What fills the space between the partially ionized clouds in the local interstellar medium

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Abstract. The interstellar matter located between the warm clouds in the LISM and in the Local Cavity is now thought to be photoionized gas with temperatures in the range 10,000–20,000 K. While the hot stars ϵ CMa and β CMa are the primary photoionizing sources in the LISM, hot white dwarfs also contribute. We consider whether the Strömgren sphere gas produced by very local hot white dwarfs like Sirius B can be important in explaining the local intercloud gas. We find that the Strömgren sphere of Sirius can at least partially explain the intercloud gas in the lines of sight to several nearby stars. We also suggest that the partially ionized warm clouds like the Local Interstellar Cloud in which the Sun is located may be in part Strömgren sphere shells.

1. Properties of partially ionized warm clouds in the local interstellar medium

The Sun is surrounded by partially ionized warm gas extending out to a distance of about 15 pc in the local interstellar medium (LISM). We have learned about the properties of this gas from high-resolution spectra of absorption lines produced by interstellar gas along the lines of sight to nearby stars and from measurements of interstellar gas flowing into the heliosphere. [1] first reported that the radial velocities of interstellar absorption lines in the spectra of nearby stars are consistent with the interstellar gas flowing toward the Sun from the direction of the Scorpio-Centaurus Association. Subsequent investigations (e.g., [2, 3]) found that the interstellar gas flow has a number of velocity components with slightly different flow directions and speeds.

More recently, [4] identified 15 different velocity components of warm interstellar gas located within 15 pc of the Sun by analyzing interstellar absorption lines in HST spectra of 157 nearby stars. The flow vectors for each of these clouds predict accurate radial velocities for the interstellar gas in the directions of these clouds for all 34 new lines of sight observed by [5]. This success in predicting the radial velocities for these new sight lines indicates that these cloud vectors have accurate predictive power. Figure 1 shows the angular extent of the 15 clouds in Galactic coordinates. The Local Interstellar Cloud (LIC) is so-named because its angular extent covers nearly half of the sky, implying that the Sun is located just inside of the LIC or immediately outside. The decision as to which option is more likely to be valid requires the second type of data—measurements of interstellar gas flowing into the heliosphere.

Table 1 compares the parameters of the interstellar gas flowing into the heliosphere with the parameters of gas in the LIC obtained from absorption lines studied by [4]. The most recent measurements of the interstellar gas entering the heliosphere were obtained from IBEX satellite
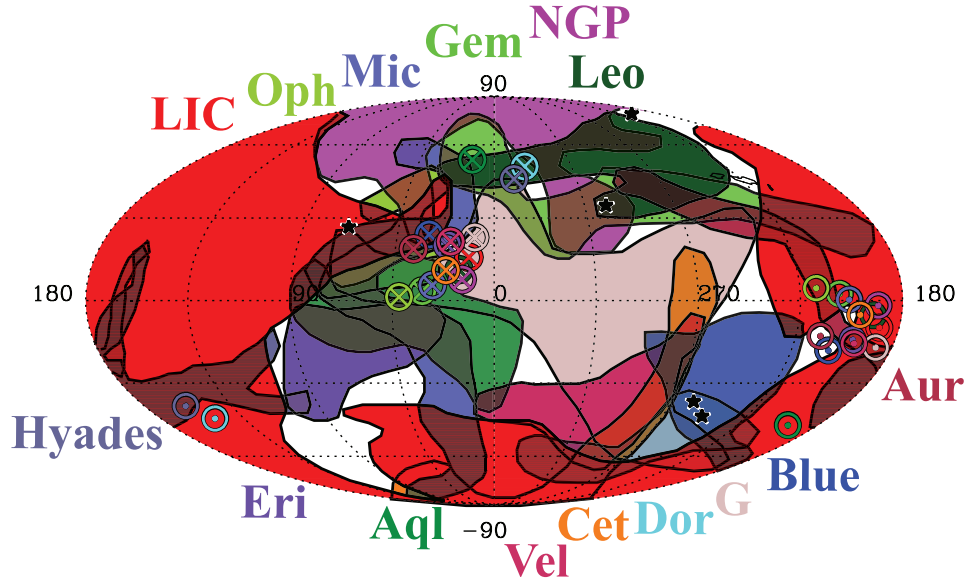
Figure 1. Morphologies of the 15 warm LISM clouds in Galactic coordinates with the Galactic Center direction in the center. The upwind heliocentric directions of the velocity vector for each cloud are indicated by the circled-cross symbols, and the downwind directions are indicated by the circled-dot symbols. The Sun is likely located just inside of the LIC (red) and the two closest clouds are the G cloud (brown) towards α Cen (1.32 pc) and the Blue cloud (dark blue) towards Sirius (2.64 pc). Figure from [4].

