Title: Limits on variation of fundamental constants from microwave and infrared transitions in atoms amd molecules

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Abstract:

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The constants which can be probed with atomic & molecular spectra:

- the fine-structure constant $\alpha=e^2/\hbar c$
- The proton-to-electron mass ratio $\mu=m_p/m_e$
- the nuclear gyromagnetic ratio g_n

Reported in the literature optical data concerning the relative variation of constants δμ/μ and δα/α at redshifts z ~ 1–3 are controversial at the level of a few ppm (1ppm = 10^{-6}).

Astronomical estimates of the physical constants

- These estimates are based on the comparison of the line centers in the spectra of astronomical objects with corresponding laboratory values.
- In order to disentangle the line shifts caused by the motion of the object and by the putative effect of the variability of constants, lines with different sensitivities to the variation of fundamental constants should be used.
- The accuracy of the method depends on the linewidths and the respective sensitivity coefficients.

ensitivity coefficients to the variation of undamental constants

he observed linewidth Γ in astrophysical spectra is usually etermined by the Doppler broadening effect, i.e.

$$\Gamma / \omega = \Delta v / c ,$$

here Δv is the velocity dispersion, c is the speed of light, and ω the transition frequency. For extragalactic observations the pical values of Δv are about 1 – 10 km/s, which means that:

$$\Gamma / \omega \sim 10^{-5}.$$

e dimensionless sensitivity coefficients can be defined as:

$$\frac{\delta\omega}{\omega} = K_{\alpha}\frac{\delta\alpha}{\alpha} + K_{\mu}\frac{\delta\mu}{\mu} + K_{g}\frac{\delta g_{n}}{g_{n}}$$

f we observe two lines with different sensitivities and the same *actual* edshift, the apparent redshifts will differ by

$$\frac{\delta z'}{1+z'} = -\Delta K_{\alpha}\frac{\delta\alpha}{\alpha} - \Delta K_{\mu}\frac{\delta\mu}{\mu} - \Delta K_{g}\frac{\delta g_n}{g_n}.$$

From the observation of one pair of lines it is impossible to distinguish between variation of different constants. Thus, we express difference in apparent redshift in terms of the variation of a following combination of undamental constants:

$$\frac{\delta z'}{1+z'} = -\frac{\delta F}{F}, \quad F = \alpha^{\Delta K_{\alpha}}\mu^{\Delta K_{\mu}}g_n^{\Delta K_{g}}.$$

Obviously we should maximize either ΔK_{α}, ΔK_{μ}, or ΔK_{g}. Note that differences ΔK_i are <u>independent</u> on the frequency units.

Sensitivity coefficients for different wavebands

Transition	K_α	K_μ	K_g
Optical and UV range			
typical E1-transition in atom	10^{-2} - 10^{-1}	10^{-3}	10^{-7}
electronic transition in light molecule	10^{-2}	10^{-2}	10^{-7}
Microwave and infrared range			
fine-structure M1-transition	**2**	0.0	0.0
vibrational transition	0.0	−0.5	0.0
rotational transition	0.0	−1.0	0.0
21-cm hyperfine line in hydrogen	**2.0**	−1.0	**1.0**
18-cm Λ-doublet line in OH	**−2**	**−3**	10^{-1}
1.25-cm inversion line in NH_3	0.0	**− 4.5**	0.0

We see that:

- Sensitivity coefficients in microwave and infrared ranges are several orders of magnitude larger, than in optical and UV ranges.
- There are lines of different types here, and sensitivity coefficients change drastically from one type to another.
- For example, the splitting between the components of the Λ-doublet of the ground $\Pi_{3/2}$ state in the OH molecule appears in the 3rd order in Coriolis interaction and is extremely sensitive to fundamental constants α and μ [*Kanekar et al*].
- Inversion line in ammonia corresponds to the tunneling transition of three hydrogen atoms from one minimum of a double-well potential to another. The tunneling frequency exponentially depends on the reduced mass for the respective vibrational mode and is, therefore, extremely sensitive to μ-variation [*van Veldhoven et al*].

Limits on variation of fundamental constants at redshifts $z\sim1$ (*timescale of few Gyr*) from microwave and IR spectra

n 1996 *Varshalovich & Potekhin* compared apparent redshifts of rotational and ptical lines to place following bound at z=1.9:

$$\delta\mu/\mu = (70 \pm 100) \times 10^{-6}$$

n 2001 *Murphy et al* compared redshifts of 21 cm hydrogen line and a number of otational lines for the object *B0218+357* at the redshift z=0.68 to get the bound on ariation of the product:

$$\delta F'/F' = (1.6 \pm 5.4) \times 10^{-6}, \quad F' = \alpha^2 g_n$$

Λ-doublet OH line from the same object *B0218+357* was recently used to place very stringent bound on the variation of different combination of constants [*Kanerar et al*, 2005]:

$$\delta F/F = (3.5 \pm 4.0) \times 10^{-6}, \text{ where } F = \alpha^{3.14} \mu^{1.57} g_n$$

Finally, NH_3 inversion line from *B0218+357* allows to place limit on the variation of μ [*Flambaum and Kozlov*, 2007]:

$$\delta\mu/\mu = (0.6 \pm 1.9) \times 10^{-6}$$

The above limits are based on the analysis of different microwave lines of the same object *B*0218+357 at *z*=0.68. Simultaneous analysis of all these lines allow to have a *complete* experiment, i.e. to study all three fundamental constants relevant to atomic physics and place three model-independent limits on their time-variation:

$$\begin{cases} \delta\mu/\mu = (0.6 \pm 1.9)\times 10^{-6}, \\ \delta\alpha/\alpha = (0.9 \pm 6.4)\times 10^{-6}, \\ \delta g_n/g_n = (0 \pm 17)\times 10^{-6}. \end{cases}$$

It would be extremely interesting to get new high precision data for this object for a dedicated and comprehensive analysis.

Using fine-structure lines to place bounds on time-variation at very high redshifts

The redshift of the fine-structure [C II] 158 μm line is compared to that of the rotational CO line. Both lines are observed in emission for the quasars J1148+5251 and BR 1202-0725 with respective redshifts z=6.42 and z=4.69. The absence of the meaningful differences in apparent redshifts allowed to place bounds on the variation of the parameter

$F'' = \alpha^2 \mu$ [*Levshakov et al*, 2008]:

$$\begin{cases} \delta F''/F'' = (0.1 \pm 1.0) \times 10^{-4}, z = 6.42, \\ \delta F''/F'' = (1.4 \pm 1.5) \times 10^{-4}, z = 4.69. \end{cases}$$

Note that z=6.42 corresponds to the look-back time of approximately 12.9 Gyr, which constitutes 93% of the age of the Universe.

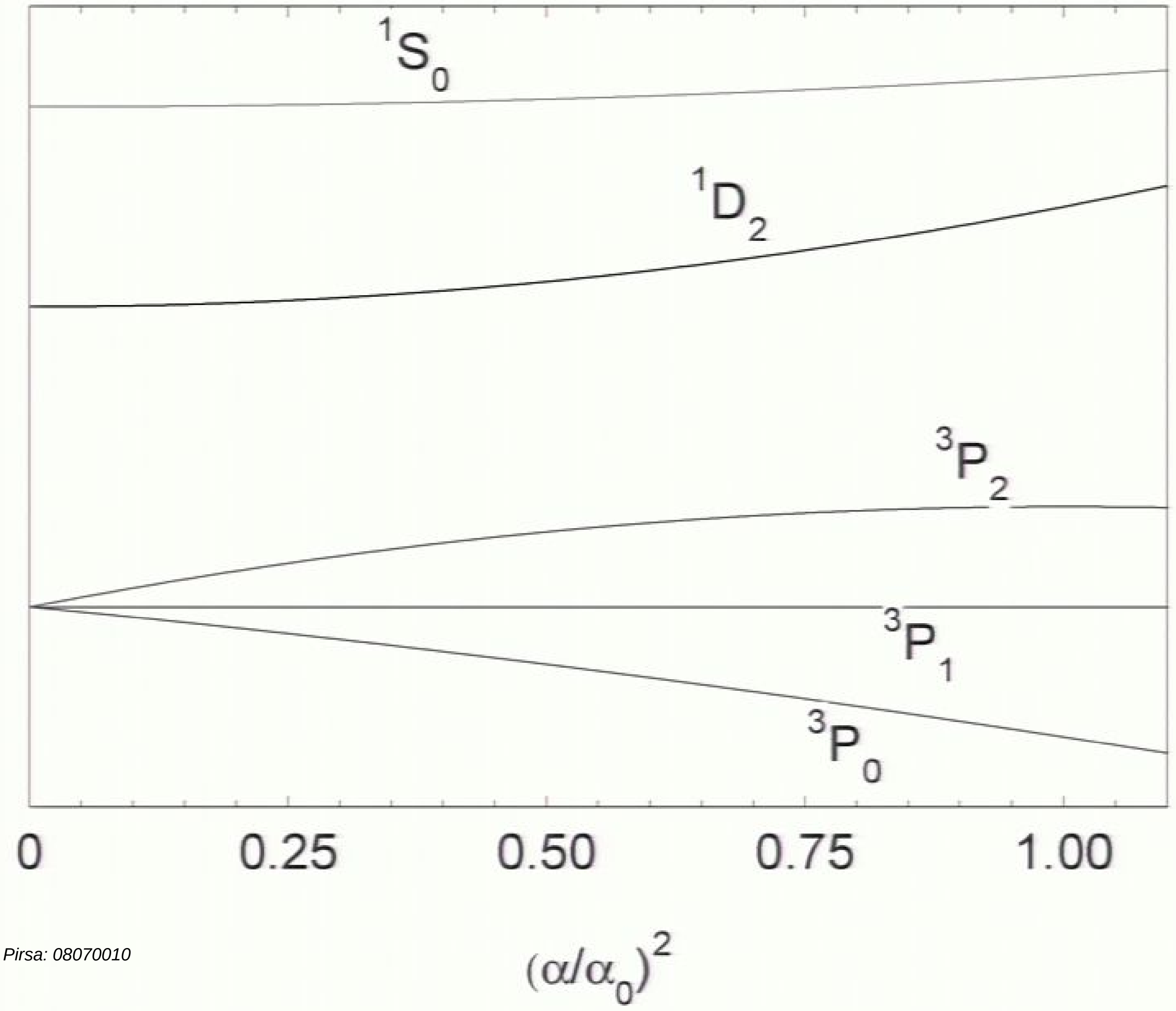
Using transitions in the same species to reduce Doppler noise

