The Physical Properties of the Local Interstellar Medium

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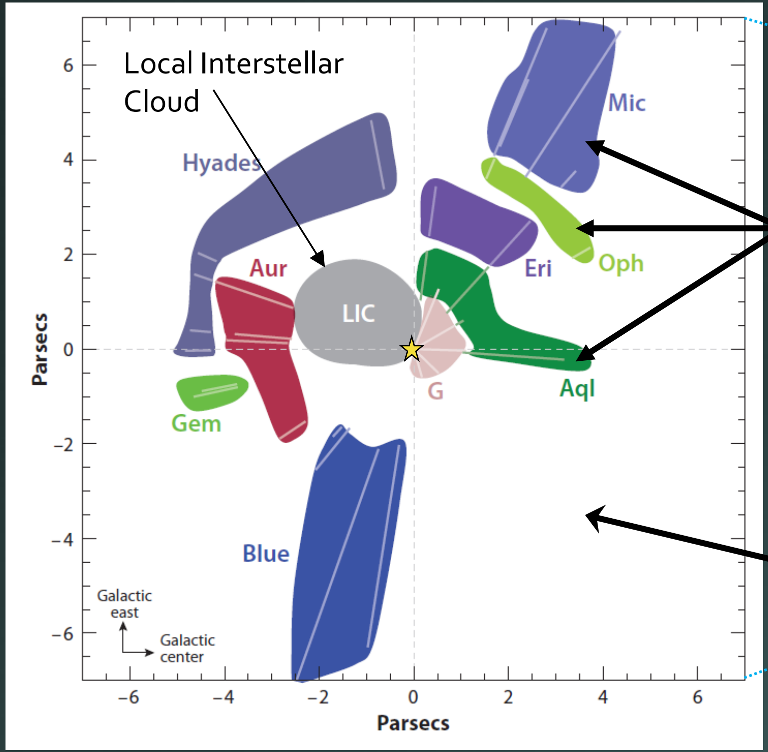
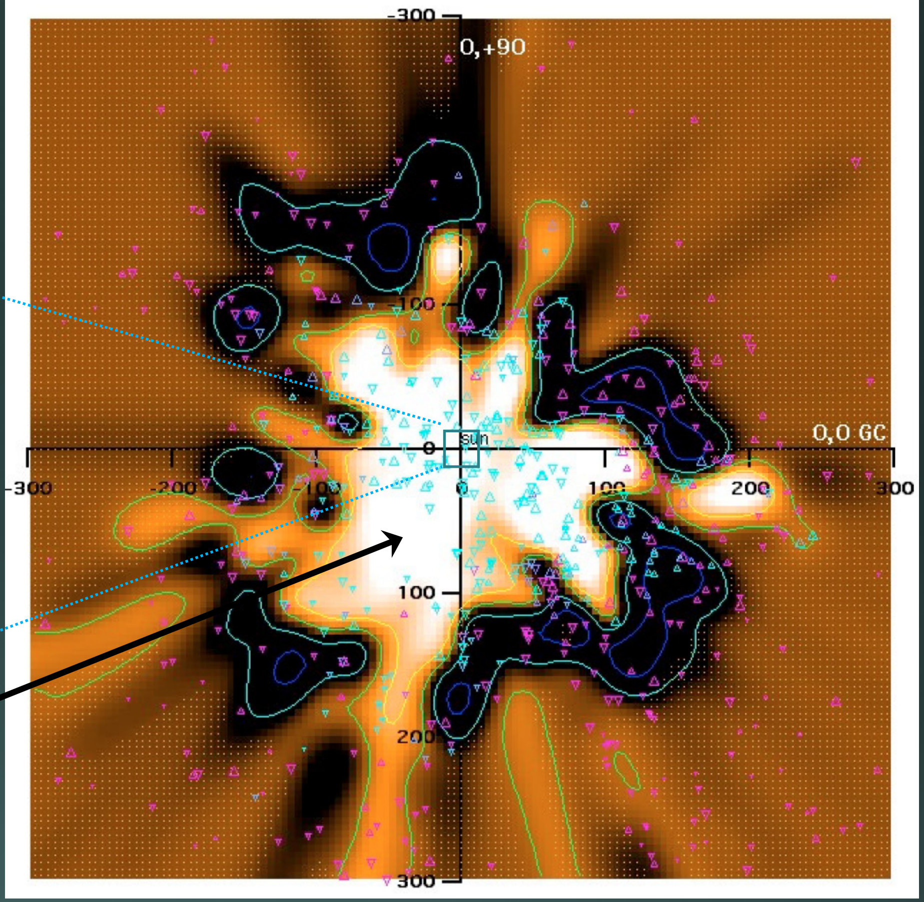
Orientation to the Local Interstellar Medium

The Complex of Local Interstellar Clouds



From Frisch, Redfield & Slavin (2011)

The Local Bubble/Local Cavity



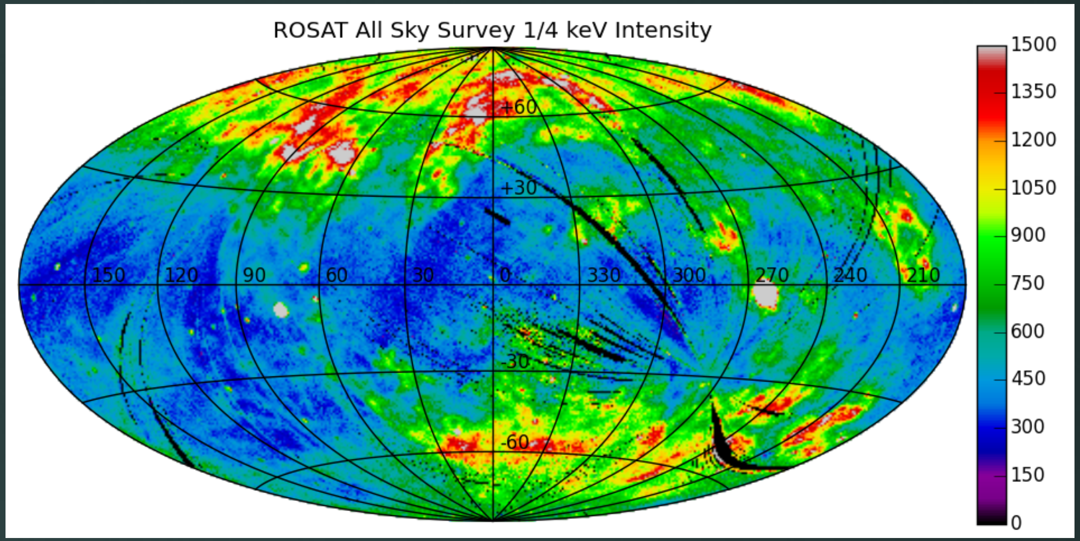
From Welsh et al. (2010) based on NaI data

