Oumuamuas Passing through Molecular Clouds

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Abstract

The detections of 1I/‘Oumuamua and 2I/Borisov within just two years of each other impressively demonstrate that interstellar objects (ISOs) must be common in the Milky Way. Once released from their parent system, these ISOs travel for billions of years through interstellar space. While often imagined as empty, interstellar space contains gas and dust most prominent in the form of molecular clouds. Performing numerical simulations, we test how often ISOs cross such molecular clouds (MCs). We find that the ISOs pass through MCs amazingly often. In the solar neighborhood, ISOs typically spend 0.1%–0.2% of their journey inside MCs, for relatively slow ISOs (<5 km s⁻¹) this can increase to 1%–2%, equivalent to 10–20 Myr per Gyr. Thus the dynamically youngest ISOs spend the longest time in MCs. In other words, MCs must mainly contain relatively young ISOs (<1–2 Gyr). Thus the half-life of the seeding process by ISOs is substantially shorter than a stellar lifetime. The actual amount of time spent in MCs decreases with distance to the Galactic center. We find that ISOs pass through MCs so often that backtracking their path to find their parent star beyond 250 Myr seems pointless. Besides, we give a first estimate of the ISO density depending on the distance to the Galactic center based on the stellar distribution.

Unified Astronomy Thesaurus concepts: Giant molecular clouds (653); Oort cloud objects (1158); Free floating planets (549)

1. Introduction

During the planet formation process, enormous numbers of planetesimals are produced which function as building blocks for planets. However, many of these planetesimals are never incorporated into planets and remain unused. Many of them are ejected from their parent system altogether. This ejection can happen by various mechanisms (for example, Brasser et al. 2010; Kaib et al. 2011; Veras et al. 2014; Do et al. 2018; Hanse et al. 2018; Moro-Martín 2019) that stretch over the entire life of a star, from its formation phase to its eventual end. Once ejected, these planetesimals become interstellar objects (ISOs) that drift through the Galaxy. The vast majority of these icy rocks are long lived and cruise the Galaxy for billions of years (Guilbert-Lepoutre et al. 2015).

For a long time, it was unclear how many ISOs are present in the Milky Way. The estimates ranged from as few as 10⁶ pc⁻³ to as many as 10¹⁶ pc⁻³ (e.g., Whipple 1975; Francis 2005; Engelhardt et al. 2017). This long-standing argument about the abundance of ISOs was, if not solved, at least considerably constrained by the recent detections of the 140 m near-inert object 1I/‘Oumuamua (Meech et al. 2017) and the active comet 2I/Borisov (Fitzsimmons et al. 2019; Jewitt & Luu 2019). The efficiency of the detection of 1I/‘Oumuamua during the relevant surveys is the basis for a first observational estimate of the ISO density in interstellar space. The result is an amazingly high ISO density of ≈10¹⁵ pc⁻³ ISOs in local interstellar space (Meech et al. 2017; ‘Oumuamua ISSI Team 2019).

It is often implicitly expected that these ISOs will have relatively little interaction while traveling through interstellar space, remaining in a more or less pristine state. However, even interstellar space is not empty as it contains gas and dust mainly concentrated in giant molecular clouds (GMCs). GMCs are transient features with a median lifetime of 40 Myr (Williams & McKee 1997; Vallini et al. 2016). Within GMCs, the gas can condense to form dense cores, and further contraction may ultimately lead to the formation of stars. The angular momentum of the infalling material leads to the formation of gaseous disks around these protostars, from which a planetary system may form under favorable conditions. ISOs within protoplanetary disks may possibly even help seed planet formation (Pfalzner & Bannister 2019).

Here we will investigate the connection between ISOs and GMCs from two perspectives—that of the ISOs and that of the GMCs. When ISOs interact with the dust and gas of the GMC, their dynamics and surface properties might change. The expected effect depends on how often ISOs pass through GMCs and also the relative velocities. These processes have not yet been studied in detail. Here we determine the relative importance of the interaction of ISOs with GMCs. The prime parameters are the frequency of the passage of ISOs through GMCs and the relative velocity of such encounters.

The general assumption is that GMCs contain only gas and dust, and eventually the stars forming from them. However, the ISO density in the interstellar medium (ISM) inevitably leads to the conclusion that GMCs must contain ISOs as an additional component. The question is whether the presence of ISOs plays any role in the context of molecular clouds. The relevance of ISOs depends on their number within GMCs at any given time, which we will determine here.

We use the simulations performed by Kokaia & Davies (2019) to infer the trajectories of stars and GMCs in the Galaxy. These trajectories allowed them to determine how often stars pass through GMCs. For instance, they found that the Sun hits 1.6 ± 1.3 GMCs per Gyr. These simulations can be generalized to ISOs by employing the fact that the velocity of the ISOs is the velocity of the stars plus the velocity component that led to the ISOs leaving their parent system. In

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most cases the ISO velocity relative to the star is much smaller than the stellar velocity itself.

