On spatial variations of the electron-to-proton mass ratio in the Milky Way

S. A. Levshakov\textsuperscript{1}, P. Molaro\textsuperscript{2}, and M. G. Kozlov\textsuperscript{3}

\textsuperscript{1}Ioffe Physico-Technical Institute, Politekhnicheskaya Str. 26, 194021 St. Petersburg, Russia
\textsuperscript{2}INAF-Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 I, Trieste, Italy and
\textsuperscript{3}Petersburg Nuclear Physics Institute, Gatchina, 188300, Russia

(Dated: August 5, 2008)

We aim at applying the ammonia method, recently proposed to explore the electron-to-proton mass ratio $\mu = m_e/m_p$, to Galactic sources. Emission lines due to ammonia are originated in the numerous interstellar molecular clouds allowing to probe $\mu$ at different galactocentric distances. High quality radio-astronomical observations of molecular cores in lines of NH$_3$ ($J, K$) = (1,1), CCS $J_N = 21 - 10$, HC$_3$N $J = 5 - 4$, and N$_2$H$^+$ $J = 1 - 0$ are used to measure the relative radial velocity offsets, $\Delta V$, between the NH$_3$ (1,1) and other molecular transitions. Robust statistical analysis is applied to the $n = 207$ individual measurements in the Perseus molecular cloud (PC), the Pipe Nebula (PN), and the infrared dark clouds (IRDCs) to deduce the mean value of $\Delta V$ and its uncertainty. The measured values of $\Delta V$ from the PC, PN, and IRDCs show statistically significant positive velocity shifts between the line centers of NH$_3$ and other molecules. The most accurate estimates are obtained from carefully selected subsamples of the NH$_3$/CCS pairs observed in the PC ($n = 21$) and the PN ($n = 8$), $\Delta V = 36 \pm 5_{\text{stat}} \pm 13_{\text{sys}}$ m s$^{-1}$ and $53 \pm 11_{\text{stat}} \pm 13_{\text{sys}}$ m s$^{-1}$, respectively, and from the $n = 36$ NH$_3$/N$_2$H$^+$ and $n = 27$ NH$_3$/HC$_3$N pairs observed in the IRDCs, $\Delta V = 148 \pm 32_{\text{stat}} \pm 13_{\text{sys}}$ m s$^{-1}$ and $115 \pm 37_{\text{stat}} \pm 31_{\text{sys}}$ m s$^{-1}$, respectively. Being interpreted in terms of the electron-to-proton mass ratio variation, this gives $\Delta \mu/\mu \sim (4 - 14) \times 10^{-5}$, which is an order of magnitude more sensitive than previous astronomical constraints on this quantity. If $\Delta \mu/\mu$ follows the gradient of the local gravitational potential, as suggested in some scalar field models, then the obtained result is in sharp contradiction ($\sim 5$ orders of magnitude) with laboratory atomic clock experiments carried out at different points in the gravitational potential of the Sun. However, the measured signal might be consistent with chameleon-type scalar field models which predict a strong dependence of masses and coupling constants on the ambient matter density. The confirmation of a spatial variation of $\Delta \mu/\mu$ will help to distinguish between many theoretical proposals suggested to explain the nature of dark energy. New control measurements of the velocity offsets involving other molecules and a wider range of objects along with verification of rest frequencies are needed to investigate different instrument systematics and to come to a more certain conclusion.

PACS numbers: 06.20.Jr, 32.30.Bv, 95.36.+x, 95.85.Bh, 98.38.Bn, 98.38.Dq

I. INTRODUCTION

A fundamental characteristic of the universe is that decelerating expansion changed to accelerating at redshift $z \sim 1$ \cite{1,2,3}. This late time acceleration is usually attributed to some negative-pressure component of the bulk of energy density, referred to as ‘dark energy’. The nature of dark energy remains unknown in spite of a good deal of theoretical and experimental efforts \cite{4}. The most popular scenario is a dynamically evolving scalar field $\varphi$, named ‘quintessence’ \cite{5}, with the energy density subdominant at a matter dominated (decelerating) epoch ($1 \lesssim z \lesssim 1000$), and dominant at lower redshifts \cite{6}. Scalar field models allow to alleviate the so-called ‘cosmic coincidence’ problem – the fact that matter and vacuum energy contribute by comparable amounts to the energy density at the present cosmological epoch \cite{5}. The scalar field(s) coupling to ordinary matter leads unavoidably to long-range forces and variability of the physical constants violating the Equivalence Principle. Thus, any laboratory or space-based experiments as well as astronomical studies aimed at probing the variations of the physical constants, are the most important tools to test new theories against observations.

Present experimental facilities allow us to probe the variability of the fine-structure constant $\alpha = e^2/hc$ and the electron-to-proton mass ratio $\mu = m_e/m_p$, or different combinations of the proton gyromagnetic ratio $\nu_p$ with $\alpha$ and $\mu$ \cite{6}. The most accurate laboratory constraint on the temporal variation of $\alpha$ of $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}$ yr$^{-1}$ is obtained from atomic clocks experiments \cite{4}. Being linearly extrapolated to redshift $z \sim 2$, or $t \sim 10^{11}$ yr, this laboratory bound leads to $\Delta \alpha/\alpha = (-1.6 \pm 2.3) \times 10^{-7}$ which is well below a conservative upper limit on $|\Delta \alpha/\alpha| < 10^{-5}$ stemmed from the analysis of quasar absorption-line systems \cite{10,11,12}. Here $\Delta \alpha/\alpha = (\alpha' - \alpha)/\alpha$, with $\alpha, \alpha'$ denoting the values of the fine-structure constant in the laboratory and the specific absorption/emission line system of a galactic or extragalactic object (the same definition is applied to $\Delta \mu/\mu$). However, laboratory experiments and quasar absorption spectra investigate very different time scales and different regions of the universe, and the connection between them is somewhat model dependent \cite{13,14}. The direct and model-free estimate of time variation of $\mu$ was deduced from comparison of the frequency of a rovibrational transition in SF$_6$ molecule with the fundamental hyperfine transition in Cs: $\nu/\nu = (3.8 \pm 5.6) \times$
$10^{-14}$ yr$^{-1}$ [15] . Astrophysical estimates of $\mu$ at high redshifts are controversial in the claims of nonzero and zero changes of $\mu$: $\Delta \mu / \mu = (-2.4 \pm 0.6) \times 10^{-5}$ was inferred from the analysis of the $H_2$-bearing clouds at $z = 2.6$ and $3.0$ [16], but this value was not confirmed later [17, 18]. A better accuracy bound was obtained at lower redshift $z = 0.68$ from the analysis of radio-frequency transitions in NH$_3$, CO, HCO$^+$, and HCN: $\Delta \mu / \mu = (-0.6 \pm 1.9) \times 10^{-6}$ [19], which favors a non-variability of $\mu$ at the level of $\sim 3 \times 10^{-6}$.

In these studies it was assumed that the rate of time variations dominates over the rate of possible spatial variations. However, this may not be the case if scalar fields trace the gravitational field inhomogeneities [20, 21]. The spatial variation of constants in a changing gravitational potential of the Sun were studied in laboratory measurements of the atomic clock transition $^{1}\!S_0$–$^{3}\!P_0$ in neutral $^{87}$Sr relative to the Cs standard and of the radio-frequency $E1$ transition between nearly degenerate, opposite-parity levels of atomic dysprosium (Dy). The values for the couplings of $\alpha$ and $\mu$ to the gravitational field were reported to be $k_\alpha = (2.3 \pm 3.1) \times 10^{-6}$, $k_\mu = (-1.1 \pm 1.7) \times 10^{-5}$ [22] , and $k_\mu = (-8.7 \pm 6.6) \times 10^{-6}$ [23], respectively.

Thus, the current laboratory and astrophysical estimates of the temporal and/or spatial changes of the coupling constants and fermion masses do not exhibit any meaningful features which could be interpreted in terms of scalar field effects. On the other hand, we do observe the late time acceleration of the universe driven most probably by ultra-light scalar fields. To reconcile these results chameleon-type models were suggested [24, 25, 26, 27, 28, 29, 30] which allow scalar fields to evolve on cosmological time scales today and to have simultaneous strong couplings of order unity to matter, as expected from string theory. The key assumption in this scenario is that the mass of the scalar field depends on the local matter density. This explains why cosmological scalar fields, such as quintessence, are not detectable in local tests of the Equivalence Principle since we live in a dense environment where the mass of the field can be sufficiently large and $\varphi$-mediated interactions are short-ranged. On the other hand, the cosmological matter density is about $10^{30}$ times smaller and thus the mass of the scalar field can be very low, of order of $H_0$, the present Hubble constant. This allows the field to evolve cosmologically today. Laboratory experiments aimed at detections of chameleon particles are nowadays carried out at Fermilab [31].

In this paper we explore the astrophysical implications of the scalar field effect on the electron-to-proton mass ratio, $\mu$, following suggestions on experimental tests of $\Delta \mu / \mu$ in our Galaxy as formulated in [30]. We consider the constraints on the spatial variations $\Delta \mu / \mu$ caused by the relative Doppler shifts of molecular transitions in cold molecular cores observed in the Milky Way disk at different galactocentric distances.

Our assumptions and basic physical properties of dense molecular cores which will be needed in the sequel are discussed in Sect. III. The statistical analysis of the line position measurements in the Perseus molecular complex, the Pipe Nebula, and the infrared dark clouds are presented in Sect. III. The obtained results are discussed in Sect. IV and conclusions are given in Sect. V.

### II. INTERSTELLAR MOLECULES AS PROBES OF $\Delta \mu / \mu$ SPATIAL VARIATIONS

Extremely narrow molecular lines observed in cold dark clouds provide a sensitive spectroscopic tool to study the spatial variations of fundamental constants under different environments and gravitational fields. Among numerous molecules detected in the interstellar medium (ISM), ammonia (NH$_3$) is of particular interest due to its high sensitivity to changes in the electron-to-proton mass ratio, $\mu$. As was firstly shown for ammonia isotopomer $^{15}$ND$_3$ [32], the inversion frequency in the $(J, K) = (1, 1)$ level changes as

$$\frac{\Delta \nu}{\nu} = 5.6 \frac{\Delta \mu}{\mu},$$

which is nearly an order of magnitude more sensitive to $\mu$-variation than molecular vibrational frequencies which scale as $E_{\text{vib}} \sim \mu^{1/2}$.

