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Astrophysical constraints on the proton-to-electron mass ratio with FAST

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Abstract That the laws of physics are the same at all times and places throughout the Universe is one of the basic assumptions of physics. Astronomical observations provide the only means to test this basic assumption on cosmological time and distance scales. The possibility of variations in the dimensionless physical constant μ - the proton-to-electron mass ratio, can be tested by comparing astronomical measurements of the rest frequency of certain spectral lines at radio wavelengths with laboratory determinations. Different types of molecular transitions have different dependencies on μ and so observations of two or more spectral lines towards the same astronomical source can be used to test whether there is any evidence for either temporal or spatial changes in the physical fundamental constants. μ will change if the relative strength of the strong nuclear force compared to the electromagnetic force varies. Theoretical studies have shown that the rotational transitions of some molecules which have transitions in the frequency range that will be covered by FAST (e.g., CH_3OH, OH and CH) are sensitive to changes in μ. A number of studies looking for possible variations in μ have been undertaken with existing telescopes, however, the greater sensitivity of FAST means it will open new opportunities to significantly improve upon measurements made to date. In this paper, we discuss which molecular transitions and sources (both in the Galaxy and external galaxies) are likely targets for providing improved constraints on μ with FAST.

Key words: ISM: molecules — radio lines: ISM — techniques: radial velocities — elementary particles

1 INTRODUCTION

Theories beyond the standard model of physics have predicted the possibility of space-time variation in the fundamental constants. Over the last few decades a number of laboratory studies, theoretical calculations and astronomical observations have been conducted to search for the signatures of such variations (for a recent review of the field see Uzan 2011). Astrophysical spectroscopic studies have mostly focused on searching for variations in the fine structure constant $\alpha = e/\hbar c$ and the proton-to-electron mass ratio $\mu = m_{\rm p}/m_{\rm e}$. Astrophysical spectroscopy can be used to search for changes in the dimensionless constants α and/or μ by comparing the rest frequency of different transitions in atoms and molecules as a function of time and/or position. The energy levels of different quantum states can be expressed in terms which include the dimensionless constants α and μ. Where a transition takes place between energy levels with different dependencies on these constants, a variation in either will cause a change of the transition frequencies compared to the laboratory value (e.g., Webb et al. 1999; Reinhold et al. 2006). The change in frequency caused by a change in either of these dimensionless constants is characterized by the sensitivity coefficient of transition K_α or K_μ (which is defined as the proportionality constant between the fractional frequency shift of the transition, $\Delta\nu/\nu$ and the fractional shift in α or μ) as follows

$$\frac{\Delta\nu}{\nu} = K_\alpha\frac{\Delta_\alpha}{\alpha} + K_\mu\frac{\Delta_\mu}{\mu}. \quad (1)$$

The rest frequency of electron transitions in atoms is generally more sensitive to the fine structure constant α, whereas rotational transitions in molecules have a stronger dependence on the proton-to-electron mass ratio μ. The mass of the proton is set by the strong nuclear force, while the mass of the electron is set by the relatively weak electromagnetic force, and any change in the relative strength of these two fundamental interactions will change μ and hence the rest frequency of rotational transitions. One mechanism which may cause variability of the two constants is through the scalar fields which are potential candidates for producing dark energy, which is responsible for the observed cosmic acceleration. The chameleon mechanism proposes that the scalar fields are ultra-light in the cosmic vacuum but effectively possess a large mass locally when they are coupled to ordinary matter (Khoury & Weltman 2004). Therefore the searches for changes in μ and α are especially important for not only understanding the nature of the fundamental laws of physics, but also providing direct observational tests for some cosmological theories.

Furthermore, models of dynamical scalar fields predict relationships between variations in different dimensionless constants such as μ and α with time, for example

$$\frac{\dot{\mu}}{\mu} = R\frac{\dot{\alpha}}{\alpha}, \tag{2}$$

where R is a scalar assumed to be of order –40 to –50 (Avelino et al. 2006; Thompson et al. 2013; Thompson 2013). Values of R of this order imply that variations in μ will be easier to detect than those in α. This means that upper limits on variations in μ at relatively low redshift can significantly constrain variations in α at higher redshift for example if rolling scalar fields are the mechanism through which they are produced.

