

The local ISM in three dimensions: kinematics, morphology and physical properties

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Abstract We summarize the results of our long-term program to study the kinematics, morphology, and physical properties of warm partially ionized interstellar gas located within 100 pc of the Sun. Using the *Space Telescope Imaging Spectrograph (STIS)* and other spectrographs on the *Hubble Space Telescope (HST)*, we measure radial velocities of neutral and singly ionized atoms that identify comoving structures (clouds) of warm interstellar gas. We have identified 15 of these clouds located within 15 pc of the Sun. Each of them moves with a different velocity vector, and they have narrow ranges of temperature, turbulence, and metal depletions. We compute a three-dimensional model for the Local Interstellar Cloud (LIC), in which the Sun is likely embedded near its edge, and the locations and shapes of the other nearby clouds. These clouds are likely separated by ionized Strömrgren sphere gas produced by ϵ CMa, Sirius B, and other hot white dwarfs. We propose that some of these partially ionized clouds are shells of the Strömrgren spheres.

Keywords Interstellar medium · Interstellar gas · Hot stars · Extreme ultraviolet radiation

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1 Objectives and methodology of the LISM program

For many decades interstellar gas in our Galaxy has been studied by absorption line spectroscopy (e.g., Savage and Sembach 1996), theory (e.g., Wolfire et al. 2003; Cox 2005), and simulations (e.g., de Avillez and Breitschwerdt 2005). The nearby region of space provides an important test of the theoretical models and simulations since short lines of sight to nearby stars through the local interstellar medium (LISM) should contain fewer velocity structures containing a less diverse range of physical properties than longer lines of sight. For nearby stars, the high-resolution spectrographs on the *Hubble Space Telescope (HST)*, in particular the *Space Telescope Imaging Spectrograph (STIS)*, provide excellent platforms for observing the rich array of interstellar ultraviolet absorption lines with resolutions as high as $R = \lambda/\Delta\lambda \approx 100,000$ (3.0 km/s). For a comprehensive review of the LISM, see Frisch et al. (2011).

Absorption line measurements towards a few nearby stars permitted Crutcher (1982) to show that the measured radial velocities are consistent with a flow direction of nearby interstellar gas away from the Scorpio-Centaurus Association. With measurements for more lines of sight, Lallement and Bertin (1992) found that the interstellar gas in lines of sight toward and away from the Galactic Center direction have slightly different flow directions, which they called the Galactic (G) and anti-Galactic clouds (AG). The latter is now called the Local Interstellar Cloud (LIC). With additional lines of sight Frisch et al. (2002) could identify seven velocity vectors indicating seven warm gas clouds. These studies suggested that a more thorough study of the kinematics of the LISM would identify additional clouds, their morphologies, and their physical properties that could test the theoretical models and simulations.

We, therefore, began a long-term study of the LISM with the objective of developing a three-dimensional model of

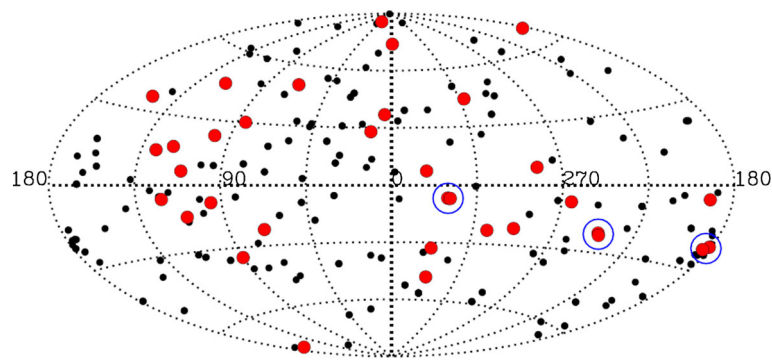


Fig. 1 This figure shows all of the lines of sight for which we have high resolution spectra that show the radial velocities and broadening parameters for one or more velocity components. Most of the data were obtained with the *STIS* instrument on *HST*. The *black points* indi-

cate lines of sight analyzed by Redfield and Linsky (2008), and the *red points* indicate the more recently observed and analyzed data presented in Malamut et al. (2014). The *lines of sight* are displayed in Galactic coordinates. Figure reproduced from Malamut et al. (2014)

