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Searching for spatial variations of α^2/μ in the Milky Way

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ABSTRACT

Aims. We probe the dependence of α^2/μ on the ambient matter density by means of spectral observations in submm- and mm-wave bands.

Methods. A procedure is suggested for exploring the value of $F = \alpha^2/\mu$, where $\mu = m_e/m_p$ is the electron-to-proton mass ratio, and $\alpha = e^2/(\hbar c)$ is the fine-structure constant. The fundamental physical constants, which are measured in different physical environments of high (terrestrial) and low (interstellar) densities of baryonic matter are supposed to vary in chameleon-like scalar field models, which predict that both masses and coupling constant may depend on the local matter density. The parameter $\Delta F/F = (F_{\rm obs} - F_{\rm lab})/F_{\rm lab}$ can be estimated from the radial velocity offset, $\Delta V = V_{\rm rot} - V_{\rm fs}$, between the low-laying rotational transitions in carbon monoxide ^{13}CO and the fine-structure transitions in atomic carbon [C I]. A model-dependent constraint on $\Delta\alpha/\alpha$ can be obtained from $\Delta F/F$ using $\Delta\mu/\mu$ independently measured from the ammonia method.

Results. Currently available radio astronomical datasets provide an upper limit on $|\Delta V| < 110$ m s^{-1} (1σ). When interpreted in terms of the spatial variation of F, this gives $|\Delta F/F| < 3.7 \times 10^{-7}$. An order of magnitude improvement in this limit will allow us to independently test a non-zero value of $\Delta\mu/\mu = (2.2 \pm 0.4_{\rm stat} \pm 0.3_{\rm sys}) \times 10^{-8}$, recently found with the ammonia method. Considering that the ammonia method restricts the spatial variation of μ at the level of $|\Delta\mu/\mu| \leq 3 \times 10^{-8}$ and assuming that $\Delta F/F$ is the same in the entire interstellar medium, one obtains that the spatial variation of α does not exceed the value $|\Delta\alpha/\alpha| < 2 \times 10^{-7}$. Since extragalactic gas clouds have similar densities to those in the interstellar medium, the bound on $\Delta\alpha/\alpha$ is also expected to be less than 2×10^{-7} at high redshift if no significant temporal dependence of α is present.

Key words. line: profiles – ISM: molecules – techniques: radial velocities – cosmology: observations

1. Introduction

The dimensionless physical constants, such as the electron-to-proton mass ratio, $\mu = m_e/m_p$, or the fine-structure constant, $\alpha = e^2/(\hbar c)$, are expected to be dynamical quantities in modern extensions of the standard model of particle physics (Uzan 2003; Garcia-Berro et al. 2007; Martins 2008; Kanekar 2008; Chin et al. 2009). Exploring these predictions is a subject of many high-precision measurements in contemporary laboratory and astrophysical experiments. The most accurate laboratory constraints on temporal α- and μ-variations of $\dot\alpha/\alpha = (-1.6 \pm 2.3) \times 10^{-17}$ yr^{-1}, and $\dot\mu/\mu = (1.6 \pm 1.7) \times 10^{-15}$ yr^{-1} have been obtained by Rosenband et al. (2008), and Blatt et al. (2008), respectively.

For the monotonic dependence of $\alpha(t)$ and $\mu(t)$ on cosmic time, at redshift $z \sim 2$ (corresponding look-back time is $\Delta t \sim 10^{10}$ yr) the changes in α and μ would be restricted at the level of $|\Delta\alpha/\alpha| < 4 \times 10^{-7}$ and $|\Delta\mu/\mu| < 3 \times 10^{-5}$. Here, $\Delta\alpha/\alpha$ (or $\Delta\mu/\mu$) is a fractional change in α between a reference value α_1 and a given measurement α_2 obtained at different epochs or at different spatial coordinates: $\Delta\alpha/\alpha = (\alpha_2 - \alpha_1)/\alpha_1$.

These constraints are in line with geological measurements of relative isotopic abundances in the Oklo natural fission reactor, which allows us to probe $\alpha(t)$ at $\Delta t \sim 2 \times 10^9$ yr ($z \sim 0.4$). Assuming possible changes only in the electromagnetic coupling constant, Gould et al. (2006) has obtained a model dependent constraint on $|\Delta\alpha/\alpha| < 2 \times 10^{-8}$. However, when the strength of the strong interaction – the parameter $\Lambda_{\rm QCD}$ – is also considered to be variable, the Oklo data does not provide any bound on the variation of α (Flambaum & Shuryak 2002; Chin et al. 2009).

