Local interstellar magnetic field, Loop I, and nearby interstellar clouds

P. C. Frisch, University of Chicago
Cosmic Ray Anisotropy workshop
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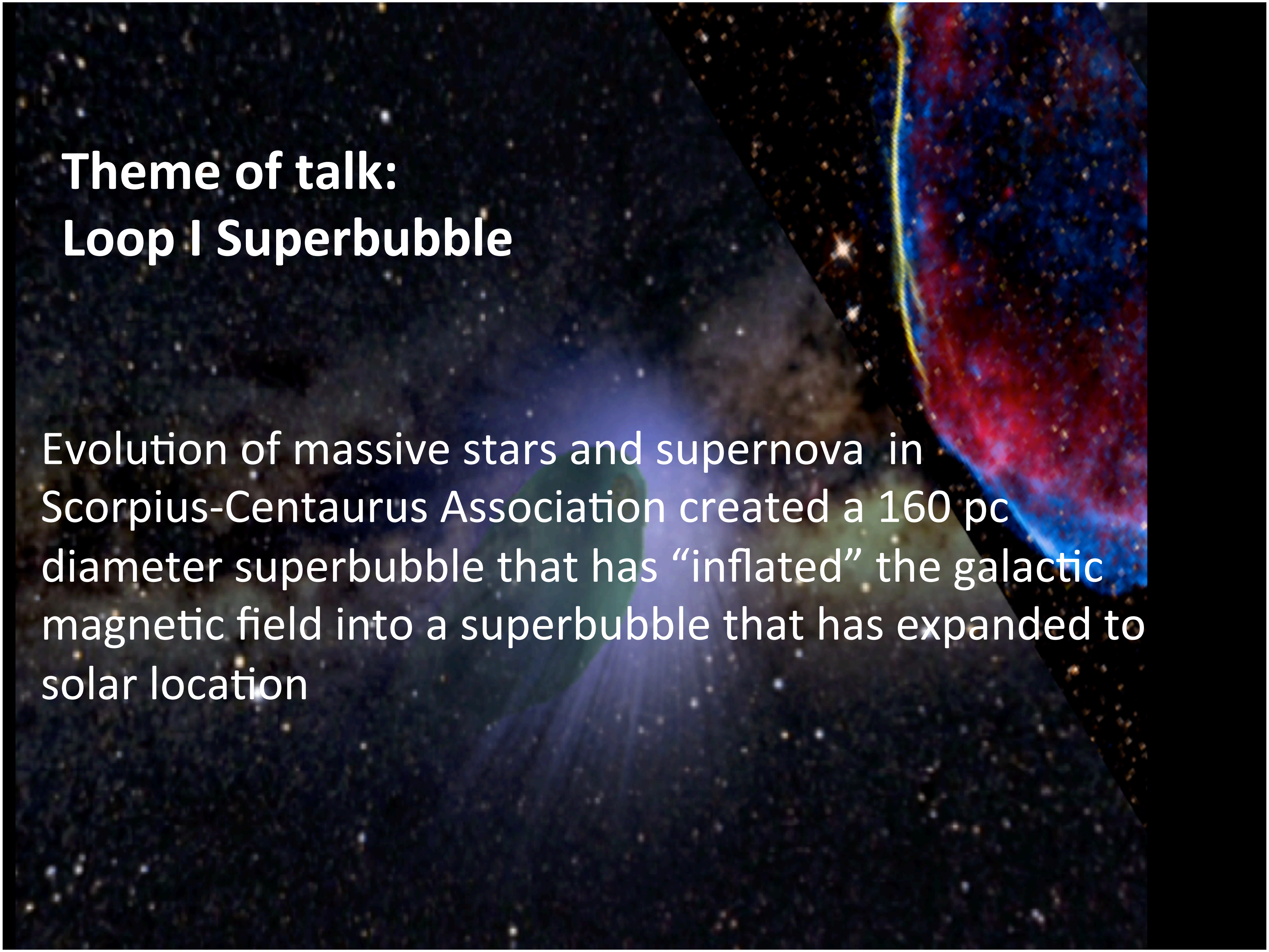
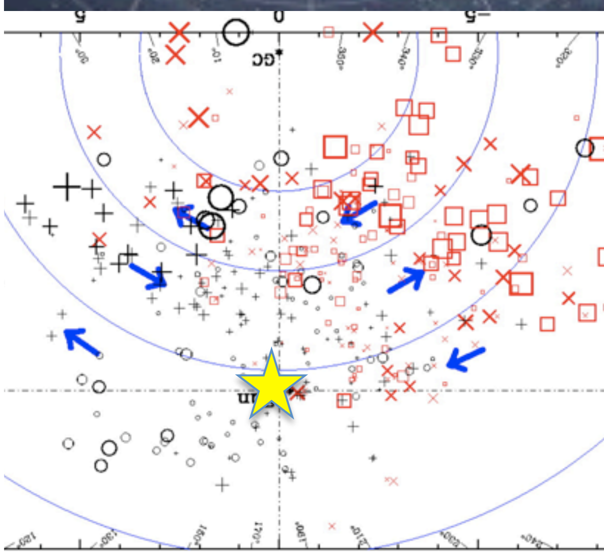

Theme of talk:
Loop I Superbubble
Evolution of massive stars and supernova in Scorpius-Centaurus Association created a 160 pc diameter superbubble that has "inflated" the galactic magnetic field into a superbubble that has expanded to solar location

Outline

- Loop I superbubble orders the kinematics of nearby interstellar clouds and the local interstellar magnetic field (ISMF)
- Magnetic "flux rope" connects pole of local ISMF to solar vicinity
- ISMF direction from IBEX Ribbon of Energetic Neutral Atoms (ENAs) is consistent with Loop I ISMF
- Is there flux freezing in local low density ISM?

Large Scale Structure of ISMF

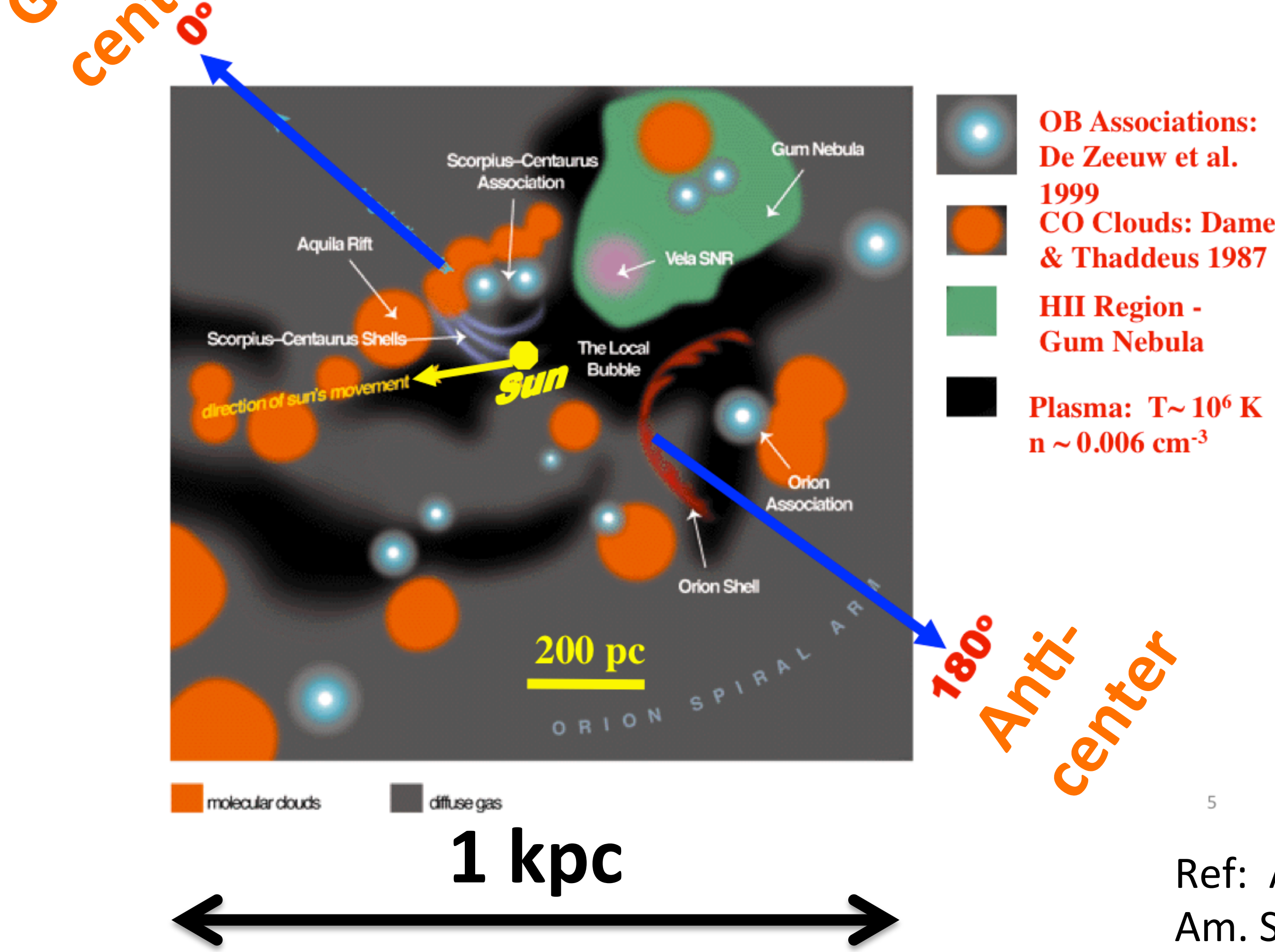


- Ratio of Faraday rotation and dispersion measures give parallel component of ISMF

$$\boxed{\langle B_{||} \rangle = \frac{\int_0^D n_e \mathbf{B} \cdot d\mathbf{l}}{\int_0^D n_e dl} = 1.232 \, \frac{\mathrm{RM}}{\mathrm{DM}}}$$