We use the existing set of simulations to determine the frequency of ISOs passing through GMCs and the resulting fate of the ISOs. In Section 2, the numerical model underlying these simulations is explained. In Section 3.1 we present the results and will see that the relative velocities between the ISOs and GMCs are the critical parameter in this context and that the interaction frequency also crucially depends on the location of the GMCs and ISOs in the Galaxy. In Section 3.2, we determine the number of ISOs typically present in a GMC and the renewal rate of the ISO reservoir. In Section 4 we discuss the consequences for our understanding of ISOs.

2. Method

We follow the orbits of the stars to assess how often ISOs pass through GMCs. Here we describe the Galactic potential used to integrate ISO trajectories with the GMC properties adopted. For further details of the calculations, we refer to Kokaia & Davies (2019).

2.1. Simulation Setup

The orbits of the stars in the Galaxy are determined by integrating their path through a three-component axisymmetric potential \( \Phi_c(R; z) \) (García-Sánchez et al. 2001) of the form

\[
\Phi_c(R; z) = \Phi_h(R; z) + \Phi_b(R; z) + \Phi_d(R; z),
\]

where the three components \( \Phi_h, \Phi_b \) and \( \Phi_d \) represent the halo, bulge, and disk, respectively. \( R \) stands for the Galactocentric cylindrical radius and \( z \) is the distance to the Galactic plane. The halo has the form of a spherical Plummer potential (Plummer 1911) and the disk is a Miyamoto disk (Miyamoto & Nagai 1975).

The GMCs are characterized by their spatial distribution, mass function, density profile, and lifetimes. GMCs are primarily located in the spiral arms of the Galaxy. Here we do not consider the spiral arm gravitational potential explicitly, but instead distribute our model GMCs in the spiral pattern observed by Hou & Han (2014). These can be fitted by

\[
\ln \frac{R}{R^*_i} = (\theta - \theta_i) \tan \psi_i,
\]

where \( R \) is the starting radius, \( \theta \) the starting angle, and \( \psi \) the pitch angle of GMCs. See Table 2 of Kokaia & Davies (2019) for the values of \( R^*_i \) and \( \psi \) used.

For the mass function of GMCs, we use the fit to observations by Rosolowsky & Leroy (2006) given by

\[
\frac{dN}{dM} = (\gamma + 1) N_0 \left( \frac{M}{M_0} \right)^\gamma, \quad M < M_0,
\]

where \( M_0 \) is the maximum mass of \( 3 \times 10^6 M_\odot \) and the minimum mass is \( 10^4 M_\odot \); \( N_0 = 36 \) and \( \gamma = 1.53 \) are constants. The GMC mass varies with age as

\[
M(t) = \left[ -0.25 \left( \frac{t - t_0}{10} \right)^2 + \frac{t - t_0}{10} \right] \times M_1,
\]

where \( M_1 \) is the mass drawn from Equation (3). The shape of this function is based on simulations from Krumholz et al. (2006) and Goldbaum et al. (2011). The typical lifetime of a GMC is 40 Myr, where the GMC increases in mass for the first 20 Myr, peaks, and then decreases for another 20 Myr. The 40 Myr lifetime is consistent with observations from, e.g., Williams & McKee (1997) and Vallini et al. (2016). We start our simulation with 6700 randomly generated clouds. This number of clouds gives the correct molecular gas mass (i.e., matches the observations), given the mass function used for the clouds. Whenever a GMC reaches the end of its life, a new one is initiated in the next time step, keeping the total number constant.

The \( \mathrm{H}_2 \) gas of the GMC is assigned to one of three categories, following the categorization by Roman-Duval et al. (2016): very dense, dense, and diffuse. Accordingly, the radii of the GMC is connected to the gas surface densities for these three categories by

\[
R_{\text{GMC}} = \begin{cases} 
\frac{1}{229} \left( \frac{M}{1 M_\odot} \right)^{1/2.36}, & \text{for } 130 M_\odot \text{ pc}^{-2} < \rho < 300 M_\odot \text{ pc}^{-2} \\
\frac{1}{78} \left( \frac{M}{1 M_\odot} \right)^{1/2.36}, & \text{for } 50 M_\odot \text{ pc}^{-2} < \rho < 130 M_\odot \text{ pc}^{-2} \\
\frac{1}{28} \left( \frac{M}{1 M_\odot} \right)^{1/2.36}, & \text{for } 25 M_\odot \text{ pc}^{-2} < \rho < 50 M_\odot \text{ pc}^{-2} 
\end{cases}
\]
where the GMC radius $R_{\text{GMC}}$ is in parsecs. The radial and vertical distributions are provided through H$_2$ observations by Nakanishi & Sofue (2006). Figure 1 shows the corresponding distributions of the GMC radii and masses. It can be seen that most GMC have radii in the range of $8\, \text{pc} < R_{\text{GMC}} < 15\, \text{pc}$.

2.2. Relative Velocities between ISOs and Parent Systems

Above we model just the movement of the stars relative to the GMC. However, this can serve as a useful approximation for the relation between the ISOs and the GMCs. The velocity of the ISOs relative to the GMC, $v_{r,\text{ISO}}^{\text{GMC}}$, results from two components—the relative velocity between the star and the molecular cloud, $v_{r,\text{GMC}}$, and the velocity between the ISOs and their parent star, $v_{r,\text{ISO}}$. The latter depends on the type of processes leading to the ejection of the planetesimal from its stellar host system which turns it into an ISO.