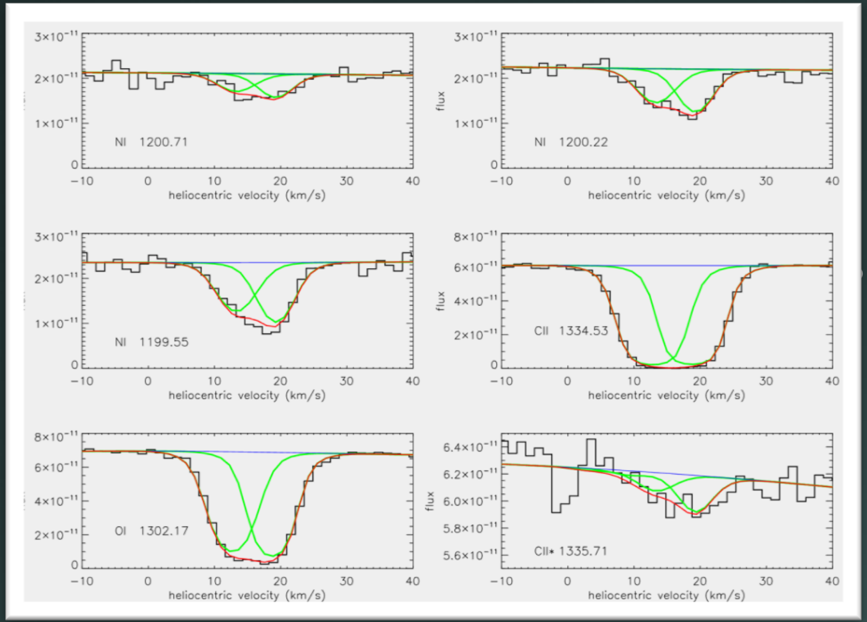
Warm gas
(T ~ 7000 K)

Hot gas
(T ~ 10^6 K)

Local ISM properties

- Local Hot Bubble
  - $T \sim 10^6$ K, very low density $n \sim 0.005$ cm^{-3}
  - observed via soft X-ray emission





- Complex of Local Interstellar Clouds (CLIC)
  - Collection of ~ 15 clouds within 15 pc of the Sun
  - Warm and partially ionized, $T \sim 4000 - 9000$ K, $X(H^+) \sim 0.25$
  - Observed mostly by UV absorption lines
  - Share (roughly) a velocity opposite Sco-Cen bubble

The Local Bubble

- Recent observations (Galeazzi et al. 2014) show ~60% of observed diffuse soft X-ray background comes from hot gas in the Local Bubble (in Galactic plane, more at high latitude) – rest is from heliospheric emission (SWCX)
- Brightness of emission varies but temperature, $T \sim 10^6$ K, appears fairly constant
- Thermal pressure needed to explain brightness is $P/k_B \sim 10^4$ cm^{-3}K – substantially larger than LIC thermal pressure of ~ 2000 – 3000 cm^{-3}K

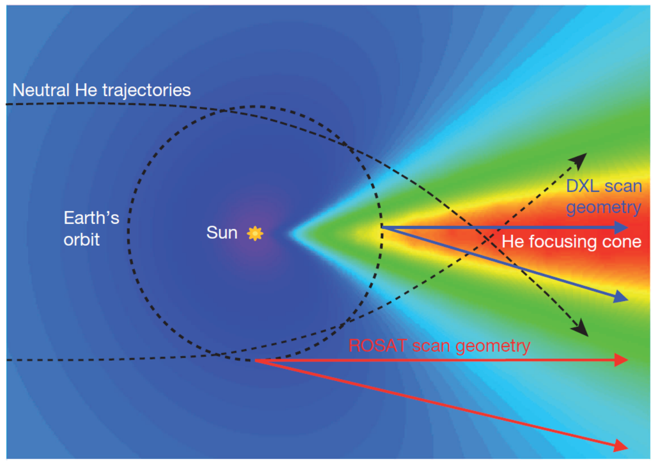
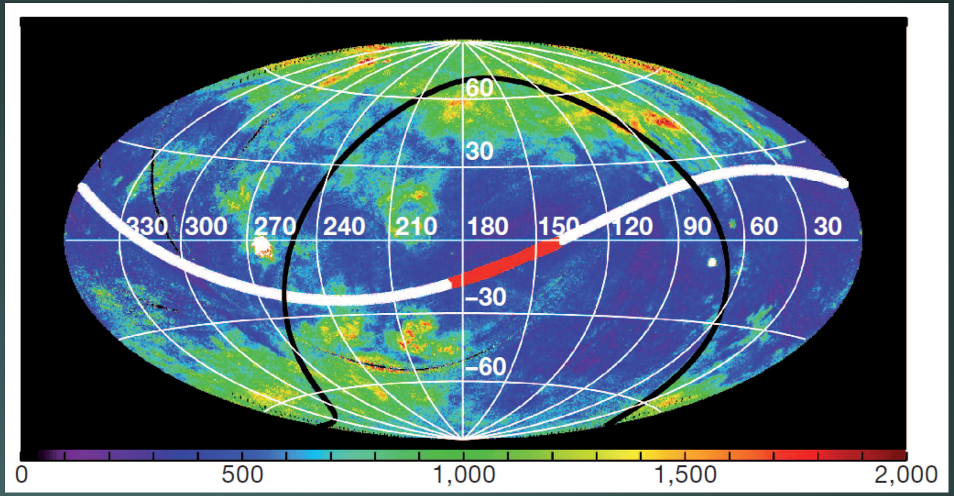


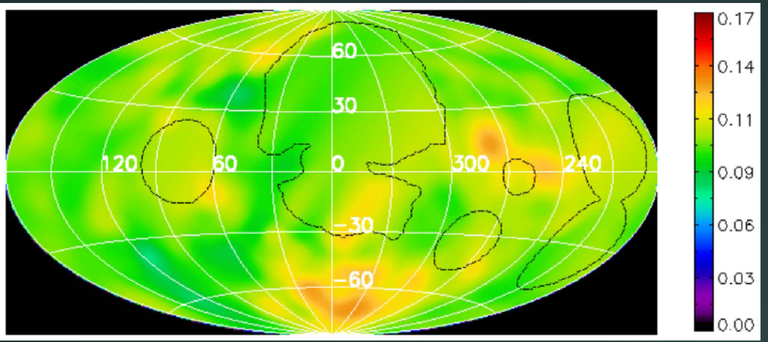
Figure 1 | The He focusing cone. Modelled interstellar He density (blue is low density; red is high density) showing the He focusing cone. Keplerian He orbits, Earth's orbit, and the DXL and ROSAT observing geometries are also shown.

From Galeazzi et al. 2014

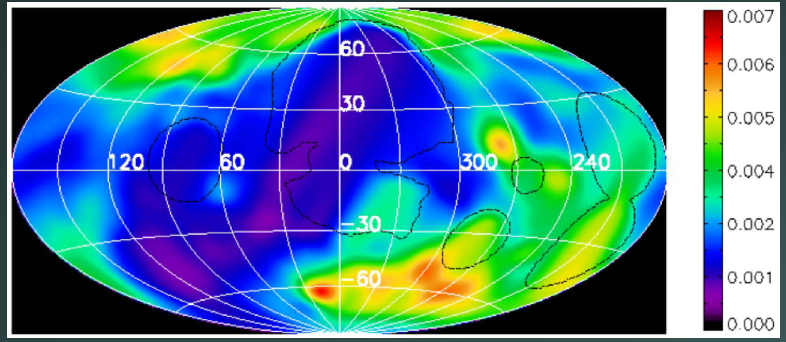


Local Bubble Structure

Assuming uniform temperature and emissivity, can go from intensity to path length. Liu et al. (2017) created background maps cleaned of SWCX emission

