Sight lines through the LISM with high Neutral Hydrogen column densities: What do they mean?

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NUVA meeting

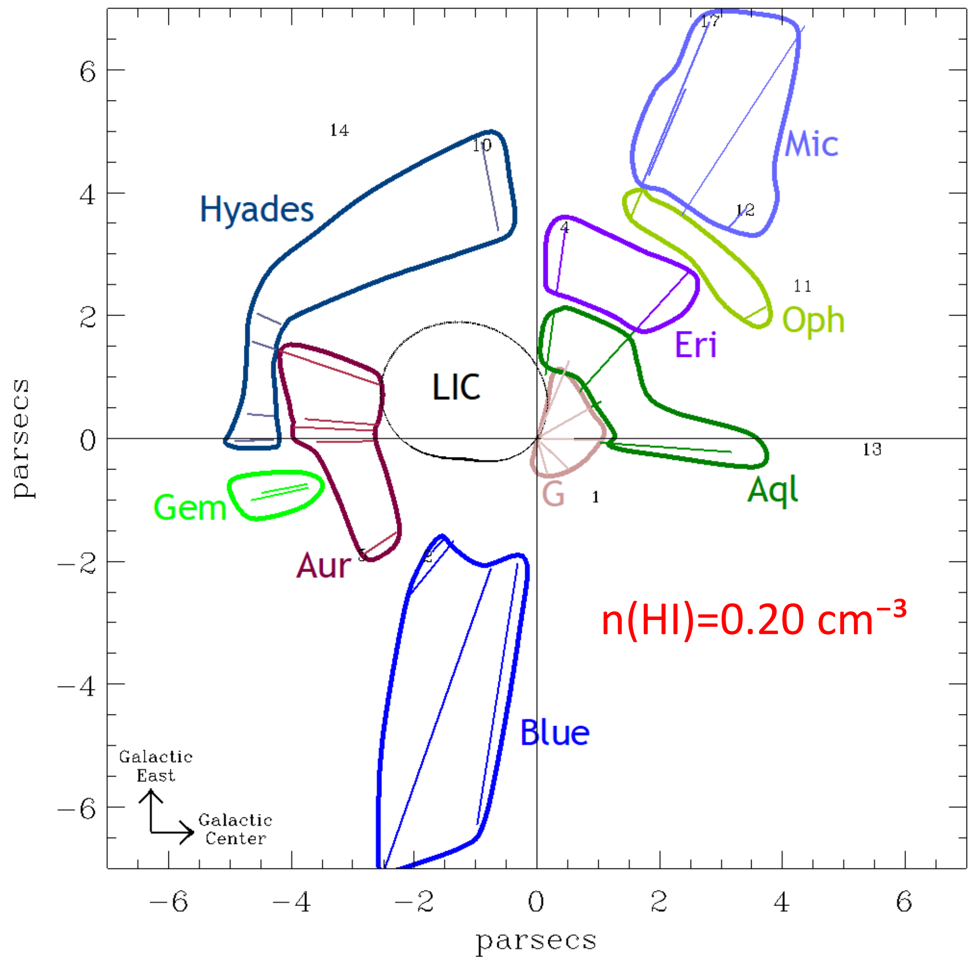
October 1, 2024

Revealing the inhomogeneity of the LISM

- Kinematic inhomogeneity: Within about 10 pc from the Sun, there are at least 15 structures defined by velocities consistent with individual velocity vectors. Each of these “clouds” has a mean temperature, density, and turbulent velocity: Linsky & Redfield (2008).
- Thermal and turbulent inhomogeneity: Within the LIC, there is a wide range of temperatures (3,000 K -12,000 K) and turbulent velocity (1 km/s to 5 km/s). The scale of thermal instability is <5,000 AU. Linsky et al. (2022).
- Morphological complexity: The reduction in neutral H density from 0.20 cm^{-3} to 0.10 cm^{-3} results in cloud overlap within at least 4 pc. Linsky et al. (2022).
- Rough pressure balance from outer heliosphere to Local Bubble. Linsky & Moebius (2023)
- Neutral H column density complexity: There are sightlines with anomalously high N(HI). Linsky & Redfield (to be submitted).
- Origen of the LIC and other clouds in the LISM (Zucker et al. submitted to ApJ)

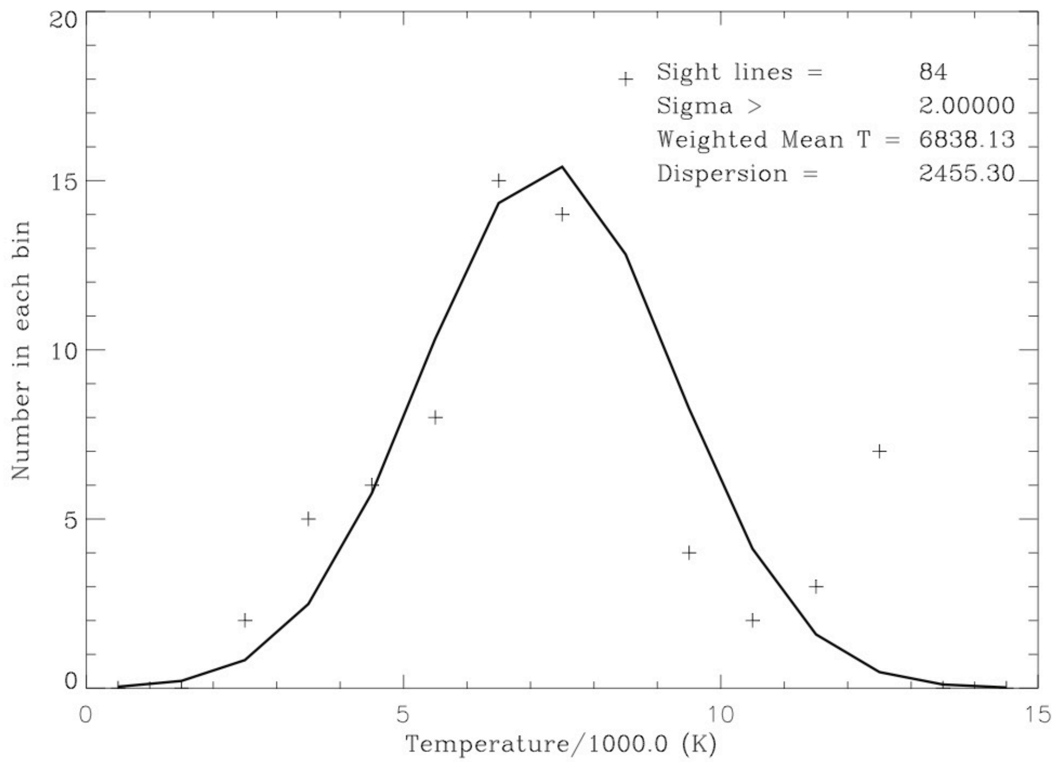
Future Model: n(HI)=0.10 cm^{-3} not 0.20 cm^{-3}

- Reducing n(HI) by a factor of 2 increases cloud sizes by a factor of 2 in all directions.
- As a result, the clouds fill all space out to at least 4 pc.
- If n(HI)≈0.10 cm^{-3} in all clouds, then there will be many regions of overlap and no inter-cloud medium within 4 pc.
- Beyond 4 pc the clouds appear to fill a decreasing fraction of space with distance and inter-cloud ionized gas between the clouds.