Current astrophysical measurements at higher redshifts are as follows. There was a claim for a variability in α at the 5σ confidence level: $\Delta\alpha/\alpha = -5.7 \pm 1.1$ ppm (Murphy et al. 2004)[1], but this has not been confirmed in other measurements that led to the upper bound $|\Delta\alpha/\alpha| < 2$ ppm (Quast et al. 2004; Levshakov et al. 2005; Srianand et al. 2008; Molaro et al. 2008).

Measurements of the cosmological μ-variation exhibit a similar tendency. Non-zero values of $\Delta\mu/\mu = -30.5 \pm 7.5$ ppm, $\Delta\mu/\mu = -16.5 \pm 7.4$ ppm (Ivanchik et al. 2005), and $\Delta\mu/\mu = -24 \pm 6$ ppm (Reinhold et al. 2006) found at $z = 2.595$ (Q 0405–443) and $z = 3.025$ (Q 0347–383) from the Werner and Lyman bands of H_2 were later refuted by Wendt & Reimers (2008), King et al. (2008) and Thompson et al. (2009), who used the same optical absorption-line spectra of quasars and restricted changes in μ at the level of $|\Delta\mu/\mu| < 6$ ppm. The third H_2 system at $z = 2.059$ towards the quasar J2123–0050 also does not show any evidence of cosmological variation in μ: $\Delta\mu/\mu = -5.6 \pm 5.5_{\rm stat} \pm 2.9_{\rm sys}$ ppm (Malec et al. 2010). More stringent constraints have been obtained at lower redshifts from radio observations of the absorption lines of NH_3 and other molecules: $|\Delta\mu/\mu| < 1.8$ ppm at $z = 0.68$ (Murphy et al. 2008),

[1] Hereafter, 1 ppm = 10^{-6}.

and $|\Delta\mu/\mu| < 0.6$ ppm at $z = 0.89$ (Henkel et al. 2009). Two cool gas absorbers at $z = 1.36$ (Q 2337–011) and $z = 1.56$ (Q 0458–020) have recently been studied in the H I 21cm and C I$\lambda\lambda$1560, 1657 absorption lines providing a constraint on the variation in the product $X = g_p\alpha^2\mu$ (here g_p is the proton gyromagnetic ratio): $\Delta X/X = -6.8 \pm 1.0_{\rm stat} \pm 6.7_{\rm sys}$ ppm (Kanekar et al. 2010). Thus, the most accurate astronomical estimates restrict cosmological variations in the fundamental physical constants at the level of ∼1–2 ppm.

The estimate of fractional changes in $\Delta\alpha/\alpha$ and $\Delta\mu/\mu$ by spectral methods is always a measurement of the relative Doppler shifts between the line centers of different atoms/molecules and their comparison with corresponding laboratory values (Savedoff 1956; Bahcall et al. 1967; Wolfe et al. 1976; Dzuba 1999, 2002; Levshakov 2004; Kanekar & Chengalur 2004). To distinguish the line shifts due to radial motion of the object from those caused by the variability in constants, lines with different sensitivity coefficients, Q, to the variations of μ and/or α are to be used[2]. It is clear that the greater the difference $|\Delta Q|$ between two transitions, the higher the accuracy of such estimates.

Optical and UV transitions in atoms, ions, and molecular hydrogen H_2 have similar sensitivity coefficients with $|\Delta Q|$ not exceeding 0.05 (Varshalovich & Levshakov 1993; Dzuba 1999, 2002; Porsev et al. 2007). For atomic spectra, the estimate of $\Delta\alpha/\alpha$ is given in linear approximation ($|\Delta\alpha/\alpha| \ll 1$) by (e.g., Levshakov et al. 2006):

$$\frac{\Delta\alpha}{\alpha} \approx \frac{(V_2 - V_1)}{2c(Q_1 - Q_2)} \equiv \frac{\Delta V}{2c\Delta Q}, \tag{1}$$

where V_1, V_2 are the radial velocities of two atomic lines, and c the speed of light. It was shown in Molaro et al. (2008) that the limiting accuracy of the wavelength scale calibration for the VLT/UVES quasar spectra at any point within the whole optical domain is about 30 m s^{-1}, which corresponds to the limiting relative accuracy between two lines measured in different parts of the same spectrum of about 50 m s^{-1}. Considering that $|\Delta Q| \simeq 0.05$, it follows from Eq. (1) that the limiting accuracy of $\Delta\alpha/\alpha$ is 2 ppm, which is the utmost value that can be achieved in observations of extragalactic objects with current optical facilities.

