Using our Heliosphere as a Probe of Low Column Density ISM

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ABSTRACT

The Sun is embedded in a tenuous, low column density, partially ionized, rapidly moving interstellar cloud that provides insight into global low column density ISM. The surrounding cloud is observed both inside of the solar system, through partially ionized Ne, Ar, and He, and towards nearby stars. The surrounding cloud is warm, T~6400 K, with n(H) ~0.3 cm^{-3}, HI/HII~2, V~17 km s^{-1} (LSR), and N(HI)<10^{18} cm^{-2}. It is part of a cluster of local interstellar clouds (CLIC), that is turbulent, FWHM(V)~10 km/s, and flowing past the Sun. The CLIC originated with star formation in the Scorpius-Ophiuchus Association. If viewed from elsewhere, the CLIC would appear to be either or both typical low column density HI gas or diffuse ionized gas, n(e)~0.1 cm^{-3}. Radiative transfer models of the surrounding ISM indicate that this closest material is in photoionization equilibrium, offering insight into the formation of global tepid tenuous rapidly moving ISM (Slavin & Frisch, 2002, 2006).

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• Low opacity ISM is understandable if the boundary conditions (heliosphere) of a sightline (stars) are known.
• ISM data collected inside of the heliosphere provide the boundary conditions for the sightlines towards stars.
• Radiative transfer models are required to interpret these data because of the low column densities.
• We can use this strategy to gain specific information on the past and future galactic environment of the Sun -- or how the PALEOHELIOSPHERE interacts with the PALEOLISM.
ISM Flow: Past and the Future

- The Past: Paleoheliosphere, PaleoLISM
- The Future

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• Pickup Ions: 
  H, He, N, O, Ne 
• Anomalous Cosmic Rays: 
  Ar + all of above 

Filtering factor $= f = \text{in/out}$ 

• He, Ne, Ar, $f \sim 0.87-0.99$ 
• H, N, O, $f \sim 0.5-1$ 

Frisch et al. (2005) 

Frisch & Slavin, Small Scale Structure Meeting, Socorro, May 2006
Best Local Interstellar Cloud (LIC) Properties derived from Ulysses He particle data + PUI + 584 Å + focusing cone

Moebius et al. (2004)
L,B-downwind: 183.7°, -15.3°
\( n(\text{He}^0) = 0.0148 \pm 0.0015 \, \text{cm}^{-3} \)
\( T = 6300 \pm 390 \, \text{K} \)
\( V = 26.2 \pm 0.5 \, \text{km s}^{-1} \)

Frisch et al. (2005)

Frisch & Slavin, Small Scale Structure Meeting, Socorro, May 2006
Pickup Ion Data: N, O, Ne, H
Anomalous Cosmic Rays: Ar

Frisch et al. (2005)

Frisch & Slavin, Small Scale Structure Meeting, Socorro, May 2006
Hydrogen Properties from Lα Glow, Pickup Ions

Copernicus

ISM $n(H^0)$, for filtration $f \sim 0.54$,

* PUI $\rightarrow n(HI)=0.18\pm0.01 \text{ cm}^{-3}$ (GG02)
* Lyα glow $\sim 0.17 \pm 0.05 \text{ cm}^{-3}$ (Ajello94)
* Hydrogen wall model $\sim 0.14$-0.20 cm$^{-3}$

Frisch et al. (2005)

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ISM inside Heliosphere versus towards Nearby Stars

- **HI/HeI**
  - Heliosphere --> $12.2 \pm 1.4$ after filtration (Ly$\alpha$, 584A, PUI)
  - White Dwarfs --> $12.8 \pm 1.4$ (5 stars, 50-79 pc)

- **OI/NI, OI/HI, ArI/OI**
  - Heliosphere --> $7.6$, $4.3e-4$, $3.4e-3$ after filtration (PUI, ACR)
  - White Dwarf stars, d<70 pc --> $8.7$, $4.0e-4$, $3.9e-3$ or $<1.6e-3$

- **Temperature**
  - Heliosphere --> 6,300 K from HeI data (particle, PUI, 584 A)
  - Stars, d<10 pc, T=1,500 to 13,000 K

- **Density**
  - Heliosphere --> $n(H) \sim 0.18$ cm$^{-3}$ (Ly$\alpha$ 1215 A)
  - Stars, d < 6 pc --> $<n(HI)> \sim 0.06$ cm$^{-3}$

- **LIC vrs Local Fluff/CLIC Velocity (optical+UV lines):**
  $26.2 +/- 0.5$ km/s vrs $28.1 +/- 4.6$ km s$^{-1}$

  ==> Conclude that ISM inside of Heliosphere is Same as towards Nearby Stars

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Synopsis: Heliosphere Interaction Products Indicate the LIC is tenuous ISM $n(\text{HI}) \sim 0.18 \text{ cm}^{-3}$

But what about charged ISM, $H^+$, $\text{He}^+$, and $e^-$?

Understanding Ions for low $N(\text{HI})$ Requires Radiative Transfer Models

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Low Column Densities Define the Characteristics of Local ISM → Radiative Transfer Models Needed

• \( N(\text{HI}) < 10^{18} \text{ cm}^{-2} \) for most \( d<10 \text{ pc} \) stars
• Filling factor for \( d<10 \) stars: \( ff \sim 0.3 \)
• Radiative Transfer Models predict \( \text{H}^0/\text{He}^0 = 8.9-13.6 \)
• White Dwarf Stars: \( \text{H}^0/\text{He}^0 = 9-16 \)

\( \text{H}^0/\text{He}^0 \) vrs. \( N(\text{H}^0) \)

\( N(D^0) \) vrs. Temp.