The most sensitive searches for possible spatial or temporal variations of μ require high signal to noise observations of the molecular transitions that have a large sensitivity coefficient K_μ. Previous searches for variations in μ on cosmological timescales have compared optical transitions of molecular H_2 (the most abundant astrophysical molecule), in highly-redshifted objects with accurate laboratory measurements (Reinhold et al. 2006). These observations show that $\Delta\mu/\mu < 3 \times 10^{-5}$ over look-back times of $\sim$12 Gyr. However, the H_2 transitions measured in these observations have relatively poor K_μ sensitivity coefficients in the range $-0.05 < K_\mu <$+0.02. Rotational transitions of molecules are generally much more sensitive to changes in μ ($K_\mu \sim 1$) than rovibrational transitions of H_2, therefore more recent observational studies have focused on searching for changes in μ using rotational transitions of molecules at radio wavelengths. Some molecular transitions have even greater sensitivity to changes in μ than the majority, for example, the inversion transitions of ammonia (NH_3) have $K_\mu = -4.46$. Hence the ammonia inversion transitions are $\sim$100 times more sensitive to variations in μ than the H_2 transitions in the optical wavelength range. Astronomical observations of NH_3 transitions at radio wavelengths have been used to constrain $\Delta\mu/\mu < 4.7 \times 10^{-7}$ (1σ) in the $z = 0.89$ lensing galaxy in the PKS 1830–211 gravitational lens system (Henkel et al. 2009) and $\Delta\mu/\mu < 1.2 \times 10^{-7}$ in the $z = 0.68$ absorbing galaxy towards the radio source B0218+357 (Kanekar 2011). In the nearby Universe, observations of NH_3 transitions towards molecular clouds in the Milky Way have been used to constrain variations in μ to be $\Delta\mu/\mu < 2 \times 10^{-8}$ (3σ; Levshakov et al. 2013). However these limits are achieved by comparing the spectral profile of NH_3 inversion transitions with less sensitive ($K_\mu \sim 1$) transitions from different species, such as cyanopolyynes in particular HC_3N transitions. This approach suffers from the difficulty of quantifying systematic effects due to the unknown degree of chemical segregation between the different molecular species (i.e. due to different and inhomogeneous spatial distributions of the different molecules along the line of sight).

The major limitation on observations of molecular transitions at radio and millimeter wavelengths is that most common astrophysical molecules have the same, or very similar, dependency on μ, for all of their transitions. A recent breakthrough has been the discovery that the hindered internal rotation which produces the rich microwave spectra observed in some polyatomic molecules (e.g. methanol CH_3OH, and methyl mercaptan CH_3SH) also causes a significant enhancement in K_μ compared to those observed in rotational transitions in any other molecule commonly found in interstellar space, including NH_3 (Jansen et al. 2011a; Levshakov et al. 2011; Jansen et al. 2013). Furthermore, the different transitions of these molecules have different K_μ coefficients, meaning that they offer the opportunity to tightly constrain μ using observations of a single molecular species, thus avoiding chemical segregation issues that arise when comparing transitions associated with different molecules. The high K_μ transitions are generally those between near degenerate levels of these molecules, hence they are typically at low radio frequencies. The low radio frequency range will be well covered by the Five-hundred-meter Aperture Spherical radio Telescope (FAST). FAST will open new possibilities for making sensitive observations of weak molecular emission from high-z astronomical objects. In this paper, we discuss the molecular transitions and sources (both in the Galaxy and external galaxies) which are likely to provide the best opportunity to make sensitive searches for possible variations in μ with FAST.

2 PERFORMANCE OF FAST

FAST is a current Chinese mega-science project to build the largest single dish radio telescope in the world. The telescope consists of a 500-meter aperture with an illuminated aperture of 300-meters. The telescope is located in Guizhou province, China, and the first phase covers a continuous frequency range, 70 MHz – 3 GHz, using a set of nine receivers (see Nan et al. 2011; Li et al. 2018). The L-band 19-beam receiver is the main instrument for surveys of HI and pulsars in the Galaxy and nearby galaxies. The design specifies the system temperature and resolution at the L band to be $\sim$25 K and $3'$, respectively. The declination range of FAST is –15° – 65°. The combination of large collecting area and advanced receiver and backend systems means that FAST will be an important instrument for advancing our understanding of cosmology, galaxy evolution, the interstellar medium life cycle, star formation and exoplanets. A spectroscopic survey of Galactic and extragalactic objects with continuous coverage between 70 MHz – 3 GHz is one of the main scientific programs which has been started with FAST (Li et al. 2013, 2018). This frequency range includes a number of important molecular transitions with different sensitivities to variations in μ and these are discussed in Section 3.

3 MOLECULAR TRANSITION CANDIDATES FOR FAST

Table 1 summarizes the molecular transitions which are sensitive to variations in the proton-to-electron ratio and have rest frequencies in the 70 MHz–3 GHz range which will be covered by FAST.

