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THE MASS BUDGET DISCREPANCY OF 3I/ATLAS

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ABSTRACT

I show that the recently inferred radius and interstellar number density of 3I/ATLAS-like objects, imply a local mass density that is larger by orders of magnitude than the available reservoir of heavy elements locked in low metallicity stars. This association was suggested by recent isotope abundance measurements. Either the inferred radius or number density are overestimated or the association with metal-poor stars is incorrect.

1. INTRODUCTION

The interstellar object 3I/ATLAS (Seligman et al. 2025; Jewitt et al. 2025) offers new insights into the mass reservoir of planetary systems across the Milky-Way galaxy.

The latest data from the Hubble Space Telescope was used to derive a nucleus radius of $R_n = 1.3 \pm 0.2$ km and an interstellar number density of $n \sim 7 \times 10^{-3}$ au^{-3} (Hui et al. 2026). For a typical bulk density of $\rho_n \approx 0.5$ g cm^{-3} (Sosa & Fernández 2009), the inferred radius implies a nucleus mass of $m_n \approx (4\pi R_n^3 \rho_n/3) = 4.6 \times 10^{15}$ g. Hence, the local interstellar mass density of the population of 3I/ATLAS-like objectsis,

$$\rho_{3I} \approx n \times m_n = 10^{-26} \text{ g cm}^{-3} \ . \tag{1}$$

Two recent papers reported anomalous isotope abundances in the material that makes 3I/ATLAS. Based on JWST observations, Cordiner et al. (2026) had found an isotope composition unlike any Solar System body. The water in 3I/ATLAS is enriched in deuterium at a level of D/H = $(0.95 \pm 0.06)\%$, which is an order of magnitude higher than in known comets, suggesting a metal-poor origin. In addition, the ^{12}C/^{13}C isotope ratios (141-191 for CO_2 and 123-172 for CO) exceeds typical values found in the Solar System, as well as in nearby protoplanetary disks. Chemical evolution models imply that the carbon isotopic composition originated 10-12 Gyr ago. A similar conclusion was reached by Opitom et al. (2026), who reported measurements of carbon and nitrogen isotope ratios in 3I/ATLAS from observations of the cyanide (CN) molecule by the VLT. This data suggests a ^{12}C/^{13}C ratio of 147^{+87}_{-40} and a ^{14}N/^{15}N ratio of 343^{+454}_{-124}, more than twice above the value of ~ 150 usually measured for Solar System comets.

Below, I show that a low-metallicity origin for 3I/ATLAS generates untenable tension with the inferred mass budget of the 3I/ATLAS population of interstellar objects.

2. INTERSTELLAR MASS BUDGET

The Galactic orbit of 3I/ATLAS suggest a likely origin in the disk of the Milky-Way galaxy (Hopkins et al. 2025; Kakharov & Loeb 2024; Taylor & Seligman 2025; Guo et al. 2025). The composition of the coma of 3I/ATLAS in terms of carbon, oxygen and nitrogen - based molecules (Lisse et al. 2025; Cordiner et al. 2025; Lisse et al. 2026; Belyakov et al. 2026), implies that most of its mass is associated with heavy elements.

For reference, the Galactic mass density of stars in the neighborhood of the Sun is (McKee et al. 2015),

$$\rho_\star \approx 0.04 M_\odot \text{pc}^{-3} = 2.7 \times 10^{-24} \text{ g cm}^{-3}. \tag{2}$$

Only a tenth of all stars in the Milky-Way's disk have metallicities below a tenth of the solar value, $Z_\odot$ (Chiti et al. 2021). Considering those metal-poor stars as the suggested source population of 3I/ATLAS and adopting their metal mass fraction to be $\sim 2 \times 10^{-3}$, we find the corresponding local mass density of heavy elements in them to be,

$$\rho_z \approx 2 \times 10^{-3} \times 0.1 \times \rho_\star = 5.4 \times 10^{-28} \text{ g cm}^{-3}. \tag{3}$$

Since $\rho_z \sim 0.05\rho_{3\mathrm{I}}$, we conclude that the total mass density of heavy elements locked in low-metallicity stars is more than an order of magnitude below the required mass density in interstellar objects like 3I/ATLAS.

3. CONCLUSIONS

Planetary systems - which serve as the natural birth sites of interstellar objects - originate from debris disks that contain at least ten times less mass than the host star (Hughes et al. 2018). In addition, one expects a mass spectrum of ejected interstellar objects to contain at least ten times more mass in objects with masses that are orders of magnitude different from that of 3I/ATLAS (Peña-Asensio & Seligman 2025). When these additional factors are included, we find that low-metallicity stars miss the required mass budget by at least 3 orders of magnitude. They cannot account for the interstellar population of 3I/ATLAS-like objects unless they are capable of ejecting to interstellar space more than a thousand times the heavy-element content of their planetary disks.

In conclusion, either the inferred radius or number density of the population of 3I/ATLAS-like objects are overestimated or their association with metal-poor stars is incorrect.

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