**High-drag Interstellar Objects and Galactic Dynamical Streams**

T. M. Eubanks

Space Initiatives Inc., Clifton, VA 20124, USA; tme@asteroidinitiatives.com

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**Abstract**

The nature of 1I/‘Oumuamua (henceforth, 1I), the first interstellar object (ISO) known to pass through the solar system, remains mysterious. Feng & Jones noted that the incoming 1I velocity vector “at infinity” \( \mathbf{v}_\infty \) is close to the motion of the Pleiades dynamical stream (or Local Association), and suggested that 1I is a young object ejected from a star in that stream. Micheli et al. subsequently detected nongravitational acceleration in the 1I trajectory; this acceleration would not be unusual in an active comet, but 1I observations failed to reveal any signs of activity. Bialy & Loeb hypothesized that the anomalous 1I acceleration was instead due to radiation pressure, which would require an extremely low mass-to-area ratio (or area density). Here I show that a low area density can also explain the very close kinematic association of 1I and the Pleiades stream, as it renders 1I subject to drag capture by interstellar gas clouds. This supports the radiation pressure hypothesis and suggests that there is a significant population of low area density ISOs in the Galaxy, leading, through gas drag, to enhanced ISO concentrations in the galactic dynamical streams. Any ISO entrained in a dynamical stream will have a predictable incoming \( \mathbf{v}_\infty \); targeted deep surveys using this information should be able to find dynamical stream objects from months to as much as a year before their perihelion, providing the lead time needed for fast-response missions for the future in situ exploration of such objects.

**Key words:** Galaxy: kinematics and dynamics – minor planets, asteroids: individual (1I/‘Oumuamua)

1. Introduction

1I/‘Oumuamua was discovered near opposition on 2017 October 19 by Pan-STARRS1 at a distance from Earth of \( \sim 0.23 \) \( \text{au} \) (Bacci et al. 2017). It was rapidly recognized as being on a strongly hyperbolic orbit, and given a new designation (1I/2017 U1) and the name ‘Oumuamua. 1I does not exhibit the broad visual and near-IR absorption bands present in the spectra of many asteroids (Fitzsimmons et al. 2018), and so its composition remains very poorly constrained. Comparisons with stellar catalogs reveal that 1I has not passed extremely close to any star within the last few million years, and its original source system remains unknown (Gaidos et al. 2017; Portegies Zwart et al. 2018; Bailer-Jones et al. 2018).

Stellar perturbations make it hard to predict the detailed galactic trajectories of asteroid-sized InterStellar Objects (ISOs) over intervals much longer than a few million years (Zhang 2018). However, that does not mean that ISO velocities will become randomized about the local standard of rest (LSR). The dynamical LSR, defined as the circular orbit velocity at the Sun’s location, would be the mean motion near the Sun for an axisymmetric galaxy. The Milky Way’s velocity fields however are nonuniform, with a substantial fraction of the stars in the solar neighborhood being concentrated in unbound collections of stars called in this paper dynamical streams (but also known as associations or moving groups; see, e.g., Famaey et al. 2005; Kushniruk et al. 2017; Gaia Collaboration et al. 2018).

2. Stellar Streams in the Galactic Disk

The study of the galactic stellar streams began in 1846 with the discovery of a distribution of stars sharing the proper motions of the Pleiades open cluster (Kushniruk et al. 2017). For a long time it was thought that this and other streams were simply due to cluster evaporation (the gradual loss of stars from an open cluster), implying that the stars in the Pleiades stream should be no older than the cluster itself (\( \sim 80–120 \) million years). As more data became available it became apparent that this was not so, with, for example, over half of the stars in the Pleiades stream being substantially older than the age of the Pleiades open cluster, rendering the evaporation model untenable (Chereul et al. 1998; Famaey et al. 2008; Bovy & Hogg 2010).