3.1 CH_3OH and Its Isotopes

Methanol (CH_3OH) is one of the simplest molecules that exhibits hindered internal rotation and thus has been the subject of a number of theoretical and observational studies relating to variations in the proton to electron mass ratio (e.g., Jansen et al. 2011a,b; Levshakov et al. 2011; Ellingsen et al. 2012). Methanol is a widespread interstellar molecule observed in numerous regions in the Galaxy and in some external galaxies (e.g., Herbst & van Dishoeck 2009; Sjouwerman et al. 2010; Martín et al. 2006). In the local Universe, methanol emission is commonly observed in the vicinity of high-mass star forming regions exhibiting both maser and thermal emission from hot cores. Absorption is also detected toward cold clouds in the foreground of continuum sources. There are more than 30 methanol transitions known to exhibit maser emission with wavelength in the range from centimeter to millimeter. These transitions are empirically classified into two types which are known as class I or class II transitions on the basis of the locations where they are observed to arise in the star forming region – class I methanol masers usually arise from multiple positions within a star forming region and are distributed on scales of 0.1–1.0 pc, whereas class II methanol masers are found within $\sim 1''$ of high-mass young stellar objects (e.g., Batrla & Menten 1988; Plambeck & Menten 1990). Over one thousand methanol maser sources have been detected in our Galaxy, including $\sim$900 class II (e.g. Green et al. 2009) and $\sim$400 class I methanol maser sources (see the review of Chen et al. 2014). Observations of both class I and class II methanol masers within the Milky Way have recently been applied to constrain spatial variations in μ at the level of $\Delta\mu/\mu < 3\times10^{-8}$ (1σ; Levshakov et al. 2011; Ellingsen et al. 2011). However, at cosmologically interesting distances there is only one detection of methanol and that is in absorption towards PKS B1830–211. This system is a gravitationally lensed quasar and the absorption occurs in the lensing galaxy which is at a redshift of $z = 0.89$. Observations of three different methanol transitions with rest frequencies of 12.2, 48.3 and 60.5 GHz have been used to constrain variations in μ on temporal scales of around 7 Gyr (the look-back time to z = 0.89) (Muller et al. 2011; Ellingsen et al. 2012; Bagdonaite et al. 2013b,a). The most sensitive of these observations by Bagdonaite et al. constrain $\Delta\mu/\mu$ to be less than 1×10^{-7} (2σ). An important point to note for FAST searches is that the rest frequencies of the methanol transitions detected in the PKS B1830–211 system far exceed the upper frequency limit of the first phase of FAST (3 GHz). The class II and class I methanol masers with the lowest rest frequencies are the $5_1 - 6_0\ A^+$ transition at 6.7 GHz and the $9_{-1} - 8_{-2}\ E$ transition at 9.9 GHz, respectively. These two transitions are also very sensitive to variations in μ with $K_\mu = -42$ and 12, for the 6.7 and 9.9 GHz transitions, respectively. These transitions cannot be used to look for variations in μ in the Milky Way or nearby galaxies with FAST, however, where they may be present in galaxies at redshifts of > 2, they would be within the detectable frequency range.

Theoretical calculations show that some lower-frequency methanol transitions which have not been the target of previous searches for variations in μ possess larger sensitivity coefficients than the most commonly observed methanol maser transitions (Jansen et al. 2011a,b). We have collated a list of those transitions of methanol and its isotopologues which lie within the FAST frequency