ISOs are ejected from a star throughout its entire life (Pfalzner & Bannister 2019). Judging from the still small sample provided by 11/’Oumuamua and 21/Borisov, ISOs are typically a few tens to hundreds of meters in size. In the earliest phases probably a lot of small dust aggregates leave the disks, as indicated by the steep decline of disk mass during the first 100,000 yr (Alexander 2014). However, unless dust growth is rapid, these particles will mostly be of millimeter to centimeter size and therefore much smaller than the ISOs.

However, after 2 Myr quite a large number of planetesimals should have grown to sizes of 10 m and above. During that phase, most stars are still part of the stellar cluster they formed in (Kuhn et al. 2019), therefore close flybys between the cluster stars are relatively common. Such flybys can lead to the truncation of the outer parts of the disk (Vincze & Pfalzner 2016; Pfalzner et al. 2018) and as a consequence many planetesimals become unbound, turning into ISOs. The frequency of close flybys depends on the stellar density of the particular group of stars (Vincze & Pfalzner 2016, 2018). Similarly, the velocity of the created ISOs depends on the actual masses of the involved stars and their periastron distance; typically, they lie in the range of $0.5–2\, \text{km s}^{-1}$ (S. Pfalzner & L. L. Aizpura Vargas, in preparation). The velocity of these ISOs relative to the GMCs is then the combination of the stellar velocity and the escape speed and amounts for young stars to approximately $5\, \text{km s}^{-1}$ (Hands et al. 2019).

While the planets migrate in the still young planetary system, they interact with the debris planetesimal disk. Predominantly, close encounters with the giant planets of the system lead to the ejection of many of a system’s remaining planetesimals (Duncan et al. 1987; Charnoz & Morbidelli 2003; Raymond & Izidoro 2017). It is mainly planetesimals residing between a few to tens of astronomical units from the host star that are affected. This type of planetesimal ejection leads to ISOs with typical velocities of $4–7\, \text{km s}^{-1}$ relative to the host star (Adams & Spergel 2005).

Afterwards, throughout the star’s lifetime, predominately icy planetesimals will be gently lost, as they drift from the distant fringes of the star’s Oort cloud under the nudging of the Galactic tide and passing field stars (Brasser et al. 2010; Kaib et al. 2011; Hanse et al. 2018). This drifting away happens at quite low velocities relative to that of the star ($<0.5\, \text{km s}^{-1}$). Finally, the remainder of the system’s Oort cloud will be shed to interstellar space once the star leaves the main sequence and loses mass (Veras et al. 2011, 2014; Do et al. 2018; Rafi'kov 2018; Moro-Martín 2019). The velocity of the ISOs created this way depends on the mass of the star but rarely exceeds $0.3\, \text{km s}^{-1}$ (D. Veras, 2019, private communication).

As mentioned above, it is still unclear which of these processes is the dominant source of ISO production. However, the ISOs’ ejection velocities rarely exceed $10\, \text{km s}^{-1}$. In most cases, the ejection velocity will be $\ll 5\, \text{km s}^{-1}$, which means that the velocity of the ISOs differs only slightly from those of the parent stars. Thus the approximation we adopt here—namely that the ISO velocities within the Galaxy follow the same distribution and evolution as their host stars—is valid. Throughout this study we assume that the velocity of the ISOs remains unchanged after ejection. This simplification will be discussed in Section 4.

3. Results

3.1. ISOs’ Perspective

In the simulations, we followed the trajectories of 400,000 particles to determine how often an ISO passes through a GMC. Naturally, the frequency of these “passages” depends on the relative velocity between the ISOs and the clouds. Figure 2(a) shows the distribution of these relative velocities for 1–3 Myr-old ISOs in the solar neighborhood (Galactic center distance, $R_{\text{GC}}$, between 7.5 and 8.5 kpc). The relative velocities between stars/ISOs and the GMCs cover a vast parameter space with most ISOs having a relative velocity in the range of $30–40\, \text{km s}^{-1}$. Thus the relative velocity to the GMCs is dominated by that of the stars relative to the GMCs.

![Figure 2](image_url)
The ejection speed from the parent stars is of minor importance, being on average less than 10% of that of the stellar contribution.

ISOs moving with high velocity through the GMC are dynamically less affected than those with low velocities. In turn, fast ISOs are less likely to be captured within a GMC or to be strongly deflected. On the other hand, erosion might be more of a problem for fast ISOs when small dust particles hit them at high velocities (Housen & Holsapple 2011).

Figure 1(b) shows an enlargement of the regime of the low-velocity ISOs. These are the ones that are more likely to be captured. Their number decreases nearly linearly with relative velocity. However, of the 1–3 Myr-old ISOs in the solar neighborhood, about 66% have a velocity below 10 km s\(^{-1}\) relative to the GMCs.

