Local Interstellar Matter: The Apex Cloud

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ABSTRACT

Several nearby individual low column density interstellar cloudlets have been identified based on kinematical features evident in high-resolution Ca$^+$ observations near the Sun (Frisch et al. 2002). One of these cloudlets, the “Aquila-Ophiuchus” cloud, is within 5 pc of the Sun and located in the solar apex direction. The velocity vector of the Aql-Oph cloud, renamed the “Apex Cloud” (AC), is reevaluated and components at this velocity are found towards 17 stars with distances 1–60 pc, and located primarily in the galactic center hemisphere. The AC has a heliocentric (HC) velocity $V = -35.0 \pm 0.7$ km s$^{-1}$, and is approaching the Sun from the HC upstream direction $l^{II} = 12.2^\circ$, $b^{II} = 13.3^\circ$. It is moving more rapidly than the bulk flow of nearby interstellar matter (ISM, $-35.0 \pm 0.7$ versus $-28.1 \pm 4.6$ km s$^{-1}$), although the upstream directions are similar ($l^{II} = 12.2^\circ$, $b^{II} = 13.3^\circ$ versus $l^{II} = 12.4^\circ$, $b^{II} = 11.6^\circ$). Interstellar absorption consistent with the velocity of the AC is seen towards the nearest star $\alpha$ Cen, indicating that indeed this cloud will be the next interstellar cloud encountered by the Sun, and also resolving a long-standing puzzle about the ISM velocity towards $\alpha$ Cen. A component at the AC velocity is seen towards the stars $\alpha$ CenB, $\alpha$ CenA, $\alpha$ Aql, $\alpha$ Oph, $\beta$ Cas, $\iota$ Cen, $\alpha$ Hyi, $\zeta$ Aql, $\gamma$ UMa, $\lambda$ And, $\gamma$ Oph, $\beta$ Cet, $\alpha$ Gru, $\lambda$ Aql, $\alpha$ Peg, $\kappa$ And, and $\alpha$ Pav, although a serendipitous coincidence in velocities can not be ruled out for any particular star. The velocity difference between the closest upstream and downstream gas corresponds to the ISM sound velocity at the heliosphere, suggesting macroscopic turbulence at the isothermal sound speed and possibly colliding clouds. The Sun should enter the AC within $\sim 10^4$ years.
1. Introduction

The interstellar material (ISM) within ∼30 parsecs of the Sun is one of the few regions of the Milky Way Galaxy where there is a reasonable possibility of separating the effects of topology and kinematics, and also identifying the properties of sub-parsec sized cloudlets. Small scale ($10^2$ AU – 0.1 pc) structure is inferred from Na° absorption line data (Lauroesch et al. 2000) and H° 21-cm absorption and emission line comparisons (Heiles 1997). The first step in understanding the small-scale structure of nearby ISM requires using cloud kinematics to identify individual cloudlets. An analysis of 96 interstellar Ca°+ and ultraviolet absorption components observed towards 60 nearby stars has shown that nearby ISM consists of cloudlets flowing with a bulk motion of $V(BF)=-28.1\pm4.6$ km s$^{-1}$, from an upstream direction towards the Scorpius-Ophiuchus Association (Frisch et al. 2002; Frisch 1995, Paper I, Table 1). However, 5–7 kinematical and spatial groups are apparent when viewed in the rest frame of the bulk flow, including a cluster of components in stars located at $l^\circ=38^\circ\pm10^\circ$, $b^\circ=9^\circ\pm14^\circ$. This nearby cloudlet, seen towards α Aql (5 pc) and α Oph (14 pc), was denoted the “Aql-Oph” cloud in Paper I, and is located in the direction of the solar apex motion. The kinematics and geometry of this apex cloudlet (AC) are explored further in this letter. A second well-known cluster of absorption components was identified at the velocity of the interstellar cloud surrounding, and within, the solar system (the “Local Interstellar Cloud”, or LIC).