Antoja et al. (2012), using RAVE spectroscopic survey data, found that 14.2% of the stars in the solar neighborhood (out to 300 pc) are in one of the five major streams considered in this paper, the Pleiades, Hyades, Sirius, Coma Berenices, and Hercules streams, with another 3.1% of the stars belonging to 14 smaller dynamical streams. Francis & Anderson (2012) used 2MASS data to conclude that almost all local stars are part of unbound kinematic streams, with the Pleiades stream being located in the leading edge of the Orion arm, and the Hyades stream being part of the Centaurus arm. The dynamical streams are likely associated with resonances in the Galaxy; Michtchenko et al. (2018) used Gaia DR2 data to conclude that the Pleiades, Hyades, and Coma Berenices streams were all associated with spiral-arm corotation resonances, while the Sirius stream and Hercules stream are controlled by Lindblad resonances.

3. 1I and the Pleiades Stream

Figures 1 and 2 show, for the galactocentric \( U–V \) and \( V–W \) planes, respectively, velocity estimates for the LSR and the five major dynamical streams together with the mean 1I \( \mathbf{v}_\infty \) from Bailer-Jones et al. (2018). Table 1 provides the mean galactocentric \( U, V, W \) components for all of these data; all three components of the incoming 1I \( \mathbf{v}_\infty \) vector are close to...
The stream velocity estimates are from the data and compilations in Kushniruk et al. (2017), supplemented by Chereuil et al. (1998), Liang et al. (2017), and Gaia Collaboration et al. (2018). At least some of the scatter between the velocity estimates for individual streams seems to reflect substructure in the stream kinematics. The 1I inbound velocity is the average of the five 1I velocity solutions using anomalous acceleration models used by Bailer-Jones et al. (2018), with errors inflated to account for scatter in those solutions; the LSR velocity estimates are from Francis & Anderson (2009, 2014), Schönrich et al. (2010), Huang et al. (2015), Bland-Hawthorn & Gerhard (2016), and Bobylev & Bajkova (2017).

Figure 1. Galactocentric U and V components of velocity for 1I, the LSR, and the five largest local dynamical streams. The 1I incoming velocity is near the centroid of the determinations of the velocity of the Pleiades stream (Table 1). The stream velocity estimates are from the data and compilations in Kushniruk et al. (2017), supplemented by Chereuil et al. (1998), Liang et al. (2017), and Gaia Collaboration et al. (2018). At least some of the scatter between the velocity estimates for individual streams seems to reflect substructure in the stream kinematics. The 1I inbound velocity is the average of the five 1I velocity solutions using anomalous acceleration models used by Bailer-Jones et al. (2018), with errors inflated to account for scatter in those solutions; the LSR velocity estimates are from Francis & Anderson (2009, 2014), Schönrich et al. (2010), Huang et al. (2015), Bland-Hawthorn & Gerhard (2016), and Bobylev & Bajkova (2017).

Figure 2. Data in Figure 1, but for the galactic V and W components of velocity. Not all stream surveys report W, the component of velocity out of the galactic plane, and thus there are fewer stream data points in this image. The W component of these streams are all within 6 km s$^{-1}$ of the LSR, evidence that these are not tidal streams formed from galactic mergers, as those have much larger out of plane velocities (Seabroke et al. 2008).

| Velocity | $U$ | $V$ | $W$ | $|v|$ |
|----------|-----|-----|-----|------|
| 1I $v_c$ | $-11.6 \pm 0.1$ | $-22.4 \pm 0.1$ | $-7.9 \pm 0.1$ | 26.4 |
| LSR      | $-9.7 \pm 2.7$  | $-11.8 \pm 2.0$ | $-7.9 \pm 1.2$ | 16.7 |
| Sirius   | $5.2 \pm 11.8$  | $3.3 \pm 2.8$   | $-8.2 \pm 6.0$ | 10.3 |
| Coma Beren. | $-7.3 \pm 7.2$ | $-7.8 \pm 2.5$ | $-10.0 \pm 2.0$ | 14.6 |
| Pleiades | $-13.7 \pm 3.8$ | $-22.3 \pm 1.4$ | $-8.3 \pm 2.0$ | 27.5 |
| Hyades   | $-35.7 \pm 4.0$ | $-17.2 \pm 2.5$ | $-10.3 \pm 8.2$ | 40.3 |
| Hercules | $-36.3 \pm 12.0$ | $-47.7 \pm 4.8$ | $-13.0 \pm 2.8$ | 61.4 |
| 1I - Pleiades | $2.1 \pm 3.8$ | $-0.1 \pm 1.4$ | $0.4 \pm 2.0$ | 2.2 |

Note. Velocity Vector Components in the galactic U, V, W system, where U is radial (toward the Galactic center), V is along the direction of galactic rotation, and W is orthogonal to the galactic disk. The formal errors for 1I are inflated by the scatter of the solutions used in Bailer-Jones et al. (2018), the other formal errors are the rms scatter of the data plotted in Figures 1 and 2.