- In order to reduce systematic errors from the Doppler noise it is desirable to compare redshifts for transitions in the same species.
- We need transitions with different sensitivities.
- Usually lines of the same nature have very close sensitivities.

Therefore, one has to compare apparent redshifts of, say, inversion line and rotational lines of NH_3, etc.

- Some fine-structure transitions may have different sensitivities due to the strong interactions between multiplets [*Dzuba & Flambaum*, 2005]. For light atoms such differences are small, but they rapidly grow with nuclear charge Z.

Multiplet structure of configuration ns^2np^2



Examples:
C I, O III, Ne V,
Si I, S III, Ar V,
etc

To a first approximation the frequencies of the fine-structure transitions obey the Landé-rule:

$$\omega_{J,J-1}/\omega_{J-1,J-2} = J/(J-1)$$

n this approximation sensitivities of both transitions are the same, $K_\alpha = 2.$

nteraction between levels of different multiplets leads to violation of the andé-rule and to deviation of the sensitivities from 2. The following elation still hold:

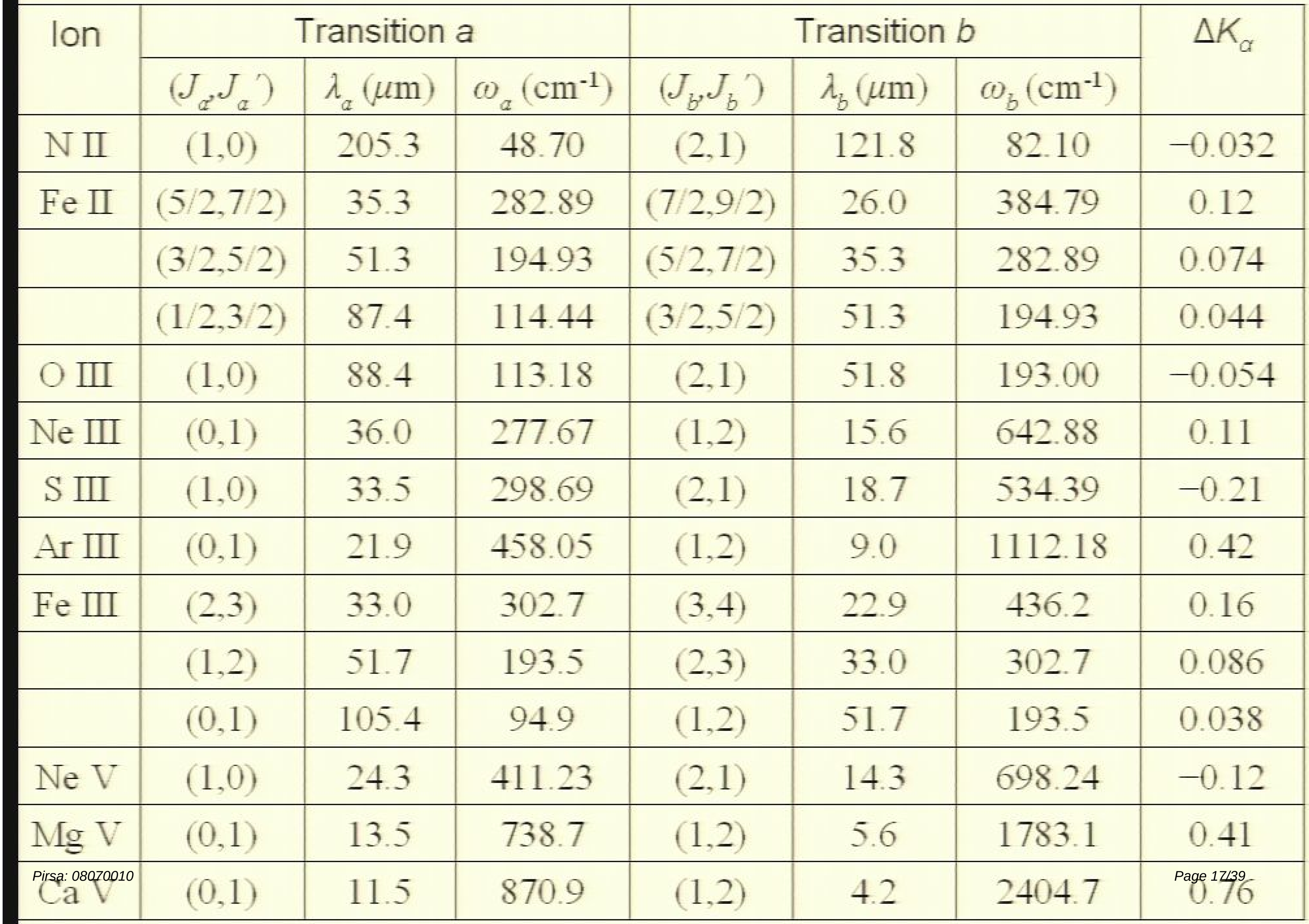
$$\Delta K_\alpha \equiv K_\alpha(J,J-1) - K_\alpha(J-1,J-2) = 2\left[\frac{J-1}{J}\frac{\omega_{J,J-1}}{\omega_{J-1,J-2}} - 1\right]$$

For the most interesting case of the multiplet ${}^3P_J$, $J = 0,1,2$, this relation reduces to:

$$\Delta K_\alpha \equiv K_\alpha(2,1) - K_\alpha(1,0) = \frac{\omega_{2,1}}{\omega_{1,0}} - 2$$

Differences in sensitivity coefficients for fine-structure transitions in light ions

Ion	Transition *a*			Transition *b*			ΔK_a
	(J_a, J_a')	λ_a (μm)	ω_a (cm^{-1})	(J_b, J_b')	λ_b (μm)	ω_b (cm^{-1})	
C I	(1,0)	609.1	16.40	(2,1)	370.4	27.00	−0.016
O I	(0,1)	145.5	68.73	(1,2)	63.2	158.27	0.042
Si I	(1,0)	129.7	77.11	(2,1)	68.5	146.05	−0.11
S I	(0,1)	56.3	177.59	(1,2)	25.3	396.06	0.23
Ti I	(2,3)	58.8	170.13	(3,4)	46.1	216.74	−0.090
Fe I	(2,3)	34.7	288.07	(3,4)	24.0	415.93	0.17
	(1,2)	54.3	184.13	(2,3)	34.7	288.07	0.086
	(0,1)	111.2	89.94	(1,2)	54.3	184.13	0.048



Ion	Transition a			Transition b			ΔK_α
	(J_a, J_a')	λ_a (μm)	ω_a (cm^{-1})	(J_b, J_b')	λ_b (μm)	ω_b (cm^{-1})	
N II	(1,0)	205.3	48.70	(2,1)	121.8	82.10	−0.032
Fe II	(5/2,7/2)	35.3	282.89	(7/2,9/2)	26.0	384.79	0.12
	(3/2,5/2)	51.3	194.93	(5/2,7/2)	35.3	282.89	0.074
	(1/2,3/2)	87.4	114.44	(3/2,5/2)	51.3	194.93	0.044
O III	(1,0)	88.4	113.18	(2,1)	51.8	193.00	−0.054
Ne III	(0,1)	36.0	277.67	(1,2)	15.6	642.88	0.11
S III	(1,0)	33.5	298.69	(2,1)	18.7	534.39	−0.21
Ar III	(0,1)	21.9	458.05	(1,2)	9.0	1112.18	0.42
Fe III	(2,3)	33.0	302.7	(3,4)	22.9	436.2	0.16
	(1,2)	51.7	193.5	(2,3)	33.0	302.7	0.086
	(0,1)	105.4	94.9	(1,2)	51.7	193.5	0.038
Ne V	(1,0)	24.3	411.23	(2,1)	14.3	698.24	−0.12
Mg V	(0,1)	13.5	738.7	(1,2)	5.6	1783.1	0.41
Ca V	(0,1)	11.5	870.9	(1,2)	4.2	2404.7	0.76