The question is how much time do ISOs spend inside molecular clouds? The in-cloud time depends on the cloud properties and individual ISO velocity. Figure 3(a) shows the average fraction of time that ISOs spend inside a GMC as a function of velocity for ISOs in the age range of 1–3 Gyr.\(^{5}\) Generally, the lower the velocity of the ISO, the longer it spends inside GMCs. The different colors indicate the distance to the Galactic center. The light green curve is relevant for the solar neighborhood. The ISOs of a velocity of \(v_z\) typically pass through a handful of GMCs per gigayear, whereas in the same period ISOs at 4.5 kpc pass through 100 GMCs. For individual ISOs, the time spent inside GMCs and the number of GMC passages can vary considerably. In the solar neighborhood, ISOs of a velocity of \(5 \text{ km s}^{-1}\) typically pass through a handful of GMCs per gigayear, whereas in the same period ISOs at 4.5 kpc pass through 100 GMCs.

Figure 3(b) shows that slow ISOs also pass through GMCs more often than fast ISOs do. In the solar neighborhood, fast ISOs \((v_z \approx 50 \text{ km s}^{-1})\) pass, on average, through 0.2 GMCs per Gyr, whereas slow ISOs encounter typically 4–6 GMCs in the same period. On first view that seems counterintuitive. The reason why slower ISOs spend more time in GMCs is that all GMCs reside within about 100 pc of the Galactic plane. Therefore, ISOs having low velocities in the z-direction are unable to reach above the GMCs as they orbit around the Galaxy; thus they strike them more often; whereas ISOs having higher speeds in the z-direction spend much of their time at larger values of \(z\) where there are no GMCs. This leads to ISOs with low values of \(v_z\) passing through more GMCs compared to ISOs having larger values of \(v_z\) and contributes to the enhanced time that slow ISOs spend in GMCs.

Already Figure 3 showed that the fate of an ISO depends strongly on its location within the Milky Way. Figure 4(a) shows even more clearly how the time spent inside GMCs depends on the distance to the Galactic center. This time decreases the further the distance to the Galactic center. This general trend holds\(^{6}\) independent of the actual velocity of the ISO. At 4.5 kpc ISOs spent about 10 times more time inside GMCs than in the solar neighborhood, which accounts for slow ISOs \((v = 5 \text{ km s}^{-1})\) in spending up to an amazing 8% of their life in GMCs. The main reason is that the GMC density is much higher close to the Galactic center. In summary, many ISOs travel for extended periods unhindered through interstellar space, however, those that move relatively slowly or close to the Galactic center can spend more time in molecular clouds other than the one in which they were formed.

Figure 4(b) shows that also the number of GMC passages depends strongly on the distance to the Galactic center. In the solar neighborhood, ISOs of a velocity of \(5 \text{ km s}^{-1}\) typically pass through a handful of GMCs per gigayear, whereas in the same period ISOs at 4.5 kpc pass through 100 GMCs.

For individual ISOs, the time spent inside GMCs and the number of GMC passages can vary considerably. In the solar neighborhood, the time inside GMCs can differ by orders of magnitude, particularly for fast ISOs. The relative spread in time spent inside GMCs is much smaller close to the Galactic center. Similarly, the number of GMC passages shows a wider relative spread for values in the solar neighborhood than at 4.5 kpc (see Figure 4(b)). For example, in the solar neighborhood, the 1σ range of the number of GMC passages stretches from none at all to eight passages. By contrast, for the same velocity ISOs at 4.5 kpc the 1σ range stretches only from 90–110 passages. At more considerable Galactic distances, a small subset of fast ISOs (\(\sim 1\%\)) exists that never pass through GMCs for 10 Gyr. However, this is such a small subgroup that these are the rare exception rather than the rule.

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5 More precisely, ISOs ejected from host 1–3 Gyr-old host stars.

6 Except for the Galactic center itself.
So far, we have looked at the total time that an ISO spends inside GMCs. Figure 5 shows the distribution of the time spent in an individual cloud. The majority of ISOs spend less than 4 Myr in a given cloud, with most staying less than 2 Myr. Only a fraction remain in a single cloud for 10 Myr. This is consistent with taking the mean GMC size \( \text{radius} \sim 10 \text{ pc}, \text{size} \sim 20 \text{ pc} \) and ISO velocity \( \sim 30 \text{ km s}^{-1} \approx 30 \text{ pc Myr}^{-1} \) as an approximation, which gives a mean passage time of 0.6 Myr. Thus the mean cloud passage time is much shorter than the lifetime of the cloud, which was assumed to be 40 Myr. One should note here that ISOs with relatively low relative speeds will be accelerated by the GMC such that all ISOs will pass through GMCs with a minimum speed slightly higher than the escape speed of the GMC (typically around 10 km s\(^{-1}\)). Thus even the slowest ISOs will pass through an average GMC in \( \sim 2 \text{ Myr} \) unless they are captured. As a consequence, there is a steady stream of ISOs passing through any individual cloud.