A considerably higher sensitivity to the variation in physical constants is observed in radio range. For example, van Veldhoven et al. (2004) first showed that the inversion frequency of the $(J, K) = (1, 1)$ level of the ammonia isotopologue $^{15}ND_3$ has the sensitivity coefficient $Q_\mu = 5.6$. Compared to optical and UV transitions, the ammonia method proposed by Flambaum & Kozlov (2007) provides 35 times more sensitive an estimate of $\Delta\mu/\mu$ from measurements of the radial velocity offset between the NH_3 $(J, K) = (1, 1)$ inversion transition at 23.7 GHz and low-lying rotational transitions of other molecules co-spatially distributed with NH_3:

$$\frac{\Delta\mu}{\mu} \approx 0.289\frac{\Delta V}{c}\cdot \tag{2}$$

The ammonia method was recently used to explore possible spatial variations[3] in the physical constants from observations of pre-stellar molecular cores in the Taurus giant molecular cloud (Levshakov et al. 2010, hereafter L10), the Perseus cloud, the Pipe Nebula, and infrared dark clouds (Levshakov et al. 2008b; Molaro et al. 2009). In contrast to the laboratory constraints on *temporal* variations mentioned above, this method reveals a tentative *spatial* variation in $\Delta\mu/\mu$ at the level of $\Delta\mu/\mu = (2.2 \pm 0.4_{\rm stat} \pm 0.3_{\rm sys}) \times 10^{-8}$ (L10). The corresponding conservative upper limit in this case is equal to $|\Delta\mu/\mu| \leq 3 \times 10^{-8}$.

In the present paper we consider fractional changes in a combination of two constants α^2 and μ, $F = \alpha^2/\mu$, which are estimated from the comparison of transition frequencies measured in different physical environments of *high* (terrestrial) and *low* (interstellar) densities of baryonic matter. The idea behind this experiment is that some class of scalar field models – so-called chameleon-like fields – predict the dependence of both masses and coupling constant on the local matter density (Olive & Pospelov 2008). Chameleon-like scalar fields have been introduced by Khoury & Weltman (2004a,b) and by Brax et al. (2004) to explain negative results on laboratory searches for the fifth force, which should arise inevitably from couplings between scalar fields and standard model particles. The chameleon models assume that a light scalar field acquires both an effective potential and effective mass because of its coupling to matter that depends on the ambient matter density.

In this way, the chameleon scalar field may evade local tests of the equivalence principle and fifth force experiments, since the range of the scalar-mediated fifth force for the terrestrial matter densities is too narrow to be detected. Similarly, laboratory tests with atomic clocks for α-variations are performed under conditions of constant local density, so they are not sensitive to the presence of the chameleon scalar field (Upadhye et al. 2010). This is not the case for space-based tests, where the matter density is considerably lower, an effective mass of the scalar field is negligible, and an effective range for the scalar-mediated force is broad. Light scalar fields are usually attributed to a negative pressure substance permeating the entire visible Universe and known as dark energy (Caldwell et al. 1998). This substance is thought to be responsible for a cosmic acceleration at low redshifts, $z \lesssim 1$ (Peebles & Rata 2003; Brax 2009).

2. [C I] and CO lines as probes of α^2/μ

The variations in the physical constants can be probed through atomic fine-structure (FS) and molecular rotational transitions (Levshakov et al. 2008; Kozlov et al. 2008). The corresponding lines are observed in submm- and mm-wavelength ranges. Along with a gain in sensitivity, using such transitions allows us to estimate constants at very high redshifts ($z > 5$) that are inaccessible to optical observations.

Let us consider radial velocity offsets between molecular rotational and atomic FS lines, $\Delta V = V_{\rm rot} - V_{\rm fs}$. The offset ΔV is related to the parameter $\Delta F/F$ as follows (Levshakov et al. 2008):

$$\Delta F/F \approx 2\Delta\alpha/\alpha - \Delta\mu/\mu \equiv \Delta V/c. \tag{3}$$

The velocity offset in Eq. (3) can be represented by the sum of two components

$$\Delta V = \Delta V_f + \Delta V_n, \tag{4}$$

where ΔV_f is the shift due to F-variation, and ΔV_n is the Doppler noise, which is a random component caused by possible local offsets, since transitions from different species may arise from slightly different parts of a gas cloud, at different radial velocities.