Table 1 Selected Molecular Transitions and K_μ Coefficients for the FAST Search

Molecule	Transition	Rest Frequency (MHz)	K_μ	Reference
$^{12}CH_3^{16}OH$	$1_1 - 1_1\ A^{\mp}$	834.280	–1.03	Jansen et al. (2011b)
	$5_1 - 6_0\ A^{+a}$	6 668.567	–42.0	Jansen et al. (2011a,b)
	$9_{-1} - 8_{-2}\ E^{a}$	9 936.137	11.5	Jansen et al. (2011a,b)
$^{12}CD_3^{16}OH$	$1_1 - 2_2\ E$	1 202.296	330.0	Jansen et al. (2011b)
	$2_0 - 1_1\ E$	1 424.219	–42.0	Jansen et al. (2011b)
	$9_2 - 8_3\ E$	2 827.262	43.0	Jansen et al. (2011b)
	$5_1 - 6_0\ A^{+}$	2 971.067	93.0	Jansen et al. (2011b)
$^{12}CH_3^{18}OH$	$9_2 - 10_1\ A^{-}$	2 604.912	93.0	Jansen et al. (2011b)
$^{12}CD_3^{16}OD$	$1_0 - 1_{-1}\ E$	2 237.883	45.0	Jansen et al. (2011b)
	$7_{-4} - 8_{-3}\ E$	2 329.088	–80.0	Jansen et al. (2011b)
$^{13}CH_3^{16}OH$	$9_{-1} - 8_{-2}\ E$	1 989.502	–63.0	Jansen et al. (2011b)
CH	$^2\Pi_{3/2}\ J = 3/2\ F = 2 - 2$	701.68	6.15	Kozlov (2009)
	$F = 1 - 2$	703.97	6.32	Kozlov (2009)
	$F = 2 - 1$	722.30	6.17	Kozlov (2009)
	$F = 1 - 1$	724.79	5.97	Kozlov (2009)
	$^2\Pi_{1/2}\ J = 1/2\ F = 0 - 1^{a}$	3 263.795	1.71	Kozlov (2009)
	$F = 1 - 1^{a}$	3 335.481	1.70	Kozlov (2009)
	$F = 1 - 0^{a}$	3 349.194	1.69	Kozlov (2009)
OH	$^2\Pi_{3/2}\ J = 3/2\ F = 1 - 2$	1 612.231	2.61	Kozlov (2009)
	$F = 1 - 1$	1 665.402	2.55	Kozlov (2009)
	$F = 2 - 2$	1 667.360	2.55	Kozlov (2009)
	$F = 2 - 1$	1 720.530	2.49	Kozlov (2009)
	$^2\Pi_{1/2}\ J = 9/2\ F = 5 - 4$	88.950	459.9	Kozlov (2009)
	$F = 5 - 5$	117.150	349.59	Kozlov (2009)
	$F = 4 - 4$	164.796	248.77	Kozlov (2009)
	$F = 4 - 5$	192.996	212.68	Kozlov (2009)
CH_3NH_2	$1(1)A_2 - 1(1)A_1$	879.859	–1.0	Ilyushin et al. (2012)
	$1(1)B_2 - 1(1)B_1$	881.386	–1.0	Ilyushin et al. (2012)
	$1(1)A_2 - 2(0)A_1$	2 166.305	–19.1	Ilyushin et al. (2012)
	$2(1)A_1 - 2(1)A_2$	2 639.491	–1.0	Ilyushin et al. (2012)
	$2(1)B_1 - 2(1)B_2$	2 644.073	–1.0	Ilyushin et al. (2012)
CH_3SH	$1_1 - 1_1\ A^{\mp}$	523.147	–1.0	Jansen et al. (2013)
	$2_1 - 2_1\ A^{\mp}$	1 569.410	–1.0	Jansen et al. (2013)
	$3_1 - 4_0\ E$	1 874.635	11.77	Jansen et al. (2013)
	$4_0 - 3_1\ A^{+a}$	3 038.566	–14.94	Jansen et al. (2013)
$C_2H_6O_2$	$1(1,1)v = 0 - 1(0,1)v = 1$	2828.6	–6.3	Viatkina & Kozlov (2014)
	$2(1,2)v = 0 - 2(0,2)v = 1$	1957.9	–9.3	Viatkina & Kozlov (2014)
	$3(1,3)v = 0 - 3(0,3)v = 1$	882.2	–16.5	Viatkina & Kozlov (2014)
	$4(0,4)v = 1 - 4(1,4)v = 0$	978.3	17.8	Viatkina & Kozlov (2014)
	$4(1,3)v = 0 - 4(1,4)v = 1$	978.3	–6.2	Viatkina & Kozlov (2014)

Notes: The frequency of these transitions is beyond the upper limit of 3 GHz of FAST frequency coverage. These transitions can be only used to constrain μ-variation for the targets with moderate redshifts.

range and list them in Table 1. We also list the information for the lowest rest frequency transitions for both class I and class II methanol masers in this table, since they are potential candidates for measuring temporal variations in μ through observations of high-z objects with FAST; we discuss this further in Section 4. The equivalent transitions of methanol isotopologues are generally more sensitive to changes in μ than those of methanol itself. The most sensitive of the methanol isotopologues with K_μ =330 is the $1_1 - 2_2\ E$ transition of $^{12}CD_3^{16}OH$ which has a rest frequency of approximately 1.2 GHz. The sensitivity of this transition to variations in μ is approximately one order of magnitude larger than that of the highest K_μ methanol transitions used in previous studies. This demonstrates that the detection of methanol isotopologues would significantly help to make more sensitive investigations for variations in μ. Emission from methanol isotopologues has been detected in both high-mass and low-mass star forming regions in the Milky Way, for example $^{13}CH_3OH$ and CD_3OH have been detected by Parise et al. (2002, 2004) and Ratajczak et al. (2011), showing that these isotopologues are present at detectable abundances in the local Universe, although it should be noted that the detections of the methanol isotopologues were from transitions at millimeter wavelengths rather than the lower frequency transitions suitable for observations with FAST.