- Field direction clockwise in local interarm region
- Strength ~1.5 microG
- Sun in Local Bubble and on inside edge of Orion spur

Stellar evolution in ISM at edge of Local Bubble creates dynamic ISM around Sun

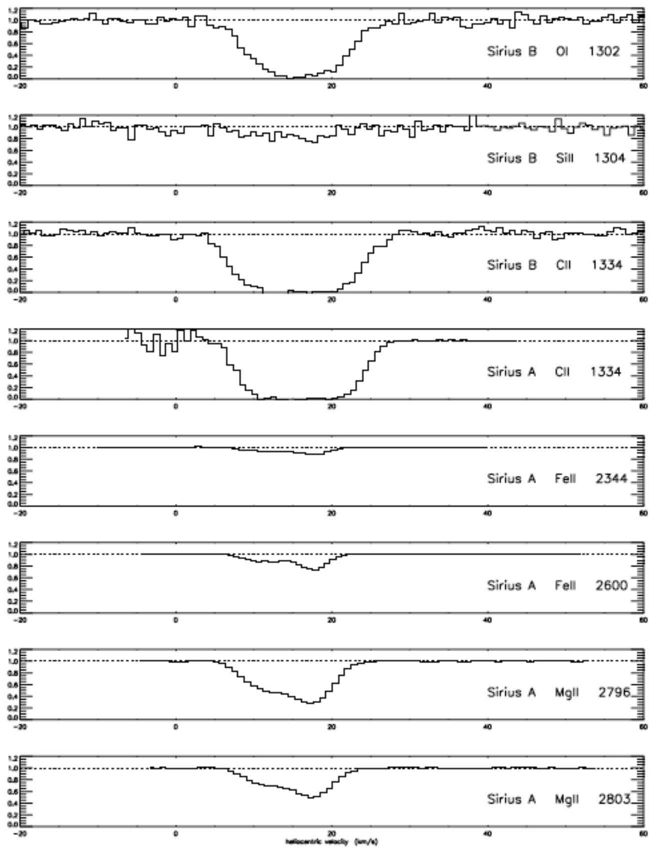


Ref: APOD, April 12, 2000
Am. Scientist, vol88, 2000

Local cloud system: the velocities

Sirius absorption lines

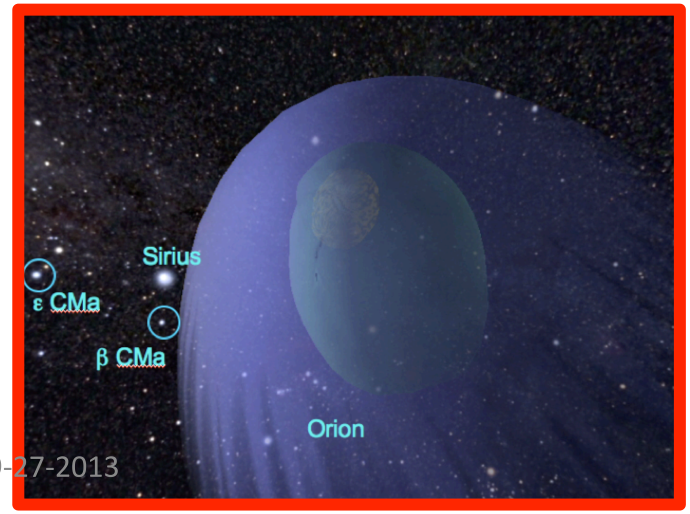
Relative intensity



Heliocentric velocity

Fig: Hebrard et al. Sirius 1999

- Get cloud velocities from interstellar absorption lines in stellar spectra
- Fit interstellar absorption lines with Voight profile
  - Gives radial velocity, column density, and FWHM of line
- 150 stars give information on interstellar clouds within 15 pc of Sun

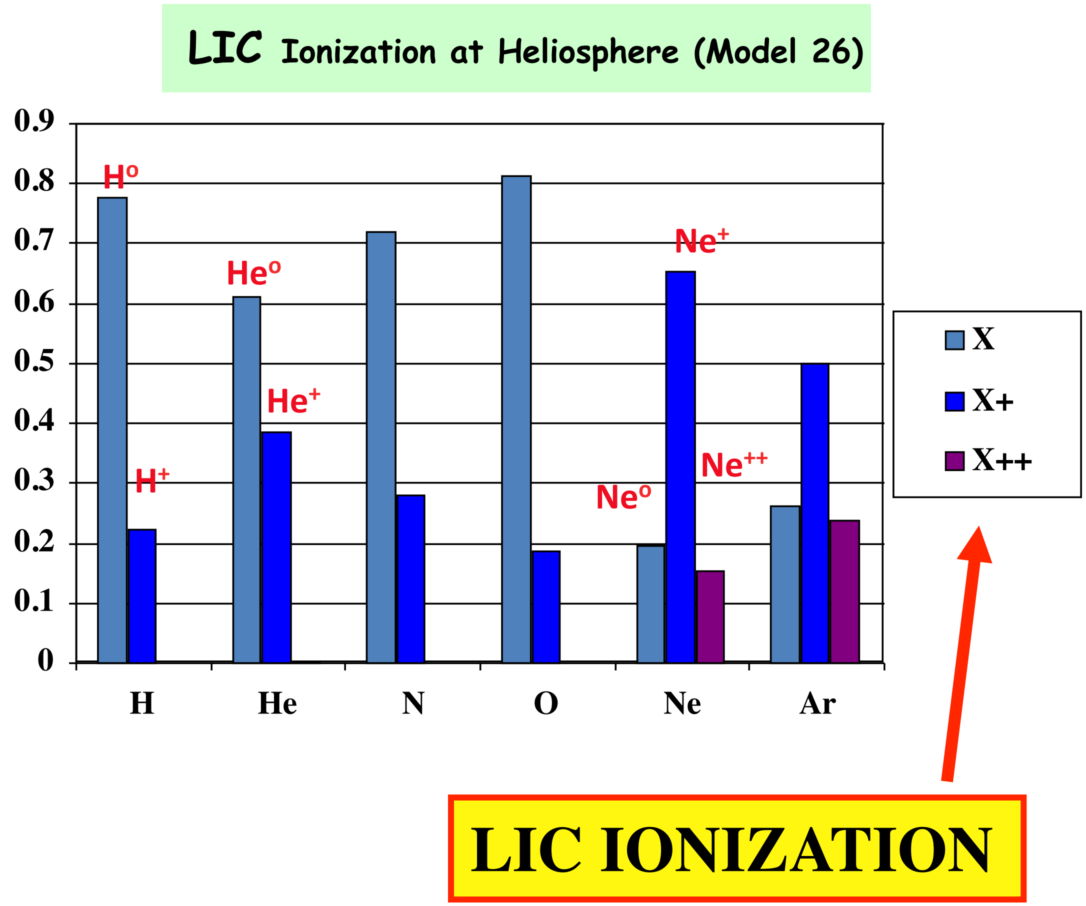


Local Interstellar cloud (LIC) around Sun

Interstellar cloud around Sun is warm, low density, and partially ionized

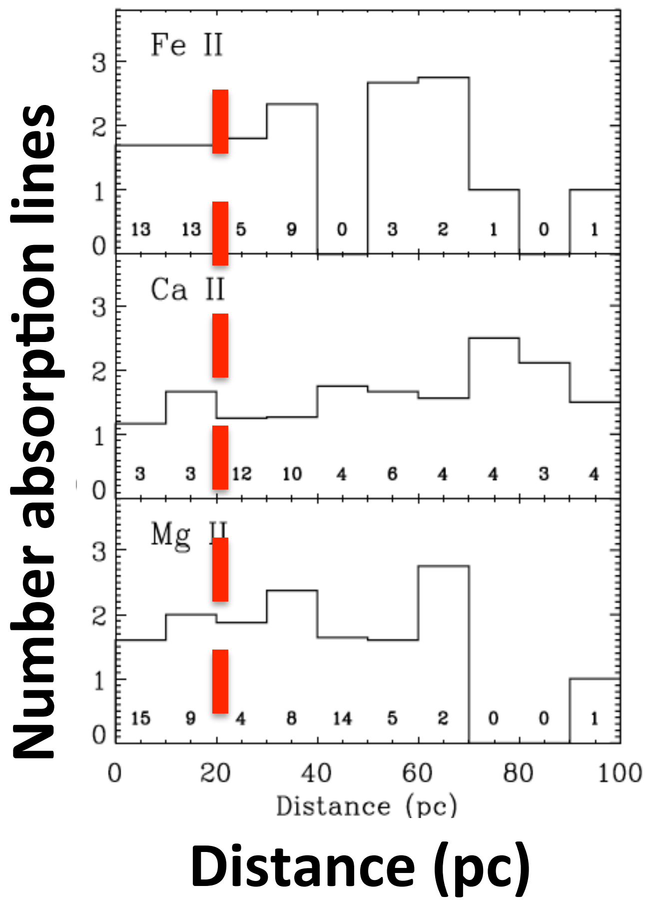
Results from radiative transfer models of LIC towards Sirius at 2.7 pc with inclusion of full interstellar radiation field

- Hydrogen ~22% ionized
- Helium ~43% ionized
- $n(H^o) \sim 0.20\ cm^{-3}$
- $n(He^o) \sim 0.015\ cm^{-3}$
- $n(e^-) \sim 0.07\ cm^{-3}$
- T = 6,300±340 K
- B=3 μG for thermal and magnetic pressures equal
- Consequence of model is that Sun is within 20,000 AU of the upwind edge of the LIC



(Slavin Frisch 2008 A&A)