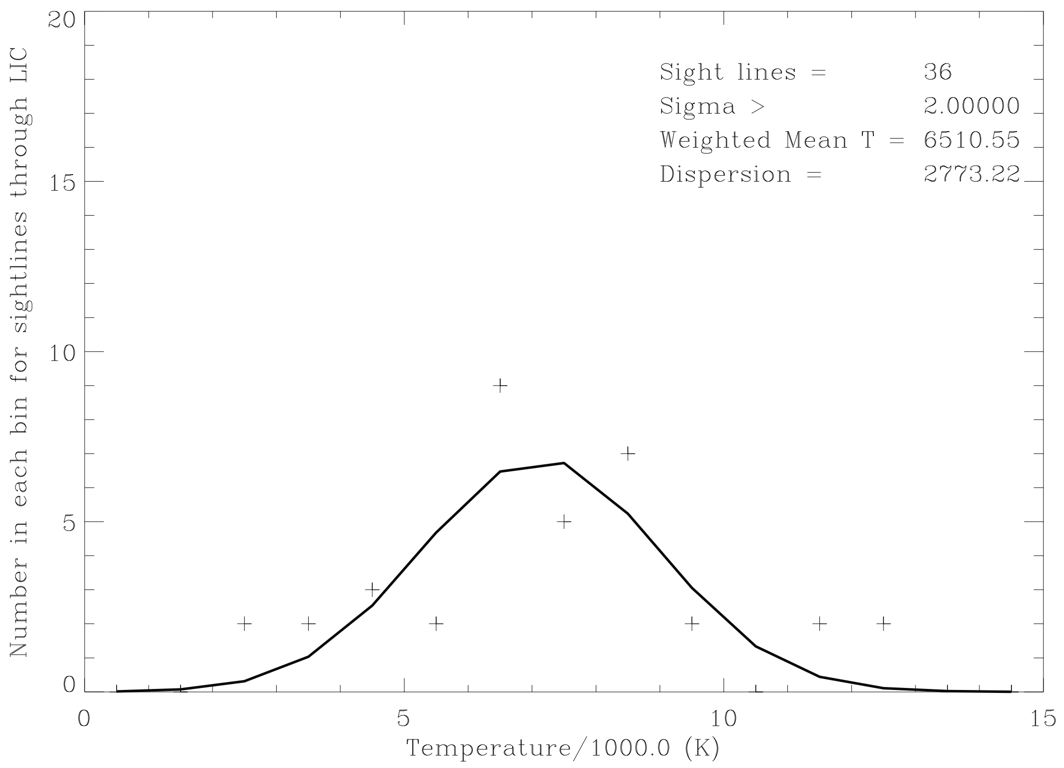


Redfield & Linsky (2002); Linsky, Redfield, & Tilipman (2019); Frisch, Redfield, & Slavin (2011)

For 84 (≥2σ) sightlines through the LISM and 36 through the LIC. What are the distributions of temperatures? Data are binned. Gaussian fits.