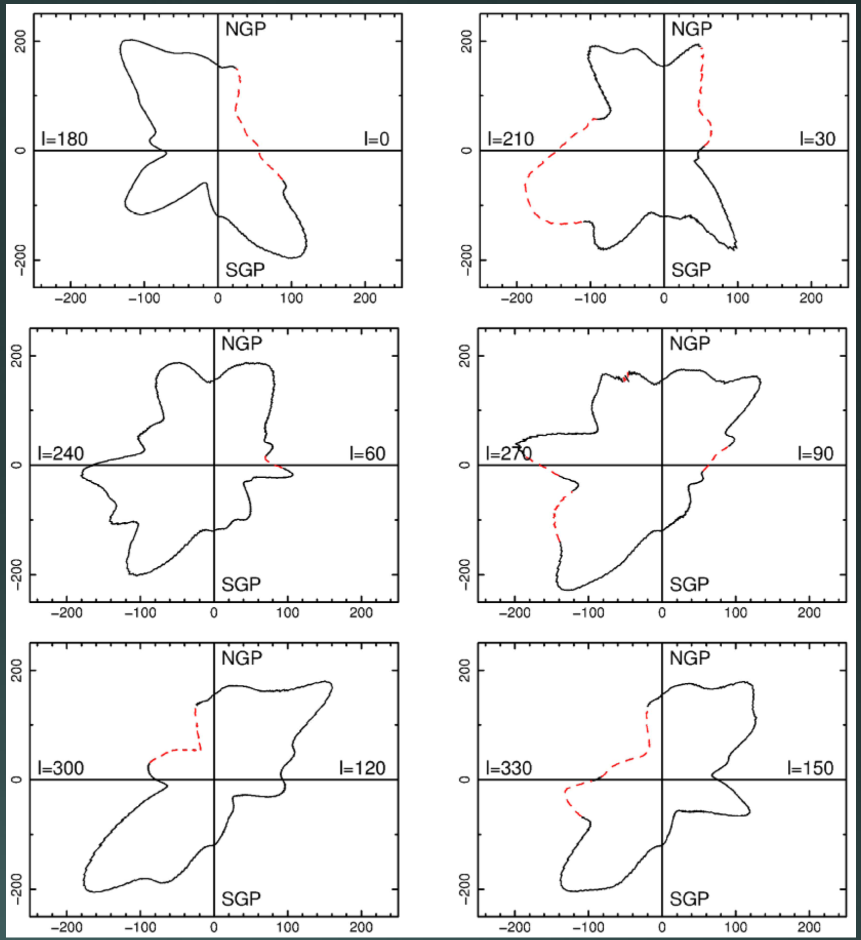


Temperature in keV



Emission measure in $cm^{-6}pc$

Derived Local Bubble shape



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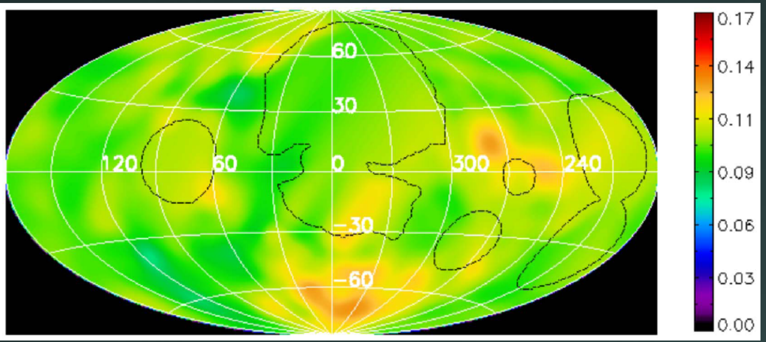
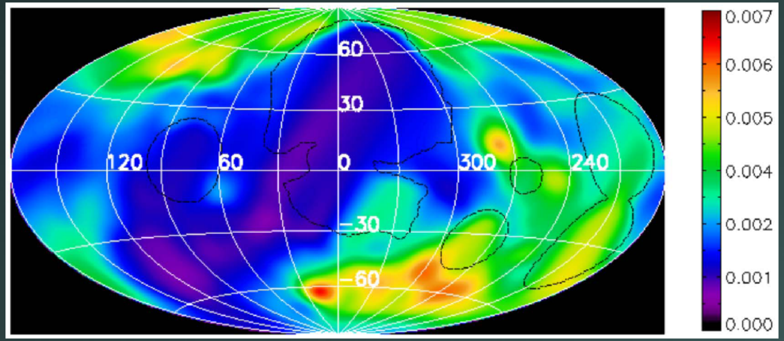


Temperature in keV



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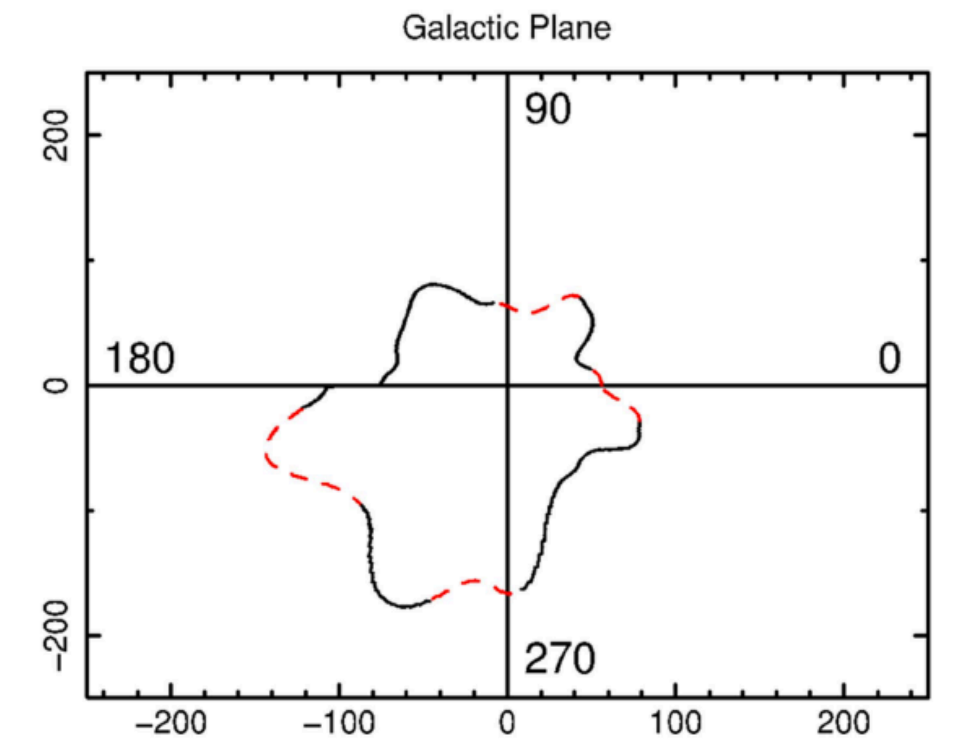
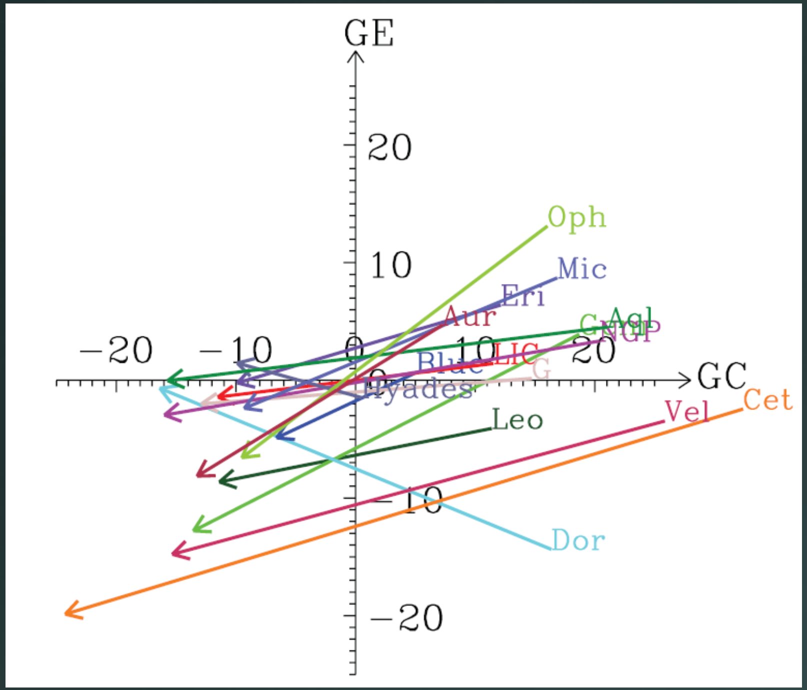