Conclusions

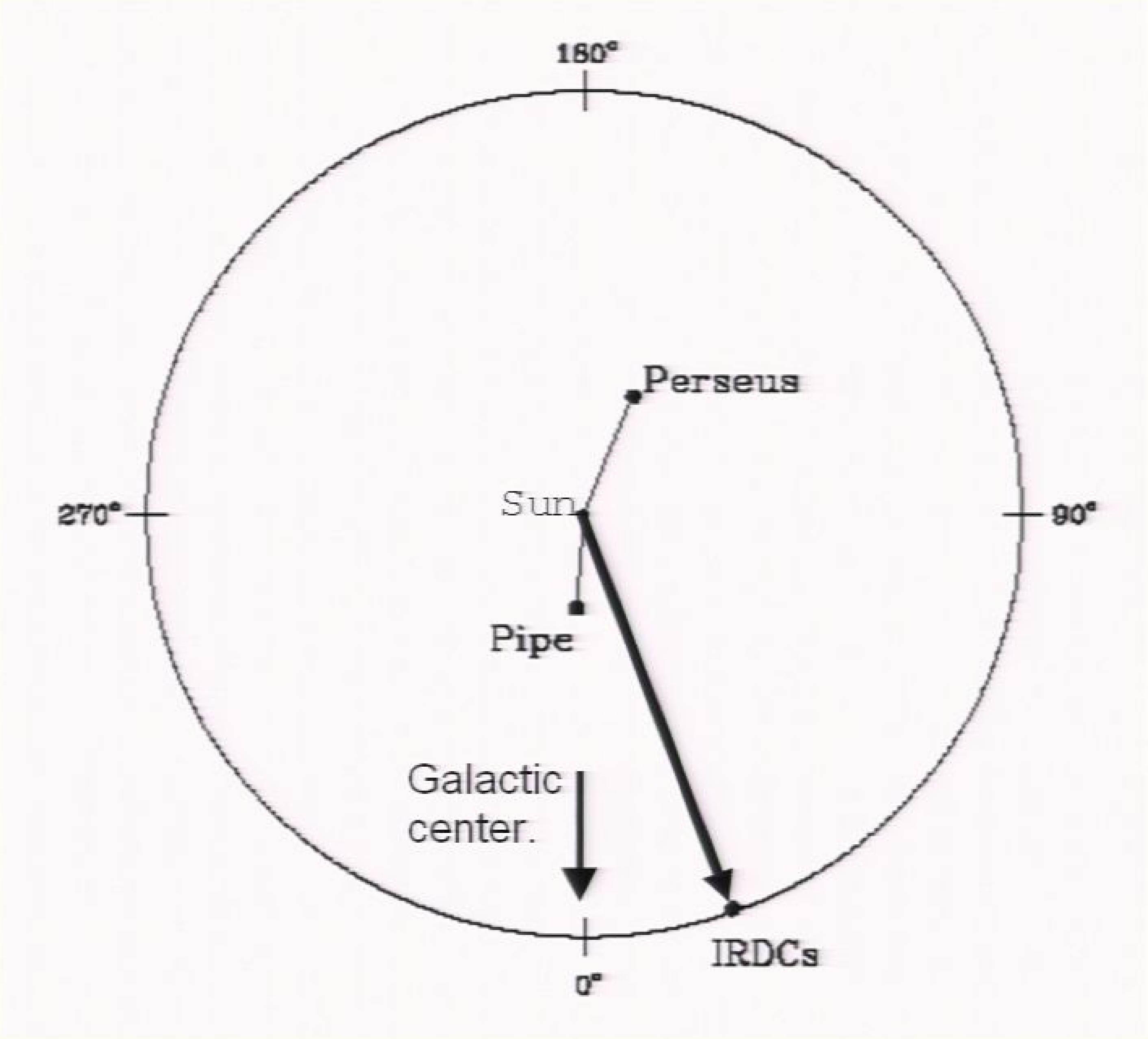
Microwave and IR lines have *higher sensitivity* to time-variation of fundamental constants compared to optical and UV bands.

Lines of different nature (fine-structure, hyperfine, rotational, Λ-doublet, inversion, etc.) are sensitive to different combinations of fundamental constants. If several lines of different types are observed for one object, *it is possible to determine the time-variation of all three constants*, α, μ, and g_n.

Some fine-structure and rotational lines are observed in emission for *extremely high redshifts*, up to $z \approx 10$. This allows to probe fundamental constants at very early epochs of the evolution of the Universe.

Observing lines of the same species one can *suppress systematic errors* caused by non-identical spatial distribution of different species in cold molecular gas clouds. For example, one can use 18 cm Λ-doublet line and rotational lines of OH. Similarly, the 1.2 cm inversion line can be used in combination with rotational lines of ammonia.

High precision data on variation of constants from microwave spectra of cold molecular clouds in our galaxy



Schematic location of the Perseus molecular cloud, the Pipe Nebula, and the IRDCs in projection onto the Galactic plane.

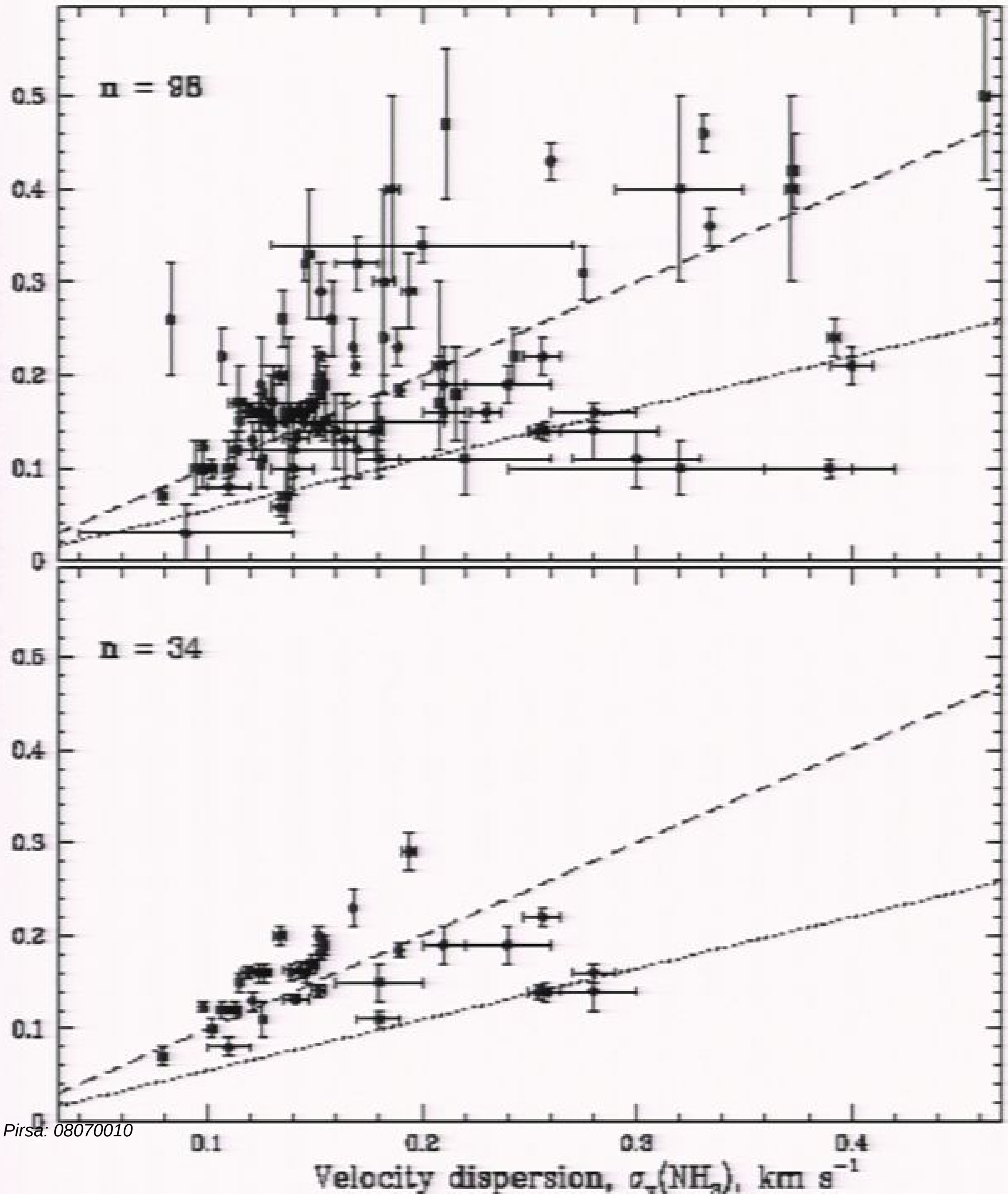
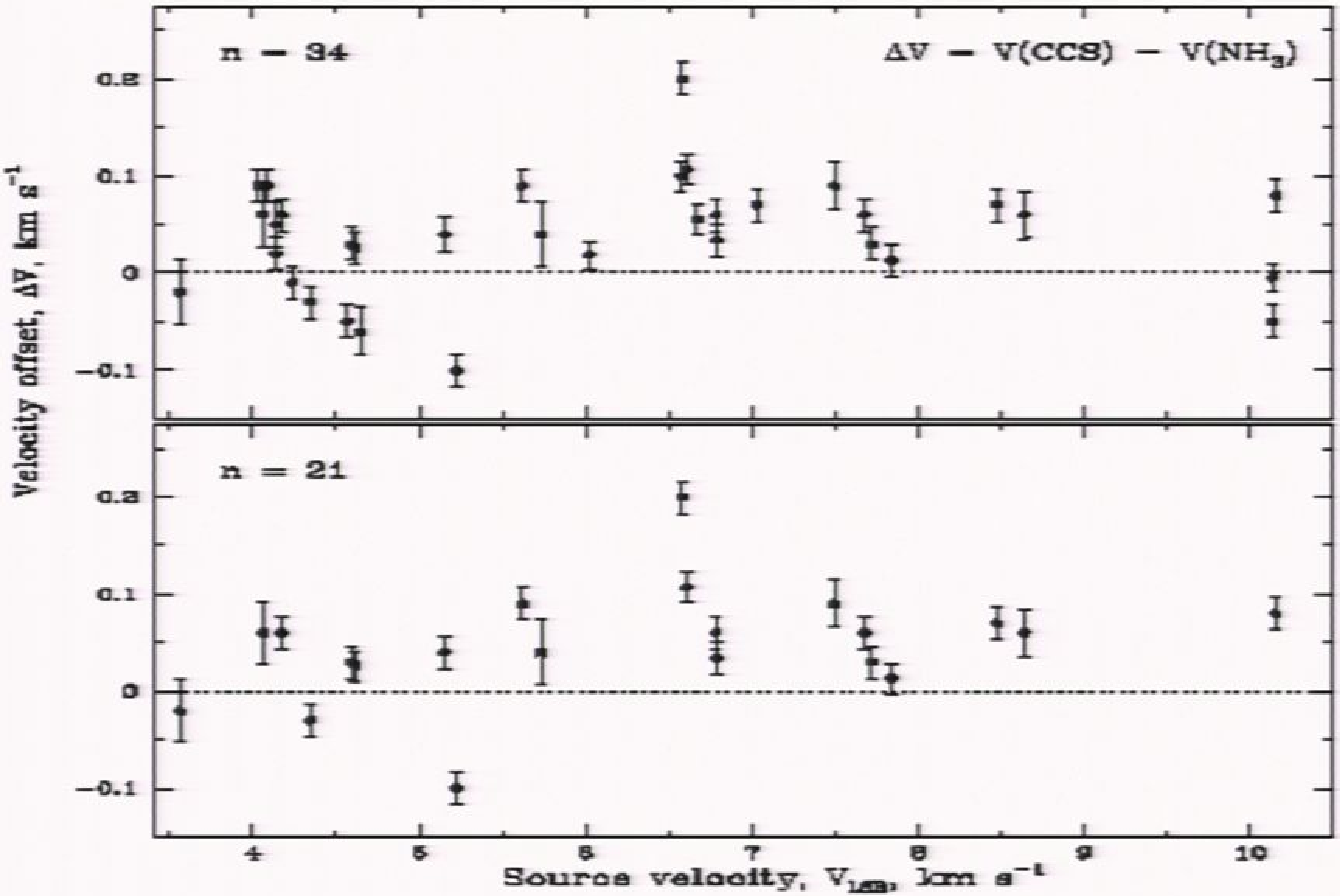