3.1. II and the Pleiades Substreams

A high-resolution study of the Pleiades stream using Hipparcos data (Chereuil et al. 1998, 1999) found two major components to that stream, which they labeled the Open Cluster (OCI) and Super Cluster (SCI) streams, with the OCI stream being associated with the Pleiades star formation region. The SCI stream is divisible into two finer-grained substreams, S1 and S2, which are kinematically adjacent but contain stars of different origins and ages. Figure 3 shows the U and V components of these velocities; the error bars on each subgroup velocity component being the rms of that velocity component for the stars in that substream. The observed 1I velocity clearly favors its membership in the SCI over the OCI; the magnitude of the three-dimensional separation of the 1I $v_c$ and the stream velocity centroid is <$2 km s$^{-1}$ for both the S1 and S2 streams, substantially less than the $\sim 3$ km s$^{-1}$ rms velocity dispersions of these streams. The chance that a randomly selected velocity would fall within 2 km s$^{-1}$ of one of 19 streams in the available 3D velocity space is <$10^{-3}$, strong evidence that 1I was entrained in the SCI stream, but not proof that it originated in a star system in that stream.

3.2. Gas Drag Capture of Low-$\beta$ ISOs

Recent research indicates that 1I had a small, but highly significant ($\sim 30\sigma$), anomalous acceleration during its period of observation (2017 October 14th–2018 January 2nd), the observed nongravitational acceleration being predominately radial and declining with distance from the Sun (Micheli et al. 2018). Anomalous acceleration in small solar system objects can be caused by cometary activity, but no outgassing was detected from 1I, with in particular very low limits being set on its dust, CO and CO$_2$ emissions by the Spitzer Space Telescope (Trilling et al. 2018). In addition, even a small asymmetry in the required thrust would strongly torque an elongated body the presumed size of 1I, causing faster than observed rotational variations (Rafikov 2018).
Bialy & Loeb (2018) proposed instead that the 1I anomalous acceleration was due to solar radiation pressure, which functionally fits the observed acceleration signature. This solution, however, requires a mass-to-area ratio, \( \beta \), of 0.93 ± 0.03 kg m\(^{-2}\), much lower than the \( \beta \) for any known asteroid, and comparable to the area density of a light-sail, leading to speculation that 1I could be of artificial origin. Moro-Martín (2019) showed that similarly low area densities could also be obtained from a porous icy aggregate formed outside the snowline of a protoplanetary disk.

Although there is no consensus about the nature of 1I, and many researchers prefer a cometary model with dust-free outgassing (Micheli et al. 2018; Sekanina 2019), it is worth considering the observational consequences of a population of low-\( \beta \) ISOs. The trajectories of ISOs with \( \beta \sim 1 \) kg m\(^{-2}\) will be significantly affected by drag in the Inter Stellar Medium (ISM). The Newtonian drag equation (Moe et al. 1995; Scherer 2000) is

\[
\frac{dv}{dt} = -\frac{1}{2} C_D \frac{v^2 \rho_{\text{ISM}}}{\beta},
\]

where \( C_D \) is the dimensionless drag coefficient (typically \( \sim 2.6 \) for Earth satellites), \( v \) is the magnitude of the relative ISO-ISM velocity, and \( \rho_{\text{ISM}} \) is the ISM density. If the ISM is assumed to be predominately atomic hydrogen,

\[
\rho_{\text{ISM}} = \left( \frac{n_0}{1 \, \text{cm}^{-3}} \right) \times 1.7 \times 10^{-21} \, \text{kg m}^{-3},
\]