The sightline towards the nearest star, α Cen (1.3 pc) has been a longstanding puzzle. The velocity and upstream direction for the LIC are determined by Ulysses observations of interstellar He° inside of the solar system and EUVE observations of the He° 584 Å backscattered emission. These results yield a LIC velocity vector $V=-26.3\pm0.4$, flowing from $l^\circ=3.6^\circ$, $b^\circ=+15.3^\circ$ (and $n$(He°)=$0.014\pm0.002$ cm$^{-3}$, Witte et al. 2003; Flynn et al. 1998). The projected LIC velocity towards α Cen ($-17.0^{+0.3}_{-0.5}$ km s$^{-1}$) is $\sim1$ km s$^{-1}$ difference from the velocity inferred from ISM velocity determined from UV lines of D°, Mg°, and Fe° ($-18.0^{+0.2}_{-0.4}$ km s$^{-1}$, Landsman et al. 1984; Lallement et al. 1995; Linsky & Wood 1996). It will be seen below that the Aql-Oph cloudlet, located in the direction of the solar apex motion (and referred to here as the Apex Cloud, AC) is in fact the interstellar cloud seen towards α Cen.

I use a solar apex motion with velocity $V=13.4$ km s$^{-1}$, towards $l^\circ=27.7^\circ$ and $b^\circ=32.4^\circ$, based on Hipparcos data (Dehnen & Binney 1998).
2. Analysis

The analysis in this letter is based on the method, results, and data in Paper I, with the addition of $\alpha$ CenA data to the input cloudlet component list (e.g. Table 1 in Paper I). In Paper I, the Aql-Oph cloud was identified towards 5 stars, $\alpha$ Aql, $\alpha$ Oph, $\zeta$ Aql, $\gamma$ Oph, and $\lambda$ Aql. A possible identification of the cloudlet towards $\delta$ Cyg was indicated by velocity, although the coldness of the $\delta$ Cyg feature ($b$(Na$^\circ$) = 0.42 km s$^{-1}$, Welty et al. 1994) suggested it does not originate in the Aql-Oph cloud (a fact confirmed by this study, see below). The AC is within 5 pc of the Sun since it is observed towards $\alpha$ Aql. That opens the possibility that it is within $\sim$1 pc, indicating it may extend in front of $\alpha$ Cen (1.3 pc). Therefore, a best-fit velocity vector was formed for the AC components towards the original 5 stars sampling the Aql-Oph cloud combined with the interstellar absorption features towards $\alpha$ CenA,B. The results of that fit indicated that both the $\alpha$ CenA,B and Aql-Oph components have a velocity consistent with a single velocity vector, $V$(AC), to within $\sim$ ±1.3 km s$^{-1}$. This new velocity vector was then used to search for other velocity components consistent with $V$(AC) from among the original 96 component sample in Paper I. This process was repeated several times, and a final $V$(AC) vector was determined.

The 17 stars listed in Table 2 were found to have components at the correct projected $V$(AC) velocity, to within $\sim$ ±1.3 km s$^{-1}$. Column 10 in Table 2 gives $dV_i$, which is the difference between the observed component velocity and the projected $V$(AC) velocity, and column 9 is the observed HC velocity (from Table 1 of Paper I). Since the $\delta$ Cyg $-$16.3 km s$^{-1}$ component (tentatively listed in Paper I as belonging to the AC cloud) is cold and has $dV_i$(AC) = $-$1.5 km s$^{-1}$, which is larger than the components in Table 2, it is not attributed here to the AC cloud. Additional data on cold ISM close to the Sun would be required before accepting this component as formed in the AC cloud. The stars in Table 2 range in distance between 1.3 pc and 56 pc, and are generally located in the galactic center hemisphere of the Sun. Of course, a serendipitous coincidence in velocities can not be ruled out for any particular star. However, the fact that components at $V$(AC) are seen towards several of the nearest stars in the galactic center hemisphere lends credibility to the assumption made here that they are all formed in the AC.