Fig.1

Perseus Cloud

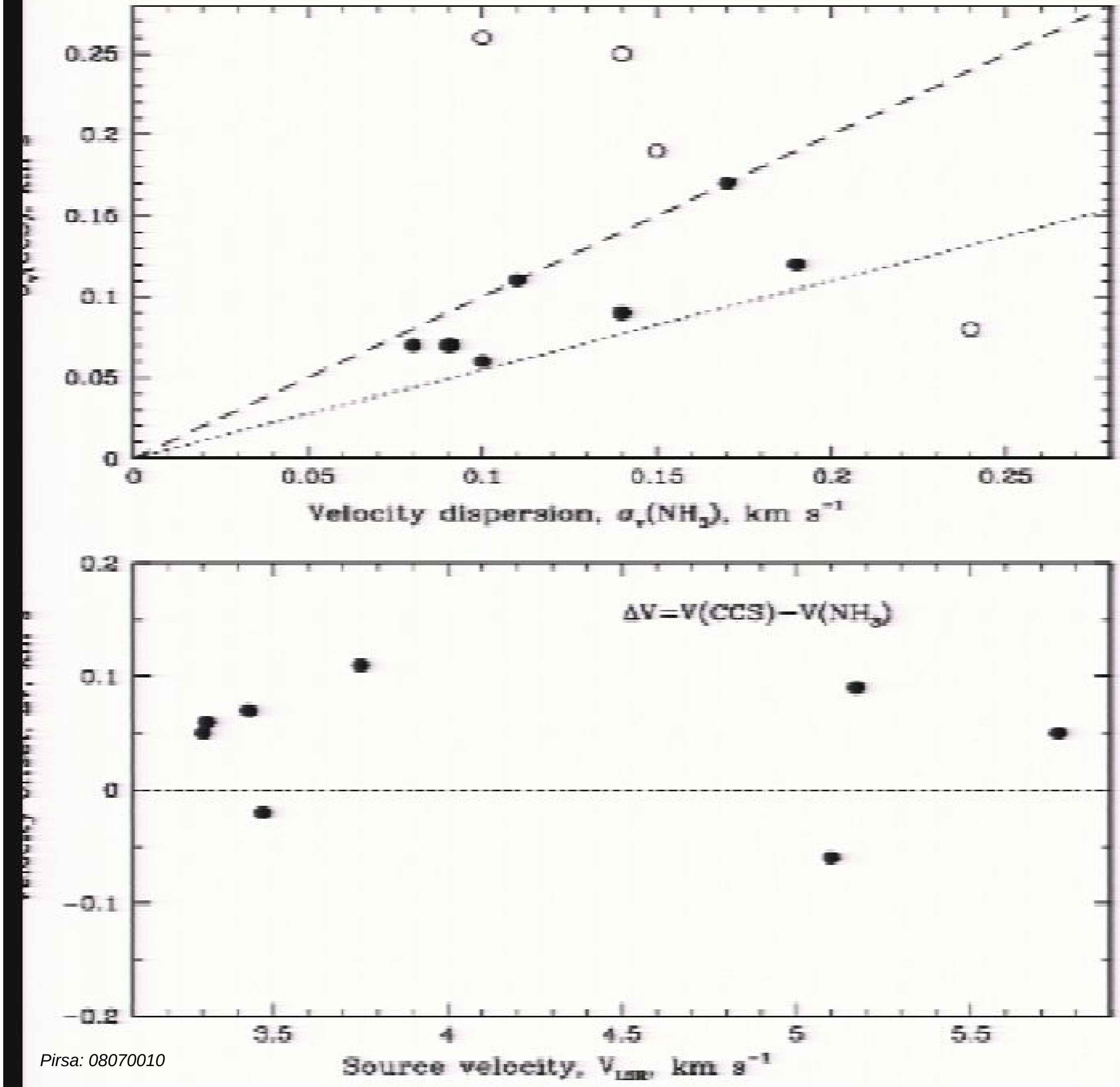
Upper panel:
C_2S (2_1-1_0) versus NH_3 (1,1) linewidths for cores in the Perseus molecular cloud from the total sample of Rosolowsky et al. (2008).

Lower panel:
Subsample of the best single-component profiles of C_2S and NH_3 selected from the full set.



Jpper panel: Velocity offset $\Delta V_{CCS\text{-}NH3}$ versus the source radial velocity for points shown in the lower panel of Fig. 1.

