Efficient Searches for Galactic Stream Interstellar Asteroids

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1I: The First (Known) Interstellar Object

1I/'Oumuamua (or simply 1I), the first known interstellar object to pass through the Solar System, had an incoming velocity "at infinity" (v_∞) near a minimum in the detection efficiency of terrestrial surveys, suggesting that it was drawn from a population with a relatively large density of Interstellar Objects (ISOs). There is indeed a close co-incidence, significant at the 99.9% level, between the 1I $\mathbf{v}_\infty$ and the peculiar velocity of the Pleiades dynamical stream, one of the major dynamical streams in the Galaxy; 1I is thus presumably a member of that stream. Before it encountered the solar system, 1I appears to have had an orbit in the kinematic center of the stream. This is consistent with the hypothesis that 1I has an unusually low mass-to-area ratio, β, of 0.93 ± 0.03 kg m^{-2}, much lower than the β for any known asteroid, which would allow its capture in the Pleiades stream by gas drag in dense Molecule Clouds.

The Galactic Dynamical Streams

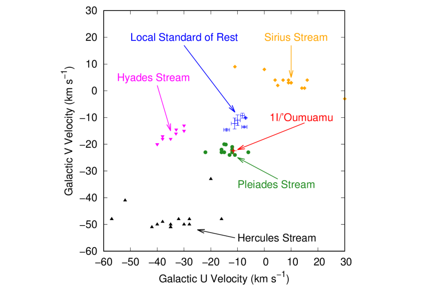
Many stars in the solar neighborhood (within ~300 pc of the Sun), belong to one of several dynamical streams, the five principle ones being the Coma Berenices, Pleiades, Hyades, Sirius and Hercules streams. The Pleiades stream is associated with the familiar open star cluster bearing the same name, and for a long time it was thought that the stream was simply due to cluster evaporation (the gradual loss of stars over time), implying that the stars in the stream should be no older than the cluster itself (~80 - 120 million years). As more accurate data became available this was shown not to be so, with over half of the stars in the Pleiades stream being substantially older than the age of the cluster, rendering the evaporation model untenable and suggesting that these streams are maintained dynamically in the Galaxy, possibly by rotational resonances with the Galactic Bar.

Implications of a very low 1I Mass-Area Ratio

Recent research indicates that 1I had a small, but highly significant (~30 σ), radial anomalous acceleration during its period of observation. This could be due to cometary activity, but no such activity was observed. Bialy & Loeb (2018) proposed that the 1I anomalous acceleration was instead due to Solar radiation pressure, which functionally fits the observed acceleration signature, but requires a mass-area ratio (β) of 0.93 ± 0.03 kg m^{-2}, comparable to the area density of a light-sail, leading to speculation that 1I could be of artificial origin. Moro-Martin (2019) showed that such low area densities could instead be obtained from a porous icy aggregate formed outside the snowline of a protoplanetary disk.

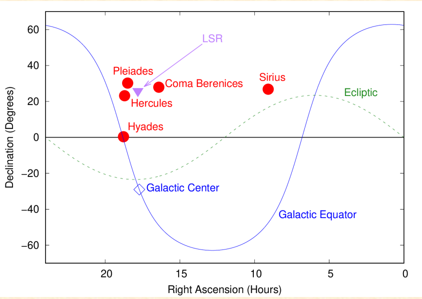
Planetary systems will clearly eject large numbers of ordinary comets and asteroids during their lifetimes. If 1I truly is a low-β object, there therefore **must** be two populations of ISOs in the 100-meter size range, one with mass-area ratios similar to solar system asteroids, and the other, possibly more numerous, being 1I-type low-β objects sensitive to drag in the Interstellar Medium (ISM). Low-β ISOs the size of 1I would in particular be rapidly stopped by ISM drag in star formation regions, possibly leading to both a low-β object role in planetary formation (through the seeding of planetesimals, possibly resolving the "meter barrier" in their formation) and an enhanced low-β object number density in the dynamical streams (which tend to contain star-formation regions).

1I is in the Pleiades Stream, not at the LSR



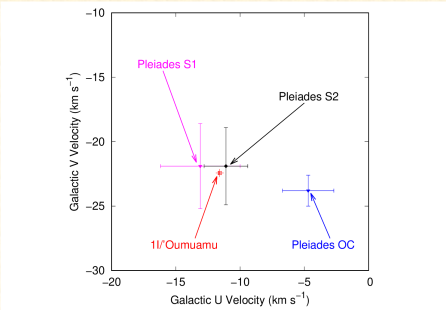
The galactocentric U and V (anti-radial and longitudinal) components of velocity for 1I, the Local Standard of Rest (LSR) and the five largest local dynamical streams. The 1I incoming velocity is near the centroid of the velocity determinations for the Pleiades stream. The stream velocity estimates are from (Kushniruk et al. 2017), supplemented by (Chereul et al. 1998; Liang et al. 2017; Gaia Collaboration et al. 2018). The 1I inbound velocity is the average of the five 1I anomalous acceleration velocity solutions in (Bailer-Jones et al. 2018), the LSR velocity estimates are from (Schönrich et al. 2010; Francis & Anderson 2009, 2014; Huang et al. 2015; Bland-Hawthorn & Gerhard 2016; Bobylev & Bajkova 2017). The dynamical LSR is the velocity vector of a circular orbit at the Sun's location, and will not be the preferred end-state of the orbital evolution of small bodies in a non-axisymmetric galaxy with a bar.