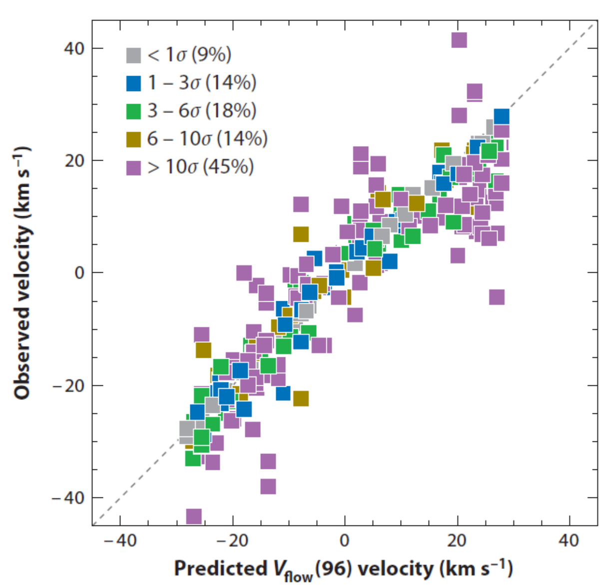
Figure 8. The radius of the LHB in great-circle cuts through the Galactic plane. The red dashed line corresponds to directions of non-LHB bright extended sources.

From Liu et al. (2017)

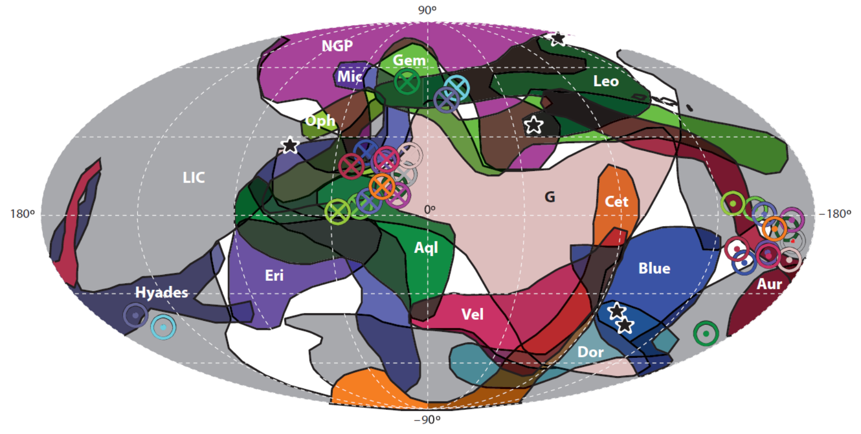
The Complex of Local Interstellar Clouds (CLIC)



Derived space velocities of the clouds in the CLIC



CLIC velocity components relative to mean velocity



Distribution of CLIC over the sky

The CLIC is a grouping of warm interstellar clouds within 15 pc of the Sun, surrounding us in all directions and moving with a similar velocity

Cloud Interactions in the CLIC

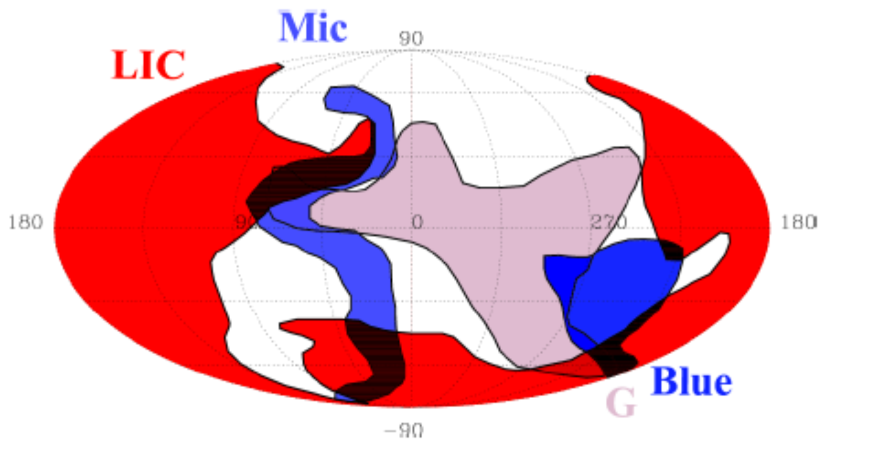


Figure 1. The four closest LISM clouds (LIC, G, Blue, and Mic) to the heliosphere plotted in Galactic coordinates. The Galactic Center is at the center of the plot. Figure from [1].

From Linsky et al. (2016)

Signatures of cloud-cloud interactions? Morphology of LIC/Blue Cloud/Mic suggests it

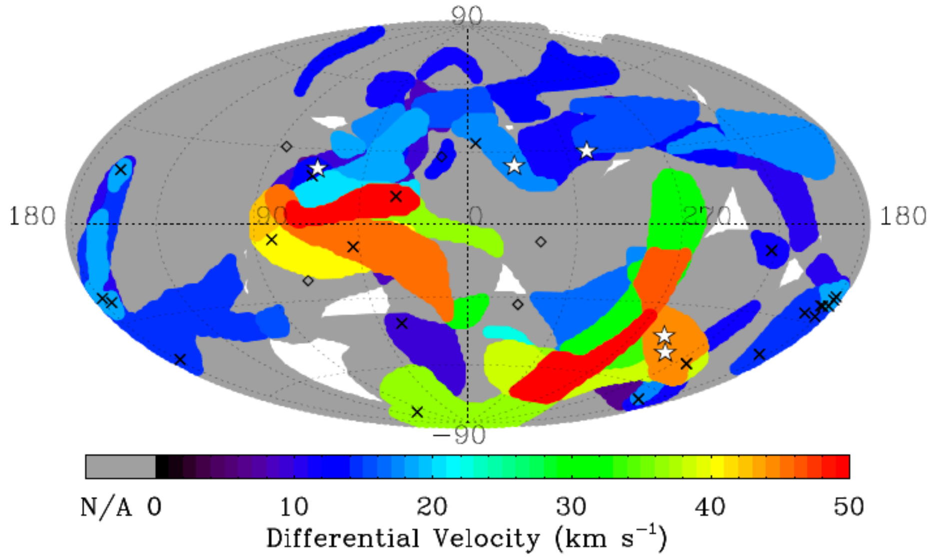
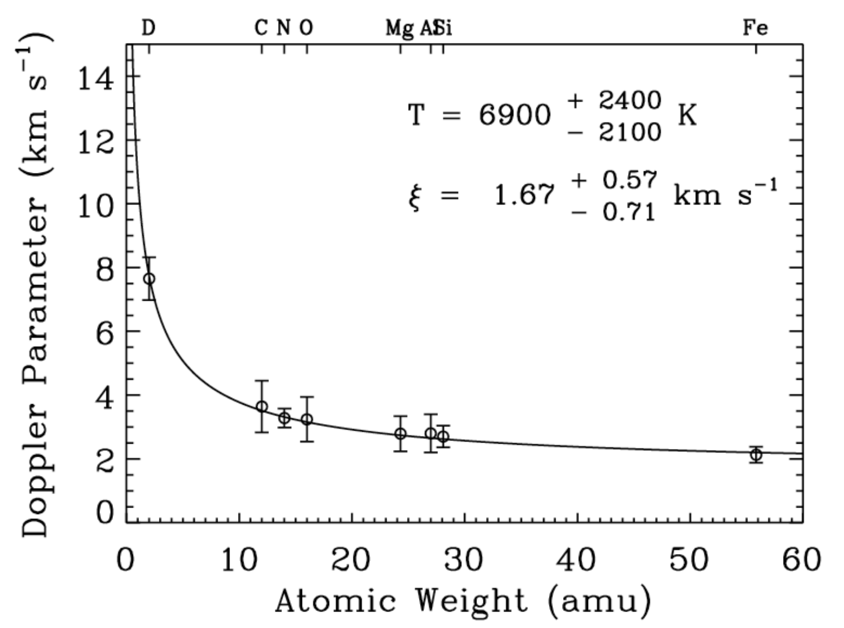