The deuterated ammonia shows, however, low abundances in the ISM molecular clouds, $n$(ND$_3)/n$(NH$_3$) $\approx 10^{-4} - 10^{-2}$ [33]. For more abundant ammonia form of NH$_3$, the sensitivity coefficient of the inversion transition $\nu = 23.69$ GHz was calculated in [19]:

$$\frac{\Delta \nu}{\nu} = 4.46 \frac{\Delta \mu}{\mu}.$$  

By comparing the observed inversion frequency of NH$_3$ $(1, 1)$ with a suitable rotational frequency (scaling as $E_{\text{rot}} \sim \mu$) of another molecule arising co-spatially with ammonia, a limit on the spatial variation of $\mu$ can be determined [19]:

$$\frac{\Delta \mu}{\mu} = 0.289 \frac{V_{\text{rot}} - V_{\text{inv}}}{c} \equiv 0.289 \frac{\Delta V}{c},$$

| Transition | $\nu_{\text{rest}}$, GHz | $\lambda_{\text{rest}}$, cm | $\varepsilon_v$, m s$^{-1}$ |
|------------|---------------------|------------------|------------------|
| CCS $J_N = 2_1 - 1_0$ | 22.344033(1)$^a$ | 1.34 | 13.4 |
| NH$_3$ $(J, K) = (1, 1)$ | 23.694955(1)$^a$ | 1.27 | 1.3 |
| HCN $J = 5 - 4$ | 45.4903102(3)$^b$ | 0.66 | 2.8 |
| N$_2$H$^+ J = 1 - 0$ | 93.173777(4)$^b$ | 0.32 | 13.5 |

$^a$Rest frequency from Ref. [31].
$^b$Rest frequency from Ref. [32].
clouds (IRDCs), and low-mass cores (\( M < 10 \, M_\odot \)) dynamically stable against gravitational contractions of dense molecular gas preceding gravitational collapse. The latter provide information on the physical conditions where these molecules are detected. The input uncertainties of the adopted rest frequencies (see Table I) range the errors in the molecular line position measurements are mainly restricted by the uncertainties in laboratory frequencies, \( \varepsilon_v \sim 0.1 - 1 \, \text{kHz} \), which correspond to the \( V_{\text{LSR}} \) uncertainties of \( \varepsilon_v \sim 1 - 10 \, \text{m s}^{-1} \). Taking into account that \( \Delta \mu / \mu \sim 0.3 \Delta v / c \), the expected precision of the \( \Delta \mu / \mu \) measurements in the ISM is restricted by the level of \( 10^{-8} \), i.e. they are about 100 times more accurate than the \( \Delta \mu / \mu \) estimate deduced at \( z = 0.68 \).

This level of accuracy can be achieved, however, only ideally since it assumes that molecules are identically (cospatially) distributed within the cloud, and are observed simultaneously with the same receiver, beam size, system temperature, and velocity resolution. Violation of any of these conditions leads to shifts of the line centers which are referred to as the Doppler noise. The input of the Doppler noise to a putative \( \Delta \mu / \mu \) signal can be reduced to some extent if the velocity shifts due to inhomogeneous distribution of molecules and to instrumental imperfections are of random nature. All molecular transitions listed in Table I require for their excitation high gas density, \( n_H \sim 10^5 \, \text{cm}^{-3} \), at a typical kinetic temperature of \( T_{\text{kin}} \sim 10 \, \text{K} \). Ammonia is easily detectable in many interstellar clouds. The inversion transition \( (J, K) = (1, 1) \) has 18 hyperfine components which can be resolved into nine separate features for quiescent nearby dark clouds. Since hyperfine components have different intensities, a single NH\(_3\) spectrum allows to determine optical depth, radial velocity, intrinsic linewidth, and excitation temperature and thus to separate the effects of optical depth and excitation temperature.

The second N-bearing molecule, which is a good tracer of cold and quiescent dense gas, is the molecular ion N\(_2\)H\(^+\). The seven hyperfine components of the N\(_2\)H\(^+\)...
TABLE II: Parameters of dense cores in the Perseus molecular cloud \( (D \approx 260 \text{ pc}) \) taken from Ref. [34] and representing the best quality single component profiles of CCS \( (2_1 - 1_0) \) and NH\(_3\) \( (1,1) \). Asterisk marks objects with \( 0.55 \sigma_v (\text{NH}_3) \lesssim \sigma_v (\text{CCS}) \lesssim \sigma_v (\text{NH}_3) \) (see Fig. 1).

| NH3SRC source | Other name | \( V_{\text{LSR}} \) \( (\text{km s}^{-1}) \) | \( \sigma_v (\text{NH}_3) \) \( (\text{km s}^{-1}) \) | \( \sigma_v (\text{CCS}) \) \( (\text{km s}^{-1}) \) | \( \Delta V_{\text{CCS-NH}_3} \) \( (\text{km s}^{-1}) \) |
|---------------|------------|---------------------|---------------------|---------------------|---------------------|
| 3             | B16        | 4.136(1)            | 0.115(1)            | 0.15(1)             | 0.02(1)             |
| 6             | B11        | 4.030(3)            | 0.134(3)            | 0.20(1)             | 0.09(1)             |
| 7             | B30        | 4.135(1)            | 0.168(1)            | 0.23(2)             | 0.05(2)             |
| 9             | B57        | 4.090(1)            | 0.155(1)            | 0.19(1)             | 0.09(1)             |
| 11            | B13        | 4.563(2)            | 0.124(2)            | 0.16(1)             | -0.05(1)            |
| 11*           | B1         | 4.236(8)            | 0.163(8)            | 0.163(8)            | -0.05(1)            |
| 13*           | B27        | 4.06(1)             | 0.24(2)             | 0.19(1)             | 0.06(2)             |
| 15            | B27        | 4.648(3)            | 0.194(3)            | 0.29(2)             | -0.06(2)            |
| 16*           | B4         | 4.614(7)            | 0.141(6)            | 0.132(4)            | 0.026(8)            |
| 19*           | B45        | 0.356(9)            | 0.21(1)             | 0.19(2)             | -0.02(3)            |
| 20*           | B22        | 4.345(7)            | 0.256(9)            | 0.22(1)             | -0.03(1)            |
| 21*           | B21        | 4.17(1)             | 0.28(1)             | 0.16(1)             | 0.06(1)             |
| 21*           | B20        | 3.550(9)            | 0.21(1)             | 0.19(2)             | -0.02(3)            |
| 22*           | B10        | 5.150(2)            | 0.146(2)            | 0.16(1)             | 0.04(1)             |
| 24*           | B9         | 4.591(3)            | 0.149(3)            | 0.17(1)             | 0.03(1)             |
| 28*           | D7         | 5.62(1)             | 0.111(1)            | 0.08(1)             | 0.09(1)             |
| 30*           | L24        | 5.22(1)             | 0.111(1)            | 0.11(1)             | -0.10(1)            |
| 46            | B45        | 7.030(1)            | 0.152(1)            | 0.20(1)             | 0.07(1)             |
| 60*           | D4         | 7.73(2)             | 0.102(2)            | 0.10(1)             | 0.03(1)             |
| 87*           | B85        | 7.10(1)             | 0.126(1)            | 0.11(1)             | 0.09(2)             |
| 93            | B18        | 6.022(1)            | 0.088(1)            | 0.123(5)            | 0.019(5)            |
| 96*           | B34        | 7.383(8)            | 0.152(3)            | 0.141(7)            | 0.013(8)            |
| 97*           | B32        | 7.724(2)            | 0.102(2)            | 0.10(1)             | 0.03(1)             |
| 111           | B40        | 6.673(1)            | 0.139(1)            | 0.161(9)            | 0.055(9)            |
| 112*          | B75        | 6.583(7)            | 0.257(8)            | 0.14(1)             | 0.20(1)             |
| 113           | B41        | 6.570(1)            | 0.153(1)            | 0.182(8)            | 0.100(8)            |
| 114*          | B42        | 6.609(1)            | 0.189(9)            | 0.184(7)            | 0.107(7)            |
| 124*          | B44        | 6.786(1)            | 0.121(1)            | 0.13(1)             | 0.06(1)             |
| 126*          | B48        | 6.790(4)            | 0.254(5)            | 0.139(8)            | 0.034(9)            |
| 128*          | B58        | 7.678(2)            | 0.097(2)            | 0.07(1)             | 0.06(1)             |
| 142*          | B91        | 8.475(3)            | 0.12(1)             | 0.07(1)             | 0.07(1)             |
| 151*          | B99        | 8.64(1)             | 0.12(1)             | 0.12(1)             | 0.08(1)             |
| 151*          | B99        | 10.151(2)           | 0.107(2)            | 0.12(1)             | -0.05(7)            |
| 190           | L44        | 10.130(5)           | 0.119(3)            | 0.161(6)            | -0.005(7)           |
| 191           | D28        | 10.131(3)           | 0.127(3)            | 0.16(1)             | -0.05(1)            |

\( J = 1 - 1 \) transition were studied with high spectral resolution in [42]. \( N_2H^+ \) is mainly formed in well-shielded regions where photoprocesses are unimportant [43]. The intensity distribution of \( N_2H^+ (1 - 0) \) in dense cores closely matches that of \( \text{NH}_3 (1,1) \), and the relative abundances of these molecules are almost constant across the starless core. However, in some cases there were detections of ammonia abundances increased by a factor of \( \sim 10 \) towards the core center [44]. High angular resolution observations of nearby protostellar objects show that \( N \)-bearing molecules trace the inner cores where the density approaches \( 10^5 \text{ cm}^{-3} \) and the carbon-chain molecules disappear from the gas-phase because of the freeze-out onto dust grains [38]. The observed correlation between \( N_2H^+ \) and \( \text{NH}_3 \) velocities and linewidths is another indication of probable co-spatial origin of these two species [47].

The spectral lines of the radical CCS without hyperfine splittings and not strongly saturated \( (\tau < 3) \) make CCS a well-suited molecule for detailed studies of the velocity structure in dark clouds [46]. CCS lines are rather intense in starless, cold and quiescent dark clouds at the earliest stages of molecular cloud evolution, whereas \( \text{NH}_3 \), as mentioned above, tends to be abundant in more chemically evolved and dense central regions of molecular cores [47]. As a rule, CCS shows up as a clumpy distributed gas slightly outside these central regions. A pronounced spatial anticorrelation in the emission from CCS and \( \text{NH}_3 \) was observed on large scale maps of the Taurus Molecular Cloud 1 (TMC-1) ridge [48], pre-protostellar cores L1498 [49] and B68 [50], as well as on small scale maps with angular resolution of \( \lesssim 5'' \) \( (= 1750 \text{ AU}) \) in the infrared cloud B1-IRS where the CCS emission was detected from three clumps surrounding the central source [51]. The clumps in B1-IRS exhibit a velocity gradient from red- to blueshifted velocities with respect to the systemic velocity of the central source which can be interpreted as interaction of the CCS-emitting gas with the molecular outflow. This interaction makes CCS lines wider than their thermal widths and comparable with the measured widths of the \( \text{NH}_3 \) lines in the B1-IRS source: \( \sigma_v (\text{CCS}) = 0.9 \pm 0.1 \text{ km s}^{-1} \) and \( \sigma_v (\text{NH}_3) = 1.1 \pm 0.1 \text{ km s}^{-1} \) (CCS thermal linewidth is narrower by a factor of 0.55 than that of \( \text{NH}_3 \) due to the different masses of these molecules). Turbulent broadening could equalize the apparent linewidths if both CCS and \( \text{NH}_3 \) trace the
same volume elements. However, in 5 out of 6 low-mass young star-forming regions studied in [52], the widths of the CCS lines are too narrow, \( \sigma_{v}(\text{CCS}) < 0.55 \sigma_{v}(\text{NH}_3) \), which is consistent with both molecules tracing different regions of gas with different kinematics. The only exception in this sample is the B1-IRS cloud where the spatial anticorrelation in the CCS- and NH$_3$-emitting gas has been revealed [51]. On the other hand, from the survey of dense cores using lines of N$_2$H$^+$, C$_3$H$_2$, and CCS it was deduced [53] that velocities and linewidths of these three molecules are well correlated among themselves and with NH$_3$, indicating a kinematic consistency for these species.