Radiants of the Major Galactic Dynamical Streams



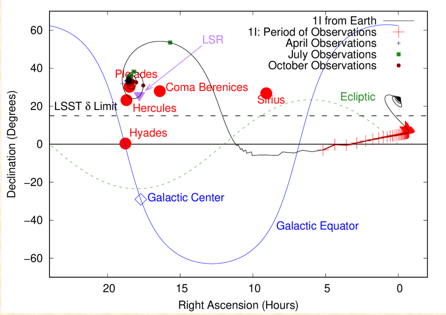
Incoming radiants of the 5 largest galactic streams in the solar neighborhood together with the Solar Apex (the incoming LSR radiant). The dispersion in the stream velocities as seen in the Gaia DR2 is comparable to or smaller than the size of the symbols; a substantial fraction of the stars in the solar neighborhood belong to one of these streams, and it is thus reasonable to assume that a substantial fraction of incoming ISOs will come from these radiants. This suggests that advanced warning of the passage of ISOs through the solar system can be obtained through deep surveys of the areas in the sky around these radiants.

1I/'Oumuamua is in the Core of the Pleiades SC Substream



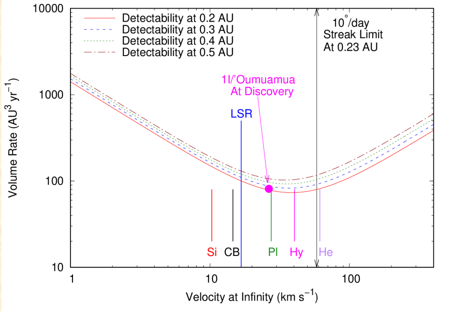
The 1I incoming velocity compared with the fine scale divisions of the Pleiades stream derived by (Chereul et al. 1998, 1999) from Hipparcos data. The OC represents a younger stream apparently populated with stars from the Pleiades open cluster, while S1 and S2 are substreams of the older SC stream. The error bars for the stream data are the stellar velocity dispersion of the indicated streams, while the error bars for the 1I data are based on the rms scatter of the various solutions in (Bailer-Jones et al. 2018). 1I is very close to the center of the Pleiades SC substream, indicating that it may be subject to drag mechanisms in the the stream ISM.

The Trajectory of 1I/'Oumuamua and the Stream Radiants



The path of 1I on its way in and out of the Solar System from the viewpoint of an observer at the Earth-Moon barycenter (ephemeris data are from JPL Horizons; the jagged appearance near perihelion is due to output quantization noise). 1I came from close to the center of the Pleiades Stream radiant, executing an expanding parallactic spiral until the Summer of 2017, when it came within the orbit of Mars (and could potentially have been observed in the Northern Hemisphere) and then swung by the Sun. Pleiades stream objects somewhat larger than 1I could be detected by existing telescopes ~ 1 year before their perihelion, by scanning regions ~10 Degrees square centered on the stream radiant.

1I Suggests ISOs May be Predominantly in Streams



The volume rate σ v_∞ sampled by surveys as a function of the velocity at infinity, v_∞, after accounting for gravitational focusing (which changes the cross section, σ). This function provides a proxy for the relative interstellar asteroid detection probability as a function of v_∞. The detection probability for the Pleiades stream is poor compared to slower moving ISOs; the detection of 1I suggests an enhanced ISO density in that stream.

Note that present surveys have a streak limit (an upper limit on the angular motions of detectable objects); shown here is the PanSTARRS streak limit of 10° day^{-1} (which applied at the time of the discovery of 1I). ISOs from the fast moving Hercules stream will be hard to detect without software improvements, such as synthetic tracking.

Conclusions

An on-going 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. A targeted search of the radiants of the Pleiades and Hercules streams (which are close together in the sky) with an 8-meter telescope might be able to scan 20 AU^3 yr^{-1} for 1 km-size bodies. If 1I represents a dense population of ISOs in the Pleiades stream, than such a survey might detect several 1I-sized ISOs per year. If, on the other hand, ISOs are distributed in the same proportion as local stars, then the same survey would yield on average one detection every 6 years.

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 and retained in the outer solar system today. Low-β ISOs captured in the Oort Cloud could be gravitationally perturbed into the inner solar system, and would be detectable as small (possibly inactive) "comets" on nearly-hyperbolic trajectories with unexpectedly large non-gravitational accelerations.

Low-β ISO could possibly enter planetary atmospheres without being destroyed, and thus could also be a means for panspermia in the Galaxy.

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