### 3.2. Cloud Perspective

So far we only considered the fate of the ISOs passing through GMCs. However, from the perspective of the GMCs, the large density of ISOs means that they continuously stream through. These wandering ISOs are inside the GMCs in addition to those ISOs captured during the cloud formation process itself. The above results imply that the ISO population passing through a GMC rejuvenates completely approximately every 4 Myr. More specifically, 90% of ISOs have left by the time the GMC disperses. Thus the population of ISOs passing through a GMC is replaced \( \sim 10 \) times during its lifetime.

The number of ISOs passing through a GMC, \( N_{\text{ISO}}^{\text{GMC}} \), can be roughly approximated by the volume of the GMC and the ISO density, \( \rho_{\text{ISO}} \). It is

\[
N_{\text{ISO}}^{\text{GMC}} = \frac{4\pi}{3} R_{\text{GMC}}^3 \times \rho_{\text{ISO}}
\]

This means that \( \sim 10^{18} \) to \( 10^{19} \) ISOs pass through a typical GMC with \( R_{\text{GMC}} = 10 \) pc (see Figure 1). However, this is only a rough estimate; the actual number depends on the size of the cloud, which itself is time dependent. The cluster radius is proportional to the cluster mass, \( R_{\text{GMC}} = C \times M_1^{1/2.36} \), where \( C \) is the same as in Equation (5) and the GMC mass is in units of solar masses. Although the number of ISOs is high, their combined mass is quite low. If we assume a density of \( \rho = 1 \text{ g cm}^{-3} \), characteristic of similarly-sized Kuiper Belt objects, the combined mass of all ISOs present in a 10 pc-sized cloud would correspond to only \( 10^3 M_{\odot} \).

As cluster mass varies with age as given in Equation (4), the number of ISOs present in a given GMC varies as a function of time accordingly,

\[
N_{\text{ISO}}^{\text{GMC}} = \frac{4\pi}{3} (C \times M_1^{1/2.36})^3 \times \rho_{\text{ISO}} = \frac{4\pi C^3}{3} M_1^{1.27} \times \rho_{\text{ISO}}
\]

Figure 6 shows the number of ISOs per GMC as a function of distance to the Galactic center. It can be seen that there are about a factor of 10 more ISOs inside GMCs at 5 kpc than at 10 kpc. This higher abundance of ISOs means that if ISO presence is in any way significant for GMCs, then GMCs closer to the Galactic center would be most affected.

So far we have assumed that the ISO density of the solar neighborhood, \( \rho_{\text{ISO}} = 10^{15} \text{ pc}^{-3} \), is representative of the entire

![Figure 4](image_url)

**Figure 4.** (a) The fraction of time an ISO spends inside GMCs and (b) the number of GMC passages per ISO for ISOs initially having a velocity in the z-direction of 5 km s\(^{-1}\). Both are shown as a function of Galactic center distance. Both values are derived for simulations following the trajectories of ISOs over a time period of 1 Gyr. For (a), the various colors indicate the results for different initial ISO velocities in the z-direction.

![Figure 5](image_url)

**Figure 5.** Distribution of the time (in megayears) ISOs spend passing through GMCs.
Galaxy. However, it is highly unlikely that the ISO density will be uniform throughout the Galaxy. We saw in Section 2.2 that the production of ISOs is tightly linked to that of the stars. Therefore, it seems logical to assume that the ISO production density throughout the Galaxy follows the stellar distribution, at least to some degree. Using the local ISO density of $10^{15} \text{pc}^{-3}$ as an anchor point, we used the stellar surface density distribution to give a first estimate of the ISO density within the Galaxy in Figure 7. It shows that the ISO density depends relatively little on the distance to the Galactic center, with the ISO density being only about a factor of 3 higher at 5 kpc than in the solar neighborhood. As a consequence, the number of ISOs per GMC would depend somewhat more on the distance to the Galactic center than is implied by Figure 6.

However, one has to be careful with the interpretation of Figure 7. Here the expected production rate is shown, which is not necessarily the same as the present ISO density. One can think of many processes that lead to the redistribution of ISOs throughout the Galaxy. For example, ISOs could diffusively spread in a manner similar to that believed to occur for stars due to encounters with spiral arms. On the other hand, ISO production per star could be more efficient closer to the Galactic center. All these issues will need further study in the future.

4. Discussion

From the results in Section 3, we conclude that the ISOs in a GMC are mainly those with a relatively low velocity. Some of these might be captured within the GMC, but most will pass unhindered through it. Predominantly, slow ISOs are produced by stars that have a low velocity relative to GMCs and were released gently from their parent star (i.e., at low ejection speeds).

Young stars have the lowest velocity dispersion. Therefore, slow ISOs mainly originate from young stars and as a consequence, are young themselves. Therefore, we can conclude that the ISOs present in GMCs are predominately younger than 1–2 Gyr and pass through them at a moderate speed, whereas the fewer old ISOs pass quickly through GMCs.

