On the Consequences of the Detection of an Interstellar Asteroid

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The arrival of the robustly hyperbolic asteroid A/2017 U1 (MPEC 2017a) seems fortuitously timed to coincide with the revival of the *AAS Research Notes* (Vishniac 2017). Both the sparse facts surrounding A/2017 U1's properties and trajectory, as well as its apparently startling ramifications for the planet-formation process, are readily summarized in less than a thousand words.

With an eccentricity, $e = 1.2$, A/2017 U1 had a pre-encounter velocity, $v_\infty = 26\,\mathrm{km\,s^{-1}}$ relative to the solar motion, and its direction of arrival from near the solar apex is entirely consistent with Population I disk kinematics (Mamajek 2017). At periastron, A/2017 U1 passed $q = 0.25$ AU from the Sun, momentarily reaching a heliocentric velocity of $88\,\mathrm{km\,s^{-1}}$. Despite briefly achieving solar irradiation levels $I > 20\,\mathrm{kW\,m^{-2}}$, deep images produced no sign of a coma (MPEC 2017b), suggesting that the object has a non-volatile near-surface composition. Its spectrum, moreover, shows no significant absorption features and is considerably skewed to the red (Masiero 2017). The object's $H = 22$ absolute magnitude, coupled with albedo assumed to be of order $A \sim 0.1$ implies that it has a diameter $d \sim 160$ meters.

Adopting an assumed solar encounter rate[1], $\Gamma = n\sigma v_\odot \sim 0.1\,\mathrm{yr^{-1}}$, a detection/interaction cross section, $\sigma \sim 3\,AU^2$ (aided by gravitational focusing), and a velocity of the Sun relative to the Population-I standard of rest, $v_\odot = 20\,\mathrm{km\,s^{-1}}$, one estimates the space density of objects similar to A/2017 U1 to be of order $n \sim 1/100\,\mathrm{AU^{-3}}$. This implies a total of $N_\mathrm{tot} \sim 2 \times 10^{26}$ such objects in the galaxy (assuming a cylindrical galaxy with $R = 3 \times 10^4$ pc and $H = 10^3$ pc). If we assume a density $\rho = 1\,\mathrm{g\,cm^{-3}}$ (characteristic of similarly-sized Kuiper belt objects), the implied galactic mass in such bodies is $M_\mathrm{tot} \sim 10^{11}\,M_\oplus$.

While extrapolations from a single event bring obvious attendant uncertainties, the A/2017 U1 encounter implies of order an Earth mass of ejected planetesimals for every star in the galaxy. The lack of a detectable coma during the A/2017 U1 flyby is additionally puzzling, reminiscent of the rare solar system Damocloids (Jewitt 2005), or, alternately, refractory-composition asteroids, rather than Oort-cloud comets.

Our own solar system has contributed many volatile-rich planetesimals to the galaxy. Specifically, within the framework of the so-called Nice model of early solar system evolution, (Tsiganis et al. 2005; Levison et al. 2008), a transient period of dynamical instability is triggered in response to interactions between the giant planets and a primordial disk comprising $\sim 30 M_\oplus$. In numerical realizations, nearly all of this material is expelled into the interstellar medium as the instability unfolds, leaving behind today's severely mass-depleted Kuiper belt. Given the universality of N-body evolution, one can speculate that similar sequences of events are a common feature of planetary system evolution.

The efficient ejection of planetesimals requires a massive secondary body with specific orbital conditions. For a planet with mass, M_p, radius, R_p and semi-major axis, a to be capable of efficiently ejecting planetesimals from a planetary system through the action of gravity assist (Bond & Allman 1996), the ratio, $f = v_o/v_c = ((M_\mathrm{p}a)/(M_\star R_\mathrm{p}))^{1/2}$, must significantly exceed unity. In our solar system, all four giant planets can induce ejections. Jupiter, with $f_\mathrm{J} = 3.2$, and Neptune, with $f_\mathrm{N} = 3.1$ are more capable than the others.

Among the known extrasolar planets (Figure 1), neither the hot Jupiters, nor the far more numerically dominant population of super-Earths – which typically have $M \sim 10 M_\oplus$, $R \sim 3 M_\oplus$, and $a \sim 0.2$ (Winn & Fabrycky 2015) – can eject planetesimals. Approximately 5-10% of solar-type stars (but not M-dwarfs) *do* harbor massive intermediate-period planets with $f > 1$ (Cumming et al. 2008; Rowan et al. 2016) that could potentially eject primarily refractory material from their systems. If A/2017 U1 points to a population bereft of volatiles, each such planet would be required to eject $>100\,M_\oplus$ in shards of rock and metal, a quantity that seems challenging to generate. In all likelihood, the comparatively low occurrence rate of these planets allows them only minor contributions to the galaxy's burden of free-floating planetesimals, implying that A/2017 U1 contains a substantial volatile component despite its lack of coma. The primary burden of generating interstellar asteroids likely falls on an as-yet unobserved population of long-period sub-Jovian planets.