Figure 2. Zones of LISM cloud interactions. Colored regions indicate directions in which multiple LISM clouds are detected along the line of sight. Figure from [5].

Cloud relative velocities also suggest cloud-cloud interactions. **Interstellar scintillation** seen toward quasars is consistent with scattering screens at locations of possible cloud interaction (Linsky et al. 2008)

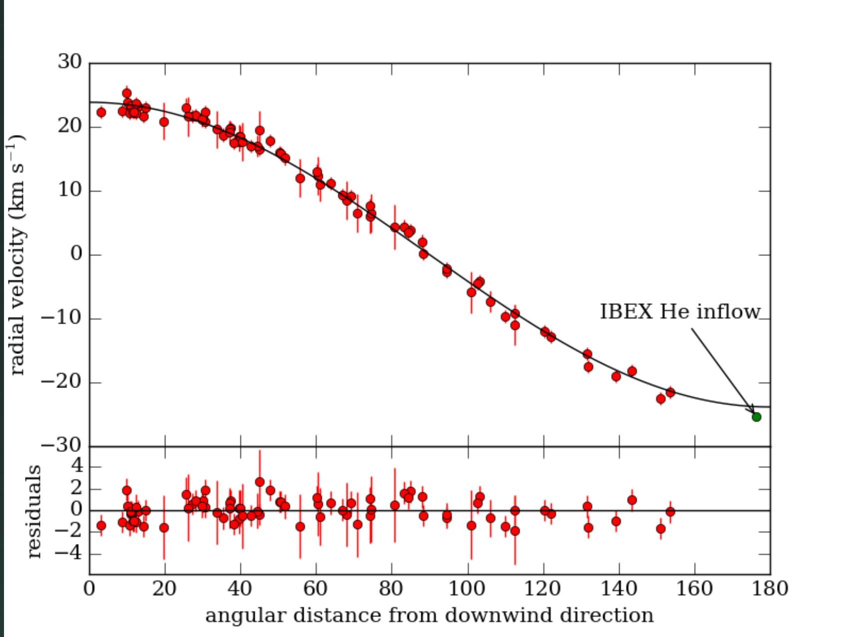
Turbulence in the CLIC

- Comparing line widths of low mass ions vs. high mass ions, e.g. D I and Fe II, and assuming $b^2 = \frac{2kT}{m} + \xi^2$, where ξ is the turbulent velocity, derive **turbulent velocities of only ~1 – 3 km/s for CLIC clouds.** For LIC value is 1.62 ± 0.75 km/s (Redfield & Linsky 2008)



- Does turbulence have other dependencies? Spangler et al. (2011) find *no evidence that turbulent broadening depends on direction or temperature. Mass dependent heating may be present but not required.*
- Redfield & Linsky (2008) found **some anti-correlation of depletion level with turbulent velocity** – possible sign of dust destruction correlated with turbulence level.

The Local Interstellar Cloud – the cloud surrounding the Solar System



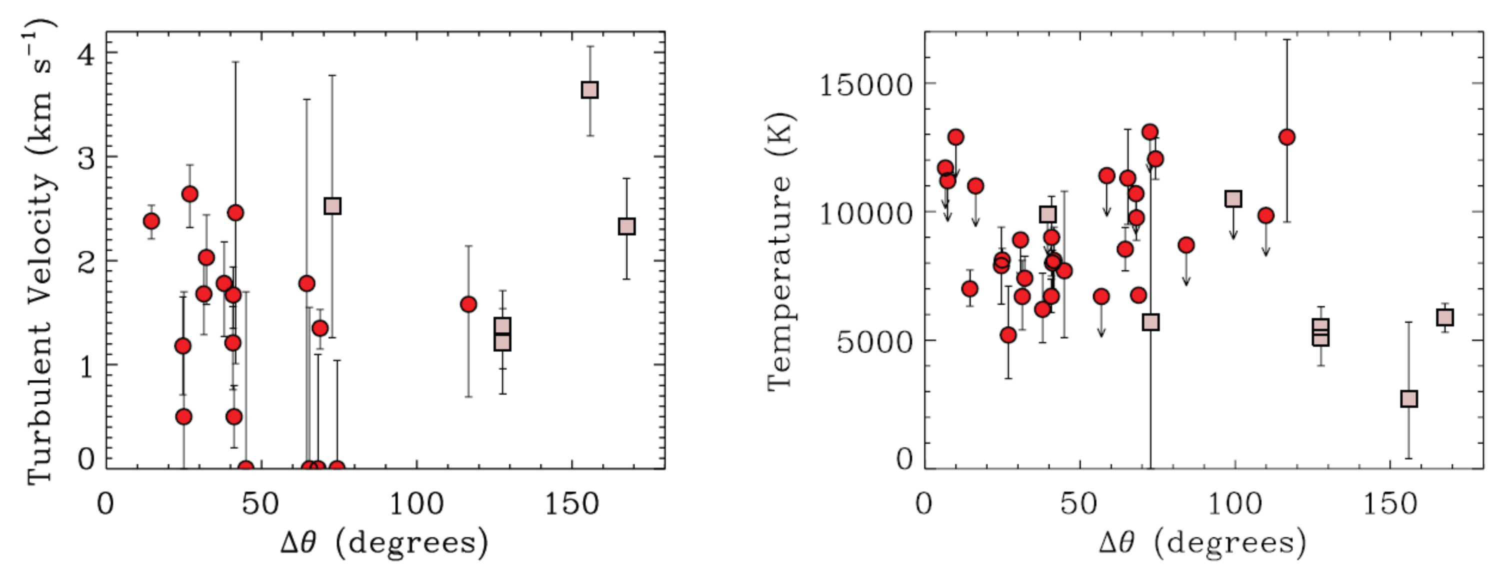
Velocities of absorption line components vs. angular distance from downstream vector

The LIC velocity component is seen in absorption lines on more than 80 lines of sight toward stars < 15 pc away.

Evidence points to a warm, $T = 7500$ K, low density, $n = 0.25\ \mathrm{cm^{-3}}$, cloud; partially ionized, H ~ 20 – 30% ionized, He ~ 40%

LIC is source of neutrals that flow into the Solar System which adds more constraints to the modeling. Equilibrium photoionization models (Slavin & Frisch 2008) match most data, though strict equilibrium is not likely.

