolution of 10 km s\(^{-1}\) in Figure 1 (right). Several other redshifted molecular transitions fall into the observed bandwidth. Some lines (indicated in the figure) might have been strong enough to be detected in RXJ0911.4+0551 based on the observed flux densities in the Orion-KL hot core (Comito et al. 2005). However, the only (but not significant) additional line feature in our spectrum is the HNC(9–8) line redshifted to 214.8 GHz.

### 3.2. Line Profiles

A comparison of the CO(7–6) and C i(2–1) spectra is shown in Figure 2 (left). Both line profiles are very similar and almost perfectly described by a single Gaussian within the uncertainties of the observations. A closer inspection of the two profiles reveals that the C i spectrum is slightly narrower than the CO line. This is shown in Figure 2 (center) where we display the difference spectrum CO–C i after scaling the C i peak intensity to the peak of the CO line. The residual shows faint but significant CO excess in the 50–150 km s\(^{-1}\) velocity intervals. From a Gaussian fit to the full line we find FWHMs of 119 ± 1.8 km s\(^{-1}\) and 107 ± 2.4 km s\(^{-1}\) for CO and C i, respectively (see Table 1).

The line profiles start to deviate from a Gaussian at 10% level of the peak intensity for both lines. The line wings are best seen in the higher signal-to-noise CO(7–6) line profile at low velocity resolution (see Figure 2, right). The wings are also detected in the C i(2–1) line albeit at lower significance. The wings are visible both toward the red and the blue side of the spectrum and are detected out to \(\approx0.7\) and \(\approx0.9\) km s\(^{-1}\).

The fitted CO(7–6) profile with two nested Gaussian yields an improved fit to the line profile including the line wings. For the broad line component this yields a peak of \(\approx4.5\) mJy and a line width of FWHM \(\approx290\) km s\(^{-1}\).
4. DISCUSSION

4.1. Line Wings

The line wings detected in our spectra toward RXJ0911.4+0551 are remarkably similar to those recently detected in deep CO observations toward two local galaxies hosting an AGN: Mrk 231 (Feruglio et al. 2010) and NGC 1266 (Alatalo et al. 2011). In both cases the CO wings have been interpreted as molecular outflows. While the projected outflow velocities in NGC 1266 are comparable to those detected in our spectra, the outflow signature in Mrk 231 is much more pronounced with wings detected out to ±750 km s\(^{-1}\). Although it is tempting to interpret the line wings in RXJ0911.4+0551 as the signatures of a molecular outflow, the situation is complicated by the fact that the source is amplified by a galaxy (visible in the HST-NICMOS image shown in Figure 1) and only to a lesser degree by a nearby galaxy cluster (see Burud et al. 1998; Kneib et al. 2000).

This implies that the caustic curves are very compact, unlike the smoothly varying caustics from cluster lensing. Thus, an alternative interpretation is that the lens only strongly amplifies a small part of the molecular gas distribution in the disk of RXJ0911.4+0551 (with correspondingly narrow CO line width) and that the faint, broader CO profile visible as wings is the true line width of the system with low or no lens magnification.

We can, however, use the observed line luminosity of the optically thick CO(7–6) line together with the excitation temperature of \(T_{\text{ex}}\approx 35\) K estimated from the C\(_{\text{i}}\) line ratio (using the intensity of the lower carbon line from Walter et al. 2011) to obtain a lower limit for the size of the amplified emission region. This calculation uses \(\Omega = \frac{L_{\text{CO(7-6)}}}{\Delta v D_{\lambda}^{-2} \mu_{\text{mag}}^{-1}}\) (Solomon et al. 1997) and assumes \(T_{\text{CO(7-6)}} \approx T_{\text{ex,CO}} - T_{\text{mb}}\). Taking the magnification of \(\mu_{\text{mag}} = 20\) into account, this yields a source diameter of ∼1 kpc which is a lower limit to the true source size because (1) it assumes an area filling factor of the emission of unity, (2) a face-on geometry, and (3) the true excitation temperature of the CO(7–6) line is likely lower than our estimate from C\(_{\text{i}}\) due to the higher critical density of the CO(7–6) transition compared to both C\(_{\text{i}}\) lines. Thus, the true underlying source size is likely similar to what has been observed in resolved, unlensed high redshift QSO host galaxies (such as J1148+5251 with \(D = 2.5\) kpc; Walter et al. 2004). This comparison suggests that the gravitational lens amplifies the entire molecular gas distribution of RXJ0911.4+0551 and not just a small fraction of the disk. This favors the interpretation that the narrow observed line width is due to a close to face-on orientation of the molecular disk and that the faint line wings indeed trace a molecular outflow.