It is worth noting that the sensitivity coefficients of the transitions of methanol and its isotopologues listed in Table 1 have both large positive and large negative values. This means that a variation in μ will shift the frequency of some transitions to higher frequencies while others shift to lower frequencies. So, the most sensitive method for accurately probing for variations in μ is through simultaneous observations of different transitions with large positive and negative values of K_μ. Observations of different isotopologues also have the advantage that they avoid many systematic effects that can affect comparisons based on transitions of different molecules (such as chemical segregation).

3.2 Other Molecules

In addition to methanol, the frequency range of FAST will also cover transitions of other important interstellar molecules which have good sensitivity to variations in μ. These other molecules and the relevant transitions are also listed in Table 1.

CH is abundant in the Universe and the two ground-state Λ-doublet transitions for $^2\Pi_{3/2}$ $J = 3/2$ and $J = 1/2$ which have rest frequencies of ~ 0.7 and ~ 3.3 GHz, respectively, have been observed towards numerous clouds in the Milky Way (e.g., Whiteoak et al. 1978; Genzel et al. 1979; Ziurys & Turner 1985). The 3.3 GHz transition has also been detected in other galaxies (e.g., Whiteoak et al. 1980). Theoretical calculations show that the two Λ-doublet transitions of CH are very sensitive to changes in μ with K_μ ranging from 1.7 – 6.3 (Kozlov 2009). Simultaneous astronomical observations of the two Λ-doublet transitions of CH have been undertaken to constrain μ-variations at 1σ upper bounds of $\Delta\mu/\mu < 3 \times 10^{-7}$ in our Galaxy (Truppe et al. 2013). It should be noted that the frequencies of $J = 1/2$ transitions are slightly above the 3 GHz upper limit of the first stage receivers being developed for FAST. This means it will not be possible to constrain variations in μ for Galactic objects with the two Λ-doublet transitions of CH simultaneously with FAST. However FAST will be suitable for simultaneously measuring both transitions for moderate redshift objects (e.g. $z > 0.1$). The higher sensitivity of FAST will open the opportunity to detect relatively weak emission from this molecule in high$-z$ objects.

OH is a very common interstellar molecule and has been widely observed in our Galaxy and external galaxies. Maser emission from the OH molecule has been observed from a number of transitions, for example the ground-state transitions ($^2\Pi_{3/2}$, $J = 3/2$ state), and many excited state-state transitions (including $^2\Pi_{1/2}$, $J = 1/2$ at 4765 MHz, and $^2\Pi_{3/2}$, $J = 5/2$ at 6035 MHz). Of the various OH maser transitions the 1665/1667 MHz ground-state transitions in star forming regions are usually the strongest. At present about $\sim$ 3000 OH maser sources have been detected in our Galaxy, and most of them are stellar masers associated with evolved stars (see Mu et al. 2010). At present only $\sim$400 OH masers have been detected in star forming regions (see Qiao et al. 2014), however, current sensitive OH maser surveys such as SPLASH (Dawson et al. 2014) and future surveys such as GASKAP (Dickey et al. 2013) will significantly increase the number of OH maser sources in the Galaxy (both evolved star and star forming regions). In external galaxies, over 100 galaxies with OH megamaser activity have been found (e.g, Baan et al. 1998; Darling & Giovanelli 2002). Similar to CH, the Λ-doublet transitions of OH potentially also provide a very sensitive indicator for searching for variations in μ (Kozlov 2009). Observations of the ground-state 18 cm OH lines in absorption at $z = 0.765$ have been used to constrain the variation in μ to be $\Delta\mu/\mu < 2.7 \times 10^{-6}$ for a look-back time of 6.7 Gyr (Kanekar et al. 2012). However, in that work the 21 cm hydrogen line was adopted as a reference. Detection of more than one Λ-doublet transition of OH offers the opportunity to further improve the constraint. Within the frequency coverage of the first stage of FAST, there are two OH Λ-doublet transitions at $^2\Pi_{3/2}$ $J = 3/2$ and $^2\Pi_{1/2}$ $J = 9/2$ which may enable such observations to be undertaken. The $^2\Pi_{1/2}$ $J = 9/2$ transitions are very sensitive to changes in μ with the sensitivity coefficient K_μ ranging from 210 – 460, which is more than two orders of magnitude greater than that of the 18 cm OH lines used in previous studies. To date, the higher $J-$transitions of OH in the 88 – 192 MHz range have not been observed in interstellar space. If these transitions can be detected in either Galactic or extragalactic objects with FAST, it opens up the possibility to make very sensitive studies for variations in