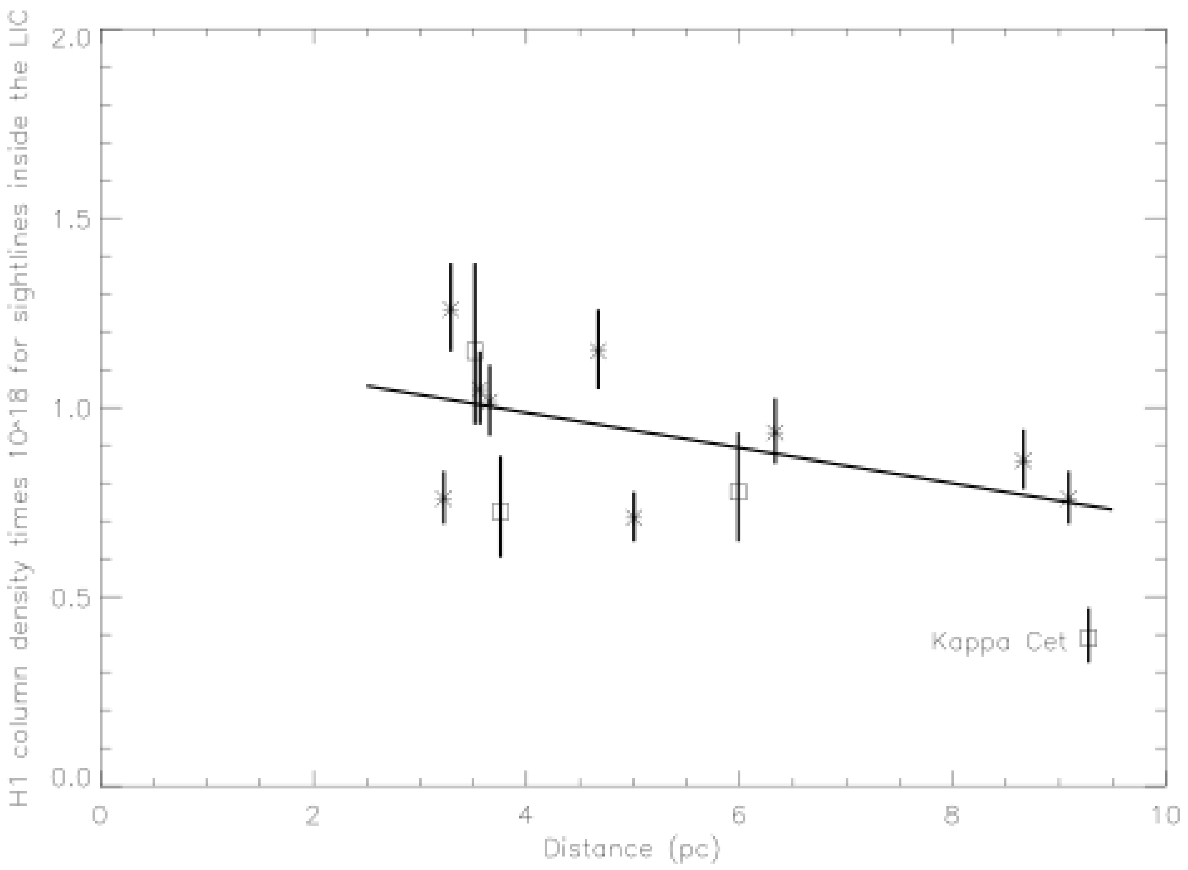
Mean=6,838±2,455 K



Mean=6,510±2,773 K

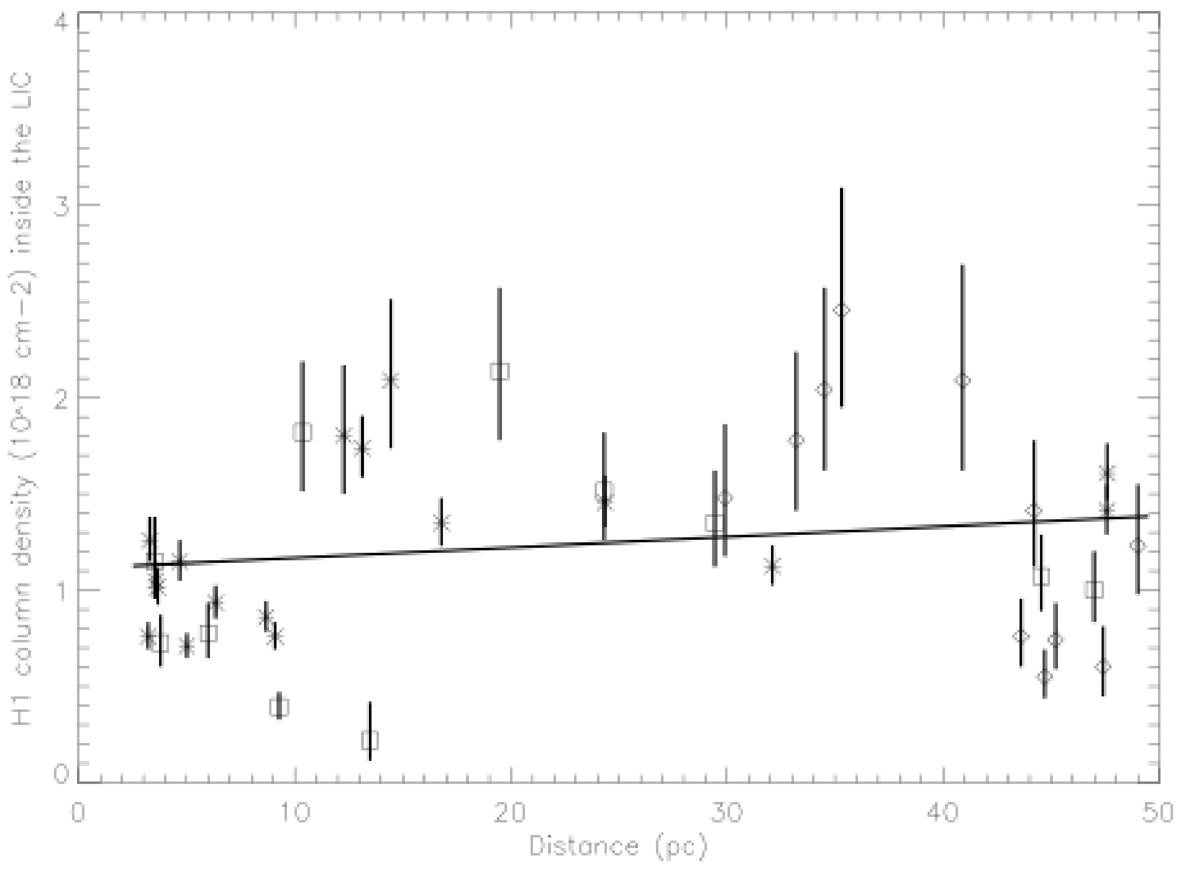
Do the HI column densities fit a simple pattern? First consider only sightlines with LIC velocities

- HI column density vs. distance to stars with interstellar absorption at the LIC cloud velocity vector and inside the LIC outer contours (HST/STIS spectra).
- * symbols for one component sightlines (errors about 10%).
- Squares are for sightlines with absorption also for other clouds (errors about 20%).
- N(HI)≈1x10^18 cm^{-2} at 3-4 pc then no additional N(HI) at larger distances.
- Mean scatter about the least-squares fit is 19%.
- Best fit line has a negative slope but addition sight lines are needed to support this negative slope.



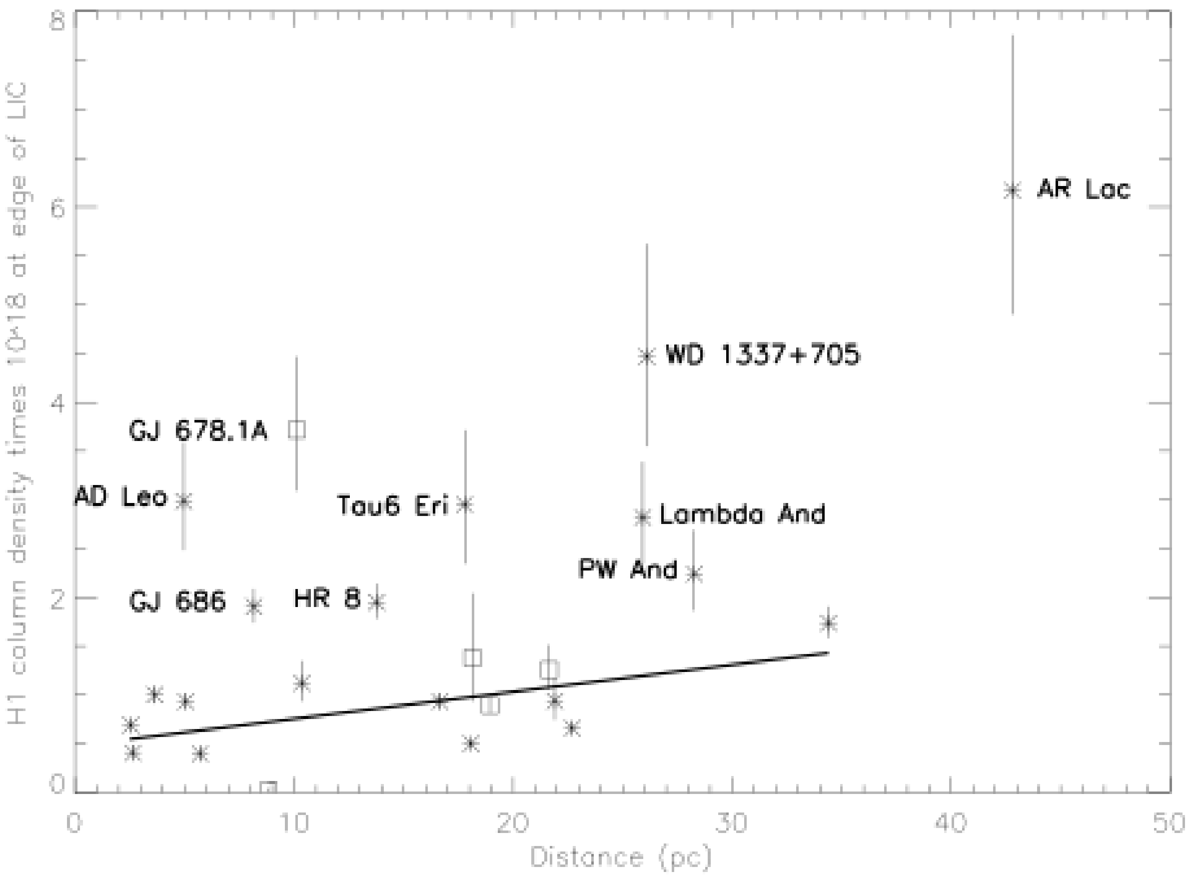
Now extend our perspective to LIC sight lines out to 50 pc?