The three strongest hyperfine components of the \( J = 5 - 4 \) rotational transition of HCN [54] were partly resolved in radio-astronomical observations [53]. HCN, as well as CCS, is abundant in the early stage of chemical evolution of the star-forming regions [56] when the ratio of the fractional abundances of HC$_3$N and CCS remains almost constant [47] and the spatial distributions of these C-bearing molecules match each other quite well. The continued chemical evolution leads, however, to the spatial variation of the relative molecular abundances (chemical differentiation) due to adsorption of the heavy elements from the gas phase onto grain mantles at high densities and dust temperatures \( T_D < 20 \, \text{K} \) [42]. In the later stages of the protostellar collapse carbon chain molecules are destroyed by high velocity outflows and radiation from protostars, whereas the same processes favor the desorption of ammonia from dust grains [47].

Thus, the spatial distribution of the emitting gas tracers in star-forming regions is governed by both the physical conditions within the dense cores and the time-dependent chemistry. The consistency of the apparent linewidths of different molecules is a necessary condition for these molecules to be co-spatially distributed, but is not a sufficient one.

Molecular line profiles are also affected by the bulk kinematics of the dense clouds. Plane-of-sky bulk motions observed in starless cores exhibit velocity gradients of \( \sim 0.3 \) to 1.4 km s$^{-1}$ pc$^{-1}$ [57, 58]. A differential rotation and angular momentum evolution in the B68 core with velocity gradients of 3.4 and 4.8 km s$^{-1}$ pc$^{-1}$ for the outer and inner material respectively was found in [59]. Similarly, the spatial variations of the velocity gradients in prestellar and protostellar cores of \( \sim 2 \) km s$^{-1}$ pc$^{-1}$ [45] indicate deviations from simple solid body rotation.

The gas kinematics along the line-of-sights studied in the isolated cores [50] shows that cores move slowly (\( \lesssim 0.1 \) km s$^{-1}$) relatively to their surroundings. Inward and/or outward motion with velocity of \( \sim 0.1 \) km s$^{-1}$ is revealed by the skewed line profiles. For instance, blue asymmetry of the hyperfine components of the N$_2$H$^+$ (1-0) transition seen in two starless cores can be produced by absorption along the line-of-sight in the foreground inward-moving gas of lower excitation [61]. Acoustic type oscillations with amplitude of \( \sim 0.1 \) km s$^{-1}$ are seen in the inward and outward gas motion across the B68 core [59]. A redshifted peak of the CCS 3$^2 - 2^1$ emission line of \( \sim 0.16 \) km s$^{-1}$ with respect to the central velocity of the NH$_3$ (1,1) line was detected in the L1551 dark cloud [58].

The turbulent component of the gas velocity derived in [44] from the intrinsic linewidths of the NH$_3$ and N$_2$H$^+$ lines is small and subsonic, \( \sigma_{\text{tur}} \lesssim 0.1 \) km s$^{-1}$ (for \( T_{\text{kin}} = 10 \) K, sound speed is 0.19 km s$^{-1}$). Earlier, a similar conclusion has been obtained from NH$_3$ observations of low-mass dense cores [62].

The velocity widths in high-mass clumps associated with IRDCs are large (\( \sim 1-3 \) km s$^{-1}$) and indicate the supersonic motion. If the IRDCs are high-mass star-forming regions, then, as noted in Ref. [56], the observed

**TABLE III:** Parameters of dense cores in the Pipe Nebula (\( D \approx 130 \) pc) taken from Ref. [62] and representing emission line profiles of CCS (2$^1 - 1_0$) and NH$_3$ (1,1). Asterisk marks filled circles in Fig. 3.

| Source | \( V_{\text{LSR}} \), km s$^{-1}$ | \( \sigma_v \), km s$^{-1}$ | Mass, \( \mathcal{M}_\odot \) |
|--------|-----------------|-----------------|-----------------|
| 6*     | 3.50            | 3.43            | 0.07            | 3.1 |
| 12     | 3.47            | 3.20            | 0.19            | 20.4 |
| 14*    | 3.45            | 3.47            | 0.09            | 9.7  |
| 40*    | 3.35            | 3.30            | 0.06            | 9.2  |
| 42     | 3.86            | 3.75            | 0.11            | 2.8  |
| 87     | 4.50            | 4.47            | 0.25            | 10.3 |
| 89     | 4.87            | 4.45            | 0.26            | 1.0  |
| 92*    | 5.04            | 5.10            | 0.12            | 1.6  |
| 93*    | 5.26            | 5.17            | 0.17            | 3.5  |
| 101*   | 3.37            | 3.31            | 0.07            | 1.9  |
| 102    | 4.84            | 4.87            | 0.08            | 6.7  |
| 109*   | 5.80            | 5.75            | 0.07            | 3.6  |
FIG. 4: Upper panel: \( \text{N}_2\text{H}^+ \) (1–0) versus \( \text{NH}_3 \) (1,1) linewidths for massive clumps associated with infrared dark clouds from the survey of Ref. [84]. The error bars represent 1σ standard deviations. Lower panel: Same as the upper panel but for the points marked by asterisks in Table IV. In both panels, the dashed and dotted lines are the boundaries for, respectively, pure turbulent, \( \sigma_n(\text{N}_2\text{H}^+)=\sigma_v(\text{NH}_3) \), and pure thermal, \( \sigma_n(\text{N}_2\text{H}^+)=0.77\sigma_v(\text{NH}_3) \), line broadening. The sample sizes are indicated in the panels.

FIG. 5: Upper panel: Velocity offset \( \Delta V_{\text{N}_2\text{H}^+ - \text{NH}_3} \) versus the source radial velocity set by \( V_{\text{LSR}}(\text{NH}_3) \). Lower panel: Same as the upper panel but for the points marked by asterisks in Table IV. The vertical error bars include both random and systematic errors caused by the uncertainties of the adopted rest frequencies (Table I).

large velocity widths are consistent with a model which suggests massive star formation in turbulence-supported cores with a high accretion rate [63]. The innermost regions of such clumps are traced by molecular transitions with relatively large excitation energies of the upper states. To excite such transitions denser and hotter regions closer to the protostar are required. The \( \text{NH}_3 \) states. To excite such transitions denser and hotter regions closer to the protostar are required. The \( \text{NH}_3 \)(2,2) and (3,3) transitions have, for example, the excitation energies of \( E_u^{(2,2)}=65 \) K and \( E_u^{(3,3)}=125 \) K, and so their velocity distributions should be broader than that of the \( \text{NH}_3 \) (1,1) line for which \( E_u^{(1,1)}=23 \) K. We may expect that other molecules, such as CCS (\( J_S=2-1_0 \)), HC\(_3\)N (\( J=5-4 \)), and \( \text{N}_2\text{H}^+ \) (\( J=1-0 \)) with excitation energies lower than 23 K, would have velocity distributions similar to that of \( \text{NH}_3 \) (1,1).

### III. RESULTS

As noted in the previous section, the observational constraint on \( \Delta \mu/\mu \) is set by the velocity offset, \( \Delta V \), measured between the ammonia inversion line and a molecular rotational line, Eq. (3). In this comparison, to minimize possible systematics in the \( \Delta V \) values, the second molecule must follow closely the spatial distribution of \( \text{NH}_3 \). The most favorable candidate which fits this condition is the molecular ion \( \text{N}_2\text{H}^+ \). As for carbon-chain molecules, it seems likely that CCS and HC\(_3\)N are anti-correlated with \( \text{NH}_3 \), albeit not all of the dense cores display chemical differentiation (Ref. [53], Sect. 4.4). When molecules trace the same gas, their turbulent component should be equal, and the lighter \( \text{NH}_3 \) should always have larger linewidth if turbulent and thermal line broadening are comparable, \( \sigma_{\text{turb}}/\sigma_{\text{therm}} \sim 1 \). If, however, the turbulent component dominates, the lines may have similar widths. We use this criterion to select molecular pairs tracing presumably the same gas velocity, i.e. arising co-spatially.

It is to note that the velocity offset \( \Delta V \) in Eq. (3) is the sum of two components, \( \Delta V = \Delta V_\mu + \Delta V_n \), with \( \Delta V_\mu \) being the shift due to \( \mu \)-variation, and \( \Delta V_n \) the shift induced by Doppler noise. Assuming the random character of the Doppler noise, the signal \( \Delta V_n \) can be estimated statistically by averaging over a large data sample. The validity of this assumption requires, however, additional tests as discussed below in Sect. III C.

#### A. Dense cores in the Perseus molecular cloud

At first we consider an ammonia spectral atlas of 193 dense protostellar and prestellar cores of low masses in the Perseus molecular cloud [34]. The spectral observations of the cores in \( \text{NH}_3 \) (1,1), (2,2), CCS (2–1_0) and CC\(_{34}\)S (21–1_0) lines were carried out simultaneously using the 100-m Robert F. Byrd Green Bank Telescope (GBT). Each target was observed in a single-pointing, frequency-switched mode allowing the entire \( \text{NH}_3 \) (1,1) complex to remain within the spectral window. The GBT beam size at 23 GHz is \( \text{FWHM} = 31'' \) or 0.04 pc at the Perseus cloud distance (\( D \sim 260 \) pc). The resulting spectral resolution was 24 m s\(^{-1}\). Thus, both molecules were observed with similar angular and spectral resolutions.

The typical cores in Perseus have the mean gas density \( n_n \sim (1-2) \times 10^4 \) cm\(^{-3}\), velocity dispersion \( \sigma_v = 0.17 \) km s\(^{-1}\), kinetic temperature \( T_{\text{kin}} = 11 \) K, radius \( R = 0.09 \) pc, and mass \( M \sim 1 \) \( M_\odot \). The Perseus molecular
cloud covers an area of 6 by 2 degrees ($27 \times 9$ pc) and contains over $10^4 \mathcal{M}_\odot$ of gas and dust that corresponds to the mean gas density of $n_H \sim 4 \times 10^2$ cm$^{-3}$.

The atlas of 193 sources is very conveniently presented on the website (see Ref. [34] for details) where the original spectra are shown along with the best fitting models, model parameters and their uncertainties. These authors found that many cores show evidence for the multiple velocity components along the line-of-sight. The total number of cores where both CCS ($2_1-1_0$) and NH$_3$ (1,1) lines were detected is 98. The central velocities of these lines, being averaged with weights inversely proportional to the variances of the measurements, reveal that CCS lines are systematically offset by 16 m s$^{-1}$. It was suggested in Ref. [34] that this offset is due to uncertainties in the assumed rest frequency of the CCS line. A similar marginally significant offset in the velocities of the C$^{18}$O (1-0) and NH$_3$ (1,1) lines was measured from 18 dark
cores in which the same position was observed in both NH$_3$ (1,1) and C$^{18}$O (1-0) [41].