\( n_0 \) being the particle density. In a region of space with a constant \( \rho_{\text{ISM}} \), the distance, \( L_D \), for a factor of 2 reduction in velocity is

\[
L_D = \frac{2 \beta}{\rho_{\text{ISM}} C_D} \approx 4 \times 10^4 \, \text{lyr} \left( \frac{1 \, \text{cm}^{-3}}{n_0} \right) \left( \frac{0.93 \, \text{kg m}^{-2}}{\beta} \right). \tag{3}
\]

In the background galactic disk, the ISM \( n_0 \) is typically \( \lesssim 1 \) cm\(^{-3}\) (Scherer 2000), so that objects with \( \beta \)-type \( \beta \) should, by Equations (1) and (3), be able to travel across much of the galactic disk without losing much of their peculiar velocity.

A small spherical asteroid or comet with a radius \( R \) and a uniform density \( \rho \) would have

\[
\beta \sim \left( \frac{R}{100 \, \text{m}} \right) \left( \frac{\rho}{1000 \, \text{kg m}^{-3}} \right) \times 10^5 \, \text{m}^{-2}. \tag{4}
\]

An object with a typical cometary or asteroid density of \( \sim 500 \)–3000 kg m\(^{-3}\) (Carry 2012) would need a radius \( \lesssim 1 \) mm to have a \( \beta \) comparable to 1I’s. Solar system asteroids and comets are thus high-\( \beta \) objects; ours and other planetary systems must have ejected large numbers of high-\( \beta \) planetesimals, asteroids, and comets over the course of their histories (Engelhardt et al. 2017). If 1I truly is a low-\( \beta \) object, there therefore must be two populations of ISOs in the 100 m size range, one with area densities similar to solar system asteroids and negligible drag even in the densest molecular clouds, and the other, possibly more numerous, being ISO-type objects sensitive to ISM drag.

The galactic spiral arms and their dynamical streams contain stellar nurseries with relatively high gas densities (Francis & Anderson 2012). Equation (3) indicates that a star formation region such as the Orion Nebula (M42), with a central gas density \( \sim 10^4 \) cm\(^{-3}\) (Johnson 1961), should be able to capture a low-\( \beta \) ISO through gas drag. The mean time between ISO-cloud interactions in the galactic disk is thought to vary from \( \sim 30 \) Myr for \( \text{H} \text{I} \) regions to \( \sim 1 \) Gyr for Giant Molecular Clouds (Yeghiykan & Fahrb 2003). The presence of 1I in the SCI instead of the OCl stream suggests that it may have been slowed by a gas cloud, possibly a stellar nursery, predating the Pleiades open cluster; finding and dating star formation regions in the SCI stream could thus potentially provide a lower bound for 1I’s age.

4. Efficient Searches for Galactic Stream Asteroids

ISOs from a given dynamical stream will appear to enter the solar system from a specific radiant in the sky; Figure 4 shows the radiants for the five major streams considered in this paper. As seen from the Earth, an incoming ISO will execute an expanding parallactic spiral centered around its radiant; preperihelion detection of incoming ISOs is thus possible using deep surveys centered about the stream radiants (Eubanks 2019).

4.1. Number Density of Interstellar Asteroids

Pan-STARRS1 detected 1I after only 3.5 yr of observing in its current survey mode. Do et al. (2018) calculated that in that period Pan-STARRS1 scanned \( \sim 5 \) au\(^2\), implying (Trilling et al. 2017; Do et al. 2018) an upper limit on \( n_{\text{IS}} \), the ISO number density, of

\[
n_{\text{IS}} \leq 0.2 \, \text{au}^{-3}. \tag{5}
\]
ellipsoidal distribution for stellar velocities and predicted that ISOs were more likely to come from a very broad angular region centered on the LSR, which the dynamical stream model resolves into a much more angularly constrained set of stream radiants.

It should be possible to discover ISOs approaching from known directions using existing telescopes. The 8 m Subaru telescope with its wide-field Hyper Suprime-Cam (HSC) camera (Miyazaki et al. 2018) would have been able to detect 1I at $M \sim 26.75$ at the beginning of 2017 June, 3 months before its perihelion and 4.5 months before its discovery, providing several months of lead time for the hypothetical fly-by mission described in Seligman & Laughlin (2018). The same limiting magnitude would suffice to discover a 10 times larger-diameter body with the same albedo (i.e., one with an absolute magnitude $H \sim 17$) a year before perihelion at a distance of $\sim 8$ au.