nearby warm partially ionized interstellar gas including the identification of structures, which we call clouds, measurement of their kinematic and physical properties, characterization of the ionized gas surrounding the clouds, and, when feasible, identification of the physical processes responsible for these structures. The volume of interstellar space of interest is limited by the extent of the Local Cavity, a low density region of space extending from the Sun outwards to a neutral hydrogen column density $\log[N(\text{HI})] \approx 19.3$ with an irregular shape very roughly 100 pc in radius (Sfeir et al. 1999; Welsh et al. 2010). It is likely that the Local Cavity was produced by supernova explosions and the winds of massive stars in the Scopus-Centaurus Association (Berghöfer and Breitschwerdt 2002). There is very little cold gas ($T < 100$ K) inside of the Local Cavity (Heiles and Troland 2003; Meyer et al. 2006; Peek et al. 2011), but much cold gas is seen as NaI absorption at its edge (Welsh et al. 2010).

We measure radial velocities of interstellar absorption lines in ultraviolet stellar spectra, including the Lyman- α lines of neutral hydrogen and deuterium, and the resonance lines of singly ionized magnesium, iron, silicon, and carbon. Most of the observations were obtained with the high- and medium-resolution echelle modes of *STIS*, although a few observations were obtained with other spectrographs on *HST*. In many of these spectra, we find several interstellar velocity components. For each component, we measure the line center heliocentric velocity, full width at half maximum (FWHM), and total absorption. Redfield and Linsky (2008) found that the radial velocities for the lines of sight to many stars over a wide angular range on the sky are consistent with a flow vector to within 1.5 km s^{-1} , the absolute precision of *STIS*. The Galactic coordinates of the lines of sight with radial velocities consistent with a specific flow vector define the morphology of a cloud. For the LIC, which covers about 45 % of the sky with 79 lines of sight, the two-dimensional morphology is well defined. For

the other clouds with 21 lines of sight (G cloud) down to only 4 or 5 lines of sight (e.g., Dor and Cet clouds), the morphologies are more poorly defined. We will be improving the morphologies of the 15 previously identified clouds and identifying additional clouds with the inclusion of 34 new lines of sight recently observed by *STIS* (Malamut et al. 2014).

We measure gas temperatures in the clouds from the absorption line widths of elements or ions with very different atomic weights to separate the thermal from nonthermal (turbulent) components. The best lines for these measurements are the thermally broadened Lyman- α line of DI and the turbulently broadened resonance lines of FeII and MgII. Redfield and Linsky (2004) list the temperatures and turbulent velocities for many lines of sight using this technique.

2 Morphology and properties of the local interstellar cloud

Figure 1 shows the Galactic coordinates of the stars located within 100 pc for which we have measured interstellar absorption lines obtained from the ultraviolet spectrographs on *HST* or the interstellar CaII H and K lines with ground-based telescopes. The parameters of these absorption lines are listed in Redfield and Linsky (2008) and the more recent measurements in Malamut et al. (2014). We find that radial velocities measured in the lines of sight covering about 45 % of the sky are consistent with a single velocity vector for the LIC. Redfield and Linsky (2000) computed the three-dimensional shape of the LIC based on 32 lines of sight that pass through their LIC. We now have more than 80 lines of sight with which to compute a more detailed three-dimensional morphological model of the LIC.

Figure 2 shows the distances in parsecs from the Sun to the edge of the LIC computed from the measured neutral hydrogen column densities, $N(\text{HI})$, and the assumption that

Fig. 2 Distances to the edge of the Local Interstellar Cloud (LIC) as seen from the Earth. The distances are inferred from the measured neutral hydrogen column densities assuming that the number density of neutral hydrogen for all of these lines of sight is $n(\text{HI}) = 0.2 \text{ cm}^{-3}$. Figure reproduced from Redfield and Linsky (2014)