Figure 6 upper panel, shows linewidths of CCS (2$_1$ – 1$_0$) vs. NH$_3$ (1,1) for a total sample of data points ($n = 98$) from [33]. In this panel, the dashed and dotted lines are the boundaries for, respectively, pure turbulent, $\sigma_v$(CCS) = $\sigma_v$(NH$_3$), and pure thermal, $\sigma_v$(CCS) = 0.55$\sigma_v$(NH$_3$), line broadening. A wide scatter of points reveals the fact that for many cores a complex structure of line profiles hampers the accurate estimate of the linewidth. As a next step, we selected from the database only those profiles which have been perfectly fitted by a single component model. The obtained subsample of $n = 34$ pairs is shown in the lower panel in Fig. 6 with the corresponding fitting parameters listed in Table II which have been taken from the online database. The original ammonia data were re-reduced with additional small Doppler corrections to eliminate IF-to-IF variations (IF stands for Intermediate Frequency – a frequency to which the radio frequency is shifted as an intermediate step before detection in the backend), but there were no significant changes from the values derived from the original data set [33].

Formal calculations of the weighted means for the total sample and subsample give $\Delta V^w_{n=98} = 0.016 \pm 0.013$ km s$^{-1}$ (which is in line with Ref. [34] and $\Delta V^w_{n=34} = 0.040 \pm 0.010$ km s$^{-1}$, respectively. However, to cancel out the Doppler noise component $\Delta V_n$, simple (unweighted) averaging of data is more appropriate (as seen from Fig. 6 the $\Delta V$ values have approximately equal error bars). The corresponding unweighted values are $\Delta V_{n=98} = 0.044 \pm 0.013$ km s$^{-1}$ and $\Delta V_{n=34} = 0.039 \pm 0.010$ km s$^{-1}$.

Now let us select only points with $\sigma_v$(NH$_3$) $>$ $\sigma_v$(CCS) $>$ 0.55$\sigma_v$(NH$_3$), i.e. points for which both emission lines arise most probably co-spatially (Fig. 6 lower panel). This gives $n = 21$ and $\Delta V_{n=21} = 0.050 \pm 0.013$ km s$^{-1}$, and $\Delta V_{n=21} = 0.048 \pm 0.013$ km s$^{-1}$.

The distributions of the selected points are shown in Fig. 7. Here the vertical error bars include both the error of the measurement and the systematic error of $\varepsilon_v = 13.5$ m s$^{-1}$, indicating approximate equidisperision of the individual measurements. It is clearly seen that points with positive offsets dominate. The scatter of the points reflects complexity of gas kinematics and effects of chemical segregation of one molecule with respect to the other in dense molecular cores discussed in Sect. I.

The unweighted mean from the $n = 21$ subsample will be considered as the final estimate of the velocity offset for the Perseus dark cores. Accounting for the systematic error due to uncertainties in the rest frequencies (Table I), we obtain $\Delta V_{n=21} = 0.048 \pm 0.013 \pm 0.0135$ km s$^{-1}$. The robust redescending $M$-estimate for the shift and scale [34] yields $\Delta V_{n=21} = 0.052 \pm 0.007 \pm 0.0135$ km s$^{-1}$ (see our final Table VI).

To understand if there are subclasses among the Perseus cores, we also investigated the measured column densities of NH$_3$ and CCS. We found the mean ratio of $N$(NH$_3$)/$N$(CCS) = 1180 $\pm$ 870. There are only two outlying clouds with $N$(NH$_3$)/$N$(CCS) $\sim$ 5500 and 25000. The plot between the column density ratio versus velocity offset does not show any trend. It seems that the dark cores are rather homogeneous with respect to the column density ratio, and this probably means that there are no strong variations in abundances among the clouds. In other words there is no evidence for the two different populations.
TABLE V: Same as Table IV but for emission lines of HC$_3$N (5 – 4) and NH$_3$ (1,1). Asterisk marks objects with $0.58 \sigma_p$(NH$_3$) $\leq$ $\sigma_v$(HC$_3$N) $\leq$ $\sigma_v$(NH$_3$) (see Fig. 8 lower panel).

| Source       | $V_{LSR}$, km s$^{-1}$ | $\sigma_v$, km s$^{-1}$ | $D$, kpc |
|--------------|------------------------|-------------------------|---------|
| G015.05+00.07 MM1 | 24.4(1) | 3.5(3) | 2.3(1) | 2.5 |
| G015.31–00.16 MM2* | 30.92(8) | 3.7(1) | 2.9(1) | 3.1 |
| G019.27+00.07 MM1 | 26.39(5) | 3.0(1) | 3.0(1) | 2.3 |
| G019.27+00.07 MM2* | 27.02(4) | 3.6(2) | 3.6(2) | 3.7 |
| G022.35+00.41 MM1* | 53.00(7) | 1.6(1) | 4.1(1) | 6.7 |
| G022.35+00.41 MM3* | 84.36(6) | 5.3(7) | 2.45(7) | 5.3 |
| G023.60+00.00 MM1* | 106.70(6) | 3.6(1) | 1.34(7) | 3.1 |
| G023.60+00.00 MM2 | 53.37(4) | 3.4(1) | 2.47(7) | 3.7 |
| G023.60+00.00 MM4* | 53.91(7) | 2.3(2) | 2.20(7) | 3.7 |
| G023.60+00.00 MM7* | 54.08(5) | 2.1(1) | 2.22(7) | 3.7 |
| G024.08+00.04 MM1* | 113.68(8) | 2.8(2) | 2.9(1) | 7.8 |
| G024.08+00.04 MM2(1)* | 52.18(7) | 1.3(1) | 1.3(1) | 3.6 |
| G024.08+00.04 MM3* | 51.67(4) | 1.6(1) | 1.89(7) | 3.6 |
| G024.08+00.04 MM4* | 51.90(2) | 1.0(8) | 1.67(7) | 3.6 |
| G024.33+00.11 MM1 | 113.69(6) | 4.0(1) | 3.4(1) | 7.7 |
| G024.33+00.11 MM2* | 118.11(1) | 3.4(2) | 3.5(1) | 7.7 |
| G024.33+00.11 MM3 | 117.2(2) | 5.1(4) | 2.16(9) | 7.7 |
| G024.33+00.11 MM5 | 117.4(1) | 4.0(3) | 3.06(6) | 7.7 |
| G024.33+00.11 MM9* | 119.4(1) | 1.3(2) | 1.90(8) | 7.7 |
| G024.60+00.08 MM1 | 53.22(5) | 3.5(1) | 2.37(7) | 3.6 |
| G024.60+00.08 MM2 | 115.20(1) | 3.0(2) | 2.2(1) | 7.7 |
| G025.04–00.20 MM1 | 63.67(7) | 3.0(2) | 2.08(6) | 4.2 |
| G025.04–00.20 MM2* | 63.63(7) | 2.4(2) | 2.56(8) | 4.2 |
| G025.04–00.20 MM4* | 63.70(8) | 2.0(2) | 2.03(6) | 4.1 |
| G034.43+00.24 MM1 | 58.04(3) | 3.8(5) | 3.39(6) | 3.5 |
| G034.43+00.24 MM2 | 57.86(3) | 4.2(6) | 3.8(1) | 3.5 |
| G034.43+00.24 MM3 | 60.05(7) | 5.8(2) | 2.56(7) | 3.6 |
| G034.43+00.24 MM4* | 57.50(3) | 3.2(2) | 3.28(9) | 3.5 |
| G034.43+00.24 MM5* | 57.81(8) | 1.8(2) | 2.3(1) | 3.5 |
| G034.43+00.24 MM6* | 58.34(6) | 2.5(1) | 2.59(9) | 3.6 |
| G034.43+00.24 MM8* | 57.7(2) | 4.4(4) | 3.14(9) | 3.5 |
| G034.43+00.24 MM9* | 58.40(5) | 2.4(1) | 2.62(9) | 3.6 |
| I18102–1800 MM1 | 21.53(5) | 4.4(1) | 2.88(8) | 2.7 |
| I18151–1208 MM1* | 33.26(5) | 2.1(1) | 2.37(8) | 2.8 |
| I18151–1208 MM2* | 30.39(1) | 2.3(1) | 2.91(1) | 2.6 |
| I18182–1433 MM1* | 59.86(3) | 2.58(7) | 3.18(9) | 4.6 |
| I18223–1243 MM1* | 45.38(6) | 2.1(1) | 1.87(7) | 3.6 |
| I18223–1243 MM2* | 45.51(1) | 2.1(3) | 2.91(1) | 3.6 |
| I18223–1243 MM3* | 45.65(7) | 2.3(2) | 2.90(9) | 3.7 |
| I18306–0855 MM1 | 78.5(1) | 4.0(2) | 2.57(8) | 4.9 |
| I18337–0743 MM1* | 58.31(4) | 3.51(8) | 3.7(1) | 3.9 |
| I18337–0743 MM2* | 58.13(6) | 2.3(1) | 3.2(2) | 3.9 |
| I18337–0743 MM3* | 55.6(2) | 3.7(4) | 3.2(1) | 3.8 |

B. Dense cores in the Pipe Nebula

The second sample of molecular lines is based on high quality data from Ref. 62 who observed a starless population of 46 molecular cores in the Pipe Nebula ($D \sim 130$ pc). The Pipe Nebula is one of the closest molecular clouds with a mass of $10^4 M_\odot$ covering an area of 48 deg$^2$ on the sky.

The observations were performed with the 100-m Robert C. Byrd Green Bank Telescope (GBT). The NH$_3$ (1,1), (2,2), CCS (2 – 1)$_1$, and HC$_5$N (9-8) transitions were observed simultaneously as in the case of the Perseus cloud (the frequency of the HC$_5$N $J = 9 – 8$ transition is 23.96 GHz, and its upper state excitation temperature $E^\nu(\nu) = 5.8$ K). The GBT beam size of $\sim 30''$ provides the angular resolution of $\sim 0.02$ pc at the Pipe Nebula distance, i.e. the internal structure of dense cores ($R \approx 0.09$ pc) was partly resolved. The velocity resolution was 23 m s$^{-1}$.