[2] Q is a dimensionless coefficient showing a relative change in the atomic transition frequency ω_i in response to a change in the physical constant F: $\Delta\omega_i/\omega_i = Q_i\Delta F/F$.

[3] Hereafter, the term “spatial variation” means a possible change in μ between its terrestrial and interstellar values.

The Doppler noise yields offsets that can either mimic or obliterate a real signal. Nevertheless, if these offsets are random, the signal ΔV_f can be estimated statistically by averaging over a large data sample:

$$\langle \Delta V \rangle = \langle \Delta V_f \rangle, \qquad \mathrm{Var}(\Delta V) = \mathrm{Var}(\Delta V_f) + \mathrm{Var}(\Delta V_n). \tag{5}$$

Here we assume that the noise component has a zero mean and a finite variance.

The Doppler noise component can be minimized if the chosen species are closely trace each other. An appropriate pair in our case is the atomic carbon FS transitions and rotational transitions of carbon monoxide ^{13}CO. The spatial distributions of ^{13}CO and [C I] are known to be well correlated (Keene et al. 1985; Meixner & Tielens 1995; Spaans & van Dishoeck 1997; Ikeda et al. 2002; Papadopoulos et al. 2004). The carbon-bearing species C^0, C^+, and CO are observed in photodissociation regions (PDRs) – neutral regions where chemistry and heating are regulated by the far-UV photons (Hollenbach & Tielens 1999). The PDR is either the interface between the H II region and the molecular cloud or a neutral component of the diffuse interstellar medium (ISM). Far-UV photons (6.0 eV < $h\nu$ < 13.6 eV) are produced by OB stars. Photons with energy greater than 11.1 eV dissociate CO into atomic carbon and oxygen. Since the C^0 ionization potential of 11.3 eV is quite close to the CO dissociation energy, neutral carbon can be quickly ionized. This suggests the chemical stratification of the PDR in the line C^+/C^0/CO with increasing depth from the surface of the PDR. Then, one can assume that, in the outer envelopes of molecular clouds, neutral carbon lies within a thin layer determined by the equilibrium between photoionization/recombination processes on the C^+/C^0 side and photodissociation/molecule formation processes on the C^0/CO side. However, observations (Keene et al. 1985; Zhang et al. 2001) do not support such a steady-state model, which predicts that C^0 should only arise near the edges of molecular clouds. To explain the observed correlation between the spatial distributions of C^0 and CO, inhomogeneous PDRs with clumping molecular gas were suggested. The revealed ubiquity of the [C I] transition $^3P_1 \rightarrow {}^3P_0$ in molecular clouds agrees with clumpy PDR models (Meixner & Tielens 1995; Spaans et al. 1997; Papadopoulos et al. 2004).

The ground state of the C^0 atom consists of the $^3P_{1,2,3}$ triplet levels. The energies of the fine-structure excited levels relative to the ground state are $E_{0,1}$ = 24 K and $E_{0,2}$ = 63 K, and the transition probabilities are $A_{1,0} = 7.932 \times 10^{-8}$ s^{-1} and $A_{2,1} = 2.654 \times 10^{-7}$ s^{-1} (Silva & Viegas 2002). The excitation rates of the [C I] J = 1 and J = 2 levels for collisions with H_2 at $T_{\rm kin} \sim 20$ K are $q_{0,1} \approx q_{0,2} \approx 10^{-10}$ cm^3 s^{-1} (Schröder et al. 1991). This implies that for the J = 1 and J = 2 levels the critical densities are 1000 cm^{-3} and 3000 cm^{-3}, respectively. The low-J rotational transitions of CO trace similar moderately dense ($n \sim 10^3$ cm^{-3}) and cold ($T_{\rm kin} \sim 20$ K) gas. It is not completely excluded, however, that some heterogeneity of spatial distributions of [C I] and ^{13}CO may occur, resulting in the radial velocity offsets.

In the chameleon-like scalar field models for density-dependent $\mu(\rho)$ and $\alpha(\rho)$, the fractional changes in these constants arise from the shift in the expectation value of the scalar field between high and low density environments. Since the matter density in the interstellar clouds is $\sim 10^{16}$ times lower than in terrestrial environments, whereas gas densities between the molecular clouds themselves are much lower ($n_{\rm gas} \sim 10^3 - 10^5$ cm^{-3}), all interstellar clouds can be considered as having similar physical conditions irrespective of their location in space. This means that the noise component in Eq. (5) can be reduced by averaging over individual $\Delta F/F$ values obtained from an ensemble of clouds for which the measurements of both [C I] and ^{13}CO lines are available.