Lower panel: Same as the upper panel but for the points, which lie in allowed region



Pipe Nebular

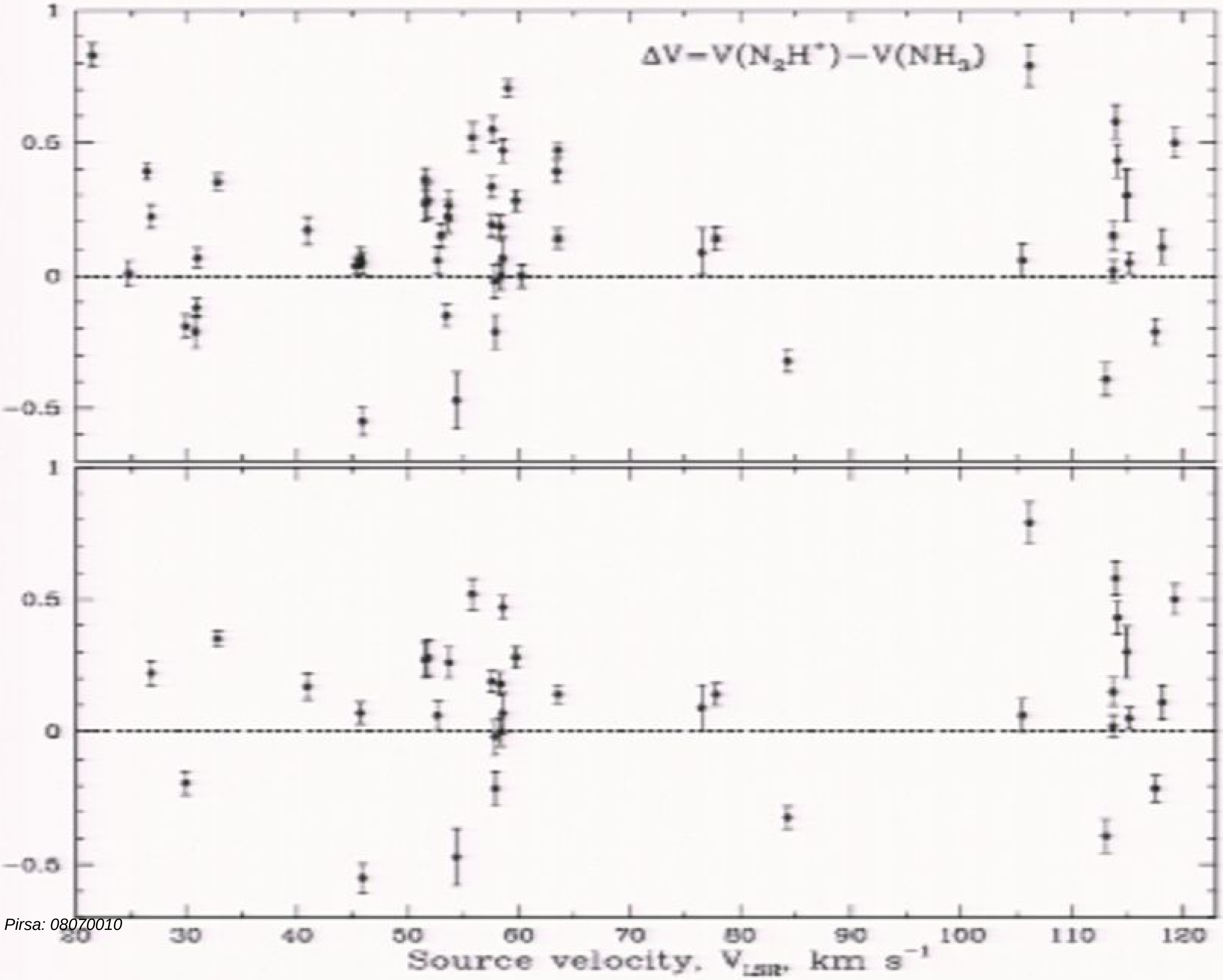
Upper panel:

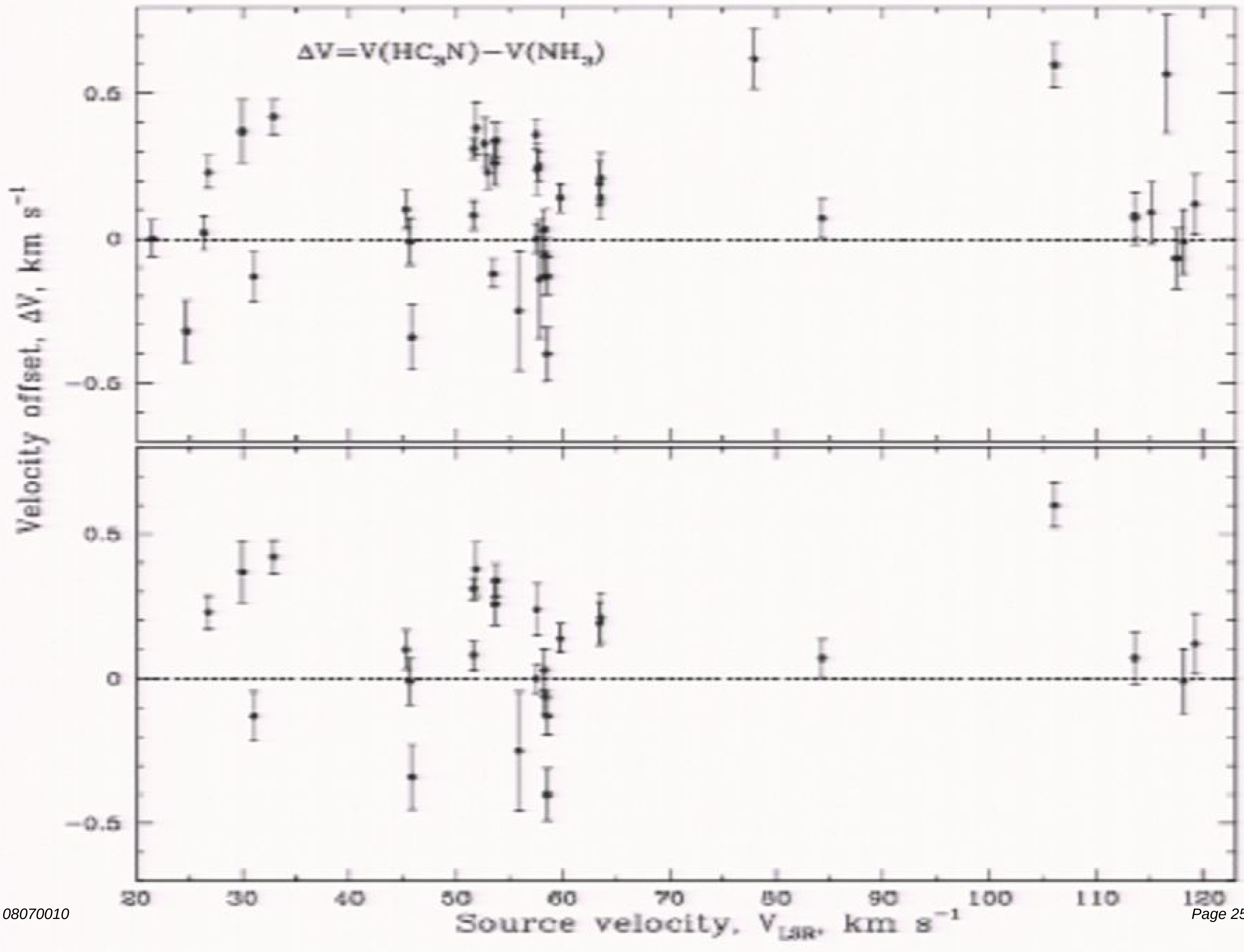
C_2S (2_1-1_0) versus NH_3 (1,1) linewidths *Rathborn et al.* (2008).

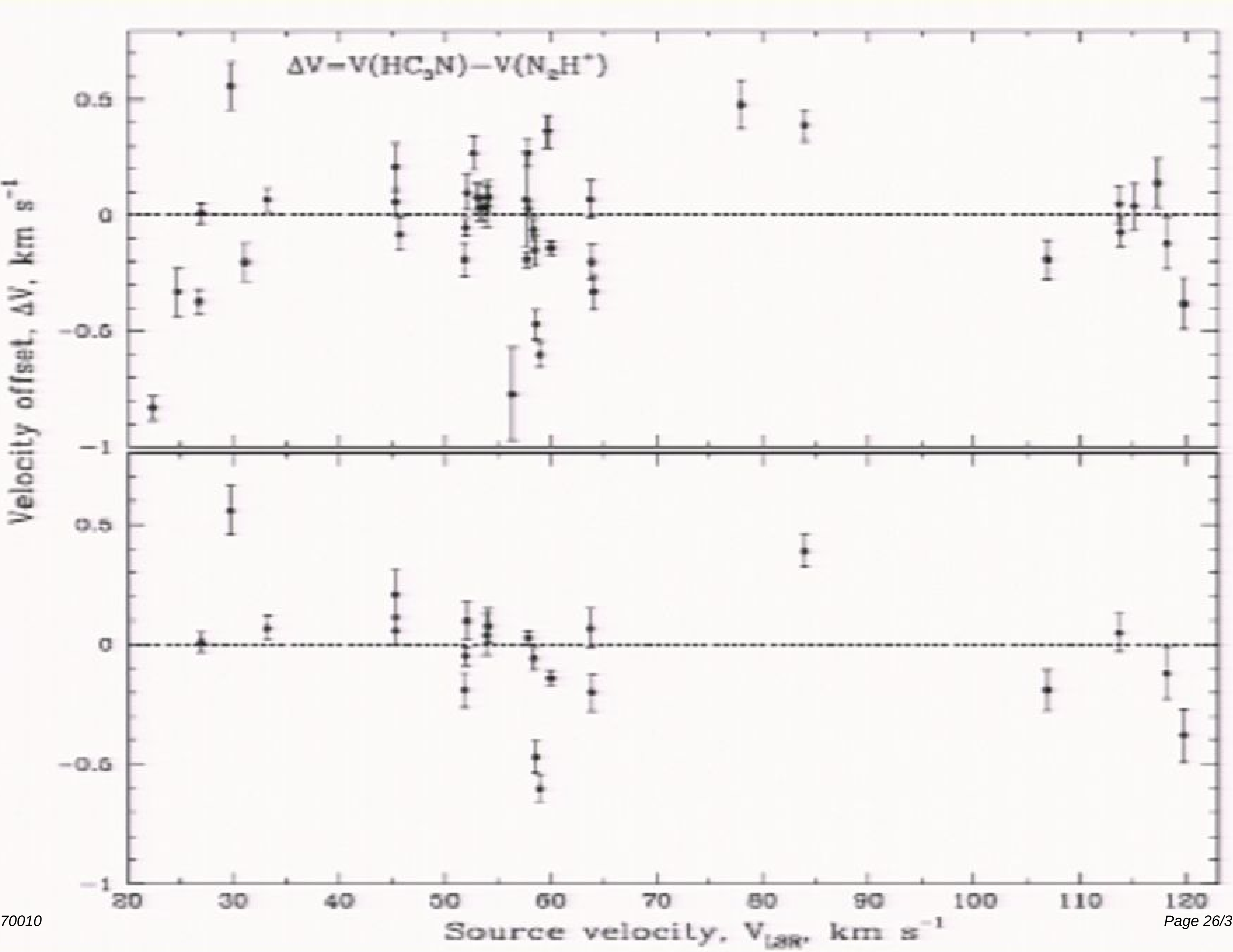
Lower panel:

Velocity offset $\Delta V_{CCS-NH3}$ versus the source radial velocity $V_{LSR}(NH_3)$.