The fact that the ISOs found in GMCs must have been relatively slow means that these ISOs cannot be predominantly produced during the planet instability process. The reason is that ISO ejection during the planet instability phase due to scattering processes leads to relatively high velocities ($5–10 \text{ km s}^{-1}$) compared to other ejection mechanisms (S. Pfalzner & L. L. Aizpuru Vargas, in preparation.) By contrast, ISOs produced at the end of the lifetime of a star are ejected at low velocity ($\ll 1 \text{ km s}^{-1}$). However, except for rare high-mass stars, the parent stars are relatively old, which means the stars have a high-velocity dispersion. Therefore, ISOs from the late stages of stars are also unlikely occupants of GMCs. Consequently, ISOs in GMCs originate predominantly from stars that are $\ll 1$ Gyr old and are either ejected during the cluster phase or drift gently away from the exo-Oort cloud of the parent star when those were still quite young.

Another consequence is that young ISOs are the ones most likely to be captured in GMCs. They might even participate in the collapse of parts of the GMC which become unstable. If ISOs function as seeds of planet formation when they become incorporated into the disk around young stars (Pfalzner & Bannister 2019), the young ISOs predominantly function as seeds for new planets.

By contrast, old ISOs wander through interstellar space with little probability of being captured in a GMC or even just passing through one. It is only these fast, old ISOs that are the lonely wanderers which we often imagine all ISOs to be. However, that older ISOs move at a high velocity through GMCs does not necessarily mean that they are no longer affected by these passages. Their relatively high speed means that they encounter the dust particles at high velocities. These high-speed encounters with dust particles might have a more substantial impact on the fast old ISOs, eroding their surface significantly. However, this process will require future detailed study.

The above conclusions are based on assuming that there is a direct correlation between ISOs being young and slow. Throughout our study, we used the host stars’ motion to estimate the velocity distribution of ISOs relative to the Galaxy and implicitly assumed that this velocity does not change during the process. However, several processes could alter an ISO’s velocity during its journey by interaction with the ISM, stars, and molecular clouds. These interactions can either lead to the slowing down of an ISO or its acceleration. The latter happens predominantly when an ISO passes close to a binary star, as in three-body encounters the lightest partner is usually the most likely to be ejected from the system. Similar ISOs can...
become accelerated as they pass the outskirts of a GMC in a slingshot action. The opposite effect can be expected when ISOs pass through the ISM or a GMC itself without being actually captured. In these cases, gravitational drag can potentially slow down ISOs. Similar magnetic fields could potentially slow down ISOs in the ISM (Zhang & Lin 2020) and sublimation by collisional heating in GMCs could also influence the motion of ISOs (Hoang & Loeb 2020). In most of these processes, large ISOs are less affected than small ISOs; here small means ISO sizes of less than tens to hundreds of meters. Consequently, the velocity distribution (Figure 2) is probably a good approximation for large ISOs in general, and the young population of small ISOs might change as they age. It will require further detailed studies that include all these processes to determine the development of the velocity distribution of small, old ISOs to see how this affects, for example, the average number of old ISOs per cloud shown in Figure 6.

Many GMCs are sites of active star formation, which also includes massive stars. Such massive stars are short lived (less than 50 Myr, see, e.g., Zapart et al. 2017) and end their lives as core-collapse supernovae. The consecutive explosions usually happen close to where they are born. Therefore, ISOs that pass through a GMC might encounter a nearby supernova that might alter the composition of the ISOs or at least that of their surface layer. As slow, young ISOs spend on average a longer time in GMCs, they are more likely to be affected by such supernovae explosions than faster ISOs.

The fate of an ISO does not only depend on its velocity but also its direction. It makes a tremendous difference whether it moves toward or away from the high-density regions closer to the Galactic center. As the ejection speed is on average lower than the velocity dispersion of the parent stars, this is only to a small degree determined by the ejection direction itself but mostly by the direction of the velocity of the parent star at the moment of ISO release.

During the last three years, there has been some effort to pinpoint the origin of Oumuamua and Borisov. The preferred method is to search trajectories for close passages to stars in the past. There is an ongoing discussion as to whether this is possible given the uncertainties in stellar positions and velocities (Bailer-Jones et al. 2018; Dybczyński & Królikowska 2018; Feng & Jones 2018; Portegies Zwart et al. 2018; Zhang 2018; Dybczyński et al. 2019; Bailer-Jones et al. 2020; Hallatt & Wie gert 2020; Higuchi & Kokubo 2020). The fact that low-velocity ISOs interact most often and intensely with GMCs also has consequences for tracing ISOs back to their parent star. In the solar neighborhood slow ISOs pass on average through four to six GMCs per billion years. During these passages, ISOs interact gravitationally with the GMC. Consequently, their path will alter, even if this change is only modest in many cases. However, the consequence is that on average, after only 0.25 Gyr, the path of an ISO is already no longer traceable. Not only that, but the GMC that changed the path of the ISO will have dissolved without a trace after just 40 Myr, making it also impossible to detect the possible points where the ISO deviated from its original root.

We looked at the distribution of ISOs as function distance from the Galactic center. However, this is only one aspect when considering variations in ISO density. The actual situation is more complicated. As illustrated in Section 1, the ISO production process is strongly linked to the star and planet formation process. Therefore, any variation in the star formation efficiency translates automatically into a difference in ISO production.

