Graduate Research Plan Statement
Impact Ejecta Transfer and Interstellar Leakage Across Different Planetary System Architectures

Overview: In the 1980's, Marvin et. al and Bogar et. al. published the first convincing arguments that meteorites found on Earth originated from the Moon and from Mars [1] [2], confirming that planetary material exchange has occurred in our Solar System's history. More recently, impact ejecta exchange has been considered a possible source of biological cross-contamination (lithopanspermia) and chemical cross-incubation that could amplify abiogenesis probabilities and molecular complexity between co-evolving planetary environments [3]. Previous N-body integration simulations within our Solar System [4] [5] and my current N-body integration simulations within the compact TRAPPIST-1 system [6] confirm the possibility of ejecta transfer occurring on timescales of 30,000 years, which Gladman et. al. argue is the longest time that biological material can survive in space [4]. These studies also indicate interstellar ejecta leakage, which could facilitate the transfer of material between systems (biological or otherwise). In this project, I propose to address the following questions: **What system architectures lead to efficient ejecta transfer? What system architectures lead to efficient interstellar leakage?** Both properties have the potential to influence our evaluation of a planetary system's "habitability", to increase our knowledge of interstellar material population statistics, and to potentially identify orbital reservoirs of ejecta from mature rocky planets in our solar system. I further plan to **release an end-to-end Python pipeline tool for simulating and analyzing impact ejecta within any planetary system**, to make my methods as accessible as possible.

Methods: My proposed strategy is to further develop and apply my current N-body integration simulation program on multiple planetary systems, both real and modeled, to develop a database of ejecta transfer efficiencies and interstellar leakage efficiencies correlated with system architectures. Machine learning algorithms will then be applied on this database to produce a predictor for determining the efficiencies of any given system. This process will not only achieve the goal of determining what kind of system architectures produce efficient transfer of material, but will also result in the creation of a powerful prediction tool that can be used well into the future.

My current N-body integration program makes use of Hanno Rein's REBOUND N-body integration code with the MERCURIUS integrator [7], which implements massless ejecta particles that do not affect the orbital evolutions of planetary bodies. Therefore, many simulations with the same initial conditions can be run simultaneously and aggregated post-computation. This allows the number of ejecta in these simulations to be orders of magnitude higher than the previous simulations of Gladman et. al. and Reyes-Ruize et. al. Thus, REBOUND provides a more robust statistical overview while also keeping computing time low. The first step will be to generalize my current N-body integration code to be applicable to different planetary systems, and to build out a special setting for investigating interstellar leakage over longer timescales. This generalized program can then be used to simulate ejecta transfer and track interstellar leakage in a system.

I will then perform a series of simulations on our Solar System as the first entries to our database, which will also confirm and augment the results of Gladman et. al. and Reyes-Ruiz et. al. Gladman et. al. investigated ejecta from multiple sources, but they had a relatively small amount of ejecta; Reyes-Ruiz et. al. had higher ejecta amounts, but only investigated ejecta originating from Earth; and neither group investigated interstellar leakage [4][5]. Thus, a series of simulations of many ejecta from multiple different sources in the Solar System will provide a thorough statistical overview of ejecta transfer in our System, and will additionally investigate the possibility and efficiency of interstellar leakage. It may also illuminate the discrepancy between Gladman et. al. and Reyes-Ruiz et. al.'s reported collision rates for Mars and Jupiter [4][5]. Finally, these simulations will show whether certain orbital regions act as repositories for ejected material from rocky planets, giving future deep-space missions new targets for sample retrieval. Thus the simulations on our Solar System can answer multiple related questions while also providing an important entry in our database of systems.

I will then perform a series of simulations on model planetary systems with varying architectures, to widely explore the parameter space of system architectures within our database. Between the extremely compact TRAPPIST-1 system (~0.06 AU) and the relatively widespread Solar System (~40 AU), I will simulate a set of similarly populated systems with system sizes within this range. This will better constrain the relationship between the compactness of a system and its ejecta transfer efficiency. I will then simulate a set of systems with varying numbers of planets, planets of varying orbital eccentricities, and varying placements of giant planets, to better correlate specific architectures to ejecta transfer efficiencies. Finally, I will perform simulations on known planetary systems, to serve as real-world training data alongside the model training data.

This database of simulations on model systems and real systems will then be used by machine learning algorithms to determine a relationship between specific system architecture features and ejecta transfer efficiencies, and between system architecture features and interstellar leakage efficiencies. The learned predictor will then concretely define what types of system architectures lead to efficient ejecta transfer within the system, and what types of system architectures lead to efficient interstellar leakage.

Intellectual Merit: The resulting database and learned predictor will add another dimension to help constrain which systems may host extraterrestrial life, and will be instrumental in deciding which systems deserve deeper investigation. As we discover new systems, these tools can continue to be used and updated, thus serving a constant purpose in determining habitability. Previous studies of impact ejecta transfer within planetary systems have been limited by either scope (only on our Solar System), magnitude (few ejecta), or precision (back-of-the-envelope estimates). My proposed broad survey of both known and modeled systems, using high-precision, high ejecta-count N-body integration simulations, will provide a comprehensive understanding of how system architectures affect material exchange both within and between systems. Additionally, my proposed simulations on our Solar System will identify orbital areas where impact ejecta from rocky planets may have accumulated, providing concrete targets for future deep-space missions geared towards sample retrieval. Results from my proposed studies can also illuminate the possible histories of impacts that have occurred within our System, and further explain our System's evolution through time. Finally, we will develop a better understanding of the population of interstellar material, as well as the potential for interstellar material transfer, which has yet to be precisely evaluated.

Broader Impacts: Releasing the Python pipeline for simulation and analysis of impact ejecta within planetary systems will make both the data and the process fully accessible to other researchers who may wish to undertake similar projects. This enables future collaborations, especially with researchers who may have less computational expertise, and with researchers from related disciplines such as biology or chemistry. I also intend to develop and release a scaled-down version of the pipeline alongside accompanying lesson plans, interactive walk-throughs, and informative media. This package will be extremely versatile in scientific outreach, acting simultaneously to engage the public in research methods, inform them of scientific results, and excite them about developments in SETI. In more academic settings, the tool will provide a starting point to introduce students to computational simulations and statistical data analysis methods, especially for students who may be interested in computational research but feel underprepared in programming. I intend to present this tool to both public and academic audiences, with the goal of inspiring interest in SETI and showing that computational research can truly be accessible to anyone.

References:
[1] Marvin, U. B. 1983, Geophys. Res. Lett., 10 (9), 775– 778, [2] Bogar, D. D., Johnson, P. 1983, Science, 221(4611), 651-654, [3] Scharf, C., Cronin, L., 2016, Proceedings of the National Academy of Sciences, 113 (29), 8127-8132, [4] Gladman, B. J. et. al., 1996, Science, 271 (5254), 1387–1392, [5] Reyes-Ruiz, M. et. al., 2012, Icarus, 220 (2), 777-786, [6] Liu, R.Y., Scharf, C., *In prep.*, [7] Rein, H. et. al., 2019, Monthly Notices of the Royal Astronomical Society, 485 (4), 5490–549