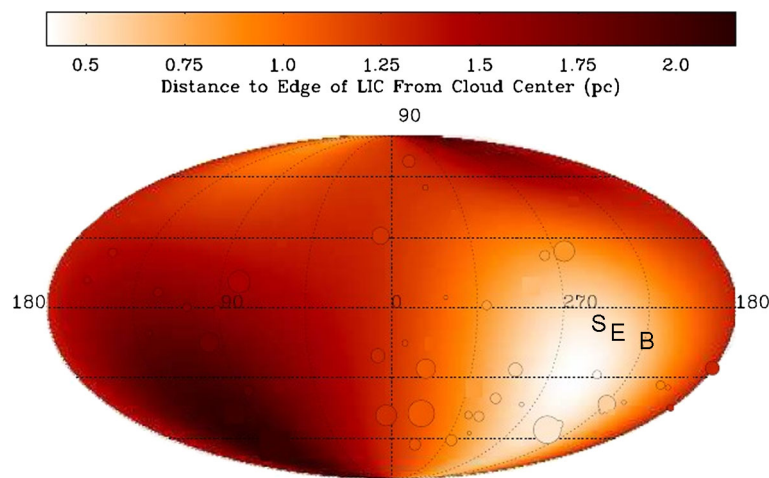
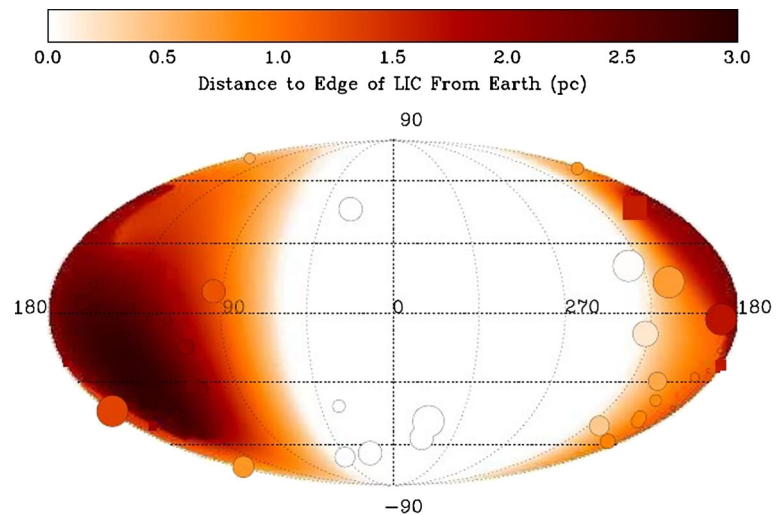


Fig. 3 Distances to the edge of the Local Interstellar Cloud (LIC) as seen from the center of the LIC. Note the very small distances near Galactic longitude $l = 245^\circ$ and latitudes $b < +15^\circ$. The figure also shows the Galactic coordinates, as seen from the center of the

LIC, of strong sources of EUV radiation: ϵ CMa (B2 Iab, symbol E), the strongest EUV source detected by the *EUVE* satellite, β CMa (B1 II/III, symbol B), and Sirius B (DA1.9, symbol S), the closest strong EUV source. Figure adapted from Redfield and Linsky (2014)

the neutral hydrogen number density $n(\text{HI}) = 0.20 \text{ cm}^{-3}$ everywhere in the LIC is the same as the measured value for gas entering the heliosphere (Slavin and Frisch 2008). Note that the distances to the edge of the LIC are too small to measure over more than half of the sky. This indicates that the Sun is located either just inside or outside of the LIC. Redfield and Linsky (2008) argued that the Sun is located outside of the LIC in a transition region between the LIC and the neighboring G cloud on the basis that the flow velocity and temperature of the interstellar gas flowing into the heliosphere have values intermediate between those of the LIC and G clouds. More recently, Möbius et al. (2012) obtained a new velocity for interstellar gas flowing into the heliosphere from *Interstellar Boundary Explorer* (IBEX) satellite data that is consistent with the LIC flow vector, indicating that the Sun is located inside of the LIC.

If the Sun is indeed located inside of the LIC, then the Sun's velocity away from the LIC in the upwind direction toward 36 Oph, the upper limit of $N(\text{HI}) < 6 \times 10^{16} \text{ cm}^{-2}$ at the predicted LIC radial velocity for this line of sight, and the assumption that $n(\text{HI}) = 0.20 \text{ cm}^{-3}$ imply that the Sun will leave the LIC in less than 3700 years (Wood et al. 2000). If the new environment is highly ionized as we predict (see below), then the new heliosphere will be very different from the present day heliosphere. This change may be occurring now as Frisch et al. (2013) finds that the upwind direction of the inflowing interstellar gas appears to have changed appreciably during the last 40 years.