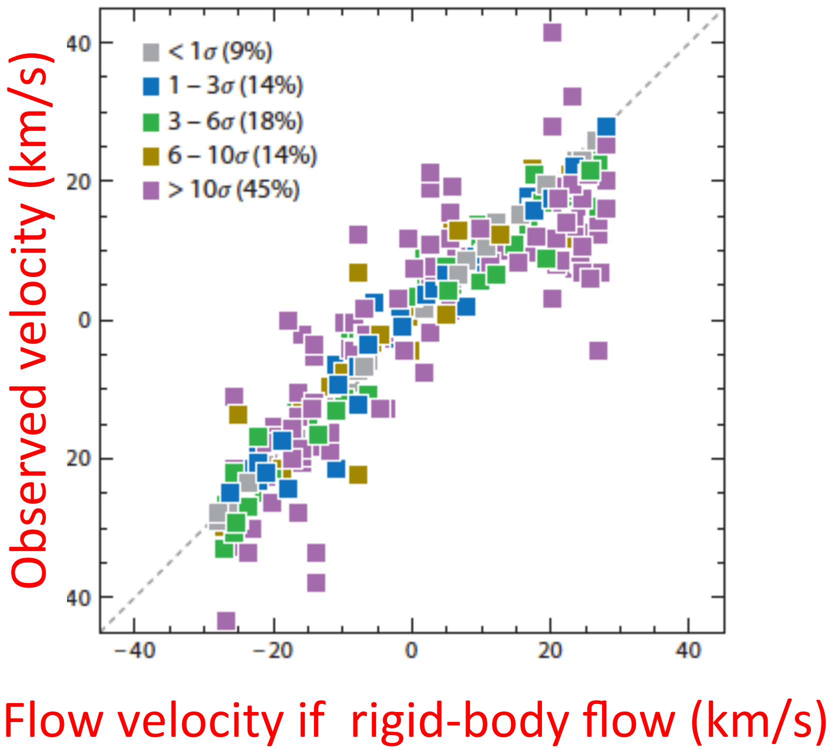
Most local interstellar gas within 20 pc



(Redfield Linsky 2008 ApJ)

- Local clouds traced by UV (eg HI, FeII, MegII) and optical (CaII, NaI) interstellar absorption lines
- Local cloud system within 20 pc since the number of absorption components steady within 20 pc
- Low average density, Log(N(HI))<18.6 cm^-2
- Volume density < 0.1 /cc

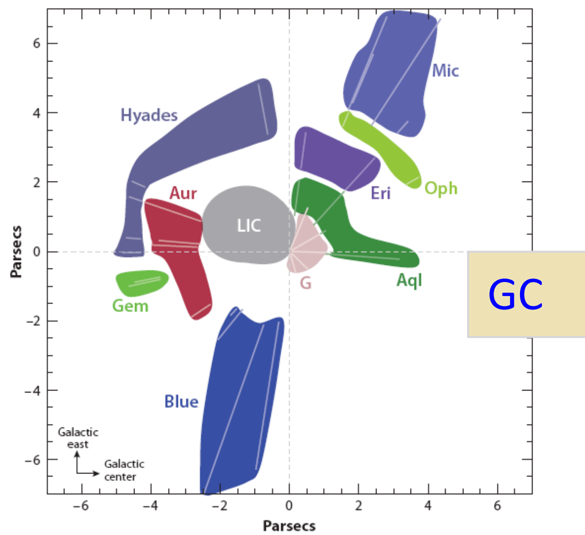
Local ISM flows together through space



Ref: Frisch et al. 2011 ARAA

- Linear fit to observed velocities of absorption lines in nearby stars gives the heliocentric flow velocity of 28.1 +/- 4.8 km/s
- Excess negative velocities in upwind (left) and downwind (right) imply decelerating flow
- Must remove solar motion to get velocity of cloud in space
- *Convert observed velocity to local standard of rest (LSR) velocity frame*
- *Upwind LSR direction:*
  - *L,B = 335, -5 deg*
- *Velocity 16.8 ± 4.8 km/s*

Defining interstellar clouds



14 pc x 14 pc

The Local Interstellar Cloud (LIC) around the Sun velocity has a velocity of 23 km/s according to both triangulation and IBEX measurements of interstellar helium

- Patterns in velocities of absorption components define interstellar ‘clouds’ through triangulation.
- Process limited by spectral resolution of data
  - As spectral resolution improves the number of clouds identified by velocity increases exponentially (Welty et al.)
- 15 clouds within 20 pc according to Redfield and Linsky (2008)
- Sirius seen through heliotail and has two foreground clouds

Ref: Frisch et al. 2011 ARAA

Overview of local cloud system (<20 pc)

Local intraday radio
Scintillation screens

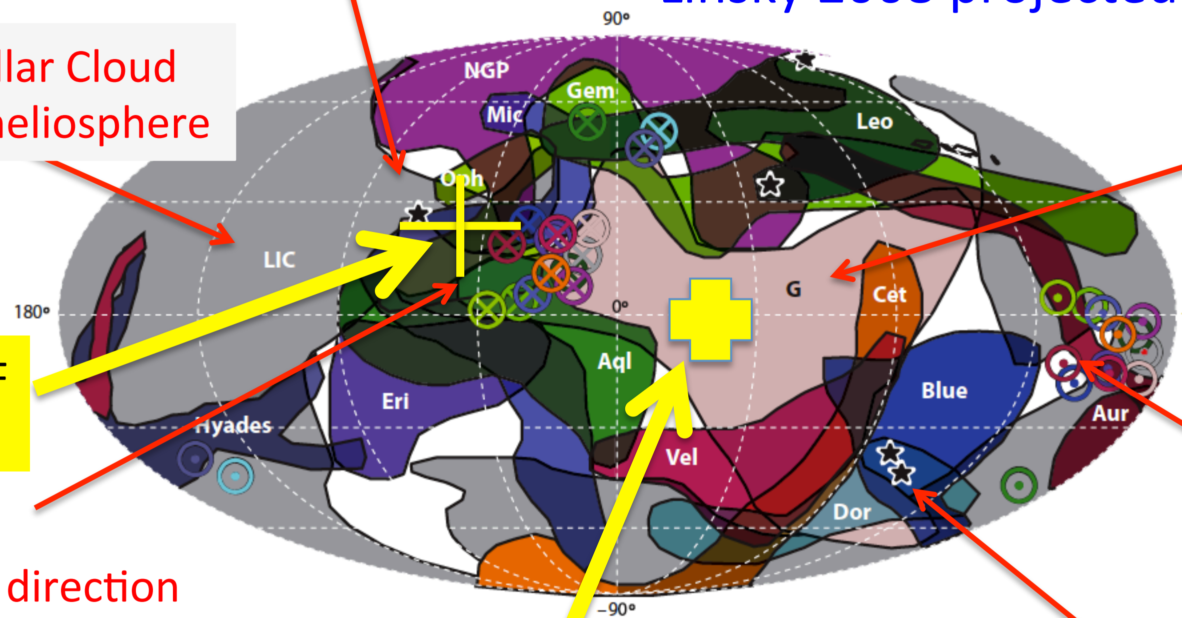
Figure: 15 clouds of Redfield
Linsky 2008 projected onto sky

Local Interstellar Cloud
Surrounding heliosphere

G-cloud within
1.3 pc

Local ISMF
direction

Heliocentric
Downwind
directions



Upwind direction
As observed from Earth
(heliocentric)

Upwind direction of
Interstellar flow in LSR

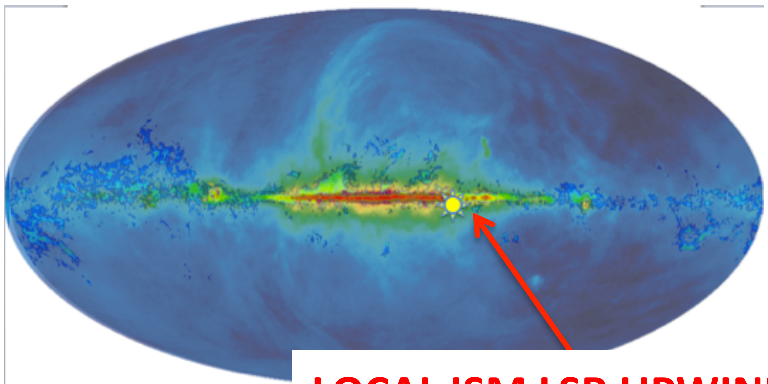
Local intraday radio-variable
Plasma scintillation screens