- Sight lines with LIC velocity and located within the LIC outer contours.
- Mean scatter about the least-squares fit is much larger, 52%
- No evidence of a systematic increase in N(HI) with distance but greater range in N(HI)



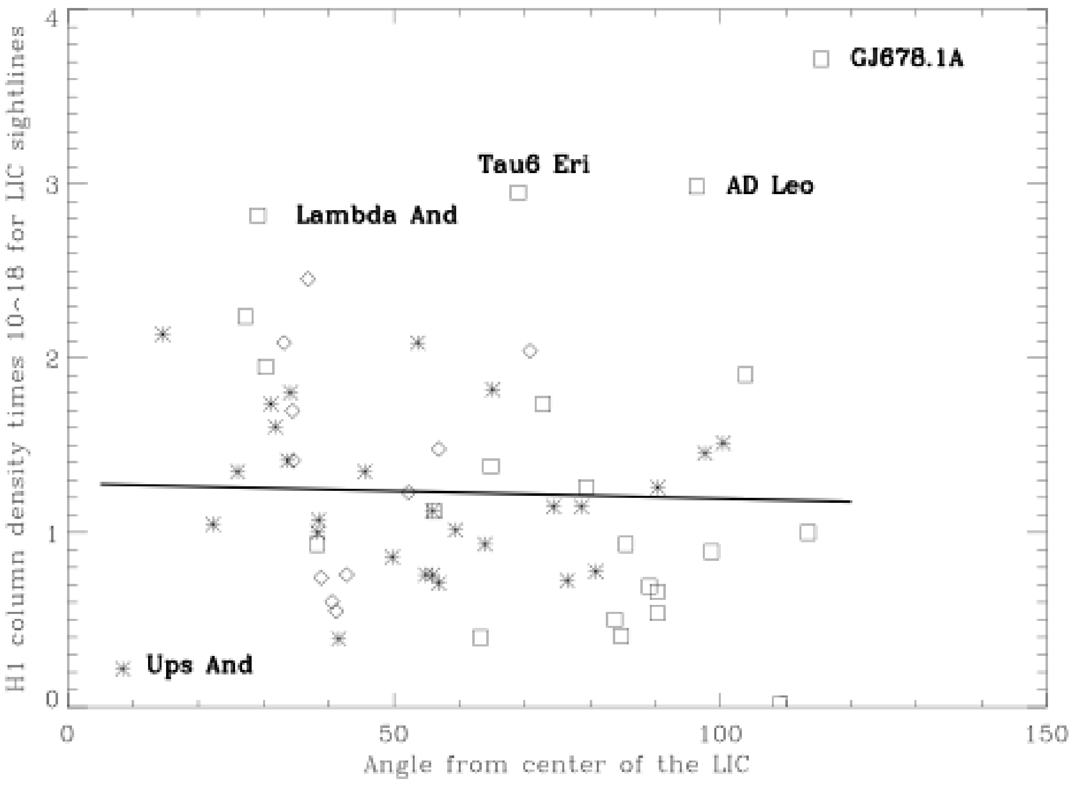
Now consider sight lines at the edge of or just beyond the LIC

- All of these sight lines have the LIC velocity.
- * symbols are the sight lines at the edge of the LIC outer contours.
- Square symbols are for sight lines just beyond the edge of the LIC outer contours.
- Note the sightlines with high N(HI) larger than 3×10^{18}.



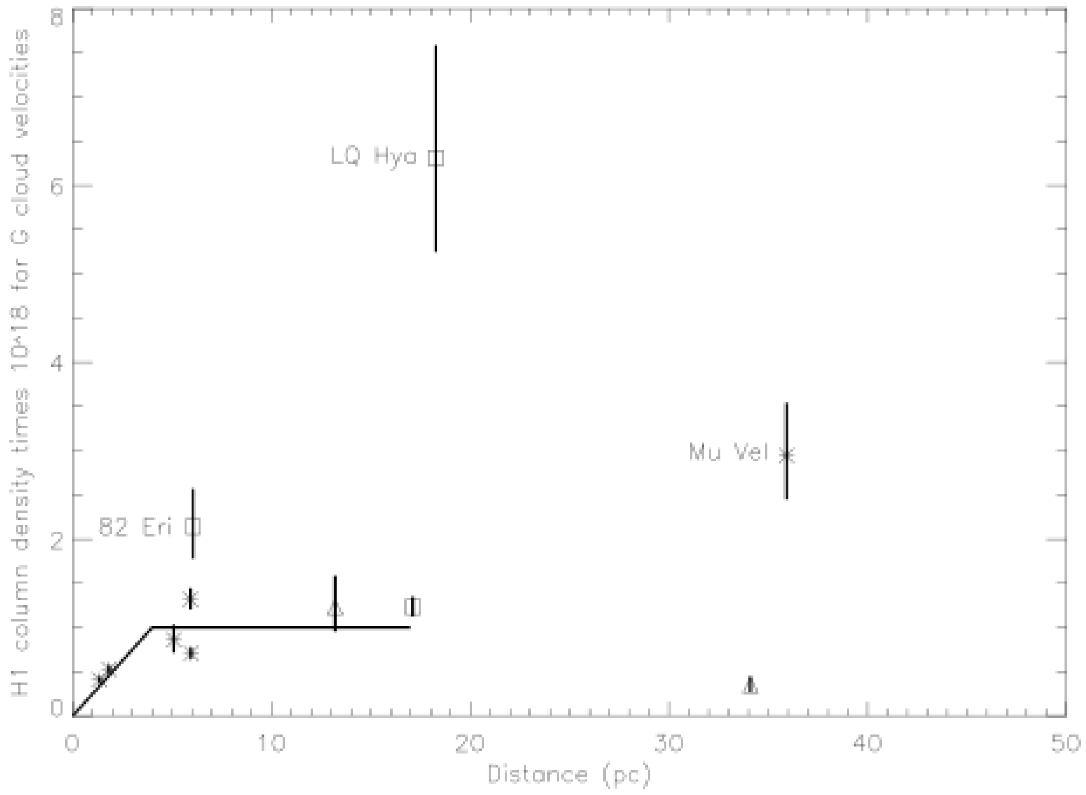
N(HI) for LIC sight lines as a function of angle from the center of the LIC (l=140°, b=-17°)

- All data plotted as a function of angle with respect to LIC center direction have LIC velocities.
- * and diamond data are inside the LIC outer contours.
- Square data are for sight lines at the edge of the LIC outer contours or just beyond.
- Note that the edge and beyond sight lines are either very high or very low. Why?