From the three-dimensional model of the LIC (Redfield and Linsky 2014), we can compute the distances from the geometric center of the LIC to its edge in all directions. Figure 3 shows that from this perspective, the LIC is very thin

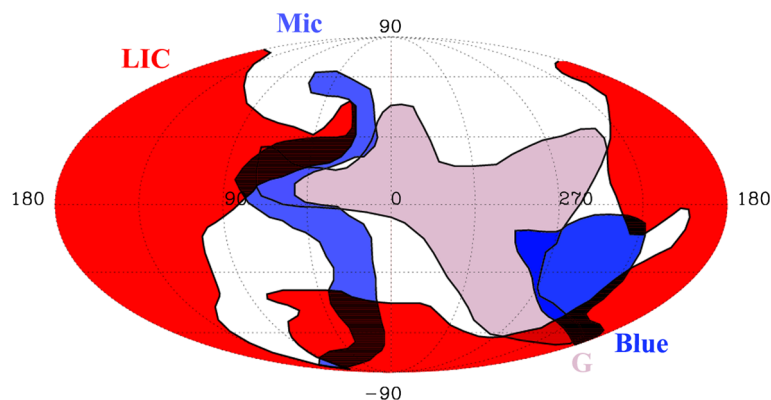


Fig. 4 The morphology of four nearby interstellar clouds as seen from the Earth. The clouds are identified by the radial velocities of interstellar absorption lines of H I, D I, Mg II, Fe II, and other neutral and singly ionized atoms that are consistent with a common velocity vector. The

clouds are partially ionized with neutral hydrogen column densities of order 10^{18} cm^{-2} . Many of the clouds located within 15 pc of the Sun are filamentary in shape like the Mic cloud. Figure reproduced from Redfield and Linsky (2008)

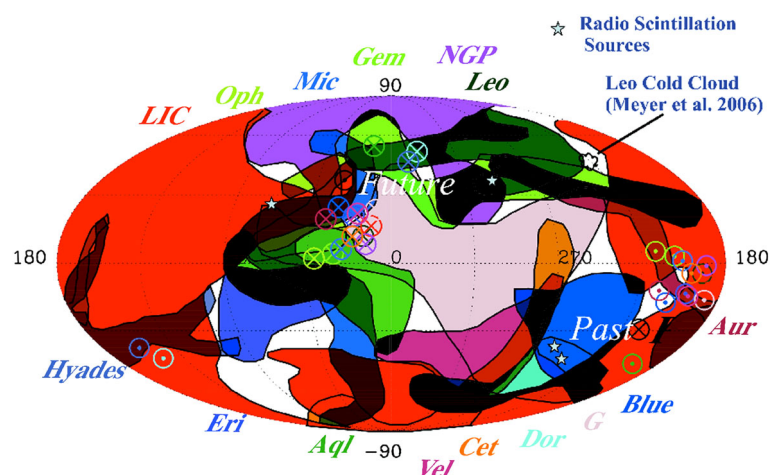


Fig. 5 The morphology of the 15 partially ionized interstellar clouds identified by Redfield and Linsky (2008) and located within 15 pc of the Sun. The clouds are color coded, and many overlap in the lines of sight to nearby stars. The \otimes symbols indicate the upwind flow direction, and the \odot symbols indicate the downwind flow direction for each

cloud. *Star* symbols indicate the directions toward quasars with flux variations that are likely due to scintillation produced near the edges of nearby interstellar clouds (Linsky et al. 2008). Figure adapted from Redfield and Linsky (2008)

in the fourth Galactic quadrant, in particular near Galactic longitude $l = 245^\circ$ and latitudes $b < 15^\circ$.

As viewed from the center of the LIC, Fig. 3 shows the Galactic coordinates of three very bright sources of EUV radiation: ϵ CMa, the strongest source of EUV radiation detected by the *Extreme Ultraviolet Explorer* (EUVE) satellite (Vallerga and Welsh 1995), β CMa, another very bright EUV source, and Sirius B, the nearest ($d = 2.64$ pc) hot white dwarf. It is no coincidence that these three very strong ionizing sources lie in the same direction as the minimum $N(\text{HI})$, which indicates that the morphology of partially ionized clouds in the LISM is shaped in large part by external ionizing-radiation fields. In a future paper we will explore in detail how the ionizing radiation from hot stars shape the structure of the warm partially-ionized clouds in the LISM

and the extent to which the intercloud gas can be explained by interlocking Strömghren spheres.