We estimate the molecular gas mass in the outflow using the optically thin C\(_{\text{i}}\)(P\(_2\) → P\(_1\)) line (see, e.g., Equation (2) in Weiß et al. 2003). We use the C\(_{\text{i}}\) excitation temperature given above and a carbon abundance, [C\(_{\text{i}}\)]/[H\(_2\)], of \(8 \times 10^{-5}\) (Walter et al. 2011) which yields a molecular gas mass (including a correction of 1.36 for Helium and correcting for the magnification) of \(M_{\text{outflow}} = 6 \times 10^{9} M_{\odot}\). This mass only includes the line wings (difference between the two component and the single component fit shown in Figure 2 right, albeit for C\(_{\text{i}}\)(2–1)) and corresponds to ∼9% of the C\(_{\text{i}}\)(P\(_2\) → P\(_1\)) line luminosity. The total mass in the broad line component (which has been used by Feruglio et al. 2010 to estimate the outflow mass in Mrk 231) is \(1.7 \times 10^{9} M_{\odot}\). However, here we use the more conservative approach to estimate the outflow properties only based on the mass in the line wings (Alatalo et al. 2011). Using the HWHM = 145 km s\(^{-1}\) from the Gaussian fit to the broad line component as a lower limit for the average outflow speed (due to the unknown outflow orientation) the kinetic energy in the outflow is \(E_{\text{kin}} > 1.2 \times 10^{56}\) erg. Thus, the outflow in RXJ0911.4+0551 is ∼3× more massive but likely less energetic than the outflow in Mrk 231 while other key parameters (\(L_{\text{FIR}}, M_{\text{BH}}, M_{\text{H}}\)) are comparable for both sources after correcting for the gravitational magnification.

For RXJ0911.4+0551 the lack of information on the size and morphology of the outflow prevents us from estimating the dynamical timescale and the outflow rate. Mapping the blue and the red line wings independently only yields an upper limit for their angular separation in the image plane of ∼0.3 (2.4 kpc), not sufficient to obtain a meaningful limit on the outflow rate. If we assume that the outflow size is comparable to the outflows observed in Mrk 231 and NGC 1266 (\(r = 0.5\) kpc), the outflow rate for RXJ0911.4+0551 is \(M > 180 M_{\odot}\) yr\(^{-1}\), larger than the star formation rate (SFR = 140 \(M_{\odot}\) yr\(^{-1}\); Wu et al. 2009) which would hint at AGN feedback as being the main driver for the molecular outflow (see the discussion in Alatalo et al. 2011). The corresponding gas depletion timescale would be only 40 Myr. Even if we use the observed upper limit of <2.4 kpc as the intrinsic radius for the outflow, the depletion timescale remains short (<200 Myr) which implies that a significant fraction (>50%) of molecular gas will be removed from the disk within the typical lifetime of 100 Myr for massive starbursts at high redshift (Tacconi et al. 2008).

4.2. Limits on the Fundamental Constants

A potential concern using mid-J CO and C\(_{\text{i}}\) emission lines as a probe of variations of the fundamental constants is whether both lines trace the same gas on galactic scales. Observations of CO and C\(_{\text{i}}\) in the Milky Way have shown that both lines indeed probe the same molecular material on large and small scales (Ikeda et al. 2002; Zhang et al. 2001) despite the expectations from photon dominated region models which predict that C\(_{\text{i}}\) should only exist in small layers surrounding the CO cloud cores. As discussed in the previous section, our experiment probably probes a region of ∼1 kpc in diameter. We would therefore expect that any potential spatial differences in the CO and C\(_{\text{i}}\) emission velocities within molecular clouds would average out to zero over these extended regions.

Given that both lines trace the same volume on large scales one would naïvely expect that their line profiles are identical. Our observations show that this is not the case and that the C\(_{\text{i}}\) line profile is ∼10% narrower than the CO profile (Figure 2, left and center; Table 1). This effect, however, is expected as the opacity of CO is typically much larger than the C\(_{\text{i}}\) opacity (for the peak of the lines in RXJ0911.4+0551 we estimate opacities of 17 and 1.0 for CO(7–6) and C\(_{\text{i}}\)(2–1), respectively, using large velocity gradient models). Since the gas column density and therefore the opacity decreases toward the wings of the lines and because the intensity in each velocity bin scales as \((1 - e^{-\tau})\), the intensity in the wings of the C\(_{\text{i}}\) line decreases more rapidly than in the case of CO which in turn gives rise to a narrower line profile in C\(_{\text{i}}\). This effect, however, is not expected to be a critical limitation for the precise determination of the line centroid (i.e., the systemic velocity or redshift of the galaxy): the line profiles of galaxy-averaged molecular emission lines are not only determined by opacity and excitation effects but also by the effective source solid angle as a function of velocity. The latter typically does not saturate (i.e., clouds do not overlap in velocity space and spatially at the same time) which prevents galaxy-averaged CO lines from saturating at their
peak. As systematic instrumental effects (e.g., LSR corrections) cancel out in our simultaneous observations of both lines and local oscillator variations (defining the frequency accuracy of the spectrometer) can safely be neglected, we conclude that systematic uncertainties are small compared with the statistical uncertainties, i.e., our ability to determine variations of the fundamental constants is solely limited by the signal-to-noise ratio and line width of our spectrum.