Turbulence and Temperature in the Local Interstellar Cloud and G cloud



From Redfield & Linsky (2008)

LIC and G cloud show a range of *T* and turbulent velocities for different lines of sight.

There is some evidence for real variations in temperature and turbulence velocity, though the variations are not large.

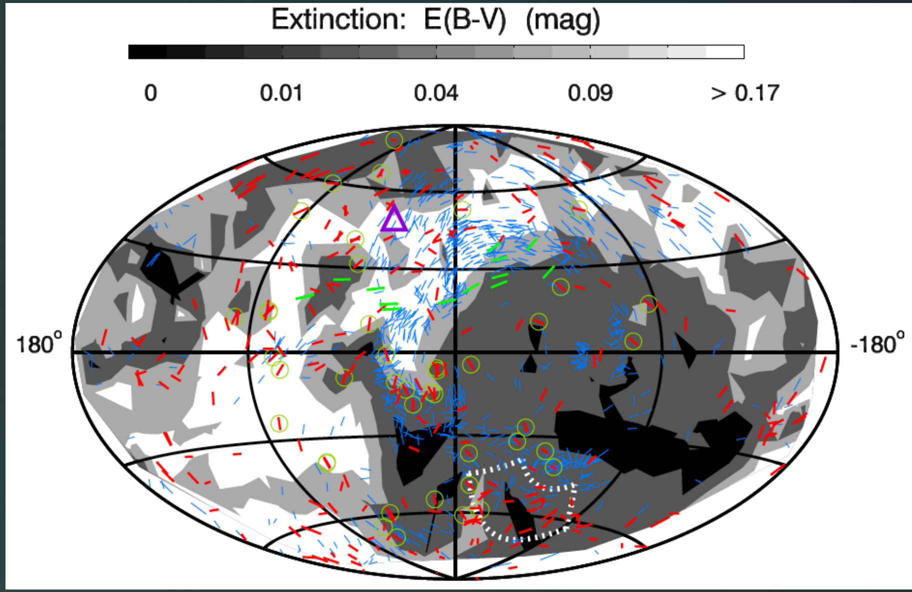
Magnetic Field in the LISM

2 primary source of information on *B* in LISM:

- **polarization measurements** toward nearby stars (e.g. Frisch et al.)
- **heliosphere models & data** (IBEX, Voyager 1) – get point measurement of the field

Models give "pristine" ISM strength and direction, though only in the upwind LIC

Polarization observations provide plane of sky orientation, but not direction or strength. Level of turbulence found in direction for field is $9° \pm 1°$



Polarization vectors for nearby stars (from Frisch et al 2015) along with extinction map.

We have no measure of the magnetic field in the hot gas

Numerical modeling of the LISM

For CLIC we hope to match:

- cloud temperatures – get conversion of cold gas into warm gas
- densities – observed values ~0.1 – 0.3 cm^{-3}
- separate clouds that could be identified as coherent in velocity
- not too much turbulence

For Local Bubble:

- temperature in range of observations, $T \sim 10^6$ K
- uniformity and absolute level of soft X-ray intensity
- size of the cavity, radius ~ 40 – 150 pc

Methods for Numerical Modeling of the LISM

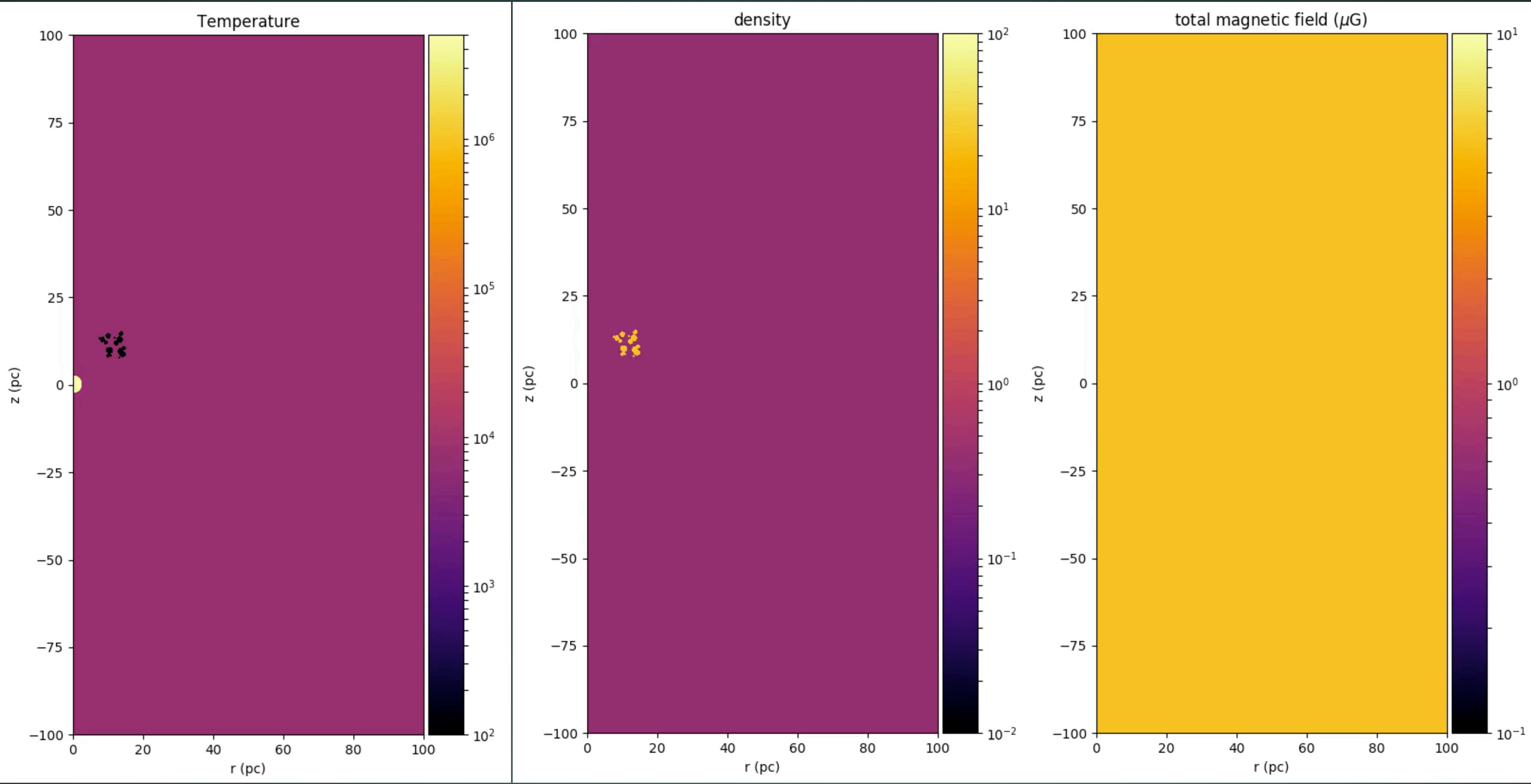
Using FLASH v 4.3 with AMR – *so far only 2D* (cylindrically symmetric, R-Z)

Initial conditions:

- collection of cold (T = 100 K) dense clouds (n = 25 cm^{-3}) embedded in warm (7500 K) lower density (0.358 cm^{-3}) intercloud medium
- supernova explosion(s) ($E_0 = 10^{51}$ ergs) close (10 – 20 pc) to clouds