μ using simultaneous observations of these OH transitions in combination with ground-state OH. However, we note that these higher$-J$ transitions are at significantly higher energies $E_{\rm upper} = 875\,{\rm K}$ than the 18 cm lines, hence they may have a different spatial distribution compared to the ground-state transitions. This issue can be only clarified through detection and observation of these transitions.

CH_3NH_2 is a relatively small and stable molecule which is abundant in the Milky Way (e.g., Lovas 2004). It has also been detected in a spiral galaxy at redshift $z = 0.89$ (the lensing galaxy in the 1830–211 system; Muller et al. 2011). CH_3NH_2 has hindered internal rotation of the CH_3 group with respect to the amino group (NH_2) which is similar to what occurs in methanol. In addition to this it also has tunneling associated with wagging of the amino group. Ilyushin et al. (2012) have used this molecule to search for temporal variations in μ through observations at millimeter wavelengths towards the $z = 0.89$ intervening galaxy in the PKS 1830–211 system. However, the relatively low sensitivity K_μ for the transitions observed means that it was not possible to place tight constraints on variations in μ from those observations ($\Delta\mu/\mu < 1 \times 10^{-5}$). Within the frequency coverage of FAST, there are multiple CH_3NH_2 transitions, one of which is very sensitive to variations in μ (Ilyushin et al. 2012). The sensitivity of the various transitions have K_μ spanning the range –1 – –19 and observations in these transitions offer the potential to make sensitive searches for variations in μ with FAST.

CH_3SH is the sulphur analog of methanol, therefore similar to methanol it experiences hindered internal rotation which results in larger sensitivity to variations in μ. There are multiple transitions of CH_3SH which lie within the frequency coverage of FAST, and these have a large spread in their K_μ sensitivity coefficients which span an approximate range of –15 – 12 (Jansen et al. 2013). It should be noted that the frequency of the $4_0 - 3_1\ A^+$ transition, which has the greatest sensitivity to variations in μ ($K_\mu = -14.94$) is above the 3 GHz upper limit of the FAST frequency coverage, however, this transition will be a candidate for observations in objects with moderate redshifts. To date, CH_3SH has only been detected in the Milky Way (e.g., Linke et al. 1979; Gibb et al. 2000), however, the high sensitivity of FAST will likely make it possible to detect this molecule in some external galaxies.

$C_2H_6O_2$ has recently been shown to have low-frequency transitions (within the FAST frequency coverage) which are sensitive to variations in μ, with K_μ ranging from –17 (for the 882.2 MHz transition) to 18 (for the 978.3 MHz transition). Viatkina & Kozlov (2014) have calculated the K_μ sensitivity coefficient for approximately 10 transitions which lie within the FAST frequency range (see table 3 of Viatkina & Kozlov 2014). Here we list only those transitions with larger K_μ values in Table 1. This molecule has been detected in interstellar space in the comet C/ 1995 O1 (Hale-Bopp; Crovisier et al. 2004) and in molecular clouds in the center of the Milky Way (Hollis et al. 2002), although the transitions observed to date are from higher frequency transitions beyond the upper limit of the FAST frequency coverage. It is very likely that the high sensitivity of FAST will enable the detection of the lower frequency transitions of interest here, both in the Milky Way and perhaps also in some extragalactic sources.

4 ASTRONOMICAL TARGETS FOR FAST

In this section, we discuss which sources in our Galaxy and other galaxies are prime targets for FAST observations to search for possible spatial and temporal variations in μ. We mainly focus on targets for the methanol and OH transitions because they possess the largest sensitivity coefficients to variations in μ (one to two orders of magnitude more sensitive than most molecular transitions) and are widespread throughout the Galaxy and external galaxies, compared to some of the other less abundant molecules discussed in Section 3.

