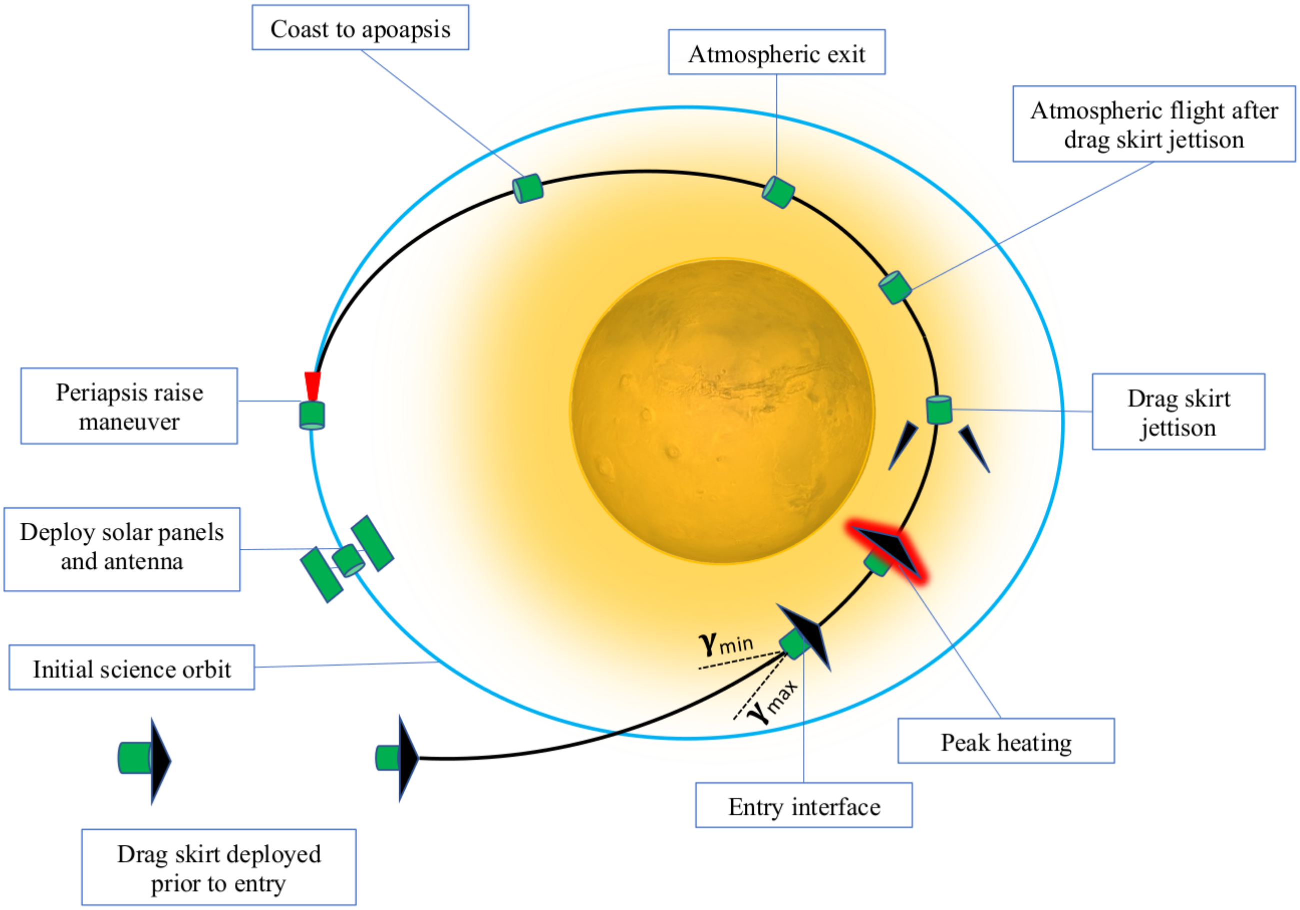
Design Reference Aerocapture Mission Architectures for Future Planetary Science Missions

Prepared by: Dr. Athul Girija



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School of Aeronautics and Astronautics, Purdue University
701 W. Stadium Ave. West Lafayette, IN 47907

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Study Point of Contact

Dr. Athul Girija

Research Affiliate

Purdue University

West Lafayette, IN 47907-2045

apradee@purdue.edu

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Executive Summary

Aerocapture is the technique of using the planet's atmosphere to decelerate a spacecraft in a single pass to achieve almost propellant-free orbit insertion. The technique has been extensively studied since the 1980s but has never been flown yet despite all the system-level technologies being considered ready for an operational mission. The entry conditions encountered during the maneuver are strongly destination dependent, as is the performance benefit offered by aerocapture. Aerocapture is applicable to all atmosphere-bearing destinations, with the exception of Jupiter and Saturn, whose extreme aerothermal conditions make it infeasible. There are two main classes of missions for which aerocapture has been most studied in recent works, one for small satellite missions to Mars and Venus, and the other for large Flagship-class missions to the outer Solar System including Titan, Uranus, and Neptune. The report compiles a list of design reference missions at Venus, Earth, Mars, Titan, Uranus, and Neptune. These reference missions can provide an initial assessment of the feasibility of aerocapture for a proposed mission and provide initial baseline values for more detailed system studies. Design reference missions provide a quick estimate of the aerocapture entry conditions, control requirements, and aerothermal loads for higher fidelity subsystem-level studies.