Infrared Dark Clouds (IRDCs)




ΔV=V(HC3N)−V(NH3)
Velocity offset, ΔV, km s⁻¹
0.5
0
−0.5
0.5
0
−0.5
20
30
40
50
60
70
80
90
100
110
120
Source velocity, VLSR, km s⁻¹


ΔV=V(HC3N)−V(N2H+)
Velocity offset, ΔV, km s-1
0.5
0
−0.5
−1
20
30
40
50
60
70
80
90
100
110
120
Source velocity, VLSR, km s-1

mple mean values (unweighted) ΔV , standard deviations σ_{rms}, and robust M-
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ject 1)	Molecular pair (2)	Sample size, n (3)	$\Delta V^{\dagger}$, km s^{-1} (4)	$\sigma_{\rm rms}$, km s^{-1} (5)	$\Delta V^{\dagger}_{M}$, km s^{-1} (6)
seus	NH_3/CCS	98	0.044 ± 0.013	0.129	0.040 ± 0.007
		34	0.039 ± 0.010	0.058	0.045 ± 0.007
		21	0.048 ± 0.013	0.060	0.052 ± 0.007
ipe	NH_3/CCS	12	0.087 ± 0.039	0.135	0.039 ± 0.023
		8	0.044 ± 0.020	0.057	0.069 ± 0.011
DCs	NH_3/N_2H^+	54	0.157 ± 0.040	0.294	0.160 ± 0.030
		36	0.122 ± 0.049	0.294	0.160 ± 0.032
	NH_3/HC_3N	43	0.138 ± 0.043	0.282	0.110 ± 0.032
		27	0.105 ± 0.045	0.234	0.120 ± 0.037
	N_2H^+/HC_3N	41	-0.056 ± 0.047	0.301	-0.020 ± 0.037
		22	-0.033 ± 0.055	0.258	-0.017 ± 0.034

Our final results for velocity offsets of NH_3 inversion line versus rotational lines of other molecules for Perseus cloud, Pipe Nebulae (C_2S), and IRDCs (N_2H^+ & HC_3N) are:

$$\Delta V_{Perseus} = 52 \pm 7_{stat} \pm 14_{sys}$$

$$\Delta V_{Pipe} = 69 \pm 11_{stat} \pm 14_{sys}$$

$$\Delta V_{IRDCs} = 160 \pm 32_{stat} \pm 4_{sys}$$

$$\Delta V_{IRDCs} = 120 \pm 37_{stat} \pm 7_{sys}$$

If we interpret these results in terms of μ-variation, we get:

$$\Delta\mu/\mu = (-5 - 15) \times 10^{-8}$$

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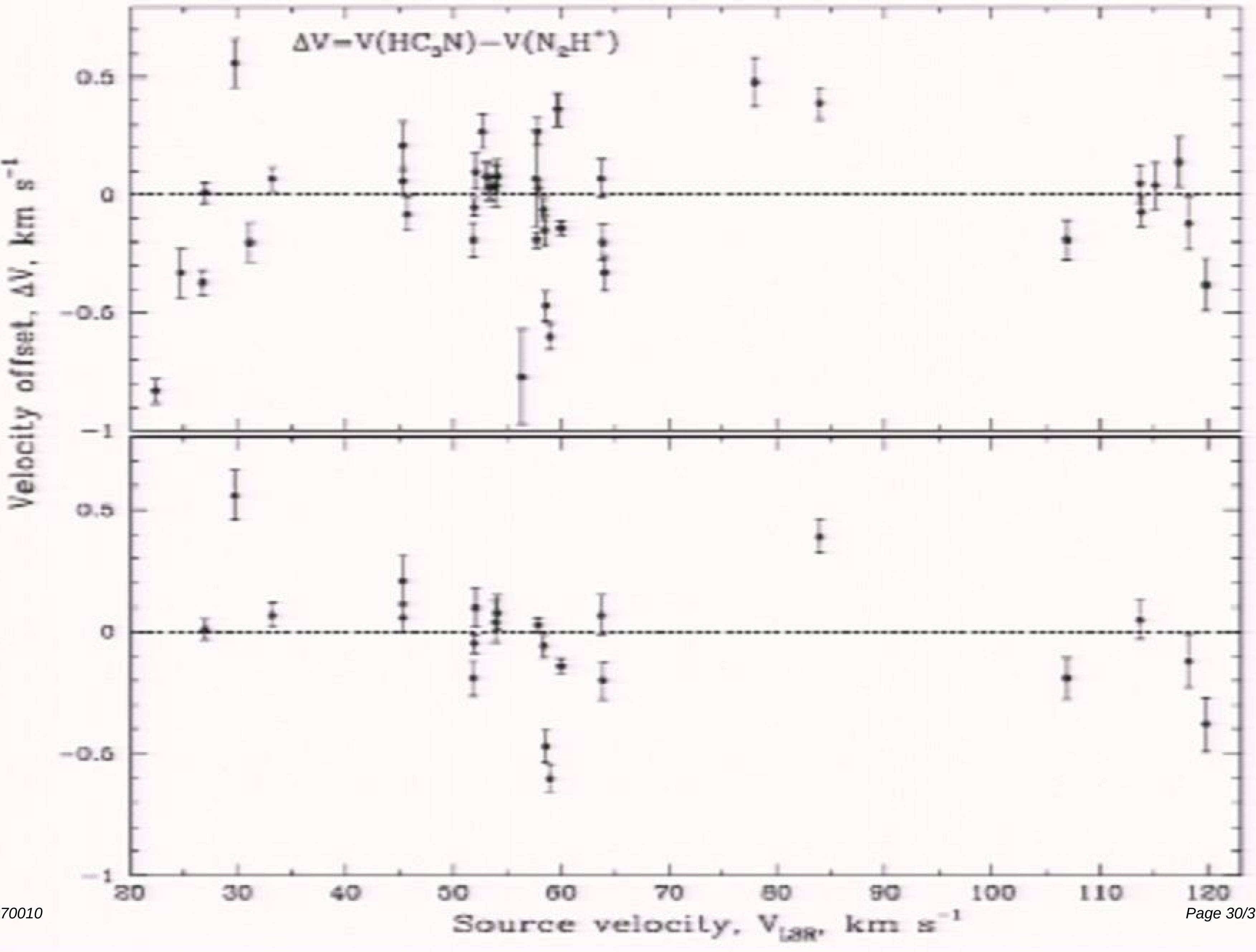
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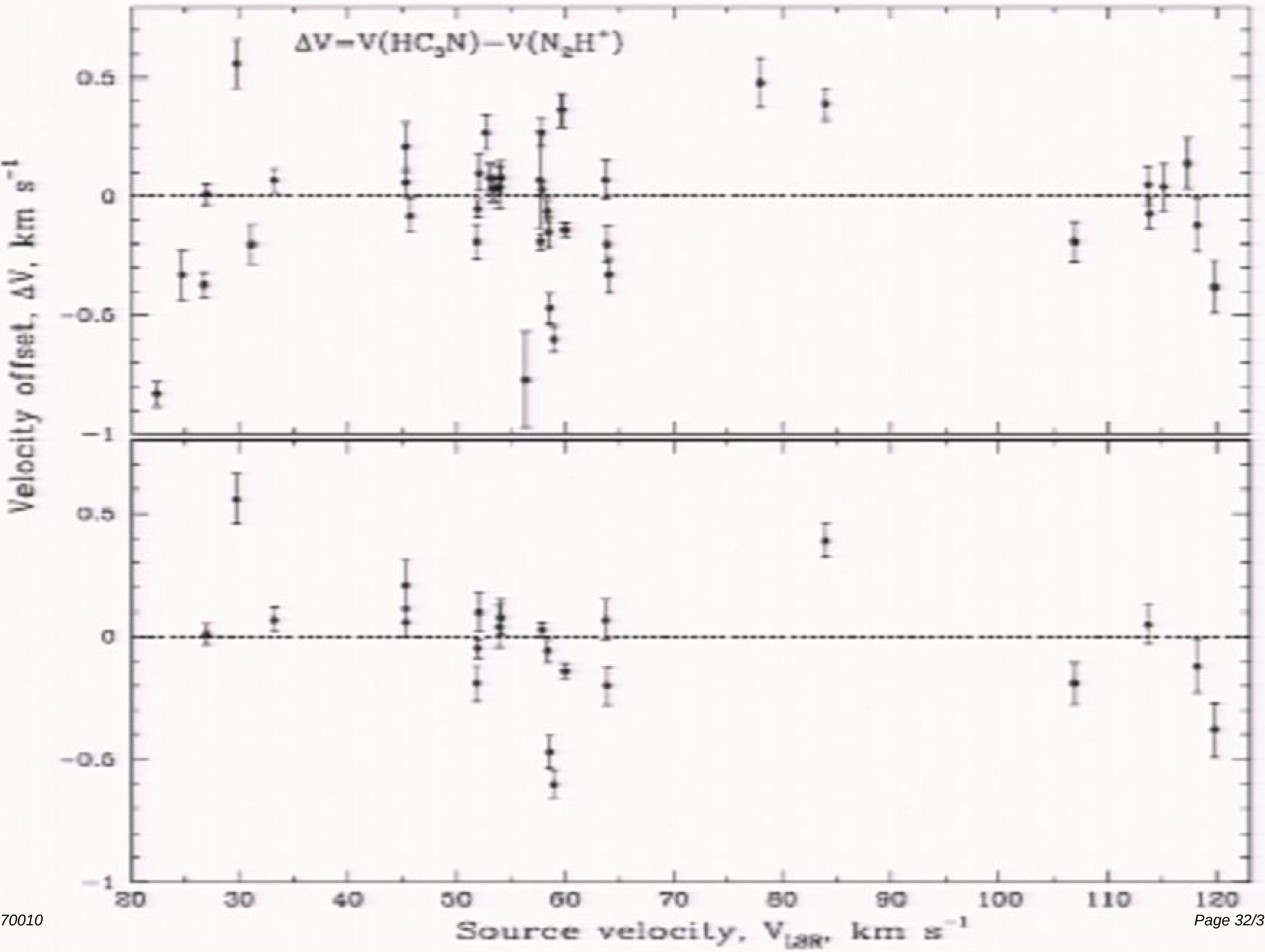
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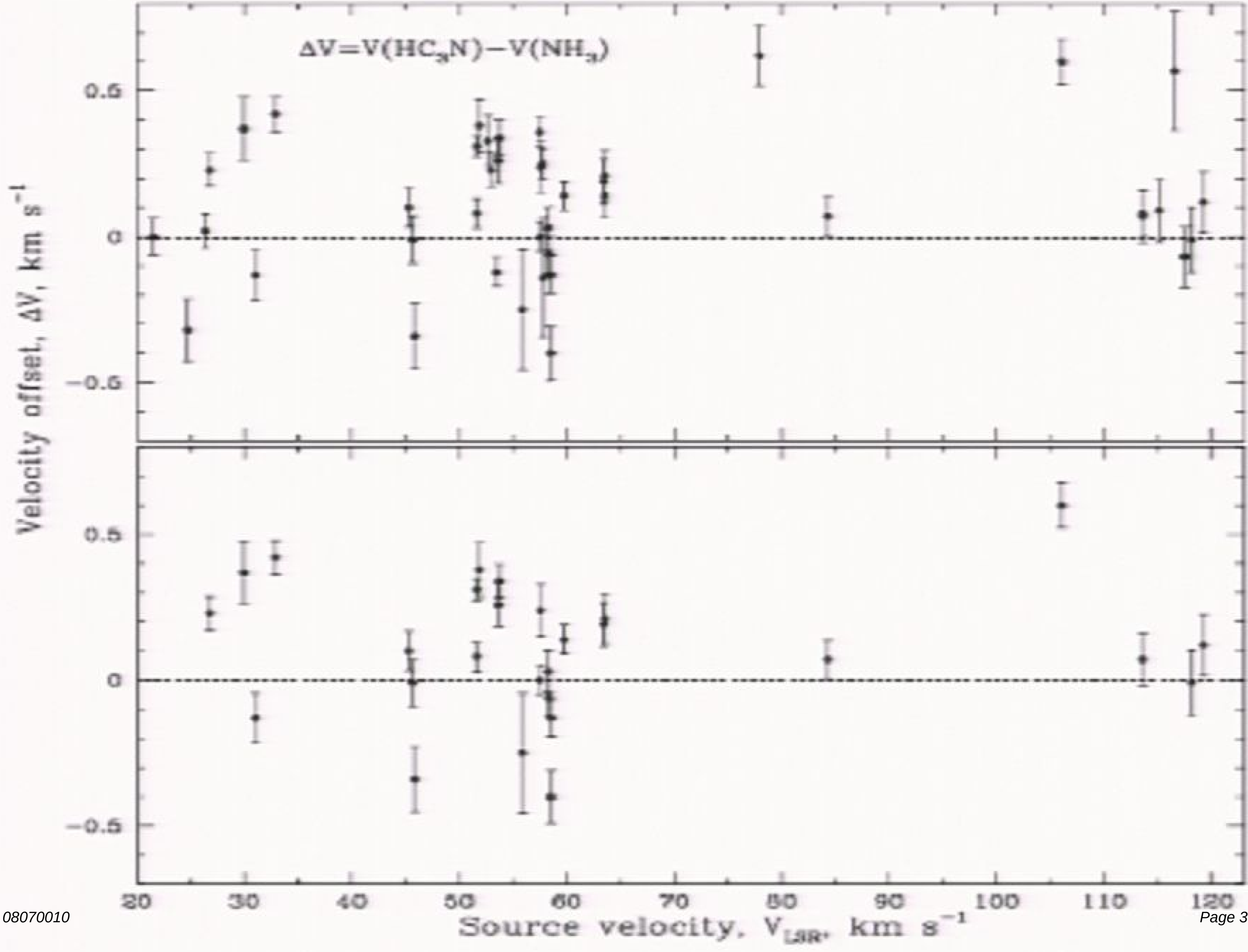
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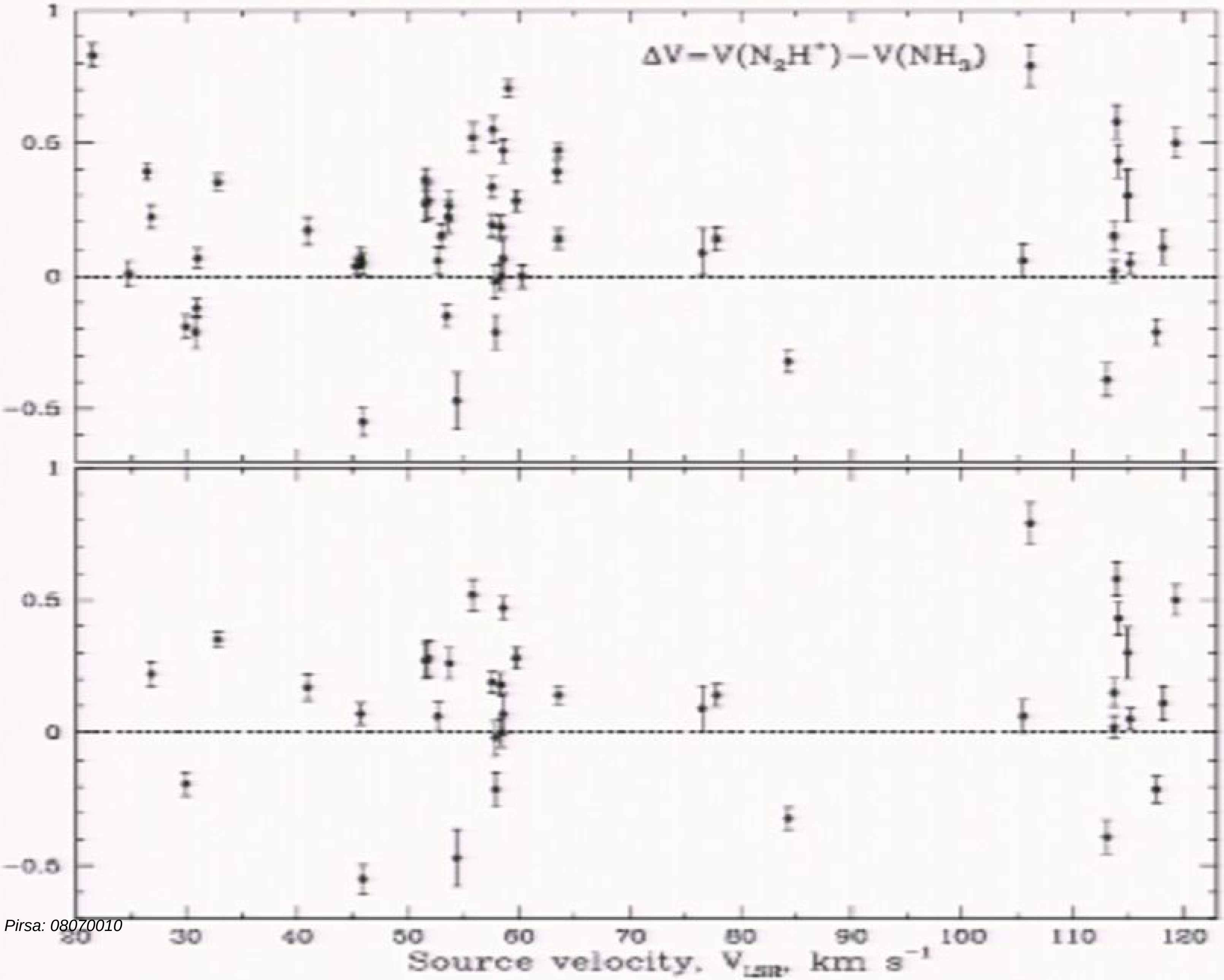
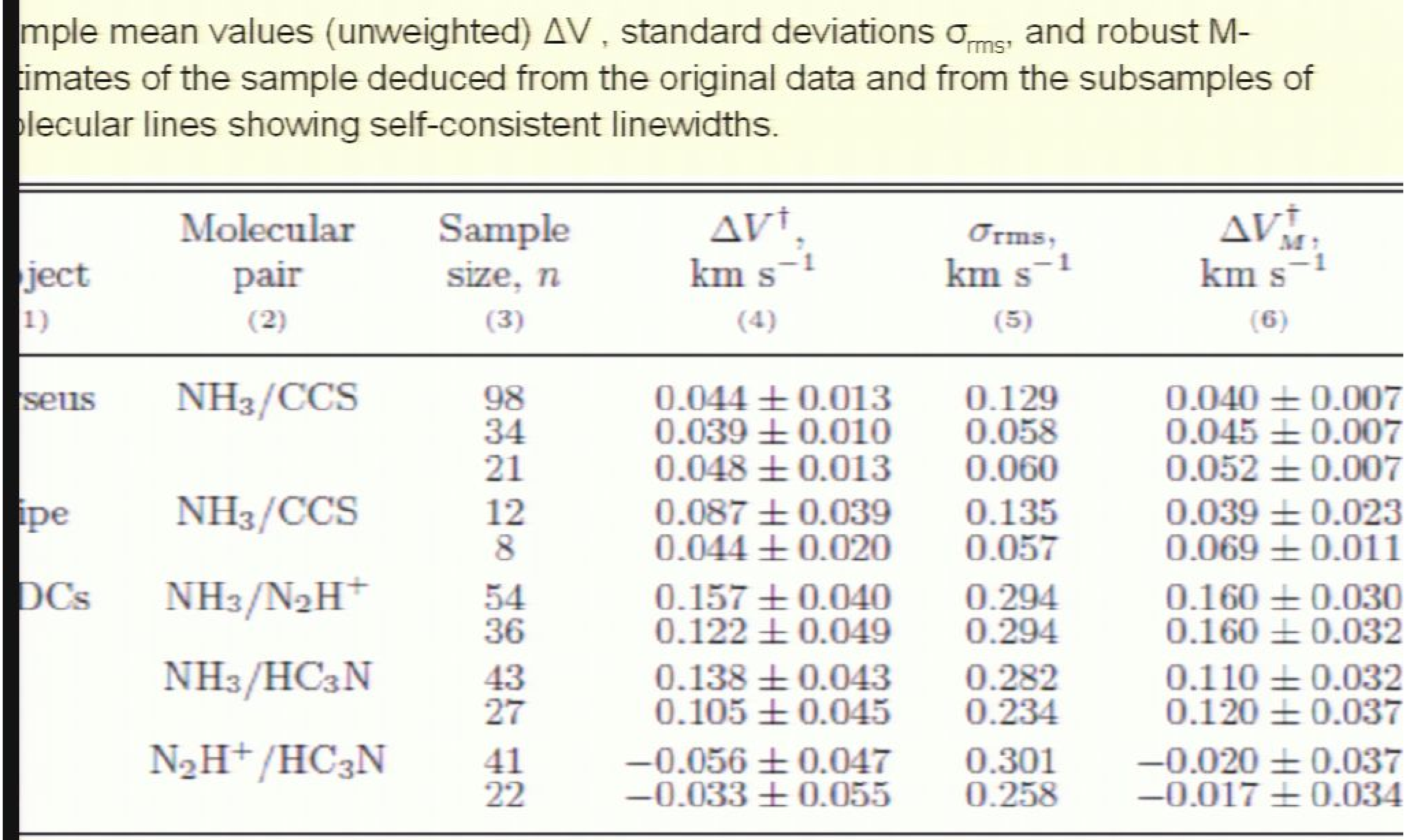
Infrared Dark Clouds (IRDCs)