So far, estimates on the variations of the fundamental constants using high redshift emission lines have only been published in two studies using C II and CO (in BR1202-0725 at \( z = 4.7 \) and J1148+5251 at \( z = 6.4 \), Levshakov et al. 2008) and C I and CO (in a sample of sources at \( z = 2.3–4.1 \), Curran et al. 2011) where the measurements were taken entirely from the literature. These attempts yielded \( \sigma \) limits on \( |\Delta F/F| \) of \( < 4.5 \times 10^{-4} \) and \( < 2.6 \times 10^{-4} \), respectively. Our experiment improves on these limits by more than a factor of 20 (at comparable look-back time) with \( |\Delta F/F| < 1.1 \times 10^{-5} (3 \sigma) \). Most absorption line studies have focused on variations in \( \Delta \alpha/\alpha \) or \( \Delta \mu/\mu \). Variations of \( \Delta F/F \) are related to both these quantities via \( \Delta F/F = 2 \Delta \alpha/\alpha - \Delta \mu/\mu \) (Levshakov et al. 2008). Centimeter and millimeter absorption line studies have recently used inversion lines of NH\(_3\) in combination with rotational lines of dense gas tracers (such as HC\(_3\)N or CS) to obtain limits on \( \Delta \mu/\mu \). This combination provides a particularly sensitive probe to \( \Delta \mu/\mu \) due to the strong coupling between their redshift difference and variations in \( \mu \) (e.g., Levshakov et al. 2010). Studies using several inversion and rotational transitions toward PKS 1810–211 at \( z = 0.89 \) give a conservative limit of \( |\Delta \mu/\mu| < 10^{-6} \) (Murphy et al. 2008; Henkel et al. 2009). The formally most accurate application of this technique to date yields a \( 3 \sigma \) limit of \( |\Delta \mu/\mu| < 3.6 \times 10^{-7} \) at \( z = 0.68 \) (Kanekar 2011) albeit on a small number of spectral lines.

Limits on variations of \( \alpha \) at high redshift do not reach such accuracy to date but some studies have reported non-zero values for \( \Delta \alpha/\alpha \) based on QSO absorption spectra (Murphy et al. 2003; Webb et al. 2011; King et al. 2012). Here we use our results to obtain an independent limit on \( \Delta \alpha/\alpha \). If we assume \( \Delta \mu/\mu = 0 \) between \( z = 0 \) and \( z = 2.79 \) (motivated by the NH\(_3\) results mentioned above) our observations yield \( \Delta \alpha/\alpha = (3.5 \pm 1.8) \times 10^{-6} \), consistent with zero variations of \( \alpha \) at a look-back time of 11.3 Gyr within the uncertainties (\( |\Delta \alpha/\alpha| < 4.8 \times 10^{-16} \) yr\(^{-1}\) (3 \( \sigma \)). As such, our experiment yields comparable accuracy on a single object as work based on HIRES/Keck and UVES/VLT absorption line spectroscopy on QSO samples which give typical accuracies of 1–2 ppm (1\( \sigma \); Levshakov et al. 2007; Murphy et al. 2008; Webb et al. 2011). Our source, RXJ0911.4+0551, lies nearly orthogonal to the proposed angular dipole distribution of Webb et al. (2011) and King et al. (2012) and thus does not provide a stringent test of that claim.

5. CONCLUDING REMARKS

Our observations demonstrate that sensitive simultaneous millimeter wave observations of CO(7–6) and C\(_2\)H(2–1) emission lines provide a powerful diagnostic to investigate possible variations of the fundamental constants at high redshift. Our observations do not show evidence that systematic effects are limiting the interpretation of the data and our results are limited by the signal-to-noise ratio of our spectra. This implies that deeper observations with even higher spectral resolution, which are now in reach with ALMA, will greatly improve our current limits. A potential concern of deep and more precise observations could arise from the different optical depth in the CO and C\(_2\)H lines, which leads to slightly different line shapes for both transitions. Such potential limitations can be eliminated by observations of reasonably sized samples of high-z CO and C\(_2\)H emitters with suitable line widths. Given ALMA’s sensitivity even CO isotopologues such as \(^{13}\)CO will eventually become accessible with high signal-to-noise ratio which will further help to remove this potential limitation. In any case the uncertainties and potential systematics of emission line studies will be substantially different from those of absorption line experiments. As such the combination of both approaches on samples of high-z galaxies will greatly improve the sensitivity and reliability of measurements probing the variations of the fundamental constants.

Our data also demonstrate the large discovery space of deep spectroscopic millimeter observations with large bandwidth. We detect for the first time a massive molecular outflow via CO and C\(_2\)H line wings in a high-redshift galaxy. Our analysis suggests that a significant fraction (>50\%) of molecular gas in RXJ0911.4+0551 will be removed from the disk within the typical lifetime of 100 Myr for massive starbursts. As such RXJ0911.4+0551 is one of the few examples for negative feedback observed in the molecular gas phase at high redshift, although higher resolution observations (e.g., with ALMA) will be required to decide whether the outflow is driven by an AGN wind or by star formation.

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