Table 1. Properties of the Local Interstellar CLoud.

Parameter	Redfield & Linsky 2008 [4]	McComas et al 2012 [6]
Flow speed (km s^{-1})	23.83 ± 0.90	23.3 ± 0.3
Galactic Longitude (deg)	187.0 ± 3.4	185.25 ± 0.24
Galactic Latitude (deg)	-13.5 ± 3.3	-12.03 ± 0.51
Temperature (K)	7500 ± 1300	6300 ± 390

observations of neutral hydrogen by [6, 7]. The flow speeds listed in Table 1 are for the inflow direction relative to the Sun's velocity through the LIC. The Galactic longitude and latitude are the direction of the upwind flows, and the gas temperatures were obtained from line widths. More precise measurements will be forthcoming from new IBEX data, but the present excellent agreement between the two sets of data provide strong evidence that the heliosphere is located just inside of the LIC. [8] computed a model for the LIC with neutral hydrogen number density $n_{\mathrm{HI}} = 0.19$–0.20 cm^{-3}, electron density $n_e = 0.007 \pm 0.01$ cm^{-3} and temperature $T = 6300$ K.

[4] find that the temperatures of other clouds lie in the range 5300–9900 K, and their neutral hydrogen column densities lie in the range $\log N_{\mathrm{HI}} = 17.2$–18.8. The values of n_{HI} and n_e are uncertain although the clouds are likely partially ionized like the LIC.

The absence of interstellar absorption in the direction of the Sun's motion implies that the Sun will leave the LIC in less than 3000 years. [9] recently proposed that the inflow direction has changed over the last 40 years, suggesting that the heliosphere's environment is changing in our lifetime. However, the data upon which this result is based are not conclusive, and more data are needed before reaching a definitive conclusion. What will be the properties of the interstellar gas that the Sun will be entering, and what are the properties of the gas between the warm clouds and in the Local Cavity that envelopes these warm gas clouds?

2. Previous models for the intercloud gas

The classic papers of [10, 11, 12] predict that the interstellar medium should consist of three components: cold neutral and molecular gas ($T \leq 50$ K), warm neutral or ionized gas ($T \sim 8000$ K), and million-degree low-density ionized plasma. These papers assumed that the three components coexist in pressure and thermal equalibrium, which we now find is highly unlikely. For example, numerical simulations by [13], which include supernova explosions and realistic thermal processes, predict a very wide range of densities and temperatures in the ISM but no pressure equilibrium and no identifiable thermal phases. Observations are needed to determine which of these two very different models, or perhaps neither one, is realistic.

The nearby warm partially ionized gas clouds have properties roughly consistent with the warm component predicted by the classical models. Cold dense molecular clouds are observed typically by CO and HI 21-cm emission in many parts of the Galaxy. The nearest cold gas with a temperature of 15–30 K is the Leo cloud located at a distance between 11.3 and 24.3 pc from the Sun [14].

Our ideas concerning the properties of the gas surrounding the warm LISM clouds have undergone a radical change in the last 20 years. The gas between the clouds and extending out to roughly 100 pc from the Sun in what is now called the Local Cavity was originally assumed to be hot (roughly 10^6 K), fully ionized, and low density (roughly 0.005 cm^{-3}). This conclusion was based upon the predictions of the classical models and observations of diffuse soft X-ray emission consistent with the properties of the hot gas. This picture is no longer viable as X-ray emission from charge-exchange reactions between the solar wind ions and inflowing interstellar neutral hydrogen can explain most or perhaps all of the observed diffuse soft X-ray emission, except for the Galactic pole regions [15, 16, 17, 18]. Also, the intercloud and Local Cavity gas must have a much cooler temperature ($T \ll 10^6$ K) or very low emission measure as indicated by X-ray shadowing experiments (e.g., [2011]) and by extreme ultraviolet spectroscopy [19]. Since interstellar O VI absorption has not been detected within 58 pc of the Sun [20], the intercloud gas must be cooler than 300,000 K, yet still be mostly ionized so as to not show neutral hydrogen absorption.