4.1 Targets in Our Galaxy

Sources which exhibit maser emission (including OH, CH_3OH and H_2O) may provide the best target samples for searches for possible variations in μ in the Milky Way. The strongest maser emission is usually observed from the molecular gas associated with massive star forming regions. These clouds consist of gas which contains relatively high abundances of both simple and complex molecular species, including the molecules which have the greatest sensitivity to variations in μ such as OH and methanol.

Observations focusing on transitions of the methanol isotopologues (such as CH_3OD, as discussed in Section 3.1) can potentially provide the most sensitive tests for variations in μ. For a source to exhibit methanol maser emission it must have a relatively high abundance of the methanol molecule, therefore such regions are likely to provide the best targets for detections of the methanol isotopologues. There are over one thousand methanol maser sources (including class I and class II transitions) which have been detected in our Galaxy. In addition to these known methanol maser detections from the past surveys, e.g. the Parkes methanol multi-beam survey at

6.7 GHz class II transition (Green et al. 2009), a number of new methanol maser surveys in our Galaxy are underway or proposed. In particular, a series of targeted surveys for class I methanol masers at the 95 GHz transition have detected about 200 new class I methanol maser sources, and combined with previous observations they have increased the number of known class I methanol masers in our Galaxy to ∼400 (Chen et al. 2011, 2012, 2013 and Gan et al. 2013). Statistical analysis of these surveys has been used to predict that our Galaxy may contain at least ∼2000 class I methanol maser sources, and suggested that the Bolocam Galactic Plane Survey (BGPS) 1.1 mm dust continuum sources provide more reliable samples for targeting further class I methanol maser searches – about 1000 class I methanol masers are expected to be detected from BGPS catalog targets. A new large survey for class I methanol masers towards BGPS-selected sources is currently underway with the Purple Mountain Observatory (PMO) 13.7-m radio telescope to significantly increase the sample of class I methanol masers known in the Galaxy. The majority of previous methanol maser surveys in both the class I and class II transitions has been undertaken in the southern hemisphere. Therefore, increasing the known number of methanol maser sources in the northern sky is especially important as this is the region accessible for FAST observations. The MALT-45 survey being undertaken by using the Australia Telescope Compact Array (ATCA) as six single-dishes (Jordan et al. 2013) has made a complete survey of 10 square degrees of the southern Galactic plane at 44 GHz. This survey is the first sensitive, complete survey for any class I methanol maser transition and will allow for a much more accurate estimate of the total number of class I methanol maser sources throughout the Galaxy.

Furthermore, the newly-built Shanghai 65 m telescope will be used in new searches for 6.7 GHz class II methanol and ground-state OH masers, towards newly-identified samples of young stellar objects from a number of surveys of the Galactic Plane at mid-infrared wavelengths, including the Spitzer Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE). These searches will increase the number of target sources for FAST μ variation observations in both OH and methanol transitions in the northern hemisphere.

4.2 Targets in Other Galaxies

The prime extragalactic targets to search for variations in μ are those which host OH megamaser emission, as observations of multiple OH transitions can provide strong constraints. OH megamaser emission has been detected in over 100 galaxies in surveys undertaken to date (e.g, Baan et al. 1998; Darling & Giovanelli 2002), however, most of the detected OH megamaser galaxies are at relatively low redshifts with $z < 0.2$. A survey for OH megamasers in high-z galaxies is required to place the most stringent constraints on variations in μ over the history of the Universe. OH megamaser searches in high-z galaxies are also one of the main early science projects for FAST (see Zhang et al. 2012 and Li et al. 2013). Moreover, simultaneous HI observations towards OH megamaser galaxies with FAST also provide opportunities to constrain variations in μ, although the systemic effects due to comparing observations from different molecules are difficult to quantify and remove, as it is never really possible to determine the extent to which they arise from different locations and to which the observed spectral differences are due to different line of sight motions from the two transitions.

There are approximately 10 extragalactic detections of CH emission (Whiteoak et al. 1980; Bottinelli et al. 1991) and these represent potential targets for searching for variations in μ. They are, however, all relatively nearby galaxies and therefore it will not be possible to simultaneously observe the two CH transitions listed in Table 1 with FAST. The galaxies towards which CH emission has been detected often also exhibit strong OH absorption and sometimes H_2O emission. Therefore, moderate redshift galaxies (z >0.1) with OH absorption/emission or H_2O emission are potential targets for future CH observations with FAST. In particular, H_2O megamaser galaxies may be good targets because they can be detected at relatively high redshifts, with the most distant source being at $z = 2.64$ (MG J0414+0534; Impellizzeri et al. 2008b).