Equations (2) and (3) show that in order to estimate $\Delta F/F$ and $\Delta\mu/\mu$ with a comparable relative error the uncertainty of the velocity offset in (3) must be ∼3.5 times less than in the ammonia method (∼5 m s^{-1}, see L10). At the moment such data do not exist. Both laboratory and astronomical measurements of the [C I] frequencies have much larger uncertainties. For example, the rest frequencies of the [C I] J = 1–0 transition 492160.651(55) MHz (Yamamoto & Saito 1991) and J = 2–1 transition 809341.97(5) MHz (Klein et al. 1998) are measured with the uncertainties of ε_v = 33.5 m s^{-1} and 18.5 m s^{-1}, respectively. For ^{13}CO the rest hyperfine frequencies of low-J rotational transitions are known with good accuracy: ν_{1-0} = 110.201354280(37) GHz, and ν_{2-1} = 220.398684129(66) GHz, i.e., $\varepsilon_v \lesssim 0.1$ m s^{-1} (Cazzoli et al. 2004). Assuming that the laboratory error $\varepsilon_v \simeq 34$ m s^{-1} dominates the errors from ΔV measurements, one obtains a $\Delta F/F$ limiting accuracy of 0.1 ppm. To put in other words, if both species arise from the same volume elements and their radial velocities are known with a typical error of ∼100 m s^{-1} (e.g., Ikeda et al. 2002), then the mean ΔV can be estimated with a statistical error of ∼30 m s^{-1} from an ensemble of $n \sim 20$ independent measurements.

Unfortunately, available observational data do not allow us to probe $\Delta F/F$ at the 0.1 ppm level. First at all, only a handful of sources are known where both [C I] and ^{13}CO radial velocities have been measured (Schilke et al. 1995; Stark et al. 1996; Ikeda et al. 2002; Mookerjea et al. 2006a,b). The line profiles from these observations were usually fitted with single Gaussians in spite of apparent asymmetries seen in some cases (e.g., Fig. 7 in Ikeda et al. 2002). Besides, the measured radial velocities were not corrected for different beamsizes. As a result, the scatter in ΔV becomes large, and the accuracy of the $\Delta F/F$ estimate deteriorates.

3. The α^2/μ estimate

In this section we consider constraints on the spatial variations of α^2/μ, which can be obtained from observations of emission lines of atomic carbon and carbon monoxide in submm- and mm-wave regions. The FS [C I] lines and low-J rotational lines of ^{13}CO are observed towards many galactic and extragalactic objects (Bayet et al. 2006; Omont 2007). For our purpose we selected a few molecular clouds located at different galactocentric distances where the radial velocities of these species were measured with a sufficiently high precision ($\varepsilon_v \sim 100$ m s^{-1}).

Table 1 lists molecular clouds with both [C I] and ^{13}CO line measurements which are available in literature. The line positions, $V_{\rm LSR}$, are given in Cols. 3 and 5, and the the line widths (FWHM), σ_v, are in Cols. 4 and 6. The numbers in parentheses are the standard deviations in units of the last significant digit. Cols. 7 lists velocity offsets $\Delta V = V^{\rm CO}_{\rm LSR} - V^{\rm C\,I}_{\rm LSR}$, and their estimated errors. The data were obtained under the following conditions.

TMC-1 – the Taurus molecular cloud ($D \sim 140$ pc). This dark molecular cloud was studied with the Caltech 10.4 m submillimeter telescope on Mauna Kea, Hawaii (Schilke et al. 1995). The beamsize at the [C I] (1–0) frequency was 15″, while it was about 30″ at the ^{13}CO (2–1) frequency. Schilke et al. observed similar shapes of the [C I] (1–0) and ^{13}CO (2–1) profiles at five positions perpendicular to the molecular ridge close to the cyanopolyyne peak. The line parameters listed in Table 1

Table 1. Parameters derived from Gaussian fits to the ^{13}CO $J = 2-1$, $J = 1-0$, and [C I] $J = 1-0$ emission line profiles observed towards Galactic molecular clouds.