There are four sources in the Pipe Nebula sample (Nos. 12, 40, 101, 109 in Table 4 in Ref. 63) where both NH$_3$ (1,1) and HC$_5$N (9,8) lines are observed. The molecule HC$_5$N is 4.4 times heavier than NH$_3$, i.e. its lines should be intrinsically narrower than ammonia lines if molecules trace the same gas. However, each of these sources exhibits HC$_5$N velocity dispersion broader than NH$_3$; in average $\sigma_v$(HC$_5$N) = (1.5 $\pm$ 0.1) $\sigma_v$(NH$_3$). An even worse relationship is seen between HC$_5$N and CCS velocity dispersions: in average $\sigma_v$(HC$_5$N) = (1.8 $\pm$ 0.5) $\sigma_v$(CCS). This could be expected if NH$_3$ and CCS trace not all the gas along the line of sight but only a part associated with the dense compact core. However, not all of the 12 NH$_3$ and CCS emission sources listed in Table III show the expected correlation of the velocity dispersion. Four sources marked by open circles in Fig. 5 upper panel,
are those where two species trace different regions. The distribution of the remaining 8 points is shown in Fig. 3 lower panel. Again, as for the sources from the Perseus molecular cloud, we find a positive offset in the radial velocities. The difference between the CCS and NH$_3$ velocity has the mean of $\Delta V_{n=8} = 0.044$ km s$^{-1}$ and the standard deviation of 0.020 km s$^{-1}$. Adding the error of the rest frequencies, we obtain the final values $\Delta V_{n=8} = 0.044 \pm 0.020 \pm 0.0135$ km s$^{-1}$, and the robust $M$-estimate $\Delta V_{n=8} = 0.069 \pm 0.011 \pm 0.0135$ km s$^{-1}$ (Table VI).

C. Massive clumps associated with Infrared Dark Clouds

The third example deals with more distant objects — cold, dense, and massive clumps ($M > 100 M_\odot$) of 1-10 pc sizes associated with the IRDCs which are located at distances larger than 2 kpc and seen in silhouette against the bright diffuse mid-infrared emission of the Galactic plane. The gas kinetic temperature of IRDCs is as low as the temperature of the dense molecular cores, $T_{\text{kin}} < 20$ K [60]. This means that massive clumps in IRDCs are either starless or in a very early stage of high-mass star formation.

A recent survey of 55 massive clumps in NH$_3$ (1,1), (2,2), (3,3), N$_2$H$^+$ (1-0), and HC$_3$N (5-4) lines has been carried out at the Nobeyama Radio Observatory 45-m telescope [36]. The N$_2$H$^+$ and HC$_3$N (5-4) lines (Table I) were observed simultaneously using two SIS receivers. The third receiver HEMT was used for NH$_3$ lines. The data were obtained within one day for each position, and different receivers used in these observations allow the Doppler tracking to be completely independent between these molecular lines [37].

The angular and velocity resolutions in these observations were different. At the frequencies of the NH$_3$, HC$_3$N, and N$_2$H$^+$ transitions the half-power beam width was $73''$, $37''$, and $18''$, and the velocity resolution was 0.50, 0.25, and 0.12 km s$^{-1}$, respectively. At a distance of $\sim$5 kpc the spatial structures of $\sim 1.8$, 0.9, and 0.4 pc can be resolved in, correspondingly, NH$_3$, HC$_3$N, and N$_2$H$^+$ lines. The inhomogeneity of the observational parameters and significant turbulence in IRDC cores ($\sigma_{\text{turb}} \sim 1 - 3$ km s$^{-1}$) increase the dispersion of the Doppler noise in massive clumps as compared with low-mass molecular cores.

Table I lists 54 sources from [36] where both N$_2$H$^+$ (1-0) and NH$_3$ (1,1) lines were detected. These molecules are expected to have similar spatial distributions. However, Fig. 4 upper panel, shows that some of the N$_2$H$^+$ lines have either too large or too small velocity dispersion as compared to NH$_3$, which may be related to a large angular resolution difference (18'' vs. 73'') in observations of these molecules. Such points were excluded from the sample, the remaining $n = 36$ points are presented in Fig. 4 lower panel. The velocity offset distributions from the total sample and the subsample are shown in Fig. 5 upper and lower panels, respectively. The weighted and unweighted means are as follows: $\Delta V_{n=36}^w = 0.124 \pm 0.043$ km s$^{-1}$, and $\Delta V_{n=36} = 0.122 \pm 0.049$ km s$^{-1}$. In this case the laboratory error is equal to $\varepsilon_v = 13.6$ m s$^{-1}$. For the final estimate we take the more appropriate unweighted mean $\Delta V_{n=36} = 0.122 \pm 0.049 \pm 0.0136$ km s$^{-1}$, and the robust $M$-estimate $\Delta V_{n=36} = 0.160 \pm 0.032 \pm 0.0136$ km s$^{-1}$ (Table VI).
The correlation between velocity dispersions of the HC₃N (5-4) and NH₃ (1,1) emission lines is shown in Fig. 6. In this case the results were obtained with more comparable angular resolutions (37″ vs. 73″). The total sample of the HC₃N/NH₃ pairs (n = 43) is given in Table VI. Several of the measured HC₃N linewidths demonstrate significant supersonic turbulence of the emitting gas with σᵥ(HC₃N) > σᵥ(NH₃). Such lines were omitted from the following analysis, the remaining n = 27 points are shown in Fig. 6 lower panel (the selected points are marked by asterisks in Table VI first column). Fig. 7 illustrates the distribution of the measured offsets. The calculated statistics are as follows: ∆Vₙ=27 = 0.147 ± 0.039 km s⁻¹, and ∆Vₙ=27 = 0.105 ± 0.045 km s⁻¹. Again, taking the unweighted estimate and accounting for the systematic error of εᵥ = 3.1 m s⁻¹ we come to the final mean value of the velocity offset ∆Vₙ=27 = 0.105 ± 0.045 ± 0.0031 km s⁻¹, and the robust M-estimate ∆Vₙ=27 = 0.120 ± 0.037 ± 0.0031 km s⁻¹ (Table VI).

The data from Ref. 58 allow us to answer the question whether the revealed positive velocity offsets are related to ammonia lines or not. Following the same procedure as above, we can compare the velocities obtained from the sources which were observed in both N₂H⁺ and HC₃N. The total sample of n = 41 pairs is shown in Fig. 8 upper panel. The heavier molecule HC₃N should have linewidths smaller or equal to that of N₂H⁺. However, a considerable number of points (~50%) lie above the dashed line constraining pure turbulent line broadening. This is expected since N₂H⁺ molecule traces more compact central regions of the dense clouds. The n = 22 points which presumably trace the same gas are shown in Fig. 8 lower panel. The corresponding velocity offset distributions are shown in Fig. 9. The mean values are ∆V_wₙ=22 = −0.053 ± 0.044 km s⁻¹, and ∆V_n=22 = −0.033 ± 0.055 km s⁻¹, and thus the final estimates are ∆Vₙ=22 = −0.033 ± 0.055 ± 0.0138 km s⁻¹, and the robust M-value ∆V_n=22 = −0.017 ± 0.034 ± 0.0138 km s⁻¹ (Table VI).

In this case both weighted and unweighted values are consistent with zero velocity offset. Since N₂H⁺ and NH₃ share similar physical conditions in their formation and destruction processes and, hence, trace each other in spatial distributions, the obtained result indicates that ammonia is a key element responsible for the revealed velocity offset.

To demonstrate that the positive velocity offset does not result from our selection criterion we summarize all measurements complemented by robust rescaling M-estimates for the shift and scale in Table VI. Both results are in good agreement within the 1σ uncertainty interval. The sample mean values reproduce a marginally significant signal (≥3σ) independently on the sample size. When ammonia lines are excluded from the analysis, the signal disappears.

IV. DISCUSSION

In the previous section we showed that different molecular clouds demonstrate statistically significant velocity offset between the ammonia inversion transition (J, K) = (1, 1) and rotational transitions of other molecules. Here we consider possible reasons of this offset.

A. Uncertainties of the rest frequencies

In cold dark clouds with the kinetic temperature T_{kin} ≈ 10K the thermal line broadening is very small (v_{th} ≈ 50 m s⁻¹ for, e.g., CCS). This means that the detailed study of velocity offsets requires accuracy of rest frequencies of about 1 m s⁻¹. Among molecules used in the present work only NH₃ fulfills this requirement. The hyperfine

| Object | Molecular pair | Sample size, n | ∆Vₙ, km s⁻¹ | σᵥ(ₙ), km s⁻¹ | ∆Vₙ,M, km s⁻¹ | σᵥ,M, km s⁻¹ | εᵥ,∆V, ∆V^corr, km s⁻¹ |
|--------|----------------|---------------|-------------|---------------|---------------|---------------|---------------------|
| Perseus | NH₃/CCS        | 98            | 0.044 ± 0.13 | 0.129         | 0.040 ± 0.007 | 0.073         | 0.0135 ± 0.024       |
|        |                | 34            | 0.039 ± 0.010 | 0.058         | 0.045 ± 0.007 | 0.043         | 0.0135 ± 0.029       |
|        |                | 21            | 0.048 ± 0.013 | 0.060         | 0.052 ± 0.007 | 0.032         | 0.0135 ± 0.036       |
| Pipe   | NH₃/CCS        | 12            | 0.087 ± 0.039 | 0.135         | 0.039 ± 0.023 | 0.081         | 0.0135 ± 0.023       |
|        |                | 8             | 0.044 ± 0.020 | 0.057         | 0.069 ± 0.011 | 0.030         | 0.0135 ± 0.053       |
| IRDCs  | NH₃/N₂H⁺       | 54            | 0.157 ± 0.040 | 0.294         | 0.160 ± 0.030 | 0.220         | 0.0136 ± 0.148       |
|        |                | 36            | 0.122 ± 0.049 | 0.294         | 0.160 ± 0.032 | 0.190         | 0.0136 ± 0.148       |
|        | NH₃/HC₃N       | 43            | 0.138 ± 0.043 | 0.282         | 0.110 ± 0.032 | 0.210         | 0.0031 ± 0.105       |
|        |                | 27            | 0.105 ± 0.045 | 0.234         | 0.120 ± 0.037 | 0.190         | 0.0031 ± 0.115       |
|        | N₂H⁺/HC₃N      | 41            | −0.056 ± 0.047 | 0.301         | −0.020 ± 0.037 | 0.240         | 0.0138 ± 0.013       |
|        |                | 22            | −0.033 ± 0.055 | 0.258         | −0.017 ± 0.034 | 0.160         | 0.0138 ± 0.010       |
structure of the observed $(J, K) = (1, 1)$ transition of NH$_3$ is known with the accuracy of $\pm 0.6$ m s$^{-1}$ \cite{69}. The available laboratory uncertainties for other molecules are significantly larger. Besides, there are shifts between rest frequencies reported in different publications. Below we estimate such systematics and their effect on the mean values of the velocity offsets obtained in Sect. [III]

The frequency 22.344033 GHz of the CCS $J_N = 2_1 - 1_0$ transition (Table I) used in Refs. \cite{34, 65} was calculated from a comparison with the three strongest hyperfine components of the HC$_3$N $J = 5 - 4$ transition observed towards a cold dark cloud L1498 assuming that the spatial distribution of CCS is the same as that of HC$_3$N \cite{55}. According to Ref. \cite{55}, the $v_{LSR}$ value obtained from the HC$_3$N transition was used to determine the frequencies of the CCS transitions without any corrections, and the frequencies of the CCS transitions were calculated from Gaussian fitting of the observed profiles. The error of 1 kHz indicated in Table I corresponds to one estimated if we consider the center of gravity for the weighted central hyperfine components of the $J = 5 - 4$ transition listed in Table VII. The frequency of the center of gravity is $v_{c, g} = 45490.3058$ MHz and thus $\Delta v_{c, g} = 29$ m s$^{-1}$. However, as seen from Table VII (Col. 9), the JPL frequencies are systematically shifted with respect to Ref. \cite{65} data and the mean value of the shift is $\Delta v_{\text{shift}} = -23.6$ m s$^{-1}$ (Col. 11). Combining both shifts, we obtain a correction of 5.4 m s$^{-1}$. This means that the velocity offset between HC$_3$N and NH$_3$ listed in Table VII should be as follows: $\Delta v_{\text{corr}}^{n=27} = 0.115 \pm 0.037 \pm 0.0031$ km s$^{-1}$ (Table VII Col. 9).