**Sun within 20,000 AU
of upwind edge of LIC**

Fig. ref: Frisch, Redfield, Slavin 2011 ARAA

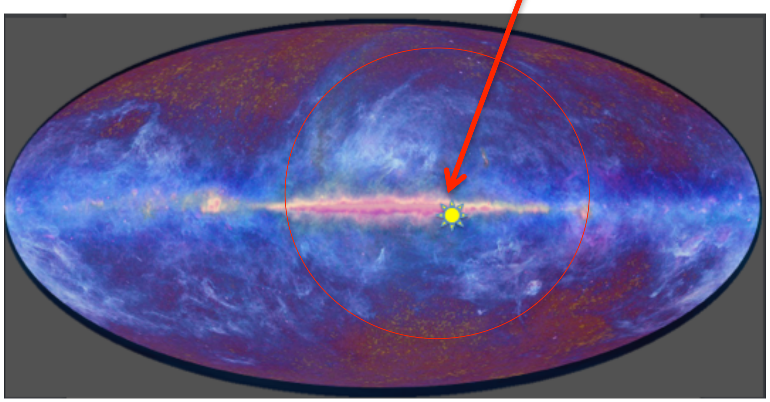
Loop I superbubble

Haslam 875 MHz radio continuum



LOCAL ISM LSR UPWIND

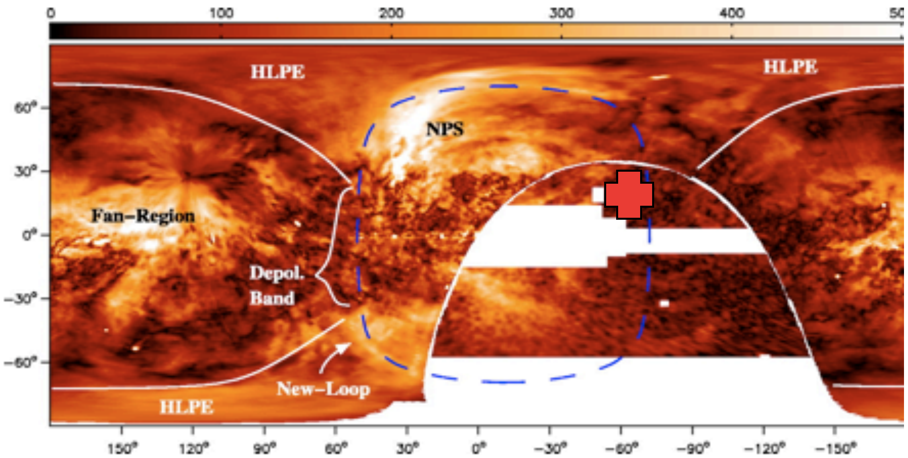
Planck composite microwave image of dust



- Loop I is magnetic superbubble dominating local ISM In northern sky
- 15 Myrs of stellar evolution in Sco-Cen Association created Loop I superbubble
- Interstellar magnetic field warped the ordered interarm field dirction during expansion of superbubble
- See bubble in dust, HI 21-cm, synchrotron emission, polarized starlight, starlight reddening
- Flow of local ISM is away from center of Loop I

Loop I modeled as two shells (Wolleben 2007)

1.4 GHz Polarized intensity (mK)



- Used 1.5 GHz radio data, and 23 GHZ WMAP data for southern hemisphere
- Model assumes expanding superbubble that "snowplows" interstellar material and the compresses galactic magnetic field into shell
- Model places Sun in rim of "S1 shell"; S1 centered 78 pc away

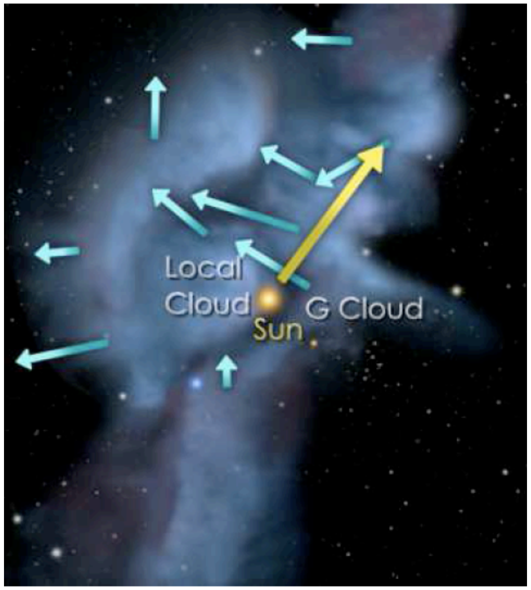
TABLE 1

Best-Fit Parameters of the Model

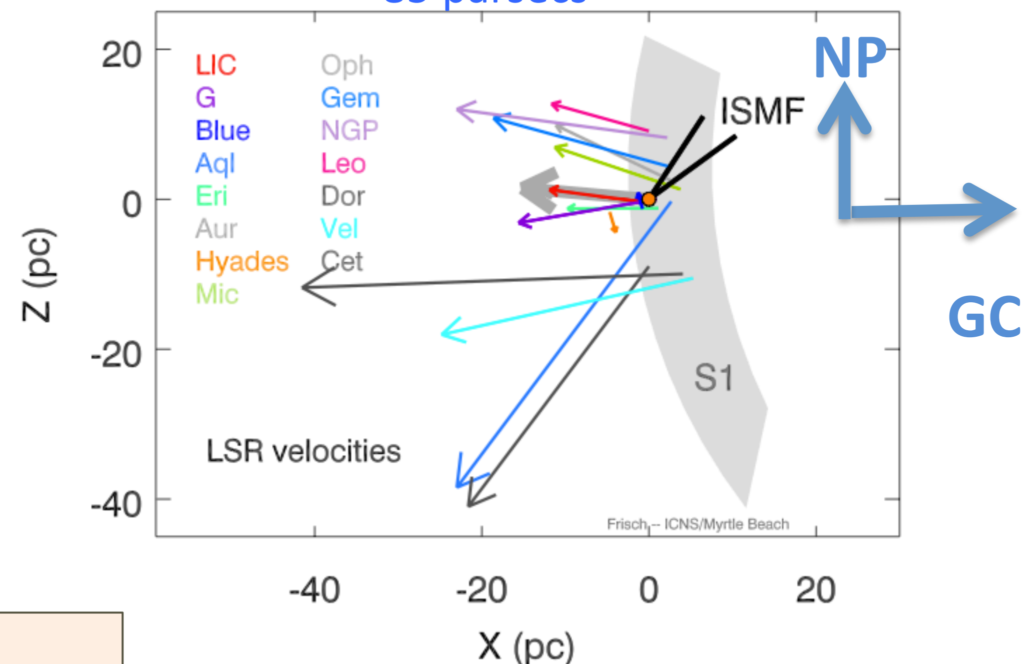
Shell	l (deg)	b (deg)	d (pc)	r_{in} (pc)	r_{out} (pc)	B_θ (deg)	B_ϕ (deg)
S1	346 ± 5	3 ± 5	78 ± 10	72 ± 10	91 ± 10	71 ± 30	−72 ± 30
S2	347 ± 15	37 ± 15	95 ± 10	63 ± 15	87 ± 10	25 ± 30	25 ± 30

Loop I-S1 organizes local cloud kinematics

14 parsecs



85 parsecs



→ Local clouds and LSR Velocities shown projected onto the galactic plane
→ Motion of Sun through LSR is in yellow

→ LSR velocities of 15 clouds.
→ Bulk cloud velocity (gray arrow) tracks S1 shell center as defined by Wolleben

REF: FRISCH SCHWADRON 2013

First clue of ISMF close to Sun

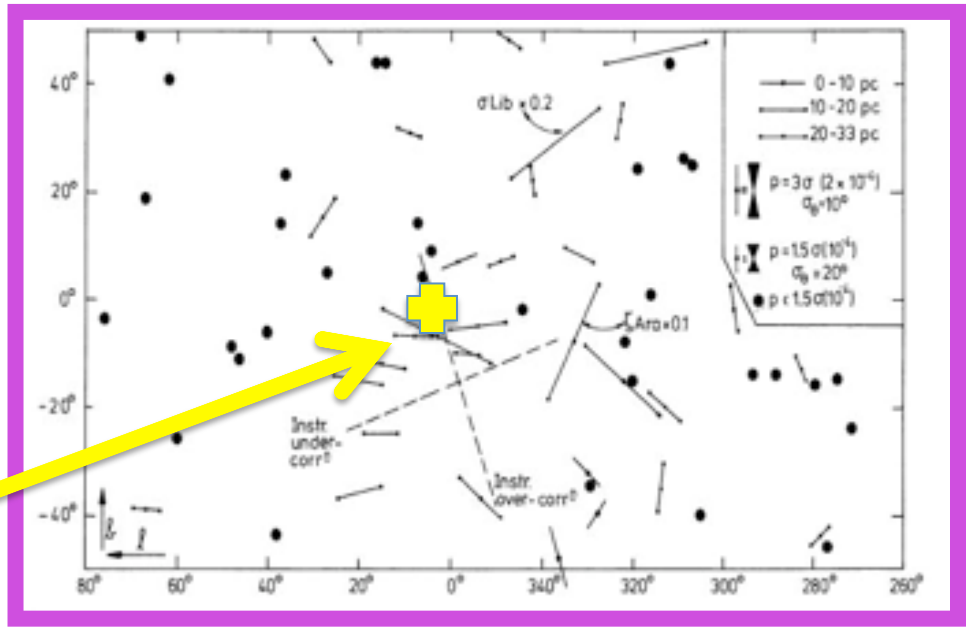
→ Tinbergen showed in 1982 that linearly polarized starlight traces the ISMF within 30 pc

→ Tinbergen only saw polarization in direction of what we now call the "G-cloud", located in the upwind flow direction

→ *Up until the launch of IBEX in 2008, linearly polarized starlight was the only way to obtain the ISMF direction close to the Sun*