\( \rightarrow \text{H}^0=10^{18} \text{ cm}^{-2} \)

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Local Bubble from E(B-V)
(filled symbols, N(H)>5 \(10^{20}\) cm\(^{-2}\))

Radiation Field: The Sun is located in the Local Bubble interior, containing \(10^6\) K plasma that is a source of Soft X-rays

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An Interface of some type must bound the Local Fluff, e.g. Conductive Interface

Aside:
Local Fluff cloud boundaries from
\[ L = \frac{N(H^0)}{n(H^0)} \], where \( n(HI) = 0.2 \text{ cm}^{-3} \), per LIC. All components in a sightline are summed.

*Frisch & Slavin, Small Scale Structure Meeting, Socorro, May 2006*
Radiation Field Model:
- Integrated starlight
- Local Bubble soft X-ray emission
- Emission from boundary

Constrain Models with He, O, N, Ne, Ar Heliospheric data, along With astronomical data In the ε CMa sightline (Gry Jenkins 2002)

A model matching LIC only:
- $T=6,300$ K
- $n(H^0)=0.19$ cm$^{-3}$
- $n(He^0)=0.0151$ cm$^{-3}$
- $n(e^-)=0.06$ cm$^{-3}$
- $\chi(H)=0.22$
- $\chi(He)=0.37$

Model 8 ($B_{\text{interface}} = 5 \mu$G)

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Results of Radiative Transfer Models

Set 1 Models (both): $T_{\text{sun}} \approx 8,300$ K

Set 2 Models (LIC): $T_{\text{sun}} \approx 6,300$ K

$\Rightarrow$ $n(e) \approx 0.06-0.1$ cm$^{-3}$, $n(\text{HI}) \approx 0.19-0.21$ cm$^{-3}$ for LIC

$\Rightarrow$ Conclude that models work well and are getting better

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Radiative Transfer Models Predict the Sun is Surrounded by Partially Ionized Warm Interstellar Gas

(ISM Ionization at Heliosphere (Set 1, Model 8))

Conclude H, N, O mainly neutral
He, Ne, Ar are more ionized

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Range of ionization levels possible for low N(H) ISM

Conclude Warm Partially Ionized gas (PWIM) common as tenuous ISM

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What about Local Fluff Velocities?

Cloud velocity and density constrain the past and future variations in the Solar galactic environment.

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1) Local Fluff Cloudlets have different Speeds but about Same Velocity Vector Direction.

2) THE LSR VELOCITY FLOWS FROM L,B~330°,0°

**Heliocentric Upwind**

- **Bulk flow of Local fluff:**
  \[ V_{\text{LF}} = -28.1 \pm 4.6 \text{ km s}^{-1} \]
  \( L,B \sim 12°, +12° \)

- **LIC cloudlet:**
  \[ V_{\text{LIC}} = -26.2 \pm 0.5 \text{ km s}^{-1} \]
  \( L,B \sim 3°, +12° \)

- **Apex cloudlet:**
  \[ V_{\text{apex}} = -35.1 \ \text{ km s}^{-1} \]
  \( L,B \sim 13°, +15° \)

- **G cloudlet:**
  \[ V_{\text{G}} = -29.1 \ \text{ km s}^{-1} \]
  \( L,B \sim 5°, +20° \)


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Conclude local fluff cloudlet velocities are similar to Generic low column density ISM

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1. The solar transition between the Local Bubble plasma and Local Fluff tenuous ISM was a remarkable variation in the galactic environment of the Sun.

2. When did it happen?

3. Can guesstimate the entry of the Sun into the Local Fluff by putting data and models together to obtain the relative motions of the Sun and very local ISM over time

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When Sun inside of Local Bubble Plasma

When Sun in emptiest Local Bubble
$V \approx 13.4 \text{ km/s}, T \approx 10^{6.1} \text{ K},$
$n(p^+)_{\text{IS}} = 0.005 \text{ cm}^{-3}$ & $n(H^0)_{\text{IS}} = 0 \text{ cm}^{-3}$
• No Bow Shock
• No ISM in heliosphere
• GCRs at Earth?? (more?)
(Zank et al., Mueller et al. 2006)

Sun Entered Local Fluff
50,000–130,000/n_0.2 years ago

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When did Sun enter LIC?
Need Cloud Structure - Two Models
Data suggest within past ~55,000/0.2 yrs

χOri Sightline l,b=189,-3 deg
Downwind \( V_{LIC} \): l,b=184°,-15°
\( V \sim 26 \text{ km s}^{-1} \),
Log \( N(\text{HI}) \sim 17.93 \text{ cm}^{-2} \)
LIC entry past ~53,000/0.2 yrs

Alternately, use Sirius ISM
and Assume \( V_{LIC} \parallel k_{surf} \text{ in LSR} \)
→ Sun entered LIC in past 10,000 years

Blob Model
Filament Model

Frisch & Slavin (2006)
Heliosphere H, He, N, O, Ne, Ar and ISM data give $n(\text{HI}) \sim 0.19 \text{ cm}^{-3}$, $n(\text{e}^-) \sim 0.06 - 0.11 \text{ cm}^{-3}$

Heliospheric ISM like generic nearby ISM (<30 pc) in composition, velocity, and ionization

A range of ionization levels and densities are possible

The Paleoheliosphere interacts with the PaleoLISM.

Sun exited Local Bubble cavity and entered the Local Fluff during past $\sim 50,000 - 130,000/n_{0.2}$ yrs

Sun entered the LIC in the past $\sim 1,000 - 55,000$ yrs

CONCLUSIONS

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