Source	No.	$V_{\rm LSR}^{\rm CO}$, km s^{-1}	$\sigma_v^{\rm CO}$, km s^{-1}	$V_{\rm LSR}^{\rm C\,I}$, km s^{-1}	$\sigma_v^{\rm C\,I}$, km s^{-1}	ΔV, km s^{-1}	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TMC-1	1	6.1(1)^a	2.0(1)	6.0(1)	1.5(2)	0.1(1)	Schilke et al. (1995)
	2	6.1(1)^a	1.6(1)	6.1(1)	1.5(1)	0.0(1)	
	3	6.1(1)^a	1.7(1)	5.9(1)	1.6(1)	0.2(1)	
	4	6.1(1)^a	1.6(1)	5.8(1)	1.2(2)	0.3(1)	
	5	6.2(1)^a	1.5(1)	6.4(1)	2.0(2)	–0.2(1)	
L183	6	2.83(3)^a	2.00(7)	2.2(2)	1.7(3)	0.63(20)	Stark et al. (1996)
	7	2.41(4)^a	1.81(9)	1.6(2)	2.2(4)	0.81(20)	
	8	2.16(3)^a	1.84(7)	2.2(1)	1.6(3)	–0.04(10)	
	9	2.05(4)^a	2.6(1)	1.6(1)	1.8(3)	0.45(11)	
	10	2.20(4)^a	2.0(1)	2.4(1)	1.4(3)	–0.20(11)	
Ceph B	11	–13.4(1)^a	2.1	–14.1(1)	1.9	0.7(1)	Mookerjea et al. (2006a)
Ori A,B	12	8.6(1)^b	4.0(1)	9.3(1)	4.7(1)	–0.7(1)	Ikeda et al. (2002)
	13	7.1(1)^b	2.4(1)	7.6(1)	3.4(1)	–0.5(1)	
	14	4.8(1)^b	2.5(1)	5.2(2)	3.3(4)	–0.4(2)	
	15	10.4(1)^b	2.9(1)	10.9(3)	3.3(1)	–0.5(3)	
	16	11.2(1)^b	2.6(1)	11.0(1)	3.3(1)	0.2(1)	
	17	9.6(1)^b	2.7(1)	9.9(1)	3.2(1)	–0.3(1)	
	18	9.6(1)^b	4.4(1)	9.5(1)	5.0(1)	0.1(1)	
	19	8.1(1)^b	3.3(1)	8.3(1)	3.7(1)	–0.2(1)	
	20	5.3(1)^b	2.3(1)	5.5(1)	3.0(1)	–0.2(1)	
	21	10.3(2)^b	3.4(4)	10.6(1)	4.2(1)	–0.3(2)	
	22	10.6(1)^b	1.8(1)	10.4(2)	2.3(4)	0.2(2)	
	23	9.6(1)^b	2.7(1)	9.8(1)	3.4(1)	–0.2(1)	
Cas A	24	–46.80(5)^b	2.1(1)	–47.4(1)	2.9(2)	0.60(11)	Mookerjea et al. (2006b)
	25	–1.10(6)^b	1.8(1)	–1.7(1)	3.1(4)	0.60(12)	

Notes. $^{(a)}$ $J = 2-1$; $^{(b)}$ $J = 1-0$.

were derived by Gaussian fits, although the line shapes were not exactly Gaussians. Therefore the errors of the line parameters are the formal 1σ errors of the fitting procedure.

L183 is an isolated quiescent dark cloud at a distance of about 100 pc (Mattila 1979; Franco 1989). The observations of the [C I] and ^{13}CO lines at six positions along an east-west strip through the center of the cloud were obtained with the 15 m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii (Stark et al. 1996). The beamsize at 492 GHz was 10″ and 22″ (*A*-band) and 15″ (*B*-band) at 220 GHz. The [C I] and ^{13}CO data were smoothed to a resolution of 0.4 km s^{-1} and 0.2 km s^{-1}, respectively. These emission lines show similar asymmetric profiles, which can be attributed to two kinematically different components closely spaced in velocity with central velocities around 1 km s^{-1} and 2 km s^{-1}. These components are marginally resolved in the [C I] spectra at two positions (# 7 and 8 in Table 1). But since ^{13}CO lines were not resolved at these positions, we include in Table 1 the results of one component Gaussian fits of both ^{13}CO (2–1) and [C I] (1–0) spectra from Stark et al. (1996).