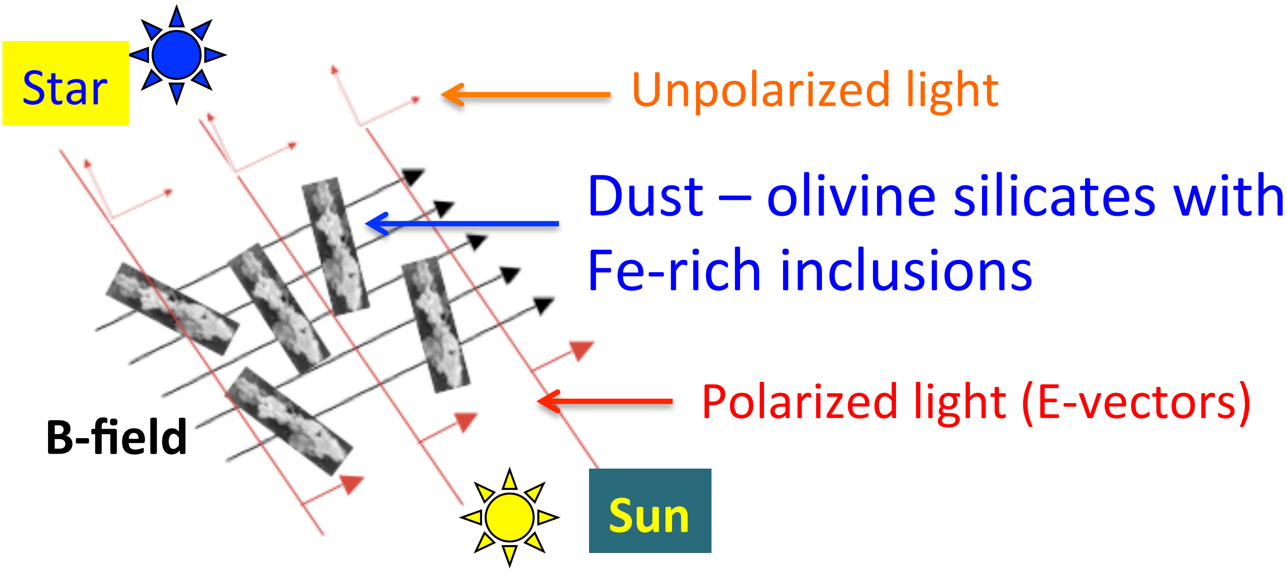
Weak polarization
P ~0.02%
Stars within ~30 pc

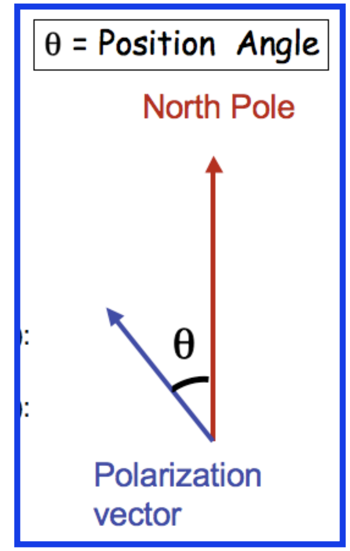
Galactic center
L=0 B=0



Polarization of starlight by magnetically aligned dust grains

Polarization Position angle





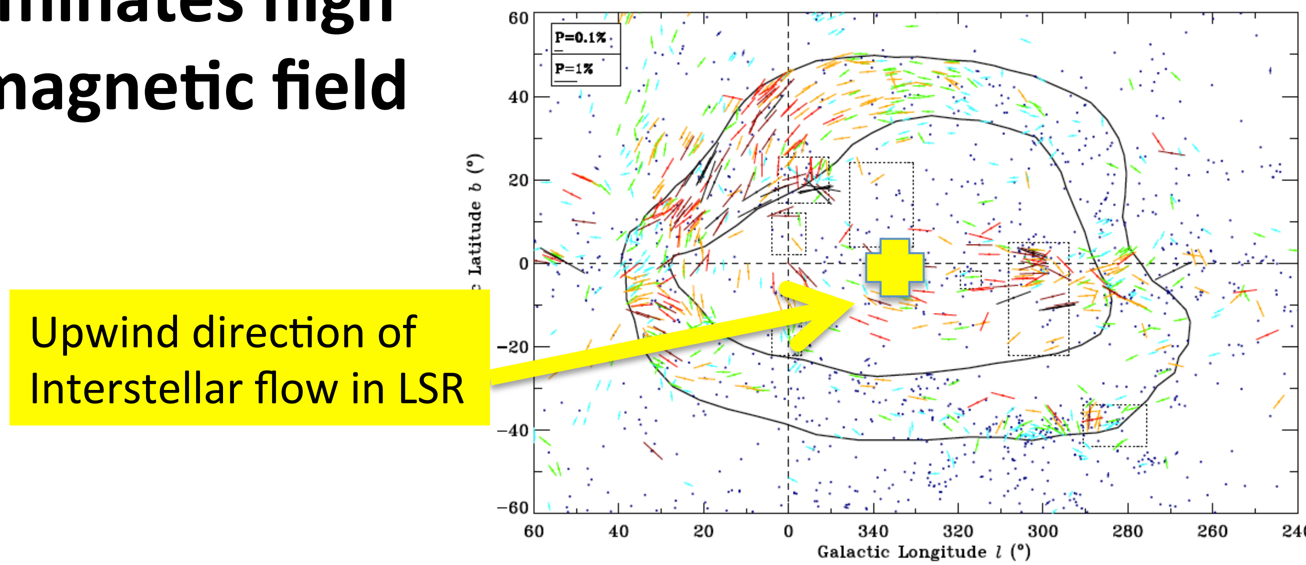
→ Linearly polarized starlight forms when light traverses ISM containing magnetically aligned dust grains

→ Torques on charged spinning dust grains dissipate momentum so that the axis of principle moment of inertia is parallel to the magnetic field and the “long axis” (eg optically thin) grain axis is perpendicular to the magnetic field

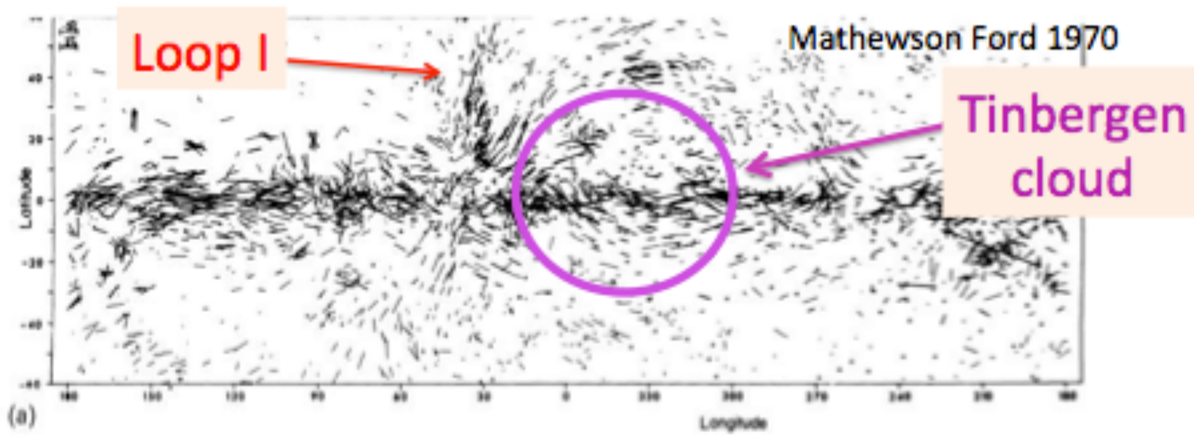
→ Direction of polarization vector is parallel to magnetic field direction

→ Confirmed by perpendicularity of synchrotron and starlight polarizations

Loop I dominates high latitude magnetic field



Santos et al. 2010



Optically polarized starlight is best way to measure structure of superbubbles

Collaborators on local ISMF study

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THE INTERSTELLAR MAGNETIC FIELD CLOSE TO THE SUN. II.

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ABSTRACT

The magnetic field in the local interstellar medium (ISM) provides a key indicator of the galactic environment of the Sun and influences the shape of the heliosphere. We have studied the interstellar magnetic field (ISMF) in the solar vicinity using polarized starlight for stars within 40 pc of the Sun and 90° of the heliosphere nose. In Frisch et al. (Paper I), we developed a method for determining the local ISMF direction by finding the best match to a group of interstellar polarization position angles obtained toward nearby stars, based on the assumption that the polarization is parallel to the ISMF. In this paper, we extend the analysis by utilizing weighted fits to the position angles and by including new observations acquired for this study. We find that the local ISMF is pointed toward the galactic coordinates $\ell, b = 47° \pm 20°, 25° \pm 20°$. This direction is close to the direction of the ISMF that shapes the heliosphere, $\ell, b = 33° \pm 4°, 55° \pm 4°$, as traced by the center of the "Ribbon" of energetic neutral atoms discovered by the *Interstellar Boundary Explorer* (*IBEX*) mission. Both the magnetic field direction and the kinematics of the local ISM are consistent with a scenario where the local ISM is a fragment of the Loop I superbubble. A

Polarization data that trace local ISMF

- Star selection:
  - Within 40 pc
  - within 90 deg of heliosphere nose (eg galactic center)
- New data from:
  - LNA (Brazil)
  - Nordic Optical Telescope (Canary Islands)
  - KVA
  - LICK (California)
- Archived data from PlanetPol, Santos et al. LNA study of Loop I, and Heiles

Polarization vrs distance for stars within ~90 deg of galactic center

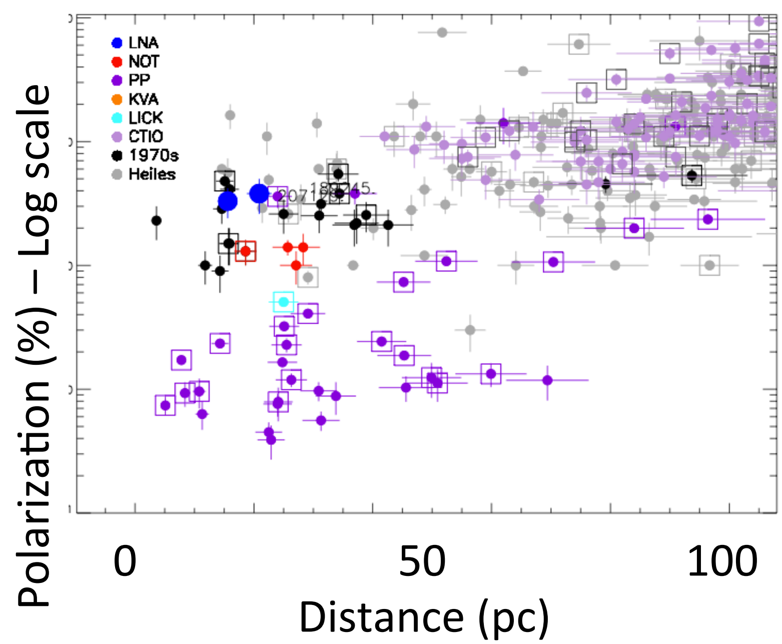


FIG: FRISCH ET AL. 2012 APJ

New method gives ISMF from polarizations

Technique: Minimize differences between polarization position angles and interstellar magnetic field direction