Recent analyses of the radius-mass relationship of extrasolar planets detected by *Kepler* have found essentially linear proportionality between the two quantities. Specifically, Wu & Lithwick (2013) find $M_\mathrm{p} \propto R_\mathrm{p}$ for planets less massive than $M_\mathrm{p} < 20 M_\oplus$, while Weiss et al. (2013) obtain $M_\mathrm{p} \propto R_\mathrm{p}^{0.93}$ as the best fit for objects with $1.5 R_\oplus < R_\mathrm{p} < 4 R_\oplus$. Crucially, a linear radius-mass relationship implies an escape velocity that is independent of the planetary

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[1] With a *single* occurrence, this once-per-ten-years encounter rate is tied to the time that Pan-STARRS (Chambers et al. 2016) and similar surveys have been operating, and is, of course, highly uncertain.

characteristics. In turn, this means that among sub-Jovian extrasolar planets, the ratio f is largely a function of the stellar mass and orbital radius.

Upon substitution of the relevant constants, we find that for solar-mass stars, the characteristic semi-major axis – beyond which ejection of planetesimals is readily accomplished by relatively low-mass planets – lies at $a \sim 5\,\mathrm{AU}$. (This "throw line" diminishes to $a \sim 1\,\mathrm{AU}$ for $M_\star = 0.2 M_\odot$) M-dwarfs. Coincidentally, these values roughly correspond to the ice-sublimation lines of the respective stars, and strongly hint at the ubiquity of sub-Jovian planets residing at stellocentric radii of order a few astronomical units.
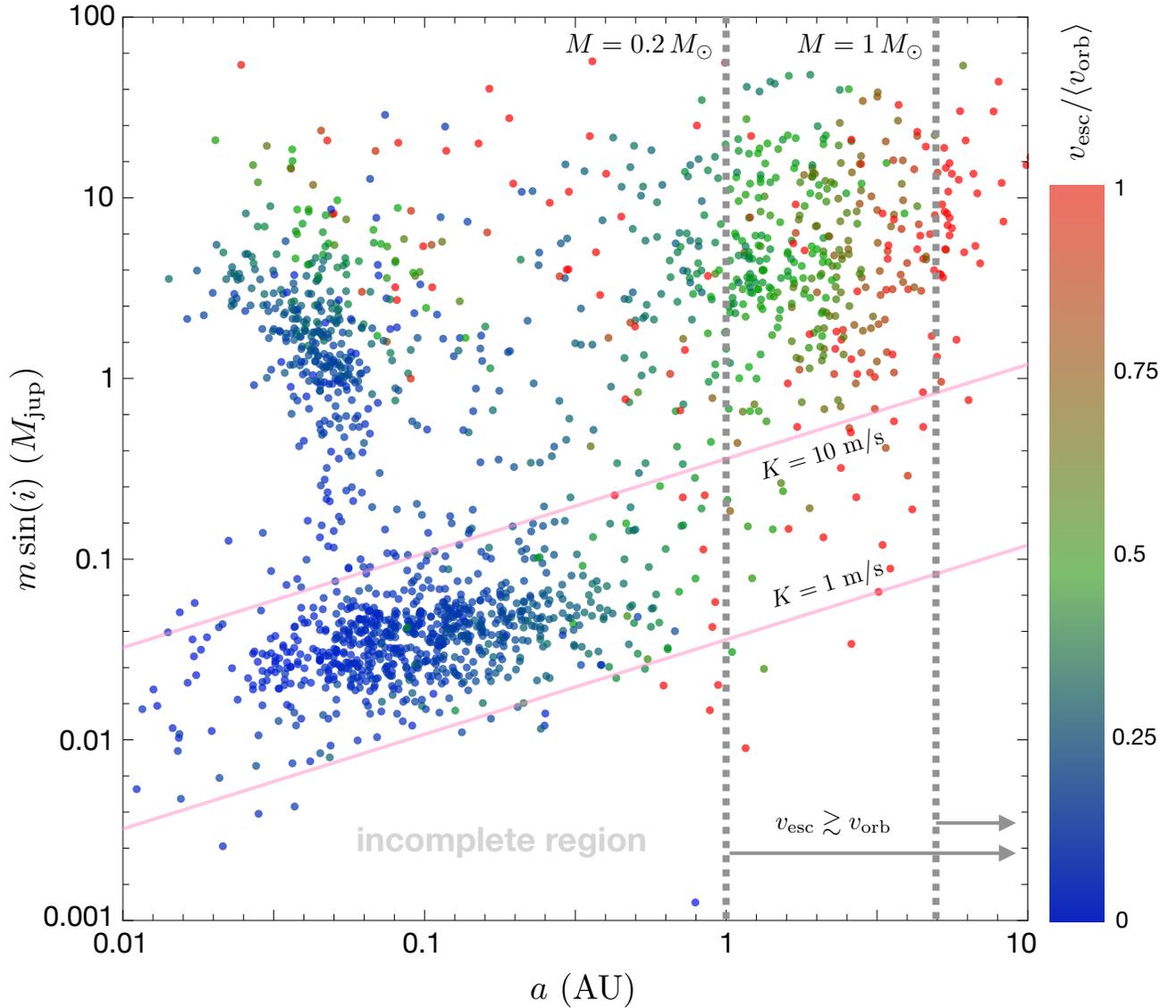
Figure 1. Confirmed extrasolar planets with properties drawn from https://exoplanetarchive.ipac.caltech.edu/. The interstellar asteroid A/2017 U1 implies a vast and cool and as-yet undetected population of planets with $f = v_{\mathrm{esc}}/v_{\mathrm{orb}} \gtrsim 1$.

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