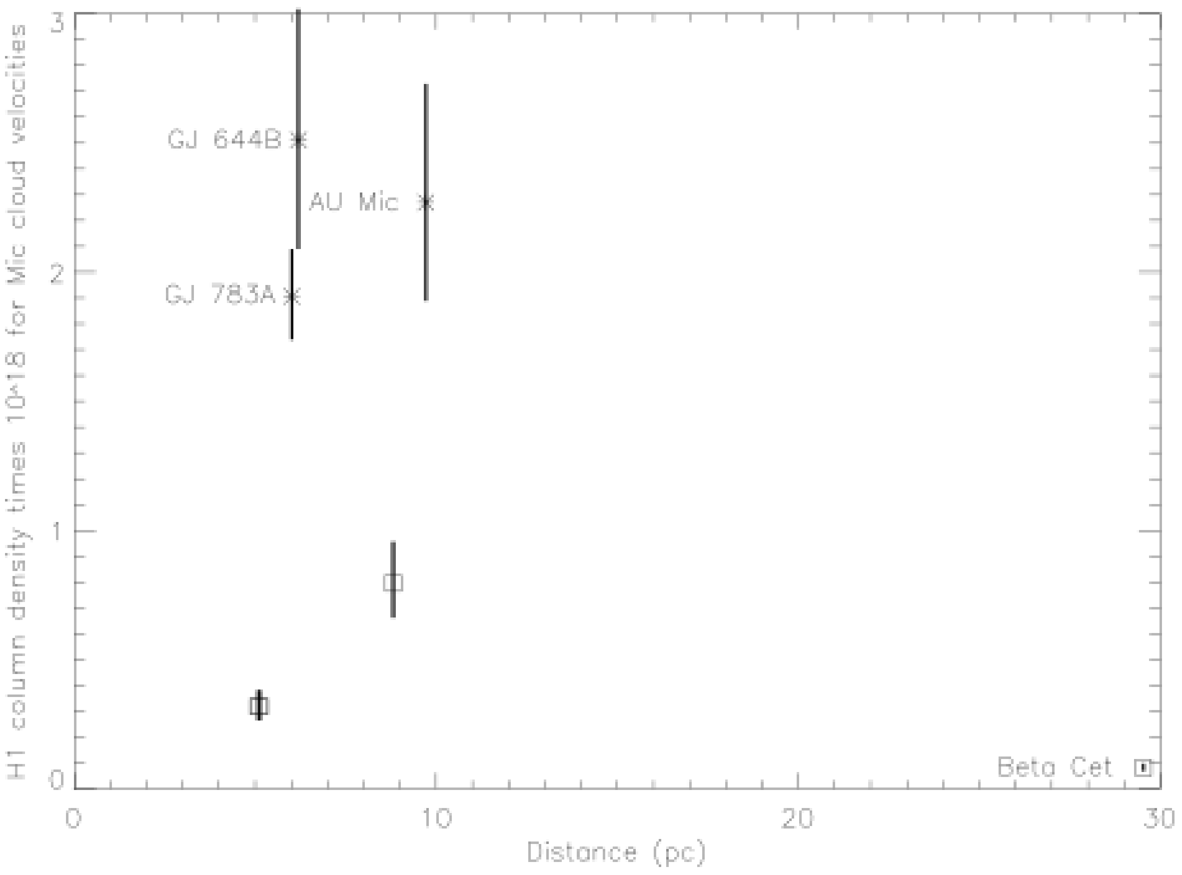
N(HI) for sight lines through the G cloud

- Fewer sight lines but all have the G cloud velocity.
- * symbols are for sight lines inside the G cloud.
- Square symbols are for sight lines at edge of the G cloud.
- N(HI) in G cloud builds up to aboiut 3 pc then little additional N(HI) beyond.
- LQ Hya is clearly anomalous and 82 Eri and Mu Vel may look high.



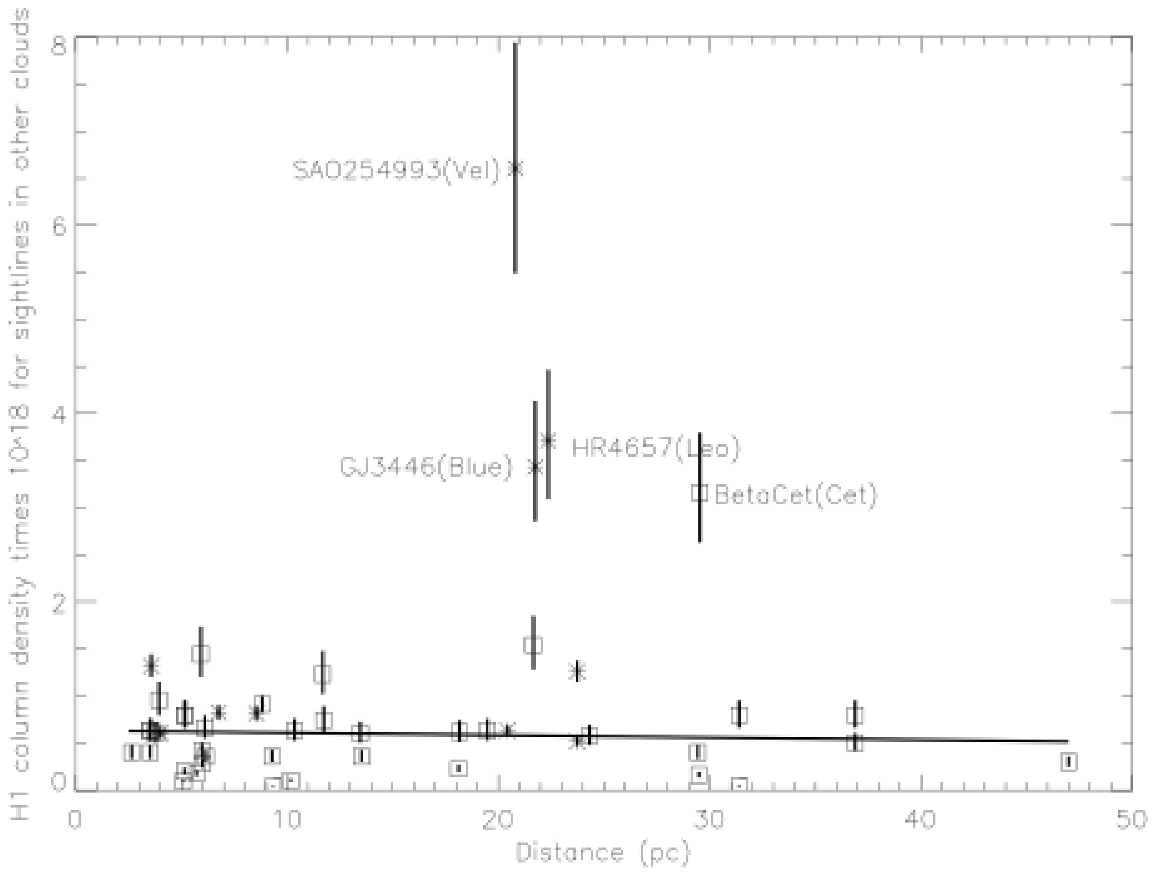
N(HI) for sight lines through the Mic cloud

- Only 6 sight lines with the Mic cloud velocity.
- 3 are high and 3 are low.
- Mic clouds is filamentary, highest T, and lowest Mg and Fe depletions of the 15 clouds.
- Could be a post-shock front with the 3 high points near the shock and the 3 low point further away.