→ Search for "true" ISMF direction by finding ISMF direction that gives sin(PA)~0 for the polarizations of stars within 40 pc in the galactic center hemisphere

→ Weight values by uncertainty variable G

→ Test: Minimize F_i to find ISMF direction B_i ; eg minimize the mean of all position angles θ_j for j stars for the assumed ISMF directions B_i

→ **Merit function for test:**

$$\boxed{F = \mathrm{N}^{-1} \sum_{\mathrm{n}=1}^{\mathrm{N}} \left| \frac{\sin(\theta_{\mathrm{n}}(B_{\mathrm{j}}))}{G_{\mathrm{n}}} \right|}$$

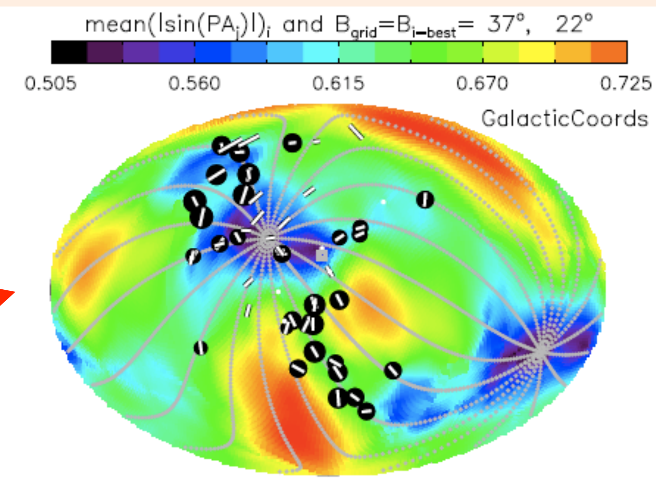
(Ref: Frisch et al. 2012, ApJ)

Direction of ISMF from position angles

Technique: Minimize differences
Between polarization position angles and
Interstellar magnetic field direction

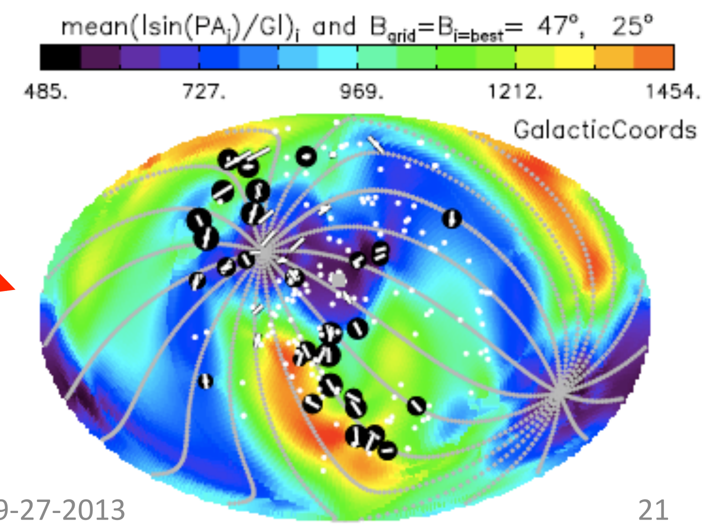
Figures show value of merit function *F*
For each tested ISMF direction

Color-coded plots of merit function *F*



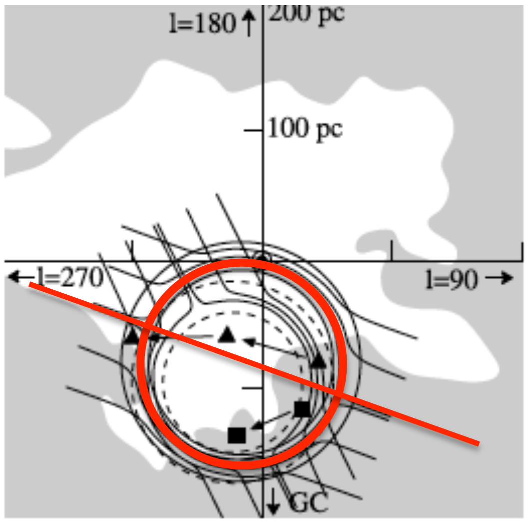
Unweighted fit, G=1:
Best fit:
$L = 37^{o} \pm 15^{o}$, $B=22^{o} \pm 15^{o}$

Weighted fit:
Best fit:
$L = 47^{o} \pm 20^{o}$, $B=25^{o} \pm 20^{o}$

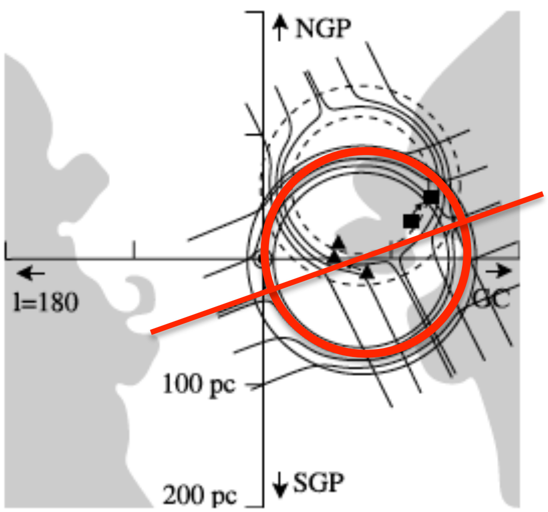


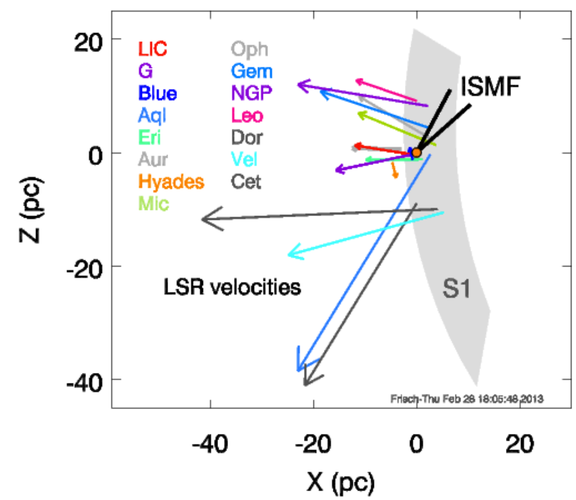
(Ref: Frisch et al. 2012)

Comparison between S1-shell model and LISM



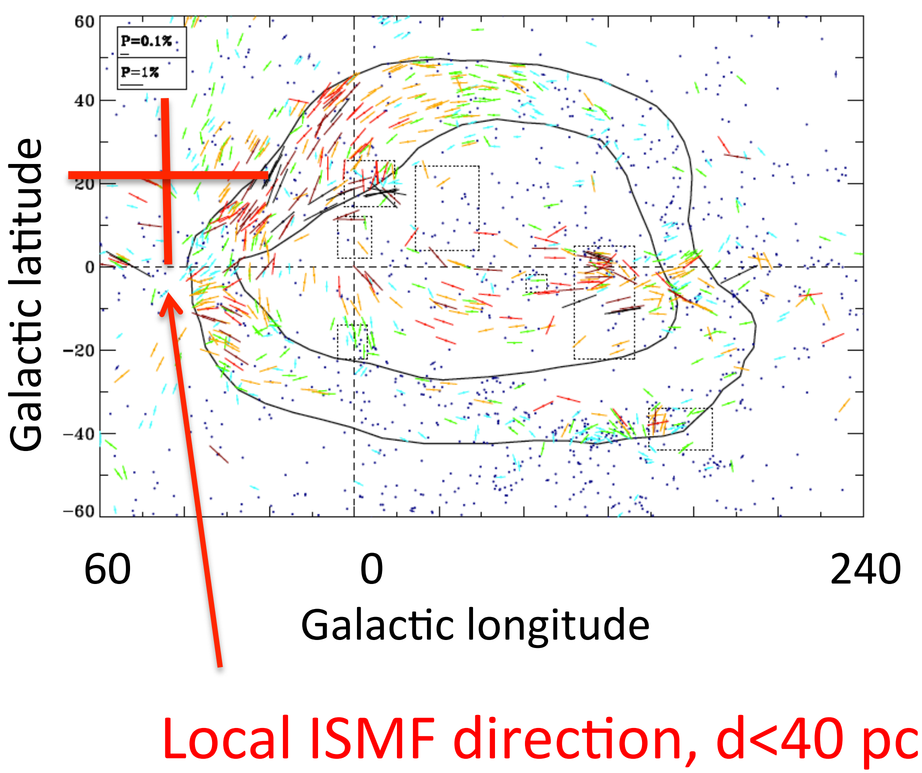
- S1 fit radio data better in eastern regions than in west. Expansion of shell into Aquila Rift molecular cloud provides shell definition
- The best-fitting local ISMF direction toward L,B=47,25 is good match to S1 shell configuration shown in the figure
- Local flow of interstellar clouds away from L,B=335, -5 deg (LSR; this direction is 14 deg from S1 center





Loop I orders local magnetic field

Optical polarization in Loop I (Santos et al. 2010)