Ceph B is a giant Cepheus molecular cloud at a distance of ~730 pc located to the south of the Cepheus OB3 association of early-type stars (Blaauw 1964). Cepheus B, the hottest ^{12}CO component of this complex (Sargent 1977, 1979), is surrounded by an ionization front driven by the UV radiation from the brightest members of the OB3 association (Felli et al. 1978). The observations of the [C I] (1–0) line were obtained using the KOSMA 3 m submillimeter telescope on Gornergrat, Switzerlaand (Mookerjea et al. 2006a). This dataset was complemented with ^{13}CO observed with the IRAM 30 m telescope (Ungerechts et al. 2000). All data were smoothed to the spatial resolution of 1′ and the velocity resolution of 0.8 km s^{-1}. Table 1 includes [C I] and ^{13}CO (2–1) lines arising around $V_{\rm LSR}$ of –13.8 km s^{-1} at the position of the hotspot in Cepheus B. The $V_{\rm LSR}$ values of the [C I] (1–0) and ^{13}CO (2–1) positions derived from Gaussian fitting were reported in Table 2 of Mookerjea et al. (2006a) without their errors. However, since the lines look symmetric (Fig. 3, Mookerjea et al. 2006a), we assign them an error of 0.1 km s^{-1}. This is slightly greater than the uncertainty of ~1/10th of the resolution element, a typical error of the line position for symmetric profiles, but does not significantly affect the sample mean value of ΔV.

Orion A, B – are giant molecular clouds located at ~450 pc (Genzel & Stutzki 1989). The observations of the [C I] (1–0) line towards 9 deg^2 area of the Orion A cloud and 6 deg^2 area of the Orion B cloud with a grid spacing of 3′ were carried out with the 1.2 m Mount Fuji submillimeter telescope (Ikeda et al. 2002). These observations were complemented with the ^{13}CO (1–0) dataset presented in Table 3 in Ikeda et al. At the frequency 492 GHz, the spatial and velocity resolutions were, respectively, 2.2′ and 1.0 km s^{-1}, whereas at frequency 110 GHz they were 1.6′ and 0.3 km s^{-1}. The profiles of the [C I] (1–0) and ^{13}CO (1–0) lines were found to be very similar. All spectra were well-fitted with one or two Gaussian functions, and the velocity centers of the [C I] and ^{13}CO lines are almost the same: $|\Delta V| = 0.2 \pm 0.1$ km s^{-1}. The results of the Gaussian fitting are given in Table 1.

Cas A is a supernova remnant at a distance of ~3 kpc (Braun et al. 1987). It was mapped in the [C I] (1–0) line on the KOSMA 3 m submillimeter telescope with a beamwidth of 55″ and the velocity resolution of 0.6 km s^{-1} (Mookerjea et al. 2006b). These observations were compared with the ^{13}CO (1–0) observations (beamsize ~60″, spectral resolution ~0.1 km s^{-1}) taken from Liszt & Lucas (1999). Both the [C I] (1–0) and ^{13}CO (1–0) emission spectra were averaged over the disk of Cassiopeia A. The results of Gaussian fitting of subcomponents resolved in the [C I] (1–0) and ^{13}CO (1–0) spectra are included in Table 1. Two strong emission feature observed in both [C I] and ^{13}CO (1–0) lines were identified with the Perseus arm at -47 km s^{-1} ($\sim$2 kpc distant) and with the local Orion arm at -1 km s^{-1}($\sim$460 pc distant).

The velocity offsets ΔV between the ^{13}CO and [C I] lines are given in Col. 7 of Table 1, and the corresponding linewidths, σ_v, are shown in Cols. 4 and 6. When both transitions trace the same material, the lighter element C should always have a larger linewidth. If the line broadening is caused by thermal and turbulent motions, i.e., $\sigma_v^2 = \sigma^2_{\rm therm} + \sigma^2_{\rm turb}$, then for two species with masses $m_1 < m_2$ we have

$$\sqrt{m_1/m_2} \leq \sigma_{2,v}/\sigma_{1,v} \leq 1. \qquad (6)$$

In practice, this inequality is only approximately fulfilled. Except for the pure thermal and turbulent broadening there are many other mechanisms that can give rise to the broadening of atomic and molecular lines. These are saturation broadening (lines have different optical depths), the presence of unresolved velocity gradients (nonthermal distribution is not normal), the increasing velocity dispersion of the nonthermal component with increasing map size (the higher angular resolution is realized for the higher frequency transitions), etc. Thus, the consistency of the apparent linewidths defined by Eq. (6) is a necessary condition for two species with different masses to be co-spatially distributed, but is not a sufficient one.