3 Morphology and properties of other clouds in the LISM

The nearest neighbor to the LIC must be the G cloud in the general direction of the Galactic Center since absorption at the radial velocity of this flow vector is detected toward the nearest stars, α Cen C (Proxima Cen at 1.32 pc) and α Cen A and B. The Blue cloud, so named because of interstellar absorption detected at shorter wavelengths than the LIC absorption observed toward Sirius (2.64 pc), must also be close to the Sun (Lallement et al. 1994). Figure 4 shows the angular distribution in Galactic coordinates of the LIC, G, Blue,

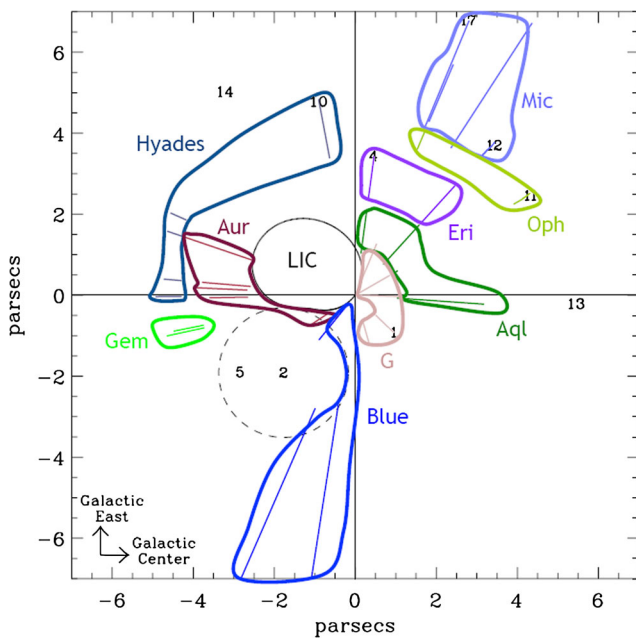


Fig. 6 A schematic morphological map of the LISM as viewed from the North Galactic Pole. The scale is in parsecs with the Sun at the center and the Galactic Center to the right. This map is based on measured neutral hydrogen column densities assuming that the neutral hydrogen number density $n(\text{HI}) = 0.2 \text{ cm}^{-3}$ for all of the clouds, except the Blue Cloud for which we assume $n(\text{HI}) = 1.0 \text{ cm}^{-3}$. The dashed circle is the estimated boundary of the Strömgren sphere surrounding Sirius B. Figure reproduced from Redfield and Linsky (2014)

and nearby Mic clouds determined from the absorption line data for 157 lines of sight by Redfield and Linsky (2008). Three of these clouds have irregular shapes as seen from the Earth, but the Mic cloud is filamentary. With only 15 lines of sight to determine its shape, the thickness of this cloud is not well determined. Figure 5 shows the angular distributions of all 15 clouds detected so far. A number of these clouds, including the Aur, Hyades, Gem, and Cet clouds, are clearly filamentary and others may also be filamentary if observed edge on.

The distance to the nearest star with a radial velocity consistent with a cloud's flow vector sets an upper limit to the closest edge of the cloud. More information on the extent and shape of each cloud requires many lines of sight through the cloud and a modelling procedure based on the observed HI column densities, assumed number density $n(\text{HI})$, and placement of all clouds not observed along the line of sight away from this direction. With this approach, Redfield and Linsky (2014) developed a three-dimensional model for the nearby clouds. Figure 6 shows the projection of these clouds onto the Galactic plane as seen from the North Galactic Pole. They drew the shape of the Blue cloud to avoid the Strömgren sphere of ionized gas surrounding Sirius B. This required an increase in the cloud's density to $n(\text{HI}) = 1.0 \text{ cm}^{-3}$ to decrease the cloud's size.