At solar location the ISMF direction is parallel to shell

- ISMF and bulk flow velocity are perpendicular
- Angle between the very local ISMF direction (D<40 pc) and bulk flow velocity is $76^o \pm 21^o$.
- Bulk velocity aligned with center of S1 magnetic shell to within $14^o \pm 8^o$.
- Therefore the ISMF direction from polarization measurements is parallel to the local shell surface

Spatially continguous local dust

- → Polarization data from PlanetPol were the largest set of very high sensitivity measurements of the LISM at ppm levels
- → Bailey et al. found that polarizations increased systematically with distance in one region of the sky with RA>17H
- → This region corresponds to the direction of the North Polar Spur
- → We selected that region (eg RA>16H) for scrutiny
- → The data suggest an interstellar flux rope

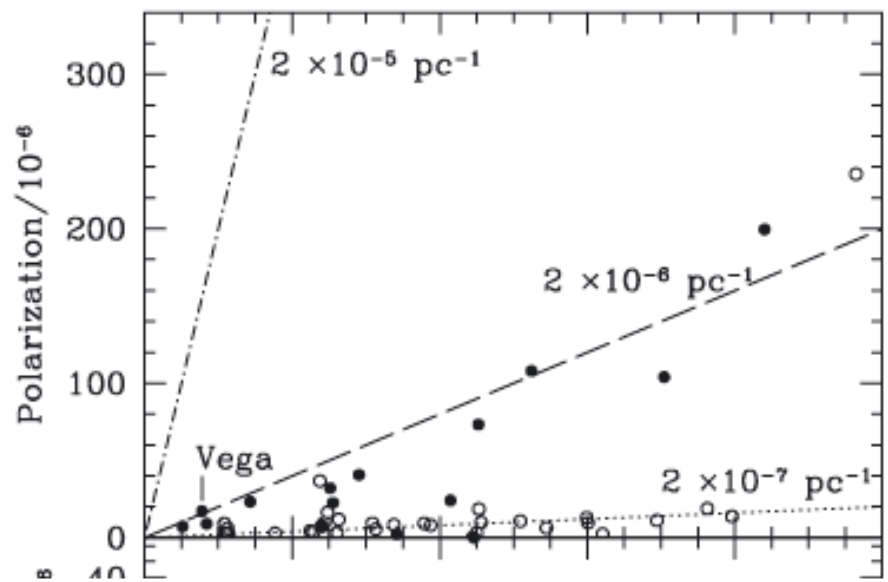
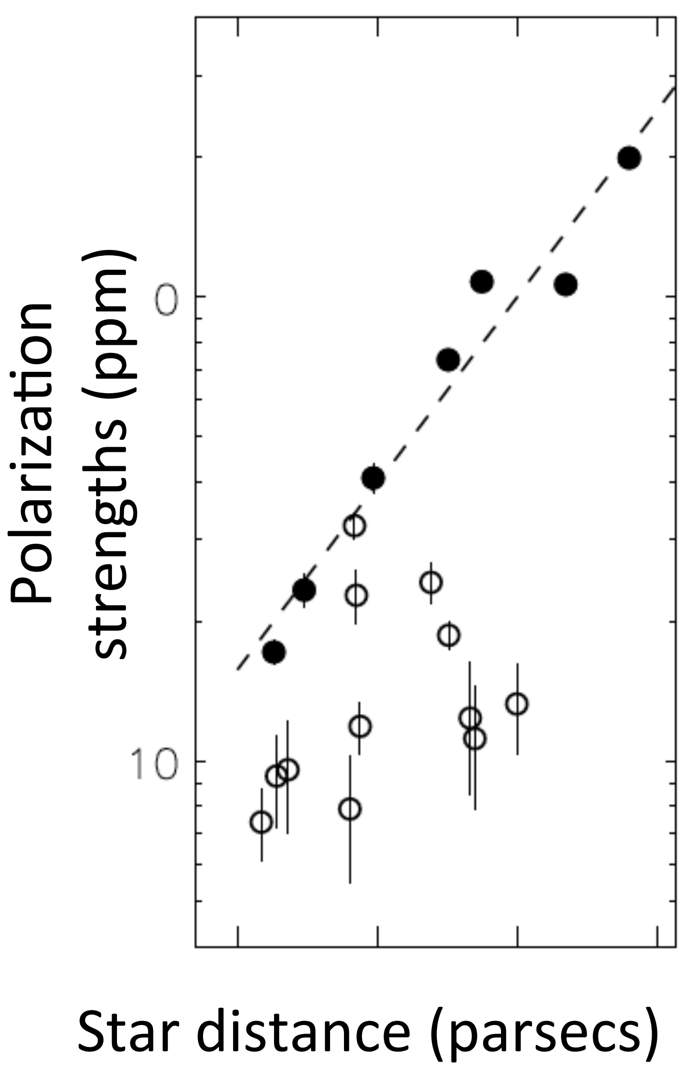


Figure 4. Polarization plotted against distance. Solid symbols are stars with RA > 17 h and open symbols are stars with RA < 17 h. The dot–dash line shows the polarization versus distance relation for distant stars and the dash and dotted lines are relationships with 10 and a 100 times less polarization

Ref: Bailey et al. 2010

Identifying local ordered ISMF in PlanetPol data



→ Stars forming "upper envelope" of polarization (**filled dots**) are special because these are clear sightlines with no foreground depolarization or field turbulence

→ Nominal polarization theoretical limit of P(%)=9*E(B-V) fits predicts H column densities to within factor of 1.35

→ Rest of stars (**open dots**) have less (or different) dust or tangled magnetic fields OR ??????

Fig ref: Frisch et al. 2012, ApJ

"Envelope stars" give ordered ISMF and turbulence

- Polarization position angle (in RA,DEC) plotted against the distance of the stars 8-52 pc with RA>16H
- Polarization increases smoothly with distance so these local clouds are not clumped close to the Sun
- The polarization position angle and therefore ISMF direction of "Upper envelope" stars varies linearly with distance
- Fit to envelope stars shows ISMF field rotates by 0.25 deg per parsec:

$$\mathrm{PA_{RA}}(D) = 35.97(\pm 1.4) - 0.25(\pm 0.03) \cdot D$$

χ^2 of 0.559,

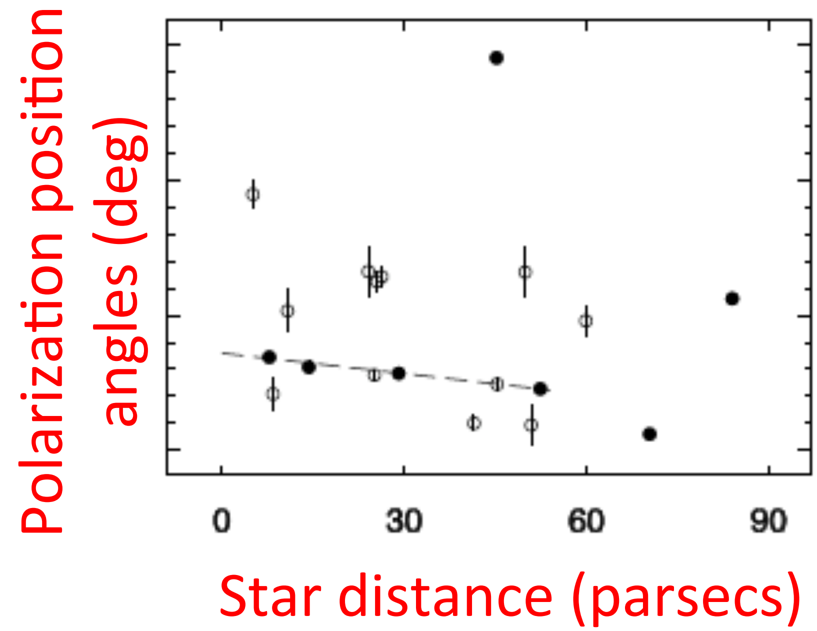


Fig ref: Frisch et al. 2012, ApJ

Turbulence of ISMF is given by the standard deviation of the ISMF position angles for RA>16H stars and is σ =+/-23 degrees around ordered component

Closest data on interstellar magnetic field is IBEX Ribbon

- IBEX Ribbon is BdotR=0 effect
- Seen in directions perpendicular to interstellar magnetic field draping over heliosphere
- ISMF predicted from MHD heliosphere models that reproduce 8 AU difference in termination shock distances of Voyager 1 and Voyager 2 also predict the ISMF direction
- Center of Ribbon arc gives direction for ISMF at Sun of L,B = 33, B=55 deg
- A $32^{o} \pm 20^{o}$ difference exists between local ISMF direction of polarization data and very local direction of IBEX Ribbon

Ribbon of energetic neutral atoms(ENA) observed by IBEX

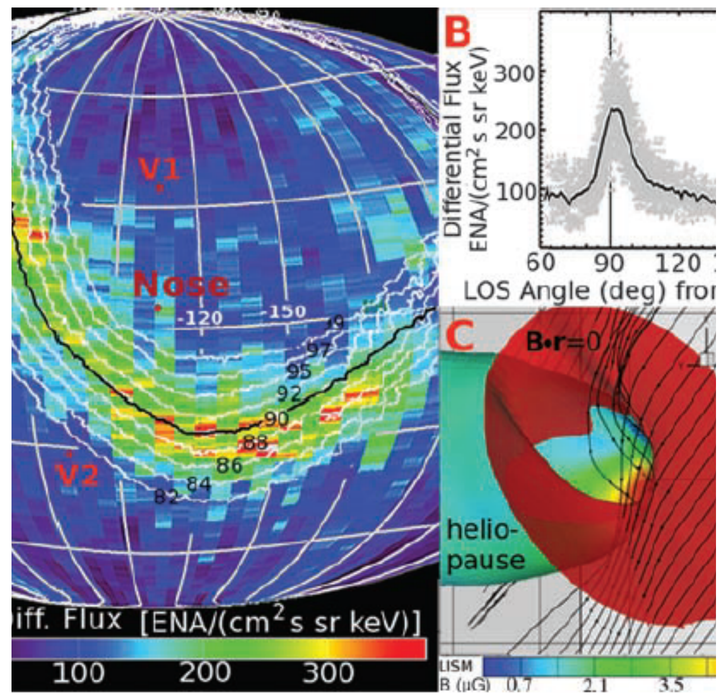


Fig from Schwadron et al. 2009, Science

Local ISMF continuous into third galactic quadrant

- $B_{||}$ from ratio of pulsar rotation and dispersion measures:

$$\frac{RM}{DM} = \frac{\int_0^{dL} B_{||}\, n_e\, dL}{\int_0^{dL} n_e\, ds}$$

- Four pulsars (130-300 pc) in third galactic quadrant where see low density ISM
- |B|=3.3 μG
- ISMF field is directed up out of the ecliptic plane, or
  - *towards L,B=5°,42°*
  - *towards λ,β=232°,18°*
- This direction is 22° from center of IBEX ENA Ribbon arc