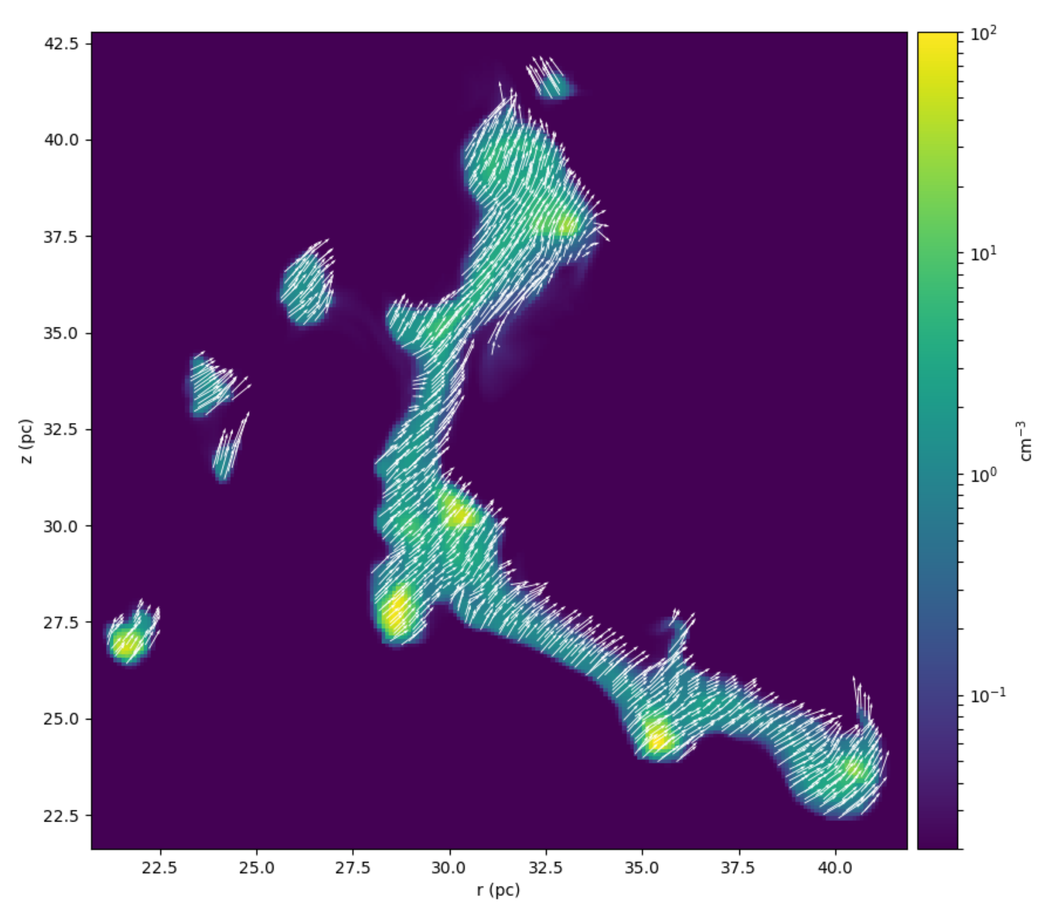
Physics included:

- thermal conduction including heat flux saturation (unsplit implicit diffusion)
- radiative cooling and heating using tables of coefficients
- MHD (unsplit staggered mesh) – with uniform initial B field (B_z = 5 μG, B_r = 0)
- anisotropy of thermal conduction not included yet



Temperature
density
total magnetic field (μG)
z (pc)
r (pc)

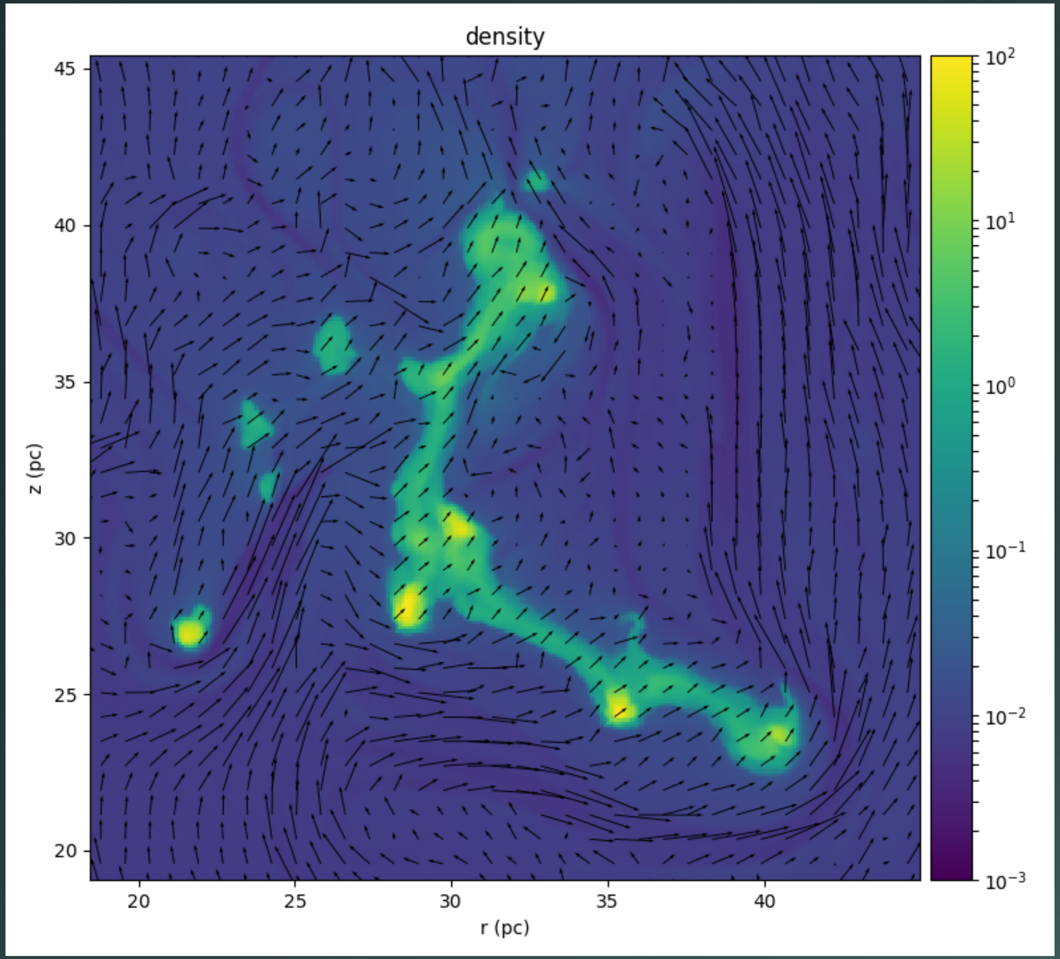
Cloud complex velocity field



Cloud complex after two explosions and 1.4x10^{6} yr

- Most parts of initial cloud complex remain together
- velocity gradients exist within cloud and between fragments
- Most of the mass has been heated to warm temperatures, but cold clumps remain
- Wide range of *T* and *n*