The final velocity vector determined for $V$(AC) is given in Table 1, in both heliocentric and local standard of rest (LSR) velocity frames. The velocity of the ISM inside of the solar system, as determined from Ulysses measurements of interstellar He$^\circ$ is also listed. The upstream directions of the AC and bulk flow are quite similar (to within $\sim$3$^\circ$), although the velocities differ by $\sim$25%. However, what is much more interesting is that the upstream and downstream clouds closest to the Sun (the AC and the LIC) are within $\sim$1 pc of each other, and have LSR velocities which differ by $\sim$7.7 km s$^{-1}$. 
3. Discussion

In the rest frame of the LIC, the relative velocity of the AC is $\sim 10$ km s$^{-1}$, which is close to the sound velocity, 8.3 km s$^{-1}$, predicted for a perfect gas at the LIC temperature $\sim 6,300$ K. This coincidence suggests that the kinematical structure of the nearest ISM may be related to sonic turbulence.

The relative velocity of the AC through the LSR ($-23.5$ km s$^{-1}$) places this cloud in the class of Routly-Spitzer clouds (McRae Routly & Spitzer 1952) with enhanced abundances of refractory elements. Observations of depletions in the AC support this view. For Fe depletion $\delta_{Fe} (=\log(A_{ISM}/A_{Sun})$, where $A$ is the element abundance) the value towards $\alpha$ Cen is $\delta_{Fe} = -1.05$ (Linsky & Wood 1996) versus values $-2.05$ found typically for cold clouds. In general, however, the AC itself is inadequately observed since ionization is unknown and Fe$^+$ is also formed in H$^+$ gas, column densities are low ($< 10^{18}$ cm$^{-2}$), and high-resolution UV data are not available for most of the AC stars in Table 2.

The relative velocity of the AC and Sun is $\sim 35$ km s$^{-1}$, which corresponds to $\sim 35$ parsecs/Myrs. Since the AC cloud is within the nearest $\sim 1$ pc, the AC cloud is likely to replace the LIC as the interstellar cloud surrounding the solar system sometime within the next $\sim 10^4$ years. If the AC has the same exact same physical properties as the LIC, the solar wind termination shock distance in the nose direction should decrease by $\sim 25\%$ (from simple equilibration of the solar wind and ISM ram pressures), which is comparable to variations expected from the solar cycle (e.g. Zank 1999; Tanaka & Washimi 1999; Scherer & Fahr 2003). In this case, the consequences for the inner heliosphere should be negligible. However, some data indicate that the ISM towards $\alpha$ Cen is colder ($\sim 5400$ K, Piskunov et al. 1997), and therefore possibly denser, compared to the LIC, so more adverse impacts on the heliosphere and interplanetary environment are possible. It is important to note in this context that $\sim 98\%$ of the diffuse material in the heliosphere today is ISM, although the inner heliosphere interplanetary medium is solar wind dominated because of the $R^{-2}$ solar wind density dependence.

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### Table 1. ISM Flows near the Sun

|           | HC Vector<sup>a</sup> | LSR Vector<sup>a,b</sup> | Notes                  |
|-----------|-----------------------|---------------------------|------------------------|
|           | Vel.                  | l  | b  | Vel.                  | l  | b  | Notes                        |
|           | (km s<sup>−1</sup>)   | (°) | (°) | (km s<sup>−1</sup>)   | (°) | (°) |                              |
| Bulk flow of nearby ISM: | | | | | | |
| V(96)     | −28.1±4.6             | 12.4 | 11.6 | −17.0               | 2.3 | −5.2 | 60 stars (Frisch et al. 2002) |
| Apex Cloud: | | | | | | |
| V(AC)     | −35.0±0.7             | 12.2 | 13.3 | −23.5               | 4.4 | 2.1 | 17 stars (this paper)        |
| Interstellar cloud surrounding solar system: | | | | | | |
| V(He)     | −26.3±0.4             | 3.6  | 15.3 | −15.8               | 346.1 | 0.2 | <em>Ulysses</em> He<sup>a</sup> data (Witte et al. 1996) |

<sup>a</sup> Galactic coordinates correspond to upstream directions.