The rest frequencies for the second molecule N$_2$H$^+$ observed towards the IRDCs Ref. \cite{36} were taken from Ref. \cite{42}. The hyperfine frequencies of the N$_2$H$^+$ $J = 1 - 0$ transition were estimated from observations of a molecular cloud L1512 in Taurus in both N$_2$H$^+$ (93 GHz) and C$_2$H$_2$ (85 GHz) lines assuming that the C$_2$H$_2$ and the N$_2$H$^+$ have exactly the same radial velocity. The absolute frequencies of the N$_2$H$^+$ hyperfine transitions measured in Ref. \cite{42} are known with precision of $\sim 7$ kHz. However, a factor of two more accurate data are given in the Cologne Database for Molecular Spectroscopy (CDMS) described in Refs. \cite{70, 71}. Both datasets are compared in Table VIII. The error of 4 kHz ($\varepsilon_v \approx 13.5$ m s$^{-1}$) reported in Table II corresponds to the CDMS. The mean shift between the data from Ref. \cite{42} and the CDMS frequencies is $\Delta v_{\text{shift}} = 12$ m s$^{-1}$. Thus, the velocity offset between N$_2$H$^+$ and NH$_3$ from Table VII should be corrected to $\Delta v_{\text{corr}}^{n=36} = \Delta v_{n=36} - 0.012 = 0.148 \pm 0.032 \pm 0.0136$ km s$^{-1}$, and between HC$_3$N and N$_2$H$^+$ to $\Delta v_{\text{corr}}^{n=22} = \Delta v_{n=22} + 0.0066 = -0.010 \pm 0.034 \pm 0.0138$ km s$^{-1}$ (Table VII Col. 9).
TABLE VIII: Hyperfine components of the N$_2$H$^+$ $J = 1 - 0$ transition. For Caselli (Ref. [42]) frequencies only the numbers after the decimal point are shown, the integer part is as in the Møller data (Ref. [71]). Col. 10 lists velocity offsets between Caselli and Møller (C–M) values.

| $J'$ | $F'_1$ | $F'_J$ | $J$ | $F_1$ | $F$ | Weight | Rest Frequency (MHz)$^\dagger$ | Δv (m s$^{-1}$) |
|------|--------|--------|-----|-------|-----|--------|-------------------------------|--------------|
| (1)  | (2)    | (3)    | (4) | (5)   | (6) | (7)    | Möller                        | (8)          |
|      |        |        |     |       |     |        | Caselli                       |              |
| 1    | 1      | 0      | 0   | 1     | 1   | 0.143  | 93171.6171(41)                | .6210(70)    |
| 1    | 1      | 2      | 0   | 1     | 2   | 0.604  | 93171.9129(42)                | .9168(70)    |
| 1    | 1      | 1      | 0   | 1     | 1   | 0.111  | 93171.9129(42)                |             |
| 1    | 1      | 1      | 0   | 1     | 2   | 0.218  | 93172.0499(42)                | .6533(70)    |
| 1    | 1      | 1      | 0   | 1     | 1   | 0.159  | 93172.0499(42)                |             |
| 1    | 1      | 1      | 0   | 1     | 1   | 0.051  | 93172.0499(42)                |             |
| 1    | 2      | 2      | 0   | 1     | 1   | 0.604  | 93173.4748(42)                | .4796(70)    |
| 1    | 2      | 2      | 0   | 1     | 2   | 0.111  | 93173.4748(42)                |             |
| 1    | 2      | 2      | 0   | 1     | 2   | 1.000  | 93173.7722(41)                | .7767(70)    |
| 1    | 2      | 2      | 0   | 1     | 2   | 1.000  | 93173.7722(41)                |             |
| 1    | 2      | 2      | 0   | 1     | 2   | 0.278  | 93173.9657(43)                | .9666(70)    |
| 1    | 2      | 2      | 0   | 1     | 2   | 0.278  | 93173.9657(43)                | .9666(70)    |
| 1    | 2      | 2      | 0   | 1     | 2   | 0.278  | 93173.9657(43)                | .9666(70)    |
| 1    | 2      | 2      | 0   | 1     | 2   | 0.278  | 93173.9657(43)                | .9666(70)    |
| 1    | 2      | 2      | 0   | 1     | 2   | 0.278  | 93173.9657(43)                | .9666(70)    |
| 1    | 0      | 1      | 0   | 1     | 1   | 0.117  | 93176.2611(43)                | .2650(70)    |
| 1    | 0      | 1      | 0   | 1     | 1   | 0.117  | 93176.2611(43)                | .2650(70)    |
| 1    | 0      | 1      | 0   | 1     | 1   | 0.117  | 93176.2611(43)                | .2650(70)    |
| 1    | 0      | 1      | 0   | 1     | 1   | 0.117  | 93176.2611(43)                | .2650(70)    |

B. Systematics due to Kinematic Shifts

Spectroscopic measurement of the absolute radial velocities at the level of 50 – 100 m s$^{-1}$ is subject to many physical effects [72]. Fortunately, relative radial velocities are less sensitive to most of them. However, some small systematic shifts, in addition to those discussed in Sect. II, may be present in the measured values of $\Delta V$.

First of all, the measurement of the relative radial velocities between two molecules requires the use of a common reference frame. In radio-astronomical observations it is usually the Local Standard of Rest (LSR). The transformation of the apparent Doppler velocity to $V_{\text{LSR}}$ introduces an error of $\sim 1 – 3$ m s$^{-1}$, stemming from the following corrections: the observer’s motion due to (1) the Sun’s motion with respect to the LSR, (2) revolution of the Earth-Moon barycenter round the Sun, (3) motion of the Earth center round the Earth-Moon barycenter, and (4) rotation of the Earth [72]. This error ought to be added to the total error budget along with the systematic errors listed in Table VIII 8th column if molecular lines were not observed simultaneously.

The second error arises from gravitational shifts of the spectral lines due to the annual variation of the observer’s distance from the Sun because of the eccentricity ($e \approx 0.01671$) of the Earth’s orbit ($A = 1$ AU). This produces the peak-to-peak variation of the radial velocity (in units of the speed of light, $c$) of

$$\delta V_g = \frac{2eGM_\odot}{Ac^2}.$$  \hspace{1cm} (4)

The numerical value of $\delta V_g$ is about 10 cm s$^{-1}$, and in our case this error can be neglected.

If we further define the dimensionless gravitational potential of the Sun on the Earth’s orbit as (positive sign is omitted)

$$\Phi_0 = GM_\odot/(Ac^2) + GM_\odot/(R_\odot c^2) \simeq 1.06 \times 10^{-8},$$ \hspace{1cm} (5)

then the gravitational redshift for photons escaping an object of mass $M$ and radius $R$ scales as

$$\delta V_g = \left(\frac{M}{M_\odot}\right)\left(\frac{A}{R}\right)\Phi_0.$$ \hspace{1cm} (6)

Different gravitational redshifts between molecular lines may occur from the chemical stratification in dense molecular cores. However, this effect is negligible because of a relatively low gas density and rather large linear sizes of the clouds. For a typical starless core shown in Fig. 3 in Ref. [38], the gravitational velocity shifts of NH$_3$ and CCS lines are $\sim 0.2$ cm s$^{-1}$ and $\sim 0.1$ cm s$^{-1}$, respectively.

Systematically redshifted CCS $2_1 - 1_0$ lines with respect to the NH$_3$ (1,1) central velocity may occur in contracting clouds when the near side of the external shell of the cloud with the CCS emission is moving towards the higher density core as suggested for, e.g, the L1551 dark cloud [34]. However, as discussed in Sect. III in dark clouds both kinds of kinematic shifts (redward and blueward) are observed. Such bulk motions should randomize the Doppler shifts and provide a zero offset for a large size sample of dark clouds. Besides, all molecular cores in the Perseus molecular cloud are probably optically thin in the CCS $2_1 - 1_0$ emission since CC$^{34}$S was not detected along any of the lines-of-sight [31] and $^{32}$S : $^{34}$S = 22 : 1. This means that the CCS emission line profile is formed in the whole volume of the cloud including both its near and distant sides. This is not the case, however, for the NH$_3$ emission. The total opacity in the (1,1) line transition varies between 0.84 and 10.9 for the cores listed in Table III. The optically thick clouds may cause some systematics of both signs (positive or...
negative depending on the character of the internal bulk motions within the core) in the central positions of the NH$_3$ lines. However, three cores with $\tau_{(1,1)} \lesssim 1$ (Nos. 20, 112, and 151) demonstrate positive velocity offsets with the mean value of $\sim 100$ m s$^{-1}$.

Among analyzed clouds the most accurate measurements of $\Delta V$ belong to the Perseus cores. We may use the $M$-estimate from the $n = 21$ sample (Sect. [11]) as a tentative value for the found velocity offset, $\Delta V = 36 \pm 7_{\text{stat}} \pm 13.5_{\text{sys}}$ m s$^{-1}$, or $\Delta V = 36 \pm 15$ m s$^{-1}$ (1$\sigma$ C.L.). Thus, the considered systematics do not explain the revealed offset. Assuming that this offset is caused entirely by the change of $\mu$, one obtains from Eq. (6) $\Delta\mu/\mu = (3.5 \pm 1.4) \times 10^{-8}$, or $|\Delta\mu/\mu| < 5 \times 10^{-8}$. This is the most accurate estimate of $\Delta\mu/\mu$ based on the spectral analysis of astronomical objects. Next we consider whether this value is in line with other constraints.

**C. Gravitational-potential dependence of $\mu$**

First we explore the dependence of the electron and proton masses on the strength of the gravitational potential. Theoretical models dealing with variations of physical constants do not require the cosmological temporal evolution of $\alpha$ and/or $\mu$ to be dominated over their local spatial changes in the Milky Way. For instance, theories like that of Ref. [74] consider direct coupling between the local matter density and the scalar fields that drive varying constants. The spatial change of the constants in these models is proportional to the local gravitational potential and the rate of spatial variation may exceed the rate of time variation (see, e.g., Ref. [57] and references cited therein). The effect of scalar fields on $\mu$ is additive (similar to gravity) and can be expressed as (Refs. [72, 70]):

$$\frac{\Delta\mu}{\mu} = k_\mu \Delta \Phi,$$

where $k_\mu$ is a dimensionless coupling constant of a massless (very light) scalar field to the local gravitational potential $\Phi$, and $\Delta \Phi$ is the difference of the gravitational potentials between two measurement points.