Given the problems of explaining the intercloud (filler) gas with hot plasma, [21] proposed that the Local Cavity is an old supernova remnant with photoionized gas at a temperature of about 20,000 K. The likely photoionizing sources are primarily the hot stars ϵ CMa and β CMa that [22] found are the brightest extreme-ultraviolet sources observed by the Extreme Ultraviolet Explorer (EUVE) satellite, but several hot white dwarf stars also contribute to the ionizing radiation field.

3. Could the Strömgren spheres of hot white dwarfs explain the intercloud gas?

We consider here the effects of hot white dwarfs on their surrounding interstellar medium to test whether their ionizing radiation may play an important role in explaining the properties of the intercloud gas. In a classic paper, [23] showed that the EUV radiation ($\lambda < 912$ K) from a hot

star completely ionizes hydrogen in its surrounding volume (an H II region) out to a distance now called the Strömgren radius where the build up of neutral hydrogen opacity absorbs the photoionizing radiation, producing a narrow partially ionized shell with neutral hydrogen gas outside. In this paper, Strömgren developed a simple model by assuming that the hot star is located in a constant density environment in which flows are ignored and time-independent photoionization of hydrogen is balanced by recombination. This model has been extended to include dust opacity, clumpiness, diffuse radiative transfer, dynamics, and the location of the star in a pre-existing cavity (e.g., [24, 25]). Here, we test whether the simple Strömgren sphere model can explain the gas-filling lines of sight to the closest stars using our LISM model. Following the suggestion of [26], we consider whether this filler gas can be understood simply as Strömgren spheres surrounding the many strong sources of extreme ultraviolet (EUV) radiation in the LISM, specifically hot white dwarfs and OB stars.

Table 2 lists the stars within 16 pc of the Sun for which absorption by neutral gas in nearby clouds has been identified by [4, 5]. We list the distances, Δd(neutral), along the lines of sight (LOS) through the identified clouds, assuming that the neutral hydrogen density is the same as that measured for the LIC ($n_{HI} = 0.195$ cm^{-3}) by [8] and that the remaining path length [Δd(ionized)] is filled by the presumably ionized filler gas.

Table 3 lists the nearby ($d < 20$ pc) sources of ionizing radiation (mostly hot white dwarfs) and the sizes of their surrounding volumes of Strömgren sphere-ionized gas. [26] computed the radii (R) of these H II regions assuming that the Strömgren spheres have stopped expanding, and that $n_e = 0.03$ cm^{-3}. We have recomputed the radii by assuming a gas-pressure balance with the LIC, $(n_{HI} + n_e + n_p + n_{He})T = 2710$ K cm^{-3}, where $n_{HI} = 0.195 \pm 0.005$ cm^{-3}, $n_e = n_p = 0.07 \pm 0.002$ cm^{-3} [8], $n_{He}/n_H = 0.1$, and $T = 7500$ K [4]. Table 3 lists $R(T)$ for various assumed temperatures computed from the values of $R(n_e = 0.03)$ in [26] scaled to higher densities using $R \sim (n_e/0.03)^{-2/3}$, which is based on equation 9-9 in [27].

Also listed in Table 3 are five more distant ionizing sources that dominate the EUV spectrum observed by the Extreme Ultraviolet Explorer (EUVE) spacecraft: ϵ CMa, whose emission dominates the 504–912 Å spectral region, β CMa, and the hot white dwarfs HZ 43, G191-B2B, and Feige 24 [8, 22, 28]. We compute their Strömgren sphere radii as a function of ionized-gas temperature scaling from the radii listed in [28] for $n_e = 0.04$ cm^{-3} and equation 9-9 in [27]. Following on the EUVE results of [22, 28] found that hot white dwarfs contibute only a small fraction of the total ionization in the Local Cavity, but we propose that for the short lines of sight to nearby stars, the Strömgren spheres of individual white dwarfs can provide much of the ionized filler gas between the partially ionized warm clouds.