N(HI) for sight lines through other clouds

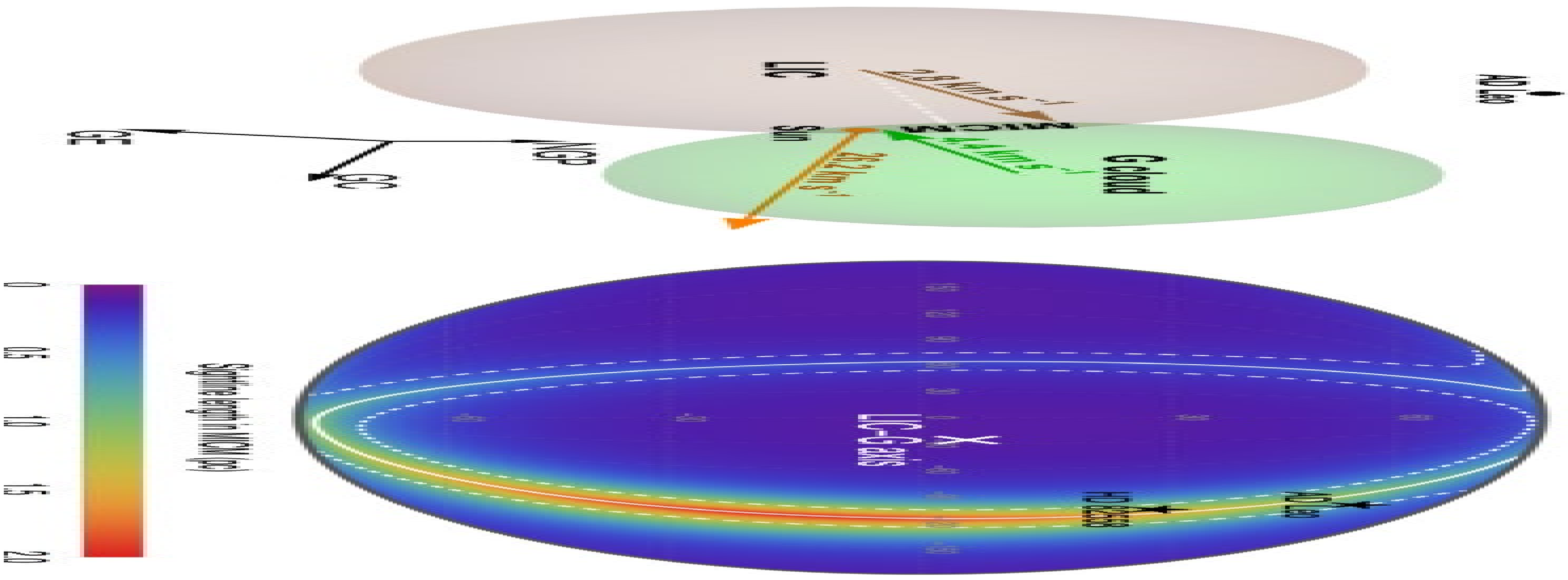
- * symbols are for single velocity components.
- Square symbols are for sight lines with multiple velocity components.
- Most of the data have N(HI) near 0.7x10^18.
- Four sight lines are anomalously high (>4 times mean N(HI)).



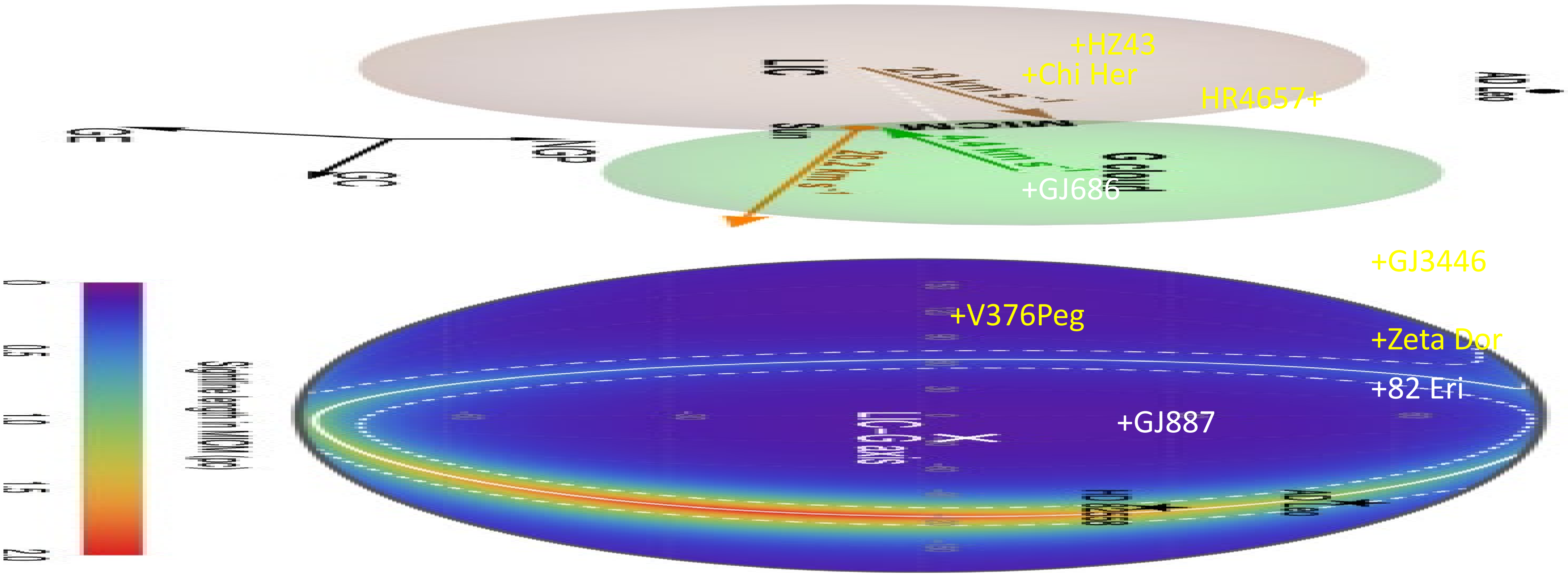
Possible explanations for the high N(HI) sight lines

- LIC/G cloud overlap region with sight line perpendicular to the LIC/G cloud axis (Swaczyna et al. ApJ 937,L32 (2022)).
- Sight line perpendicular to the axis of two other clouds.
- Sight line viewed through edge of the LIC or another cloud with a longer path length.
- Sight line through a shock or post-shock front (Mic cloud).
- Sight line through a wake or bow shock of a fast moving star through the ISM (Shull & Kulkarni ApJ 951, 35 (2023)).
- Sight line through a SN shell (almost exactly the same direction as perpendicular to the LIC/G axis (Zucker et al. submitted to ApJ).