Deep searches for incoming ISOs are thus possible with existing telescopes. Roughly 75 square degrees would have to be covered to completely scan the Pleiades radiant for incoming ISOs one year in advance, with the total exposure time to image each radiant to a magnitude $M = 26.75$ (based on the HSC Exposure Time Calculator) varying from 6 to 18 hours, depending on the phase of the Moon. The Pleiades and Hercules stream radiants are only separated by $\sim 7^\circ$; a survey of the Pleiades radiant would thus include a substantial fraction of the Hercules radiant, and could detect incoming ISOs from that stream as well.

5. Discussion and Conclusion

The presence of 1I near the kinematic center of the Pleiades stream suggests that it is a low-$\beta$ object subject to ISM drag. The association of interstellar asteroids and galactic streams hypothesized in this paper can be directly tested through the search for, and discovery of, more ISOs. In particular, the Pleiades stream apparently only contains about 3.2% of the stars in the solar neighborhood (Antoja et al. 2012). Whether the discovery of the first ISO from the Pleiades stream was simply a matter of chance, or whether that stream is for some reason especially rich in low-$\beta$ ISOs, will be straightforward to determine with additional ISO discoveries.

The discovery, observation, and eventual exploration of ISOs passing through the solar system offers a profound opportunity to determine both the physical properties of these bodies and their role in the dynamics and evolution of the Galaxy. The discovery of only a few additional ISOs will substantially reduce the uncertainties in their number density spectrum. Even with short observational arcs it should be possible to determine which objects have been entrained into a galactic stream, and thus possibly to distinguish between low and high $\beta$ objects even without the direct detection of anomalous accelerations. For ISOs discovered before perihelion, it should be possible to detect or severely limit both activity and nongravitational acceleration, and thus determine whether any anomalous acceleration is due to outgassing or to radiation pressure.

Directed ISO searches should increase their discovery rate. A targeted search of the radiants of the Pleiades and Hercules streams (which are close together in the sky) might be able to scan $20 \text{ au}^3 \text{ yr}^{-1}$ for 1 km size bodies. If 1I represents a dense population of ISOs in the Pleiades stream, then such a survey might detect several ISOs per year. If, on the other hand, ISOs are distributed in the same proportion as local stars, then roughly 3.2% and 1.4% of the incoming ISOs would be from the Pleiades
and Hercules streams, respectively; the same survey would yield on average one detection every 6 yr. An ongoing survey targeted on dynamical stream ISOs has a decent chance at detecting these objects well before their perihelion passage, providing the lead time needed for fast-response missions for the in situ exploration of these interstellar bodies.

Small objects in interstellar space are probes of the dynamics of the Galaxy. A low-β ISO, once ejected from its source system, should orbit the Galaxy until it reaches a turbulent region with high gas density, whereupon it would be likely to stop and join the bulk motion of the gas, and thereafter (if it was not trapped or destroyed in a new stellar system) be released as part of a dynamical stream. This appears to be 1I's likely nomadic history. This hypothesis could be directly tested by sending a mission to 1I (Hein et al. 2017) or by sending a future mission to other ISOs as they pass through the solar system (Seligman & Laughlin 2018).

If low-β ISOs are indeed common, a population of these objects could have been captured by gas drag during the nebula stage of the formation of the solar system (Grishin et al. 2018) and retained in the outer solar system today (radiation pressure would prevent a low-β object from having a stable orbit in the inner system). This population would be easily distinguishable from ISOs captured by three body gravitational interactions after the formation of the solar system (Siraj & Loeb 2019), and from low-β objects temporarily captured close to the Sun by solar radiation pressure perturbations. Primordially captured ISOs, perturbed into the inner solar system by the mechanisms that produce long-period comets, should thus be searched for as small inactive comets on nearly hyperbolic trajectories with unexpectedly large nongravitational accelerations.

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ORCID iDs

T. M. Eubanks © https://orcid.org/0000-0001-9543-0414

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