This class of models suggests that the coupling of the scalar field $\varphi$ to baryonic matter and fields is not too strong since otherwise it would produce a scalar-mediated ‘fifth force’ that is not observed [26]. It is also assumed that the $\varphi$-mediated force is a long-range one.

The respective contribution from the Galactic gravitational potential $\Phi_G(r, \zeta)$ and the molecular cloud gravitational potential $\Phi_{\text{cloud}}$ to the local gravitational potential is the sum

$$\Phi(r, \zeta) = \Phi_G(r, \zeta) + \Phi_{\text{cloud}},$$

where $r$ and $\zeta$ denote two of the cylindrical coordinates.

The gravitational potential of IRDCs ($M \sim 100M_\odot$, $R \sim 1$ pc) and starless cores ($M \sim 10M_\odot$, $R \sim 0.1$ pc) is much smaller than that of the Sun on the Earth’s orbit, $\Phi_0$, namely, $\Phi_{\text{cloud}} \sim 1/2000 \Phi_0$. The value of $\Phi_G(r, \zeta)$ can be calculated from analytic models of the Milky Way [77, 78, 79] which describe fairly well the galactic rotation curves. The galactic coordinates of the analyzed clouds are shown in Fig. 10. The distance of the Sun from the center of the Milky Way is $r_0 = 7.94 \pm 0.42$ kpc [80]. The Perseus molecular cloud is located towards the galactic anti-center, whereas the Pipe Nebula and the IRDCs in the direction of the galactic center. Between 3 and 8 kpc the galactic potential is about $2 \times 10^{-6}$, and $\Phi_G$ changes within this interval very slowly: $\Delta \Phi_G \sim 10^{-7}$.

With $\Delta\mu/\mu = 3.5 \times 10^{-8}$, one obtains $k_\mu \sim 1$, which is in sharp contradiction with estimates based on atomic clock experiments: $k_\mu = (-1.1 \pm 1.7) \times 10^{-5}$ [22]. There are two possible explanations for such a large discrepancy:

1. The measured velocity offset is mainly due to kinematic shifts. Then, taking the atomic clock limit $|k_\mu| < 3 \times 10^{-5}$ and the change of the galactic gravitational potential $\Delta \Phi \sim 10^{-7}$, one obtains from Eq. (7) an upper limit on $|\Delta\mu/\mu| \lesssim 10^{-12}$. Unfortunately, the level of $10^{-12}$ is below the precision of modern astronomical observations of molecular lines.

2. The electron-to-proton mass ratio does not linearly correlate with metric variations, i.e., $k_\mu \equiv 0$ in Eq. (7). The nonzero velocity offset is then caused by the change of the electron and proton masses. The corresponding theoretical background for this item is discussed below.
D. Dependence of $\mu$ on matter density

A class of models where baryon masses and coupling constants are strongly dependent on the local matter density, $\rho$, and where spatial variations of $\mu(\rho)$ and $\alpha(\rho)$ can be more pronounced than the temporal cosmological variations was considered in a number of publications discussed in Ref. [30]. In this approach it is suggested that the coupling of a scalar field to matter is much stronger than gravitational, but the fifth force problem does not arise since the linear coupling of the scalar field to matter is effectively suppressed by the matter density itself. The dynamics of the scalar field in these models depends on $\rho$: in low-density environments it is determined by the scalar field potential $V(\varphi)$, whereas in high-density regions (like the Earth’s surface) it is set by the matter-$\varphi$ coupling. The range of the scalar-mediated force for the terrestrial matter densities is then very short, less than 1 mm [30].

Because of the strong $\varphi$-coupling to matter the measurements of the frequency drifts in the atomic clock experiments ought to be insensitive to the changes in the gravitational potential at Earth caused by the eccentricity of Earth’s orbit. The minimum of $V(\varphi)$ would show no shifts and $\Delta\alpha/\alpha$ ($\Delta\mu/\mu$) would be zero with good accuracy. However, comparison of atomic clocks at high altitude satellite orbits with laboratory clocks may yield useful constraints on model parameters as discussed in Ref. [30] who also suggested to test spatial variations of the physical constants through atomic and molecular line observations of the interstellar clouds in our galaxy. In this case the difference of matter densities between the terrestrial environment ($\rho_{\oplus} \approx 3 \times 10^{21}$ GeV cm$^{-3}$) and, e.g., dense molecular cores ($\rho_{\text{cloud}} \approx 3 \times 10^5$ GeV cm$^{-3}$) may cause a shift in the expectation value of the scalar field $\varphi_m$, leading to a change in masses and coupling constants.

If we interpret the nonzero offset of $\Delta V \approx 40$ m s$^{-1}$ in terms of the change of fermion masses, then for low density environments, such as the interstellar clouds, the change in the electron-to-proton mass ratio is given by [30]:

$$\frac{\Delta \mu}{\mu} \simeq (\xi_e - \xi_p) \frac{\varphi_m^2}{2}. \quad (9)$$

In this model the scalar field is coupled to the standard model fermions through the dimensionless constants $\xi_e$ and $\xi_p$, with $\xi_p$ being normalized to one.

The factor $(\xi_e - 1)$ can be much larger than unity in accord with astrophysical constraints discussed in Ref. [30]. If we assume that $(\xi_e - 1)/2 \gtrsim 1$, then $\varphi_m^2 \lesssim 3.5 \times 10^{-8}$, or $\varphi_m \lesssim 2 \times 10^{-4}$.

Thus, considered observations of the interstellar molecular clouds being interpreted in terms of the $\Delta \mu/\mu$ variation are in agreement with models which treat the $\varphi$-mediated force as a short-range force depending on the matter density. In accord with model predictions, the estimated value of the scalar field is much less than one. The measured spatial variation of $\Delta \mu/\mu$ does not contradict the laboratory studies on atomic clocks (see Sect. IV.C) since extremely different density environment in the terrestrial measurements and in the interstellar medium prohibits direct comparison of the obtained results.

There are several extragalactic measurements of $\Delta \mu/\mu$ in which gas densities similar to those in the Milky Way clouds are observed. These results, being interpreted in terms of the spatial variations of $\Delta \mu/\mu$, can be compared with our estimate of $\Delta \mu/\mu = (3.3 \pm 1.4) \times 10^{-8}$: it is consistent with the limit on $|\Delta \mu/\mu| < 3 \times 10^{-7}$ derived from the NH$_3$-bearing clouds at $z = 0.68$ \cite{19}, but in conflict with the value $\Delta \mu/\mu = (24 \pm 6) \times 10^{-7}$ obtained from molecular hydrogen H$_2$ absorption lines at $z \sim 3$ \cite{16}. However, the same H$_2$-bearing clouds at $z \sim 3$ as analyzed in Ref. \cite{16} were studied in Ref. \cite{17}. The variability of $\mu$ was not confirmed at the level of $|\Delta \mu/\mu| \leq 4.9 \times 10^{-5}$. Recently a more stringent limit on $\Delta \mu/\mu$ was found at $z \sim 3$ in Ref. \cite{18}: $\Delta \mu/\mu = (2.6 \pm 3.0) \times 10^{-7}$. Since at densities as low as observed in the interstellar medium the dependence of $\mu$ on $\rho$ is extremely weak, the value of $\Delta \mu/\mu$ in quasar absorbers is expected to be at the same level as in the interstellar clouds, i.e. $\sim 10^{-8} - 10^{-7}$. This level of accuracy can be probed with the next generation of high resolution spectrographs such as ESPRESSO planned for the Very Large Telescope \cite{81}.

E. Temporal vs spatial variability of $\mu$

Our measurements of $\Delta \mu/\mu$ being formally divided by the distance to the sources in light years imply a time variation of $\Delta \mu/\mu$ of about $10^{-11} - 10^{-10}$ yr$^{-1}$. This variation rate is orders of magnitude larger than the laboratory bound quoted in Sect. III $|\mu/\mu| < 10^{-13}$ yr$^{-1}$, and than the extragalactic bounds based on the upper limit on $\Delta \mu/\mu$ at $z \sim 3$, $|\mu/\mu| < 6 \times 10^{-10}$ yr$^{-1}$ \cite{18}, and at $z = 0.68$, $|\mu/\mu| < 4 \times 10^{-16}$ yr$^{-1}$ \cite{19}. Such glaring discrepancy may serve as another argument in favor of chameleon-type models: due to principal dependence of couplings and masses on matter density the laboratory bounds and astronomical measurements cannot be directly compared. Taken at face values, we may suggest that the rate of the spatial variations of $\mu$ exceeds significantly the rate of temporal variations.

V. CONCLUSIONS

In this paper we propose to use the ammonia inversion transitions in conjunction with low-lying rotational transitions of other molecules to probe the spatial changes of the electron-to-proton mass ratio $\mu$ from observations of molecular clouds located in the disk of the Milky Way at different galactocentric distances.

The reported estimates of $\Delta \mu/\mu$ are obtained for the Perseus molecular cores \cite{34}, the Pipe Nebula \cite{65}, and
the infrared dark clouds. We found evidence for the spatial variability of \( \mu \) at the level of \( \Delta \mu / \mu \sim (4 - 14) \times 10^{-8} \) which is the most accurate astrophysical value to date. The statistical reliability of this result seems to be high enough but some instrument systematics could be possible. The revealed positive velocity offset between the NH\(_3\) inversion transition and rotational transitions of other molecules should be confirmed by independent observations at different radio telescopes.

The result obtained can be compared with other tests of spatial variations of physical constants in the solar system which are based on atomic clock laboratory measurements. Thus, if \( \Delta \mu / \mu \) follows the gradient of the local gravitational potential, as suggested in some scalar field models, then our estimate of \( \Delta \mu / \mu \) contradicts significantly (\( \sim 5 \) orders of magnitude) the atomic clock constraints obtained at different points in the gravitational potential of the Sun on the Earth’s orbit. However, the measured signal of \( \Delta \mu / \mu \sim (4 - 14) \times 10^{-8} \) is in agreement with chameleon-type scalar field models which predict a strong dependence of masses and coupling constants on the ambient matter density.

To be completely confident that the derived velocity shift is not due to kinematic effects in the clouds but is the appearance of the spatial variation of \( \Delta \mu / \mu \), new high precision radio-astronomical observations are needed for a wider range of objects. Such observations should include essentially optically thin lines of molecules co-spatially distributed with ammonia in order to reduce the Doppler noise. It is also desirable to increase the accuracy of the rest frequencies of the CCS (\( 2_1 - 1_0 \)) and N\(_2\)H\(^+\) (1 - 0) transitions since their present uncertainties translate into the radial velocity error of \( \sim 13 \) m s\(^{-1}\) whereas the error of the velocity shift between, for instance, CCS and NH\(_3\) in the Perseus cloud can be as small as 5 m s\(^{-1}\) (Table VII).