The ISO density probably also changed over time. As ISOs can likely survive for many billions of years while traveling through interstellar space, their absolute number should have increased with time (Pfalzner & Bannister 2019). Or in other words, the results above can only be applied for the last 2–3 Gyr, and the number of ISOs per GMC was probably considerably lower in the distant past.

In our simulations, collisions between GMCs and their subsequent mergers were not considered. However, mergers might be relevant in the central areas of the Galaxy due to the higher GMC density. In this area, a more realistic treatment of the GMC dynamics might be required.

5. Summary and Conclusions

With locally $10^{15}$ objects per cubic parsec, ISOs are quite abundant in interstellar space, so are GMCs. This naturally leads to the question of how often ISOs pass through clouds and what are the potential consequences of these passages for ISOs and molecular clouds alike. Here we performed numerical simulations to obtain a first impression on the potential consequences of such encounters. In summary, our results show that:

1. The frequency of ISOs passing through GMCs is a strong function of both the ISO velocity and distance to the Galactic center.
2. In the solar neighborhood, typical ISOs ($v \sim 30 \text{ km s}^{-1}$) spend approximately 0.1%–0.2% of their time inside GMCs. In other words, these ISOs spend approximately 1–2 Myr transversing GMCs for every Gyr they travel through “empty” interstellar space.
3. Slow ISOs ($\sim 5 \text{ km s}^{-1}$) spend on average a larger fraction of their life inside a GMC; in the solar neighborhood they are typically located inside GMCs about 1%–2% of the time (equivalent to 10–20 Myr per Gyr). The reason is a combination of longer GMC transversal times and a higher frequency of encountering GMCs.
4. Despite these general trends, the time inside GMCs can vary for individual ISOs by many orders of magnitude in the solar neighborhood.
5. ISOs close to the Galactic center also spend a larger fraction of their life inside GMCs. Typical ISOs at 4.5 kpc spend nearly 10 times more time inside GMCs than in the solar neighborhood. Here slow ISOs ($v = 5 \text{ km s}^{-1}$) spend nearly up to 10% of their life in GMCs.
6. The reservoir of ISOs inside GMCs is rejuvenated continuously, with the entire ISO population being replaced about 10 times within the lifetime of a GMC.

The conclusion is that ISOs pass surprisingly often through GMCs. This might have several consequences for ISOs and GMCs alike.

When ISOs pass through GMCs, they can be gravitationally and structurally affected. These effects have not been taken into account in this study. However, the gravitational effect of the GMCs can alter the ISO velocity and, in extreme cases, lead to their capture in the cloud. Here the slow and therefore probably preferentially young ISOs are mostly affected. Even if not
captured, they change their velocity, which often means also a change in direction. Consequently, tracing back the origin of ISOs is not only hampered by the scattering by stars but more substantially by being scattered by the GMCs they inevitably pass through.

Assuming that most ISOs do not experience a large change of their velocity during their travel, GMCs will mainly contain relatively young ISOs (<1 Gyr). Thus the recycling process of ISOs is relatively fast. Therefore, it is mostly the relatively young ISOs that might seed the next generation of planets.

ISOs can also be affected on a structural level when passing through GMCs. They face a high collision rate with the dust and the gas; however, high incident rates will lead to at least some erosion of the ISO surface. In extreme cases, this can also lead to ISO restructuring or even destruction.

The above results affect our view of 1I/’Oumuamua and 2I/Borisov. The age of 1I/’Oumuamua is not known. However, with a random velocity of ~9 km s\(^{-1}\) from the local standard of rest, 1I/’Oumuamua’s random velocity is much smaller than that of nearby stars (~50 km s\(^{-1}\); Anguiano et al. 2018). This velocity indicates that 1I/’Oumuamua is dynamically young with a statistically derived dynamical age of <2 Gyr (’Oumuamua ISSI Team 2019). If we assume 1I/’Oumuamua to have an age in the range 1–2 Gyr and also take its low relative velocity into account, 1I/’Oumuamua could have transversed through up to 4–10 GMCs spending 5–20 Myr of its journey inside GMCs. Therefore back tracking 1I/’Oumuamua’s origin beyond distances that correspond to a 250 Myr travel time is probably not well motivated.

So far, the differences seen between 1I/’Oumuamua and 2I/Borisov are attributed to them having formed differently. However, the above results also open the new option that these differences might be due to a different history during their passage through interstellar space. In this picture, 2I/Borisov would have had a comparatively uneventful journey passing through few if any GMCs, arriving here more or less unaltered leading to its appearance as a comet-like object. By contrast, 1I/’Oumuamua would have encountered many GMCs and undergo major restructuring before reaching the solar system in a somewhat battered state. However, the effect of GMCs on ISOs needs further investigation to see how likely this scenario is.