Mixed LIC+C cloud and 2 stars viewed along the great circle (Swaczyna et al. 2022)

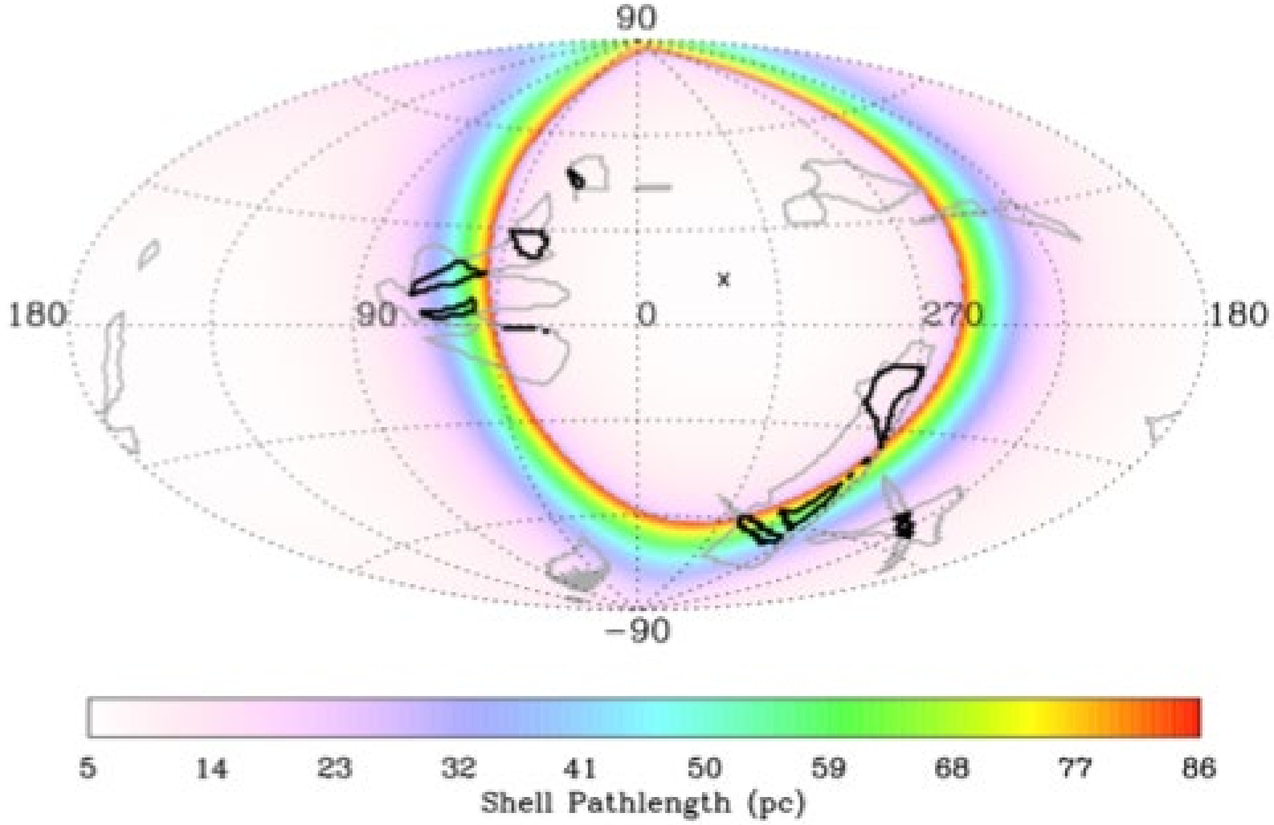


Location of 6 new stars (yellow) with other cloud velocities and high N(HI) along the great circle