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- These observations correspond to the time intervals from 400 years for Pipe Nebulae to ~10000 years for IRDCs. Such time-variation contradicts both laboratory and extragalactic observations.
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- It is possible to link such variation to the local matter density as suggested in some chamelion-type scalar field models.

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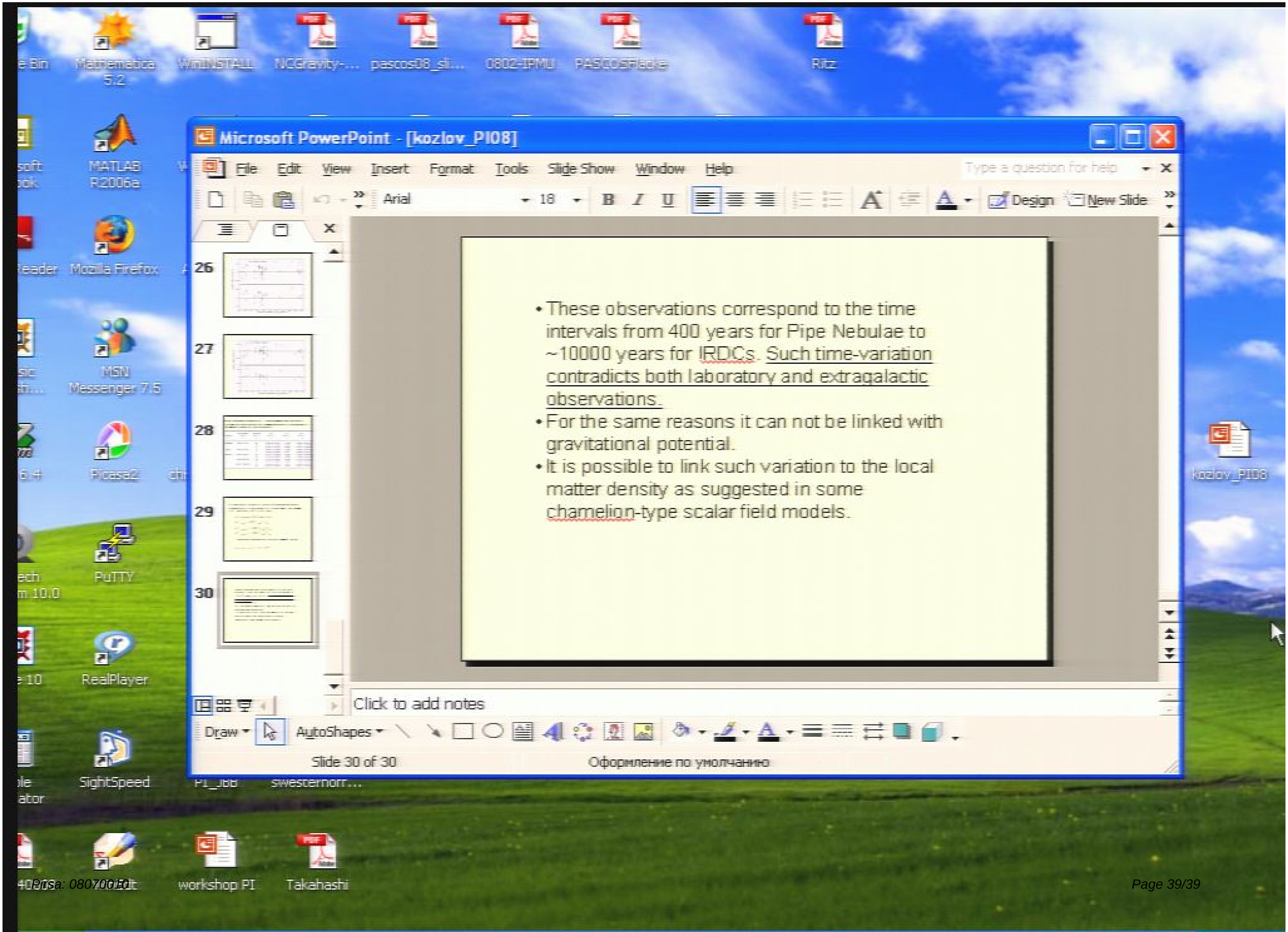

- These observations correspond to the time intervals from 400 years for Pipe Nebulae to ~10000 years for IRDCs. Such time-variation contradicts both laboratory and extragalactic observations.
- For the same reasons it can not be linked with gravitational potential.
- It is possible to link such variation to the local matter density as suggested in some chamelion-type scalar field models.