Table 1 Summary of cloud properties

Cloud name	Number of stars	Central coordinates		Closest star (pc)	$\langle T \rangle$ (K)	$\langle D(\text{Fe}) \rangle$
		$l(^{\circ})$	$b(^{\circ})$			
G	21	315	+00	1.3	5500	-0.54
LIC	78	170	-10	2.6	7500	-1.12
Blue	10	250	-30	2.6	3900	-0.84
Eri	8	70	-20	3.5	5300	-0.39
Aql	9	40	-05	3.5	7000	-0.96
Aur	9	210	+10	3.5	6710	
Hyades	14	180	-20	5.0	6200	-0.32
Mic	15	40	+15	5.1	9900	-0.92
Oph	6	45	+25	5.1	1700	
Gem	10	300	+40	6.7	6000	-1.29
NGP	15	5	+75	8.5	8000	-1.04
Leo	7	270	+55	11.1		
Dor	4	270	-50	11.7	7000	-0.80
Vel	6	300	-45	14.9	10600	
Cet	5	290	-40	15.5	6300	

In Table 1 we list the mean temperatures and iron depletions for the 15 warm clouds. Within each cloud, there is a modest range of temperatures; for the LIC the range is $T = 7500 \pm 1300 \text{ K}$. Most of the clouds have temperatures in the range 5000 to 8000 K, consistent with the ionization equilibrium models of Slavin and Frisch (2002, 2008) with the highest temperatures near 10,000 K for the Mic and Vel clouds.

4 Origin and properties of the gas outside of the clouds

The physical properties of the gas outside of the partially ionized warm clouds is a contentious topic. Since this gas is not observed as absorption in neutral hydrogen or singly ionized C, Si, Mg, or Fe, it must be very low density or be more highly ionized. The basic question is whether this gas is close to collisional ionization equilibrium and thus hot, or whether it is photoionized either in a steady-state or while recombining. The three-component theoretical models of McKee and Ostriker (1977) and Wolfire et al. (2003) predicted that the intercloud gas is hot ($T \approx 10^6 \text{ K}$), and observations of diffuse soft X-ray emission have been cited in support of this conclusion. However, the expected EUV emission from this hot gas was not detected by Hurwitz et al. (2005). Also, Cravens (1997, 2000) and Koutroumpa et al. (2009) found that charge-exchange reactions between neutral hydrogen flowing into the heliosphere and the solar wind ions can explain most or possibly all of the diffuse soft X-ray emission, except at high Galactic latitudes. Welsh and Shelton (2009) then proposed that the warm clouds are

embedded in an old supernova remnant consisting of low density photo-ionized gas with a relatively cool temperature ($T \approx 20,000$ K).

Following the suggestion of Tat and Terzian (1999), we propose that at least some fraction of the intercloud gas consists of an interlocking array of Strömgren spheres surrounding hot stars including OB stars like ϵ CMa and hot white dwarfs like Sirius B. The EUV radiation of these stars photoionizes the surrounding gas outward until the radial distance where recombinations balance photoionizations in a partially ionized shell. The closest photoionizing source is Sirius B ($d = 2.64$ pc) for which the Strömgren sphere radius is about 1.9 pc (Redfield and Linsky 2014). This region of ionized gas shapes the Blue and Aur clouds, as shown in Fig. 6, and helps to shape the LIC near $l = 245^\circ$, as shown in Fig. 3. The partially ionized outer shells of Strömgren spheres like that of Sirius B, if in a steady state, have a thickness of about 0.2 pc at pressures similar to that of warm gas in the LISM (Jenkins and Tripp 2001). We, therefore, propose that some of the warm partially ionized clouds located near the Sun are Strömgren sphere shells.

5 Conclusions

The region of space surrounding the heliosphere consists of many partially ionized warm gas clouds and an ionized-intercloud medium. We have studied the morphology and physical properties (temperature, turbulence, metal depletions) of these clouds by analyzing the interstellar absorption lines obtained with the ultraviolet spectrographs on *HST*. The clouds are identified by their flow velocity vectors. We show the shapes and locations of the LIC, in which the heliosphere is probably embedded, and 14 other clouds located within 15 parsecs of the Sun. We show that, as viewed from the center of the LIC, there is a region of very low $N(\text{HI})$ centered near Galactic longitude $l = 245^\circ$, the same direction as three very bright ionizing sources: ϵ CMa, β CMa, and Sirius B. This spatial coincidence provides strong evidence that local ionizing sources shape the partially ionized warm clouds in the LISM. In a future paper, we will study in detail whether interlocking Strömgren sphere gas produced by the ionizing radiation from hot stars can explain a portion or perhaps all of the ionized intercloud gas, and whether the partially ionized warm clouds are the outer shells of these Strömgren spheres.

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