<sup>b</sup> Based on Hipparcos solar apex motion (Dehnen & Binney 1998).
Table 2. Stars Showing Apex Cloud Velocity Components\(^a\)

| HD   | Name    | l (°) | b (°) | d (pc) | V (mag) | Spec. | N(X) (cm\(^{-2}\)) | \(dV_i\) (AC) (km s\(^{-1}\)) | Reference |
|------|---------|-------|-------|--------|--------|-------|-------------------|-----------------------------|-----------|
| 128621 | α CenA  | 315.7 | -0.7 | 1.4    | -0.01  | G2 V  | 3.89e17           | -17.8                      | 0.9        | RL02     |
| 128621 | α CenB  | 315.7 | -0.7 | 1.4    | -0.01  | K1 V  | 3.89e17           | -18.1                      | 0.6        | RL02     |
| 187642 | α Aql   | 47.7  | -8.9 | 5.1    | 0.77   | A7 V  | 0.3e10            | -26.9                      | -0.7       | FW03     |
| 159561 | α Oph   | 35.9  | 22.6 | 14.3   | 2.10   | A5 III| 1.59e10           | -32.0                      | -0.1       | CD95     |
| 432   | β Cas   | 117.5 | -3.3 | 16.7   | 2.27   | F2 IV | 1.51e18           | 10.0                       | 0.6        | P97      |
| 115892 | ι Cen   | 309.4 | 25.8 | 18.0   | 2.70   | A2 V  | 2.5e10            | -18.2                      | -0.7       | CCW97    |
| 12311 | α Hyi   | 289.5 | -53.8| 21.9   | 2.90   | F0 V  | 5.01e10           | 4.9                         | 1.0        | CCW97    |
| 177724 | ζ Aql   | 46.9  | 3.3  | 25.5   | 2.99   | A0 Vn | 1.4e10            | -29.7                      | -1.3       | FW03     |
| 103287 | γ UMa   | 140.7 | 61.4 | 25.6   | 2.43   | A0 V  | 0.8e10            | 4.4                         | 1.3        | FW03     |
| 222107 | λ And   | 109.9 | -14.5| 25.8   | 3.82   | G8III | 2.82e18           | 6.5                         | 0.1        | P97      |
| 161868 | γ Oph   | 28.0  | 15.0 | 29.1   | 3.75   | A0 V  | 3.0e10            | -33.1                      | 0.6        | CCW97    |
| 4128  | β Cet   | 111.3 | -80.7| 29.4   | 2.04   | K0III | 2.24e18           | 8.0                        | -0.8       | P97      |
| 209952 | α Gru   | 350.0 | -52.4| 31.1   | 1.74   | B7I V | 2.0e10            | -13.0                      | -0.1       | CD95     |
| 177756 | λ Aql   | 30.3  | -5.5 | 38.4   | 3.43   | B9 V  | 0.96e10           | -30.7                      | 0.8        | FW03     |
| 218045 | α Peg   | 88.3  | -40.4| 42.8   | 2.49   | B9III | 1.2e10            | -0.5                       | 0.5        | FW03     |
| 222439 | κ And   | 109.8 | -16.7| 52.0   | 4.14   | B9I Vn| 6.1e10            | 7.6                         | 1.0        | V93      |
| 193924 | α Pav   | 340.9 | -32.5| 56.2   | 0.00   | B2 IV | 1.24e10           | -19.6                      | 0.6        | CLW98    |

\(^a\)Column Densities less than 10\(^{13}\) are for Ca\(^+\), and values greater than this are based on \(N(H^o)\) measurements. \(dV_i(AC)\) is the component velocity difference from \(V(AC)\) in Table 1. References: Frisch & Welty (2003, FW03), Crawford et al. (1998, CLW98), Crawford et al. (1997, CCW97), Crawford & Dunkin (1995, CD95), Vallerga et al. (1993, V93), Piskunov et al. (1997, P97), Redfield & Linsky (2002, RL02).