ISMF in galactic quadrant III directed towards Sun

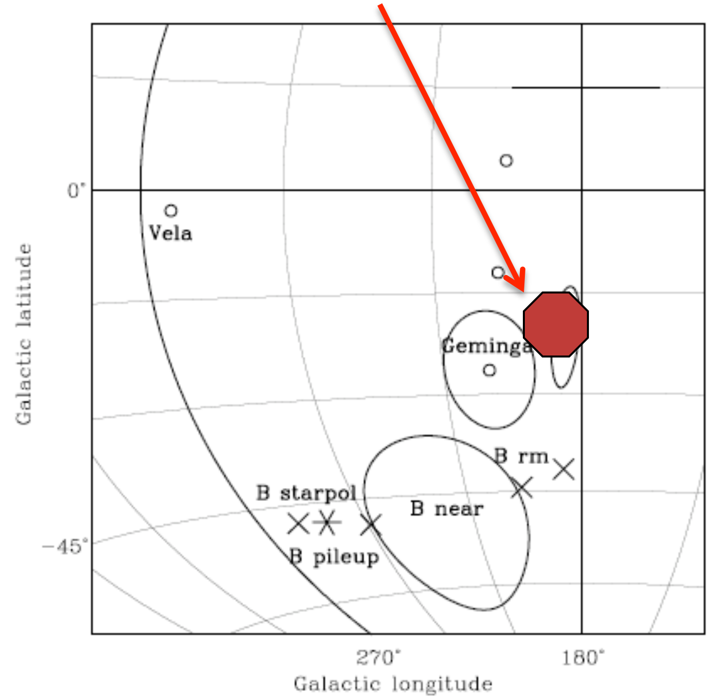


Fig. 1. Aitoff equal area projection in Galactic coordinates of the southern half of the third Galactic quadrant. See text for the meaning of the symbols. In all cases, the B field is directed out of the page towards the reader.

•Ref: Salvati 2010

Direction of local ISMF from Faraday rotation

ISMF in galactic quadrant III directed towards Sun

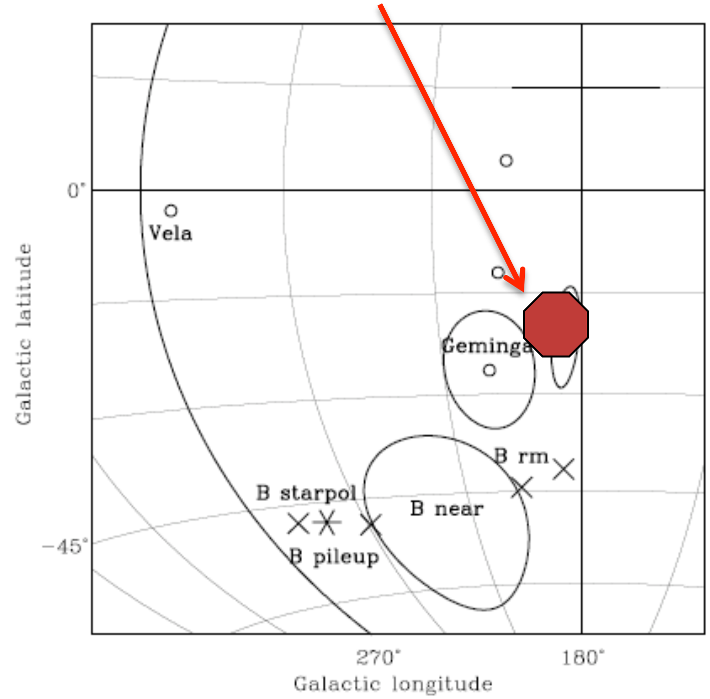
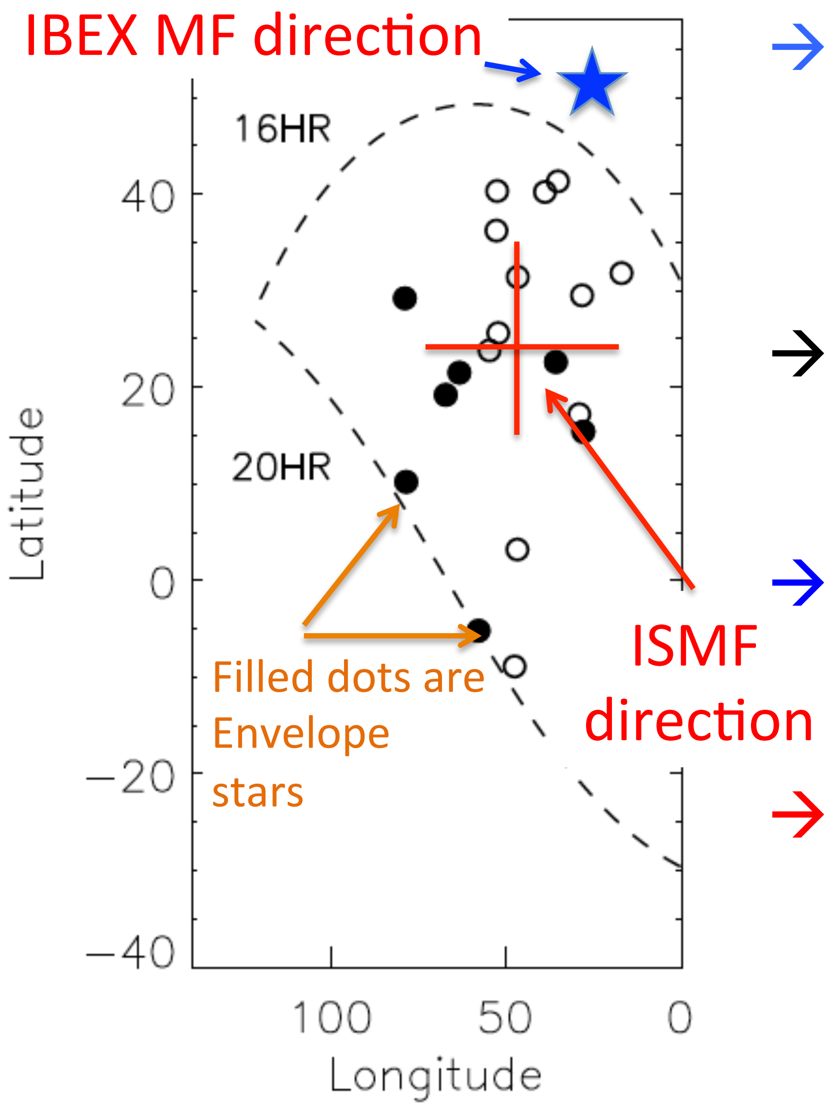


Fig. 1. Aitoff equal area projection in Galactic coordinates of the southern half of the third Galactic quadrant. See text for the meaning of the symbols. In all cases, the B field is directed out of the page towards the reader.

LISMF perpendicular to bulk velocity



→ Angle between local interstellar magnetic field and bulk interstellar flow velocity (LSR) is 76 +/- 20 degrees

→ Consistent with expectation of expanding superbubble with ISMF entrained in shell

→ Best fit ISMF direction coincides with region of ordered magnetic field

→ Is this what an interstellar flux rope would look like?

Ref: Frisch et al. 2012

Filling factors and flux freezing

- Filling factors are volume of space filled by interstellar clouds
- Assume all local clouds are like the LIC, with a neutral density of about 0.2 cm^{-3}
- 25% to 50% of space in star sightline is filled with interstellar gas (Frisch & Slavin)
- Simulations of projected cloud volumes give filling factor of 6%-19% (Redfield & Linsky)
- There is a lot of "empty" space nearby, presumed to be filled with Local Bubble 10^6 K plasma.
- Flux freezing not observed for clouds with densities n<1000 /cc (work by Crutcher et al.)
- Suggests that the local ISMF is distributed throughout local cloud system and not confined to individual clouds

What are the local ISM anisotropies that might affect GCR anisotropies?

- Interstellar magnetic field asymmetry
- Sun is very close to the surface of the LIC
  - no LIC component is found towards the G-cloud toward the upwind dirction
- Tiny dense nearby cloud in Leo
- There has to be an ionization gradient in clouds because of the geometry of the interstellar radiation field sources; this won't affect ISMF if no flux freezing occurs
- Cloud collisions occur among local clouds; may create turbulence in the ISMF

Summary

- The Loop I superbubble organizes the kinematics and magnetic field of the local ISM
- Local ISMF is perpendicular to bulk motion of local clouds
- A smooth ISMF can be traced over 150 pc from the pole at L,B=45±20 ,25±5 deg in the first galactic quadrant into the opposite third galactic quadrant. This ISMF direction has a curvature of 0.25 deg per parsec that is consistent over this interval.