Targets suitable for using methanol transitions to investigate possible changes in μ are at present limited to one extragalactic source outside the nearby galaxies. The lensing galaxy in the PKS B1830–211 gravitational lens system is at a modest redshift of $z = 0.89$ and absorption from three different methanol transitions has been detected towards it (Muller et al. 2011; Ellingsen et al. 2012; Bagdonaite et al. 2013b,a). Emission from a number of thermal methanol transitions at millimeter wavelengths (mainly the $2_k - 1_k E$ series at 96.7 GHz) has been detected towards a handful of nearby galaxies (e.g., Henkel et al. 1987; Huettemeister et al. 1997). However the detected emission from these thermal lines is weak and broad, and hence is unlikely to be able to provide useful constraints or tests for variations in μ (see Ellingsen et al. 2011). While the absorption of methanol may provide a more efficient approach for such constraints since its spectrum is usually narrow, moreover, besides the PKS B1830–211 discussed above, methanol absorption is also detected in the nearby galaxy NGC 3079 (Impellizzeri et al. 2008a), suggesting that methanol absorption may be common in external galaxies. More sensitive searches for methanol emission (preferably maser emission) or absorption in nearby extragalactic sources is required to better understand how the properties of these sources are influenced by their environment (factors such as metallicity and ultraviolet flux). A number of searches has been made for class II methanol megamasers at 6.7 and 12.2 GHz transitions towards samples selected from OH and H_2O megamaser galaxies, and/or (Ultra-) Luminous Infrared Galaxies ([U]LIRGs) (Norris et al. 1987; Ellingsen et al. 1994, Phillips et al. 1998 and Darling et al. 2003). To date more than 100 sources have been searched, without any detections. It may be, as suggested by Phillips et al. (1998), that the mechanisms which produce high methanol abundance in individual star formation regions may not operate with sufficient efficiency on the larger scales needed to produce class II megamasers. Alternatively, it may be that the sensitivity of previous searches was not high enough to detect maser emission in these sources or that appropriate targeting criteria have not been identified to search for class II methanol megamasers. A sensitive survey for class II methanol megamasers towards a large sample of sources with FAST would clarify these issues, although for the first stage of FAST, the targets of 6.7 GHz class II methanol megamaser searches must be at redshifts of $z > 1.3$, in order for the emission to be detectable in the frequency range of the telescope.

In contrast to class II methanol transitions, theoretical models suggest that it is perhaps more likely that class I methanol transitions can be excited on large scales in the central regions of luminous galaxies (Sobolev 1993). The recent detection of widespread methanol maser emission in the 36 GHz class I transition toward the center of the Milky Way (Yusef-Zadeh et al. 2013) further supports the theory. Based on these results, the first sensitive survey for class I methanol megamasers in the 36 GHz transition was undertaken towards a sample of OH megamaser galaxies with the ATCA, and has produced the first extragalactic detections of this transition towards NGC 253 (Ellingsen et al. 2014, 2017; Chen et al. 2018), Arp 220 (Chen et al. 2015), NGC 4945 (McCarthy et al. 2017), IC 342 and NGC 6946 (Gorski et al. 2018). Further comparison with the infrared, radio and molecular emission, and star formation rates of the host galaxies with/without detections will enable us to refine targeting criteria for future observations. Then by compiling a reliable target sample based on these criteria, the 9.9 GHz class I methanol transition can be searched towards galaxies meeting these criteria at redshifts $z > 2.3$ with FAST. The detection of two or more methanol megamaser transitions in high-z galaxies offers the best current prospects for making sensitive observations for variations in μ at larger look-back times.

5 SUMMARY

Thanks to the large collecting area and advanced receiver and backend systems, FAST should become one of the most important instruments for searching for possible variations in the proton-to-electron mass ratio μ on cosmological time and distance scales. Within the frequency coverage of FAST, there are a number of transitions of abundant interstellar molecules (e.g., CH_3OH, OH and CH) which are $1 - 2$ orders of magnitude more sensitive to variations in μ than those typically used in current studies. Existing and ongoing surveys for methanol and OH masers in our Galaxy appear to provide the best samples for observations to determine if μ varies spatially in the local Universe. However, further surveys for OH, CH and methanol megamasers in high-z galaxies are required to provide good quality targets for investigations of variations in μ on cosmological timescales. It is our hope that the potential importance of these molecular megamasers for testing variations in μ will stimulate broader surveys for these sources with FAST. FAST observations utilizing the most sensitive molecular transitions are likely to improve the evidence either for or against the presence of variations in the proton-to-electron mass ratio by more than $1 - 2$ orders of magnitude beyond the best current limits.

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