Cloud complex velocity field



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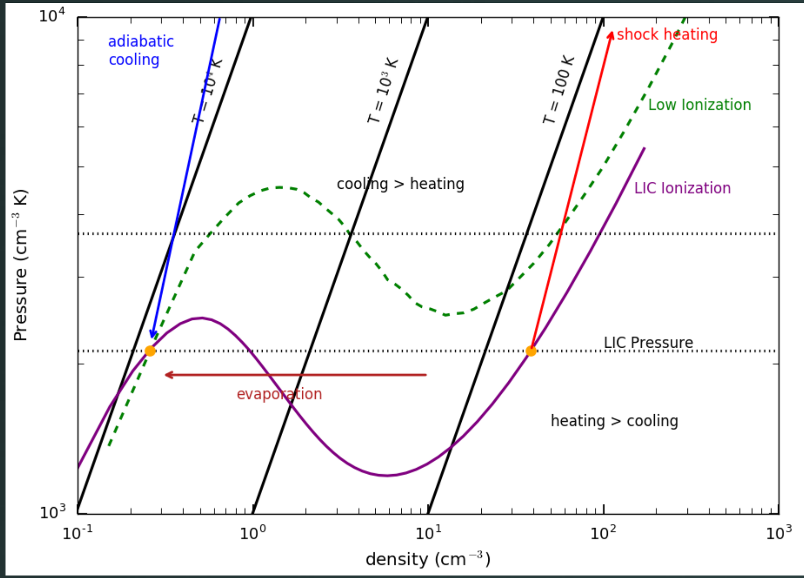
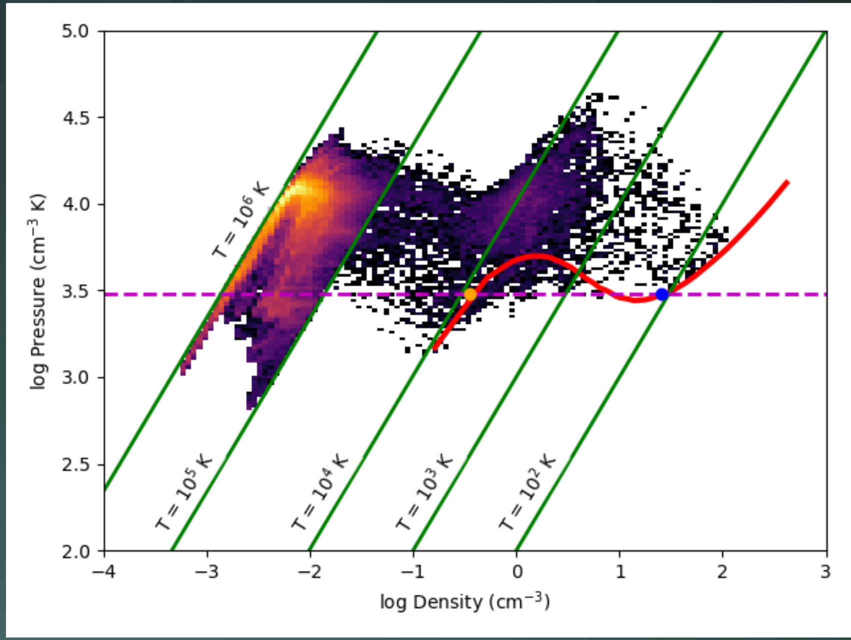
Thermal Evolution of the CLIC

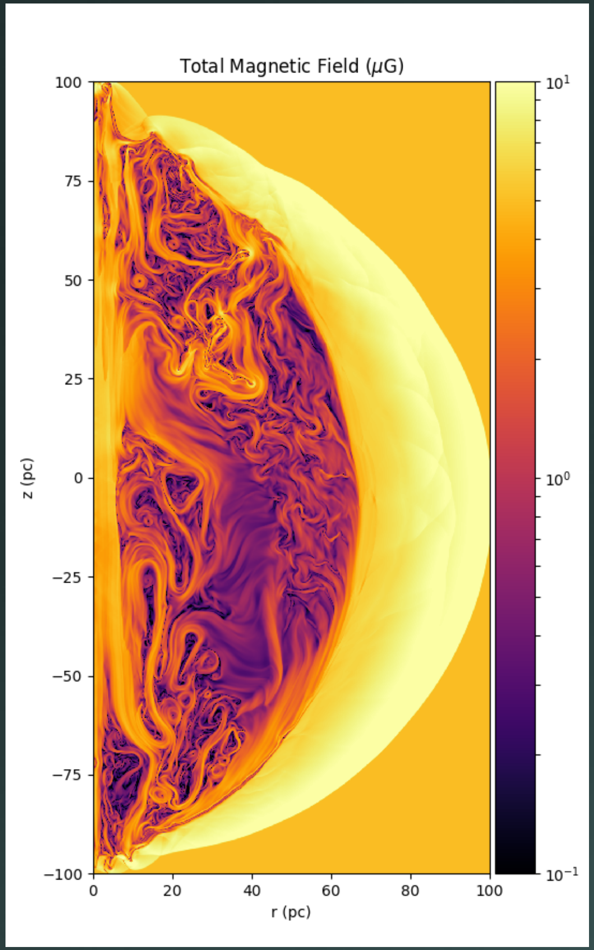


- Blast wave sends radiative shocks into the clouds
- Clouds are initially overpressured compared to surrounding hot gas
- Hot gas pressure decreases as $t^{-6/5}$ as bubble expands
- To transition to warm phase need pressure in clouds to drop below thermal equilibrium curve

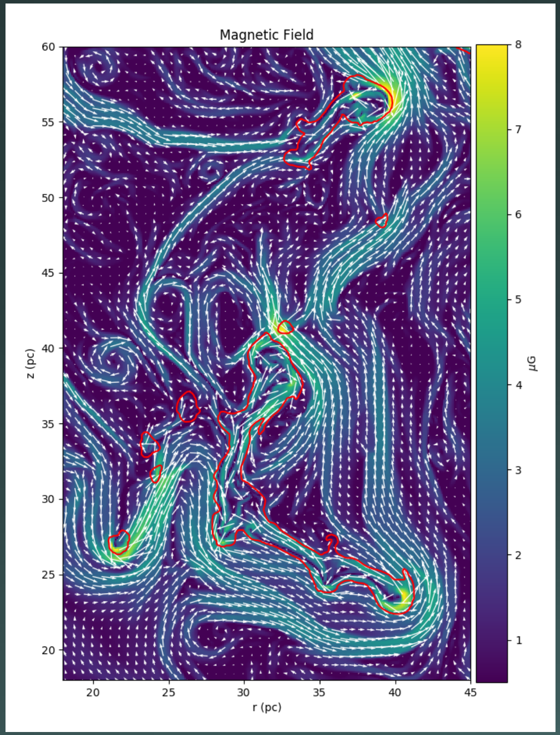


- Thermal equilibrium curves are determined by heating and cooling rates
- At certain pressures 2 stable phases are possible
- Equilibration times can be long, especially for lower density gas

Results for B field



After 2 explosions (2nd one at t = 5x10^5 yr) field is low on average in hot gas, but with large fluctuations



The multiple SNe and reflected shocks/waves create a fairly turbulent B field in the hot gas

In clouds the field is more regular in general but in some cases, field has wrapped around the cloud so that different sides of the cloud have different polarities with a null line in the middle. Also, (numerical) reconnection has lead to magnetically isolated regions.

Summary

- The Local Interstellar Cloud is a warm partially ionized cloud inside the hot Local Bubble. The LIC and other nearby clouds (CLIC) have a low level of turbulence – substantially subsonic
- The hot gas probably contains substantial turbulence though we can't detect it
- There is evidence of cloud-cloud interaction, which may lead to patches of stronger turbulence in the CLIC
- The magnetic field configuration in the LISM also shows a low level of turbulence on average
- The current state of the LISM is a result of the history of supernova explosions that created the Local Bubble, shocked and shaped the CLIC and has driven the turbulence in the LISM