In addition, the search for spatial variations of the fine-structure constant \( \alpha \) in the Milky Way using mid- and far-infrared fine-structure transitions in atoms and ions, or the search for spatial variations of the combination of \( \alpha^2 / \mu \) using the [CII] \( \lambda 158 \) \( \mu \) line and CO rotational lines would be of great importance for cross-checking the results.

Acknowledgments

The authors are grateful to Eric Rosolowsky, Takeshi Sakai, and Jill Rathborne who sent us additional comments on their observations and data reduction. We thank Paola Caselli, Irina Agafonova, Keith Olive, and Thomas Dent for useful comments and discussions on the topic, and Alexander Lapinov for computed frequencies of the HC\(_3\)N \( J = 5 - 4 \) hyperfine transitions on which Table VII and Sect. IV A are based. This work is supported by the RFBR grants 06-02-16489, 07-02-00210, 08-02-00460, and by the Program ‘Leading Scientific Schools of RF’ (grant NSh-2600.2008.2).

[1] A. G. Riess, A. V. Filippenko, P. Challis, et al., Astron. J. 116, 1009 (1998).
[2] A. G. Riess, R. P. Kirshner, B. P. Schmidt, et al., Astron. J. 117, 707 (1999).
[3] S. Perlmutter, G. Aldering, G. Goldhate, et al., Astrophys. J. 517, 565 (1999).
[4] E. J. Copeland, M. Sami, and S. Tsujikawa, Int. J. Mod. Phys. D 15, 1753 (2006).
[5] R. R. Caldwell, R. Dave, and J. P. Steinhardt, Phys. Rev. Lett. 80, 1582 (1998).
[6] P. J. E. Peebles, and B. Rata, Rev. Mod. Phys. 75, 559 (2003).
[7] A. Balbi, C. Baccigalupi, F. Perrotta, and N. Vittorio, Astrophys. J. 547, L89 (2001).
[8] V. V. Flambaum, and M. G. Kozlov, arXiv: physics.atom-ph/0711.4536 (2007).
[9] T. Rosenband, D. B. Hume, P. O. Schmidt, et al., Sciencepress Report, 6 March, p. 1 (2008).
[10] M. T. Murphy, J. K. Webb, and V. V. Flambaum, Mon. Not. R. Astron. Soc. 384, 1053 (2008).
[11] R. Srianand, H. Chaud, P. Petitjean, and B. Aracil, Phys. Rev. Lett. 100, 029902 (2008).
[12] P. Molaro, S. A. Levshakov, S. Monai, et al., Astron. Astrophys. 481, 559 (2008).
[13] D. F. Mota, and J. D. Barrow, Mon. Not. R. Astron. Soc. 349, 291 (2004).
[14] D. F. Mota, and J. D. Barrow, Phys. Lett. B 581, 141 (2004).
[15] A. Shelkovnikov, R. J. Butcher, C. Chardonnet, and A. Amy-Klein, Phys. Rev. Lett. 100, 150801 (2008).
[16] E. Reinhold, R. Buning, U. Hollenstein, et al., Phys. Rev. Lett. 96, 151101 (2006).
[17] M. Wendt, and D. Reimers, arXiv: astro-ph/0802.1160 (2008).
[18] J. A. King, J. K. Webb, M. T. Murphy, and R. F. Carsswell, arXiv: astro-ph/0807.4366 (2008).
[19] V. V. Flambaum, and M. G. Kozlov, Phys. Rev. Lett. 98, 240801 (2007).
[20] J. D. Barrow, Phys. Rev. D 71, 083520 (2005).
[21] J. D. Barrow, and J. Magueijo, Phys. Rev. D 72, 043521 (2005).
[22] S. Blatt, A. D. Ludlow, G. K. Campbell, et al., Phys. Rev. Lett. 100, 140801 (2008).
[23] J. F. Ferrell, A. Cingöz, A. Lapierre, and N. Vittorio, Phys. Rev. A 76, 062104 (2007).
[24] J. Khoury, and A. Weltman, Phys. Rev. Lett. 93, 171104 (2004).
[25] J. Khoury, and A. Weltman, Phys. Rev. D 69, 044026 (2004).
[26] S. S. Gubser, and J. Khoury, Phys. Rev. D 70, 104001 (2004).
[27] P. Brax, C. van de Bruck, A. C. Davis, J. Khoury, and A. Weltman, Phys. Rev. D 70, 123518 (2004).
[28] B. Feldman, and A. E. Nelson, J. High Energy Phys. 08,
002 (2006).

[29] A. Upadhye, S. S. Gubser, and J. Khoury, Phys. Rev. D 74, 104024 (2006).

[30] K. A. Olive, and M. Pospelov, Phys. Rev. D 77, 043524 (2008).

[31] A. S. Chou, W. Wester, A. Baumbaugh, et al., arXiv: hep-ex/0806.2438 (2008).

[32] J. van Veldhoven, J. Küpper, H. L. Bethlem, et al., Eur. Phys. J. D 31, 337 (2004).

[33] D. R. Flower, G. Pineau des Forêts, and C. M. Walmsley, Astron. Astrophys. 456, 215 (2006).

[34] E. W. Rosolowsky, J. E. Pineda, J. B. Foster, et al., Astrophys. J. Sup. 175, 509 (2008).

[35] E. W. Rosolowsky (private communication).

[36] T. Sakai, N. Sakai, K. Kamegai, et al., Astrophys. J. 678, 1049 (2008).

[37] T. Sakai (private communication).

[38] J. Di Francesco, N. J., II Evans, P. Caselli, et al., in Protostars and Planets. V., edited by B. Reipurth, D. Jewitt, and K. Keil (Uni. Arizona Press, Tucson, 2007), p. 17 (arXiv: astro-ph/0602379)

[39] E. Keto, and P. Caselli, arxiv: astro-ph/0804.0822 (2008).

[40] P. T. P. Ho, and C. H. Townes, Ann. Rev. Astron. Astrophys. 21, 239 (1983).

[41] P. J. Benson, and P. C. Myers, Astrophys. J. Sup. 71, 89 (1989).

[42] P. Caselli, P. S. Meyers, and P. Thaddeus, Astrophys. J. 455, L77 (1995).

[43] B. E. Turner, Astrophys. J. 449, 635 (1995).

[44] M. Tafalla, P. S. Meyers, P. Caselli, and C. M. Walmsley, Astron. Astrophys. 416, 191 (2004).

[45] P. Caselli, P. J. Benson, P. S. Meyers, and M. Tafalla, Astrophys. J. 572, 238 (2002).

[46] S. Saito, K. Kawaguchi, S. Yamamoto, et al., Astrophys. J. 317, L115 (1987).

[47] H. Suzuki, S. Yamamoto, M. Ohishi, et al., Astrophys. J. 392, 551 (1992).

[48] Y. Hirahara, H. Suzuki, S. Yamamoto, et al., Astrophys. J. 394, 539 (1992).

[49] T. B. H. Kuiper, W. H. Langer, and T. Velusamy, Astrophys. J. 468, 761 (1996).

[50] S.-T. Lai, T. Velusamy, W. H. Langer, and T. B. H Kuiper, Astron. J. 126, 311 (2003).

[51] I. de Gregorio-Monsalvo, C. J. Chandler, J. F. Gómez, et al., Astrophys. J. 628, 789 (2005).

[52] I. de Gregorio-Monsalvo, J. F. Gómez, O. Suárez, et al., Astrophys. J. 642, 319 (2006).

[53] P. J. Benson, P. Caselli, and P. C. Myers, Astrophys. J. 506, 743 (1998).

[54] W. J. Lafferty, and F. J. Lovas, J. Phys. Chem. Ref. Data 7, 441 (1978).

[55] S. Yamamoto, S. Saito, K. Kawaguchi, and M. Ohishi, Astrophys. J. 361, 318 (1990).

[56] H.-H. Lee, E. Herbst, G. Pineau des Forêts, F. Roueff, and J. Le Bourlot, Astron. Astrophys. 311, 690 (1996).

[57] J. A. Barranco, and A. A. Goodman, Astrophys. J. 504, 207 (1998).

[58] J. Swift, W. J. Welch, and J. Di Francesco, Astrophys. J. 620, 823 (2005).

[59] C. J. Lada, E. A. Bergin, J. F. Alves, and T. L. Huard, Astrophys. J. 586, 286 (2003).

[60] A. J. Walsh, P. C. Myers, and M. G. Burton, Astrophys. J. 614, 194 (2004).

[61] J. P. Williams, C. W. Lee, and P. C. Myers, Astrophys. J. 636, 952 (2006).

[62] P. C. Myers, Astrophys. J. 270, 105 (1983).

[63] C. F. McKee, and J. C. Tan, Astrophys. J. 585, 850 (2003).

[64] F. R. Hampel, E. M. Ronchetti, P. J. Rousseeuw, and W. A. Stahel, Robust Statistics. The Approach Based on Influence Functions (John Wiley & Sons, New York, 1986).

[65] J. M. Rathborne, C. J. Lada, A. A. Muench, J. F. Alves, and M. Lombardi, Astrophys. J. Sup. 174, 396 (2008).

[66] T. Pillai, F. Wyrowski, S. J. Carey, and K. M. Menten, Astron. Astrophys. 450, 569 (2006).

[67] A. V. Lapinov, in 15th Symp. on High-Resolution Molecular Spectroscopy, edited by Y. N. Ponomarev, S. N. Mikhailenko, and N. N. Sintitsa, Proceed. of SPIE, Vol. 6580, p. 65801B (2006).

[68] A. V. Lapinov (private communication).

[69] S. G. Kukolich, Phys. Rev. 156, 83 (1967).

[70] H. S. P. Möller, S. Thorwirth, D. A. Roth, and G. Winnewisser, Astron. Astrophys. 370, L49 (2001).

[71] H. S. P. Möller, F. Schlöder, J. Stutzki, and G. Winnewisser, J. Mol. Struct. 742, 215 (2005).

[72] L. Lindegren, and D. Dravins, Astron. Astrophys. 410, 1185 (2003).

[73] M. A. Gordon, in Methods of Experimental Physics. XII., edited by M. L. Meeks (Academic, New York, 1976).

[74] J. D. Bekenstein, Phys. Rev. D 25, 1527 (1982).

[75] V. V. Flambaum, Int. J. Mod. Phys. A 22, 4937 (2007).

[76] V. V. Flambaum, and E. V. Shuryak, in AIP Conf. Proceed., Vol. 995, p. 1 (2008).

[77] M. Miyamoto, and R. Nagai, Publ. Astron. Soc. Japan 27, 533 (1975).

[78] M. Miyamoto, C. Satoh, and M. Ohashi, Astron. Astrophys. 90, 215 (1980).

[79] H. Nishikori, M. Machida, and R. Matsumoto, Astron. Astrophys. 479, 239 (2003).

[80] Molaro, arXiv: astro-ph/0806.2438 (2008).

[81] S. A. Levshakov, D. Reimers, M. G. Kozlov, S. G. Porsev, and P. Molaro, Phys. Rev. A 77, 032119 (2008).

[82] S. A. Levshakov, D. Reimers, M. G. Kozlov, S. G. Porsev, and P. Molaro, Astron. Astrophys. 479, 719 (2008).