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References

Adams, F. C., & Spergel, D. N. 2005, AsBio, 5, 497
Alexander, R. 2014, in IAU Symposium 299, Exploring the Formation and Evolution of Planetary Systems, ed. M. Booth, B. C. Matthews, & J. R. Graham (Cambridge: Cambridge Univ. Press)
Anguiano, B., Majewski, S. R., Freeman, K. C., Mitschang, A. W., & Smith, M. C. 2018, MNRAS, 474, 854
Bailer-Jones, C. A. L., Farnocchia, D., Meech, K. J., et al. 2018, AJ, 156, 205
Bailer-Jones, C. A. L., Farnocchia, D., Ye, Q., Meech, K. J., & Micheli, M. 2020, A&A, 634, A14
Brasser, R., Higuchi, A., & Kaib, N. 2010, A&A, 516, A72
Charnoz, S., & Morbidelli, A. 2003, Icar, 166, 141
Do, A., Tucker, M. A., & Tonry, J. 2018, ApJL, 855, L10
Duncan, M., Quinn, T., & Tremaine, S. 1987, AJ, 94, 1330
Dybczyński, P. A., & Królicka, M. 2018, A&A, 610, L11
Dybczyński, P. A., Królicka, M., & Wysockińska, B. M. 2019, arXiv:1909.10952
Engelhardt, T., Jedicke, R., Vereš, P., et al. 2017, AJ, 153, 133
Feng, F., & Jones, H. R. A. 2018, ApJL, 852, L27
Fitzsimmons, A., Hainaut, O., Meech, K. J., et al. 2019, ApJL, 885, L9
Francis, P. J. 2005, ApJ, 635, 1348
García-Sánchez, J., Weissman, P. R., Preston, R. A., et al. 2001, A&A, 379, 634
Goldbaum, N. J., Krumholz, M. R., Matzner, C. D., & McKee, C. F. 2011, ApJ, 738, 101
Guilbert-Leproux, A., Besse, S., Mousis, O., et al. 2015, SSRv, 197, 271
Hallatt, T., & Wiepert, P. 2020, AJ, 159, 147
Hands, T. O., Dehnen, W., Gratton, A., Stadel, J., & Moore, B. 2019, MNRAS, 490, 21
Hanse, J., Jilková, L., Portegies Zwart, S. F., & Pelupessy, F. I. 2018, MNRAS, 473, 5432
Higuchi, A., & Kokubo, E. 2020, MNRAS, 492, 268
Hoang, T., & Loeb, A. 2020, ApJL, 899, L23
Hou, L. G., & Han, J. L. 2014, A&A, 569, A125
Housen, K. R., & Holsapple, K. A. 2011, Icar, 211, 856
Jewitt, D., & Luu, J. 2019, ApJL, 886, L29
Kaib, N. A., Roškar, R., & Quinn, T. 2011, Icar, 215, 491
Kokai, G., & Davies, M. B. 2019, MNRAS, 489, 5165
Krumholz, M. R., Matzner, C. D., & McKee, C. F. 2006, ApJ, 653, 361
Kuhn, M. A., Hillenbrand, L. A., Sills, A., Feigelson, E. D., & Getman, K. V. 2019, ApJ, 870, 32
Meech, K. J., Weryk, R., Micheli, M., et al. 2017, Natur, 552, 378
Miyamoto, M., & Nagai, R. 1975, PASJ, 27, 533
Moro-Martín, A. 2019, AJ, 157, 86
Nakanishi, H., & Sofue, Y. 2006, PASJ, 58, 847
’Oumuamua ISSI Team 2019, Natur, 3, 594
Pfalzner, S., & Bannister, M. T. 2019, ApJL, 874, L34
Pfalzner, S., Bhandare, A., Vincke, K., & Lacerda, P. 2018, ApJ, 863, 45
Plummer, H. C. 1911, MNRAS, 71, 460
Portegies Zwart, S., Torres, S., Pelupessy, I., Bédorf, J., & Cai, M. X. 2018, MNRAS, 479, L17
Raftikov, R. R. 2018, ApJ, 861, 35
Raymond, S. N., & Izidoro, A. 2017, Icar, 297, 134
Roman-Duval, J., Heyer, M., Brunt, C. M., et al. 2016, ApJ, 818, 144
Rosolowsky, E., & Leroy, A. 2006, PASP, 118, 590
Vallini, L., Gruppioni, C., Pozzi, F., Vignali, C., & Zamorani, G. 2016, MNRAS, 456, L40
Veras, D., Evans, N. W., Wyatt, M. C., & Tout, C. A. 2014, MNRAS, 437, 1127
Veras, D., Wyatt, M. C., Mustill, A. J., Bonson, A., & Eldridge, J. J. 2011, MNRAS, 417, 2104
Vincke, K., & Pfalzner, S. 2016, ApJ, 828, 48
Vincke, K., & Pfalzner, S. 2018, ApJ, 868, 1
Whipple, F. L. 1975, AJ, 80, 525
Williams, J. P., & McKee, C. F. 1997, ApJ, 476, 166
Zapartas, E., de Mink, S. E., Izzard, R. G., et al. 2017, A&A, 601, A29
Zhang, Q. 2018, ApJL, 852, L13
Zhang, Y., & Lin, D. N. C. 2020, Natur, 4, 852

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