From Table 1 it is seen that the inequality (6) is fulfilled for all selected pairs ^{13}CO/[C I] within the estimated uncertainties of the linewidths. Thus, the whole sample of $n = 25$ ΔV values can be used to estimate $\Delta F/F$. The averaging of the velocity offsets over the dataset gives the unweighted mean $\Delta V_{\rm uw} \equiv \langle V_{\rm LSR}(^{13}{\rm CO}) - V_{\rm LSR}({\rm C\,I})\rangle = 0.046 \pm 0.083_{\rm stat}$ km s^{-1}. With weights inverse proportional to the variances, one derives $\Delta V_{\rm w} = 0.029 \pm 0.077$ km s^{-1}. The median of the sample is $\Delta V_{\rm med} = 0.0$ km s^{-1}, and the robust M-estimate (L10) is $\Delta V_{\rm M} = 0.022 \pm 0.082$ km s^{-1}. The statistical error for the mean velocity offset measurement is more than what is expected from the published values of the statistical errors from the one component Gaussian fits: the mean error of the individual ΔV is 0.13 km s^{-1}, and the expected error of the mean ΔV is $\sim$0.026 km s^{-1}. A possible reason for such a high Doppler noise has been discussed in Sect. 2. The systematic error in this case is dominated by the uncertainty of the rest frequency of the [C I] (1–0) transition, $\varepsilon_v = 33.5$ m s^{-1}. Thus, taking the M-estimate as the best measure of the velocity offset, we have $\Delta V_{\rm M} = 0.022 \pm 0.082_{\rm stat} \pm 0.034_{\rm sys}$ km s^{-1}, and the 1σ upper limit on $|\Delta V| < 0.11$ km s^{-1}.

This estimate restricts the spatial variability of F at the level of $|\Delta F/F| < 0.37$ ppm. Recently we obtained a constraint on the spatial change of the electron-to-proton mass ratio $|\Delta\mu/\mu| \leq 0.03$ ppm based on measurements in cold molecular cores in the Milky Way (L10). By combining these two upper limits, the fine-structure constant can be bound as $|\Delta\alpha/\alpha| < 0.2$ ppm.

4. Conclusion

The level of 0.2 ppm represents a model-dependent upper limit on the *spatial* variations of α. Under model dependence, we assume here that both $\Delta F/F$ and $\Delta\mu/\mu$ do not change significantly from cloud to cloud, since astrophysical measurements of these parameters are made in low-density regions of the interstellar medium with $\rho_{\rm cloud} \ll \rho_{\rm terrestrial}$.

For comparison, the upper limit on the *temporal* α-variation obtained from high-redshift quasar absorbers is $|\Delta\alpha/\alpha| < 2$ ppm (Sect. 1). If dependence of constants on the ambient matter density dominates temporal (cosmological), as suggested in chameleon-like scalar field models, then one may expect that $|\Delta\alpha/\alpha| < 0.2$ ppm at high redshifts as well, since quasar absorbers have gas densities similar to those in the interstellar clouds. Considering that the predicted changes in α and μ are not independent and that μ-variations may exceed variations in α (e.g., Calmet & Fritzsch 2002; Langacker et al. 2002; Dine et al. 2003; Flambaum et al. 2004), even a lower bound of $|\Delta\alpha/\alpha| \leq 0.03$ ppm is conceivable within the framework of the chameleon models.

If a theoretical prediction $|\Delta\alpha/\alpha| \ll |\Delta\mu/\mu|$ is valid, then $\Delta F/F \approx -\Delta\mu/\mu$, so that the F-estimate with a further order of magnitude improvement in sensitivity will provide an independent test of the tentative change of μ. The factors limiting accuracy of the current estimate of $\Delta F/F$ at $z = 0$ are a relatively low spectral resolution of the available observations in submm- and mm-wave bands, a rather large uncertainty of the rest frequencies of the [C I] FS lines, and a small number of objects observed in both [C I] and ^{13}CO transitions.

Modern telescopes like the recently launched Herschel Space Observatory can provide the spectral resolution as high as 30 m s^{-1} for Galactic objects (e.g., the Heterodyne Instrument for the Far Infrared, HIFI, has resolving power $R = 10^7$). This means that the positions of the [C I] FS lines can be measured with the uncertainty of $\sim$3 m s^{-1}. In the near future, high-precision measurements will be also available with the Atacama Large Millimeter/submillimeter Array (ALMA), the Stratospheric Observatory For Infrared Astronomy (SOFIA), the Cornell Caltech Atacama Telescope (CCAT), and others. Thus, any further advances in exploring $\Delta F/F$ depend crucially on new laboratory measurements of the [C I] FS frequencies. If these frequencies are known with uncertainties of a few m s^{-1}, then the parameter $\Delta F/F$ can be probed at the level of 10^{-8}, which would be comparable to the non-zero signal in the spatial variation in the electron-to-proton mass ratio μ.

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