We list here some rough estimates of the amount of ionized-filler gas in the LOS to nearby stars and whether nearby hot white dwarfs or other hot stars can supply the ionizing radiation to fill these sightlines with ionized gas. The computed Strömgren sphere radii are approximate given possible errors in the pressure balance and thermal equilibrium assumptions.

- **The LOS to Sirius:** The LIC and Blue are two partially ionized clouds in this LOS. Since the Sun is located inside of the LIC and Sirius is surrounded by the Strömgren sphere produced by EUV radiation from Sirius A and B, the LOS from the Sun to Sirius must consist first of LIC gas, then the Blue cloud, and then Strömgren sphere gas filling the remaining 1.92 pc. This path length of ionized gas is consistent with a Sirius A+B Strömgren sphere radius corresponding to a gas temperature of 10,000 K (see Table 3).

- **The LOS to α Cen:** Absorption by only the G cloud is seen in this LOS over a distance of 0.70 pc, if we assume that n_{HI} is the same as in the LIC. The remaining 0.62 pc could be filled with ionized gas from the Sirius A+B Strömgren sphere which cuts across the midpoint of the LOS from the Sun to α Cen at a distance of 2.21 pc. Since α Cen has an astrosphere, the LOS from the Sun to this star should consist first of a very thin layer of

Table 2. Composition of Gas Along Selected Lines of Sight

Star	l	b	d(pc)	Cloud	log[N(HI)]	Δd(neutral)	Δd(ionized)
α Cen[a]	315.7	−0.9	1.32	G	17.6	0.70	0.62
Sirius A	227.2	−8.9	2.64	LIC	17.4	0.44	
				Blue	17.2	0.28	
				Sum		0.72	1.92
ϵ Eri[a]	5.8	−48.1	3.22	LIC	17.8	1.10	2.12
61 Cyg[a]	82.3	−5.8	3.49	Aql	17.8	1.10	
				Eri	17.8	1.10	
				Sum		2.20	1.29
Procyon	213.7	+13.0	3.51	LIC	17.9	1.56	
				Aur	17.6	0.70	
				Sum		2.26	1.25
ϵ Ind[a]	336.2	−48.0	3.63	LIC	16.6	0.14	3.49
61 Vir[a]	311.9	+44.1	8.53	NGP	(18.0)	(1.7)	(6.8)
β Com	43.5	+85.4	9.15	NGP	(18.0)	(1.7)	(7.4)
π^1 UMa	150.6	+35.7	14.6	LIC	17.85	2.30	12.3
τ Boo	358.9	+73.9	15.6	NGP	(18.0)	(1.7)	13.9
51 Peg	90.1	−34.7	15.6	Eri	(17.9)	(1.6)	
				Hya	(17.4)	(0.4)	
				Sum		(2.0)	(13.6)
χ Her[b]	67.7	+50.3	15.9	NGP	(18.0)	(1.7)	14.2

[a] Astrosphere detected by Wood et al 2005 [29] indicates that a cloud with neutral hydrogen must surround the star.
[b] No astrosphere detected by Wood et al 2005 [29].

LIC gas (showing no detectable absorption at the LIC velocity), then ionized gas from the Sirius A+B Strömgren sphere, and then the G cloud.

- **The LOS to ϵ Eri:** Spectra of ϵ Eri show absorption only at the LIC velocity, but the star has an astrosphere and, therefore, must be located in a partially neutral cloud. The LIC fills 1.10 pc along this LOS leaving 2.12 pc to be filled with ionized gas. Since Sirius is located 4.88 pc from ϵ Eri and 3.40 pc from the midpoint of the LOS from the Sun to ϵ Eri, we do not expect that Strömgren sphere gas from Sirius A+B can fill the missing 2.12 pc along the Sun-ϵ Eri LOS. Another hot white dwarf, 40 Eri B, is located 6.11 pc from ϵ Eri, so it is unlikely that its Strömgren sphere comes close to the Sun-ϵ Eri LOS. Instead, ϵ CMa, the largest source of ionizing radiation in the solar neighborhood [22] is the likely source for this ionized gas. If the assumptions of our model (thermal pressure equilibrium with no other sources of pressure) are appropriate, then the temperature of the ionized gas along this LOS would be about 40,000 K.