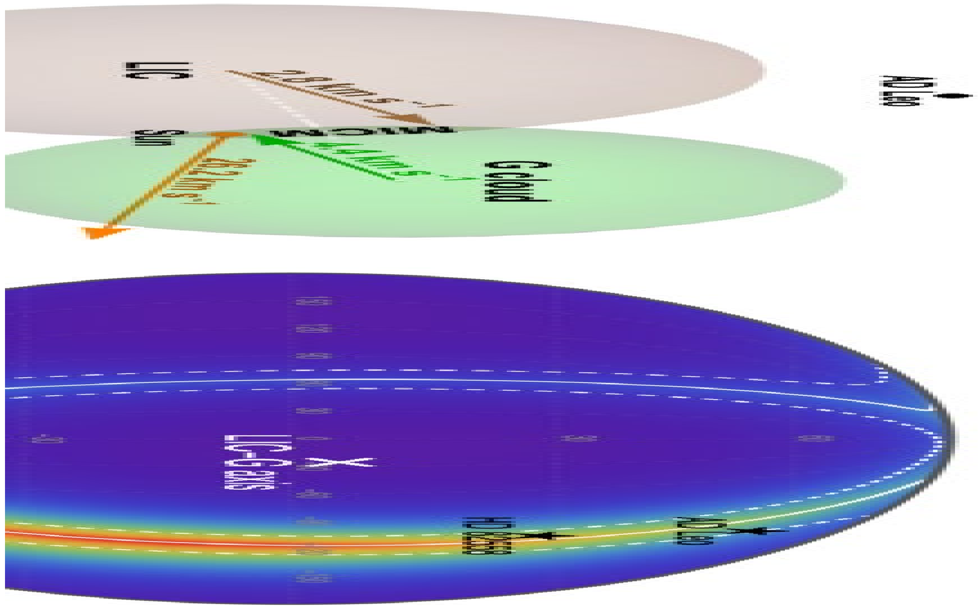


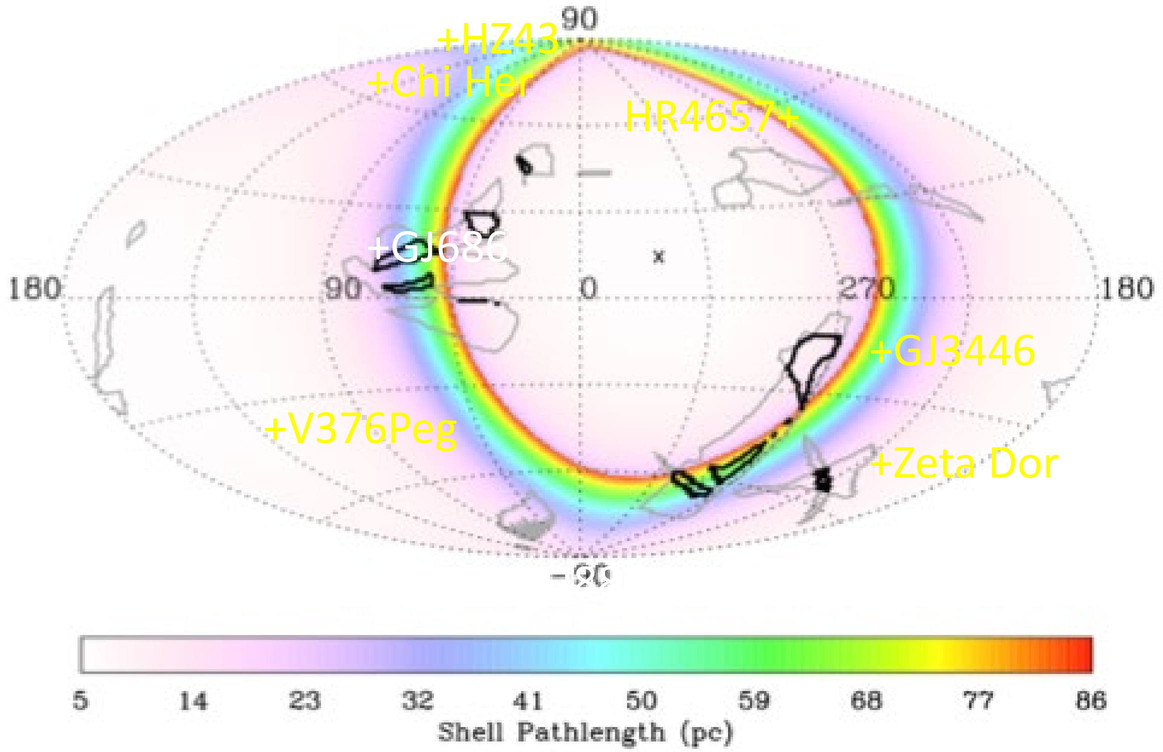
Shell of the most recent nearby SN

- Model of the evolution of the SN shock wave from the last SN 1.22 M years ago (Zucker et al. ApJ submitted).
- Produces a swept up shell located 30-90 pc from Sun.
- N(HI)≈$1.4x10^{18}$ cm^{-2} in the shell



Note that the LIC/G perpendicular circle and the SN shell circle are very similar





Axis direction: l=332.5°, b=+5°

Center of shell: l=330°, b=+14°

HD	Star name	Cloud	$N(\mathrm{HI})/10^{18}$ cm^2	d(pc)	$< n(\mathrm{HI}) >$	θ	Explanation
···	GJ754	unassigned	1.45	5.909	0.0795	34.8	unknown
152751	GJ644B	Mic	2.51	6.195	0.131	40.7	shock
203244	SAO254993	Vel	6.61	20.806	0.103	44.5	unknown
191408	GJ783A	Mic	1.91	6.012	0.103	47.6	shock
93497	μ Vel	G	2.94	35.920	0.0265	49.3	unknown
197481	AU Mic	Mic	2.37	9.714	0.0791	56.1	shock
···	GJ678.1A	LIC outside	3.72	10.117	0.119	56.5	LIC/G circle or SN shell?
106516	HR4657	Leo	3.72	22.351	0.0539	59.0	LIC/G circle or SN shell?
···	GJ686	LIC edge	1.91	8.160	0.0759	69.5	LIC/G circle or SN shell
59967	GJ3446	Blue	3.44	21.752	0.0512	83.0	LIC/G circle or SN shell
82558	LQ Hya	G outside	6.31	18.269	0.112	85.8	LIC/G circle or SN shell
142373	χ Her	NGP	1.78	15.898	0.0362	89.5	LIC/G circle or SN shell
20794	82 Eri	G edge	2.14	6.041	0.115	89.6	LIC/G circle or SN shell
nodata	AD Leo	LIC edge	2.99	4.965	0.195	100.5	LIC/G circle or SSN shell
4128	β Cet	Cet	3.16	29.533	0.0347	102.0	LIC/G circle or DN shell
166	HR8	LIC edge	1.95	13.766	0.0459	132.6	unknown
1405	PW And	LIC edge	2.24	28.270	0.0257	135.8	unknown
22107	λ And	LIC edge	2.82	25.924	0.0352	137.0	unknown
1326	GJ15A	Hya	1.32	3.562	0.119	142.6	unknown
Mean LIC column		LIC	1.1				
Mean G column		G	1.0				
Anomalous mean		All	2.91				

* Angles between the LIC/G axis and sightlines to stars are computed from θ =acos[sin(bstar)*sin(baxis)+cos(bstar)*cos(baxis)*cos(lstar-laxis)], where lstar and bstar are the Galactic coordinates of the star and laxis= 332.5° and baxis=5.0° are the coordinates of the LIC/G axis directed toward the center of the G cloud.

Conclusions

- In the LISM (d<10 pc) temperatures are inhomogeneous if a thermal plasma. If the plasma is nonthermal, then the high T could be explained by supra-thermal atoms and ions. See Linsky et al. AJ 164, 106 (2022).
- Neutral hydrogen column densities and number densities for sightlines at the LIC and G cloud velocities indicate that these clouds extend only to 2-3 pc with no additional neutral hydrogen beyond this distance.
- In some directions N(HI) are far above average for the LIC and other clouds suggesting overlapping clouds (AD Leo, GJ686, 82 Leo, etc.) Since $\langle n(HI)\rangle \approx 0.10$ cm^{-3} rather than 0.20 cm^{-3}, clouds should overlap.
- 6-9 high N(HI) sightlines lie along the LIC/G great circle and the SN shell. Other high N(HI) sightlines may lie on other great circles where clouds overlap.
- There other physical processes that could explain high N(HI) sightlines.
- More data in the pipeline.

Interstellar n(H I) is inconsistent with n(H I) flowing into the heliosphere

- Measurements of n(HeI)and theoretical models of LISM gas flowing into the heliosphere identify n(HI)=0.20 cm^{-3}.
- For the 37 stars within 10 pc, plot the filling factor (ff) assuming n(HI)=0.20cm^{-3}.
- Except AD Leo, all sightlines have ff<0.63 and ff decreases with distance.
- 4 nearby stars with only LIC absorption (red dots) have observed astrospheres, so must be surrounded by neutral hydrogen, so LIC must fill their entire sightlines, and n(HI)=0.10 cm^{-3} in the LIC.
- If the LIC is typical of nearby clouds, then within 4 pc, n(HI)≈0.10 cm^{-3}.