- **The LOS to Procyon:** Absorption by the LIC and Aur clouds leave 1.25 pc of path length to be filled with ionized gas. Ionizing radiation from Sirius A+B is the likely source of this ionized gas, since the separation of Sirius and Procyon is only 1.61 pc. This would indicate a Strömgren gas temperature of about 7,500 K.

- **The LOS to π^1 UMa, V368 Cep, MN UMa, δ Dra, 47 Cas, and ι Cep:** Spectra of these stars centered near l=130°, b=+30° with distances 14.4–35.4 pc all show absorption

Table 3. Hot White Dwarfs and their Strömgren Sphere Radii (pc)

| WD	l	b	d(pc)	R(10,000K)	R(15,000K)	R(20,000K)	R($n_e = 0.03$)
Sirius B	227.2	−9.9	2.64	1.56	2.04	2.48	4.12
Sirius A+B	227.2	−9.9	2.64	1.93	2.51	3.05	5.08
40 Eri B	200.8	−38.0	5.04	0.44	0.58	0.70	1.17
GJ3753	123.3	+62.0	14.1	0.91	1.18	1.44	2.39
GJ433.1	284.9	+27.7	14.8	0.88	1.14	1.39	2.31
UZ Sex	245.3	+46.3	18.2	0.63	0.82	0.99	1.65
GD 50	188.9	−40.1	29.	1.88	2.47	2.99	4.11[a]
G191-B2B	155.9	+7.1	59.	8.18	10.72	12.98	17.86[a]
HZ 43	54.1	+84.2	68.	4.70	6.16	7.47	10.27[a]
Feige 24	166.0	−50.3	74.	9.55	12.51	15.16	20.85[a]
ϵ CMa	239.8	−11.3	124.	31.7	41.5	50.3	69.2[a]
β CMa	226.1	−14.3	151.	12.6	16.5	20.0	27.5[a]
n_e (cm^{-3})				0.129	0.0860	0.0645	0.03
$(n_e/0.03)^{-2/3}$				0.379	0.495	0.601	1.00
$(n_e/0.04)^{-2/3}$				0.458	0.600	0.727	1.00

[a] R($n_e = 0.04$) (pc).

only at the LIC velocity with no evidence for any other neutral gas in the LOS. Since the LIC lies in the immediate vicinity of the Sun, the remainder of these lines of sight must by ionized gas. GJ3753 (14.1 pc) and especially the hot white dwarf G191-B2B (59.9 pc) may be responsible for much of the ionizing radiation from this general direction.

- **The LOS to 61 Vir, β Com, τ Boo, and χ Her:** Spectra of these stars, all located at high Galactic latitudes (b> 44°), show absorption only by the NGP cloud with no evidence for absorption by the LIC or any other cloud. Since the closest star, 61 Vir (8.53 pc), has a detected astrosphere, the NGP cloud must be located near and in front of these stars. This leaves about 6.8 pc of the LOS to 61 Vir and similar path lengths toward the other stars to be filled with ionized gas. The high Galactic latitude white dwarfs especially HZ 43 but also GJ3753, GJ433.1, and UZ Sex could provide part of this ionizing radiation in addition to ϵ CMa and β CMa.

These examples support our proposal that ionized gas in the Strömgren spheres of hot white dwarfs is a component of the gas filling the lines of sight to nearby stars between the partially ionized warm gas clouds. A more detailed description of the morphology of the local ISM requires a three-dimensional model of the LISM clouds and a recalculation of the Strömgren spheres sizes based on modern models of hot white dwarfs.

Finally, we note that the thickness of the partially ionized outer shell of a Strömgren sphere is $\delta = (n_{HI}\sigma)^{-1}$, where $\sigma \approx 10^{-17}$ cm^2 [27] is the hydrogen-ionization cross section for EUV photons near 912 Å. Thus $\delta \approx 0.2$ pc. Depending on their distance from the Sun, filamentary warm clouds like the Mic Cloud could have roughly this thickness. The distance across the LIC is about 2.7 pc for log N(HI)=18.2 [4]. Thus the outer 0.2 pc of the LIC could be a Strömgren sphere shell and many of the other nearby partially ionized clouds could be fragments of Strömgren sphere shells.

Figure 2 shows the column density of neutral hydrogen computed from the geometric center
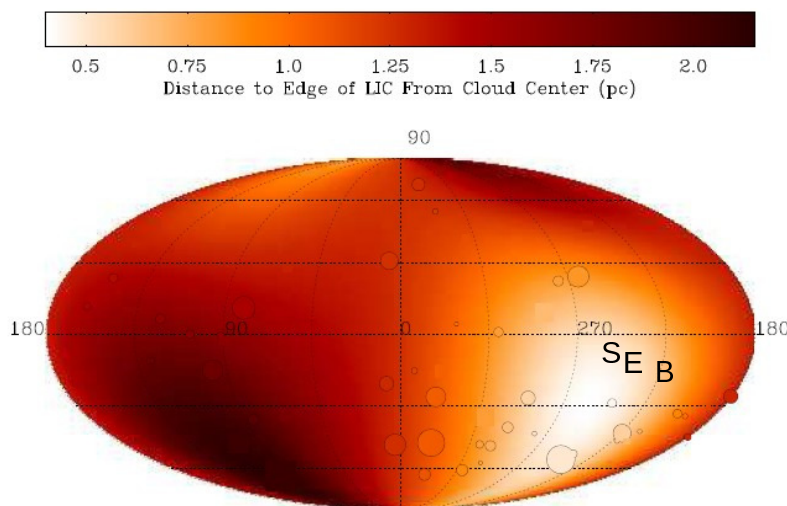
Figure 2. Column density of neutral hydrogen through the LIC as seen from its geometric center. The neutral hydrogen column density scale is above the figure. The symbols are S for the Galactic coordinates of the hot white dwarf Sirius B, E for ϵ CMa, and B for β CMa. Figure from Redfield et al. (in prep.).

of the LIC to its edge by Redfield et al (in prep.) based on the measured values of interstellar N(H I) with LIC radial velicities toward nearby stars. The region with Galactic longitude $225° \leq l \leq 300°$ and Galactic latitude $-90° \leq b \leq +30°$ shows very low H I column density corresponding to a skin depth of < 0.5 pc. The Galactic coordinates of Sirius, ϵ CMa and β CMa as seen from the center of the LIC are in this region. This is consistent with these three sources of ionizing radiation shaping the morphology of the LIC. Also, the short distance from the edge to the center of the LIC in this direction supports our proposal that the warm clouds are in part shells of Strömgren spheres.

4. Conclusions

The gas located between the warm LISM clouds and in the Local Cavity, which was previously assumed to be similar to the hot component in the classical interstellar medium models, is now thought to be photoionized gas with temperatures in the range 10,000–20,000 K. While the hot stars ϵ CMa and β CMa are the primary photoionizing sources in the LISM, hot white dwarfs also contribute. We consider whether the Strömgren sphere gas produced by very local hot white dwarfs like Sirius B can be important in explaining the local intercloud gas. We find that the Strömgren sphere of Sirius can at least partially explain the intercloud gas in the lines of

sight to α Cen, Sirius, Procyon, ϵ Eri and other nearby stars. We also suggest that the partially ionized warm clouds like the LIC may be in part Strömgren sphere shells.

This work is a pilot study based on the LISM model of [4, 26] calculations for the Strömgren spheres of nearby hot white dwarfs. Redfield et al (in prep.) are now computing a new three-dimensional LISM model including the [5] sightlines. When this is available, we will reexamine the extent to which Strömgren sphere gas may explain the properties of the filler gas between the LISM warm clouds using the EUV luminosities of hot white dwarfs computed by [28].

5. Acknowledgements

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