Dr. Athul Girija,
Lakewood, Colorado
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Aerocapture has been studied in the literature for over six decades, since the early 1960s [1, 2]. Figure 1 shows the number of publications, showing that aerocapture has been investigated at all atmosphere-bearing destinations over the years [3, 4], by several universities and research centers as seen in Fig. 2. The report compiles a list of aerocapture design reference missions at Venus, Earth, Mars, Titan, Uranus, and Neptune. These reference missions can provide an initial feasibility assessment for a proposed mission and provide baseline values for more detailed system studies.

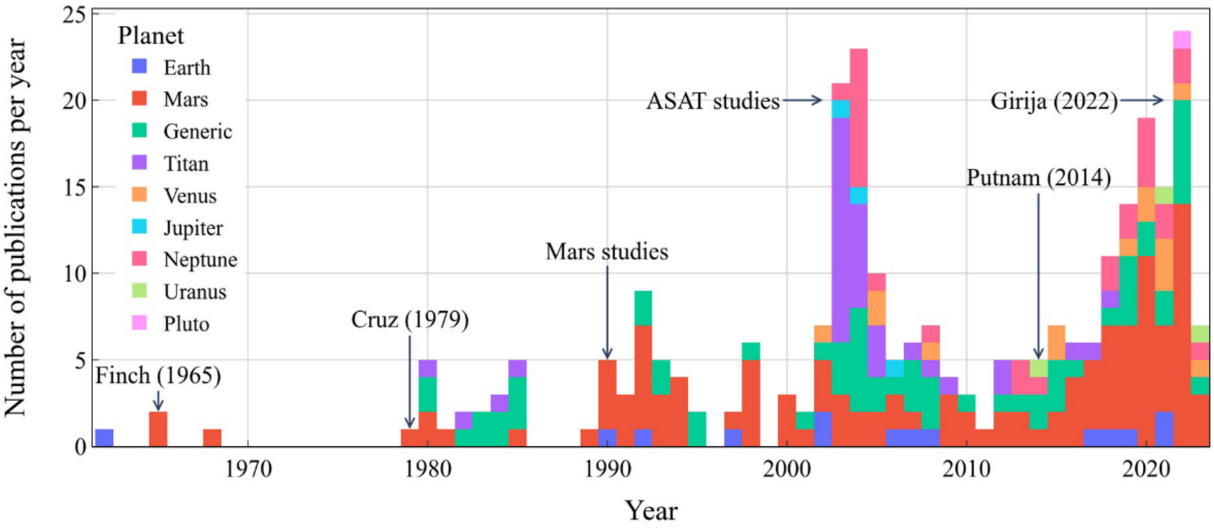

Fig. 1 Aerocapture publications over time, colored by destination.

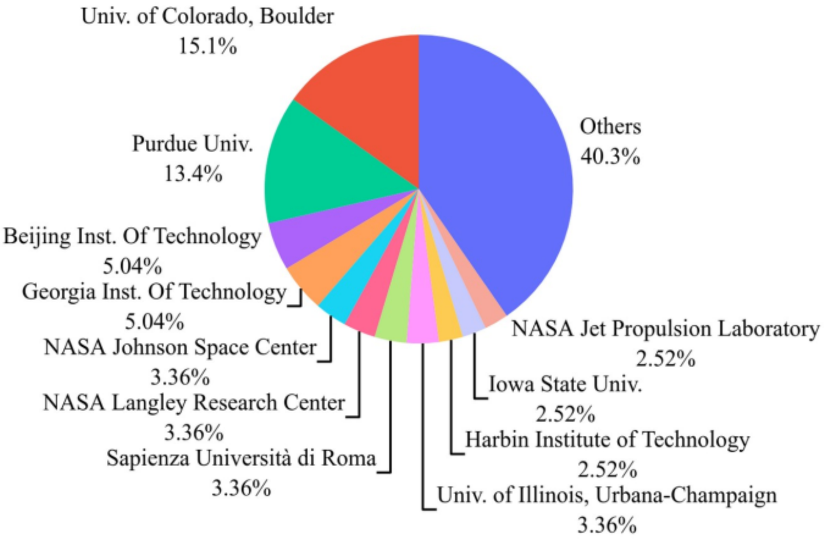

Fig. 2 Distribution of the institutions for aerocapture publications (2012–2022).

1. Venus

Aerocapture at Venus has been studied using both rigid aeroshells and low-ballistic coefficient systems [5]. Due to the demanding aero-thermal conditions posed by the thick Venusian atmosphere, rigid aeroshells require significant thermal protection system (TPS) mass and is not attractive for aerocapture [6]. Aerobraking instead is the preferred option, and is baselined for all planned missions. However, using drag modulation aerocapture to insert small satellites into Venus orbit is very attractive [7]. The low-ballistic coefficient entry system keeps the heating rates low, and has applications for delivering small payloads. The baseline design reference mission for Venus aerocapture uses a 1.5 m diameter vehicle with m = 53 kg, β_1 = 20 kg/m^2, ballistic coefficient ratio β_2/β_1 = 7.5 to deliver a 25 kg orbiter to a 200 x 2000 km orbit. The entry speed is 10.8 km/s and the aerocapture corridor is [-5.53, -5.11] deg, with a width of 0.42 deg. Figure 3 shows the reference trajectory. The peak deceleration is about 7g, and the peak stagnation point-heat rate is about 150 W/cm^2. The ΔV offered by the maneuver is 3113 m/s, and the periapsis raise ΔV is about 30 m/s.

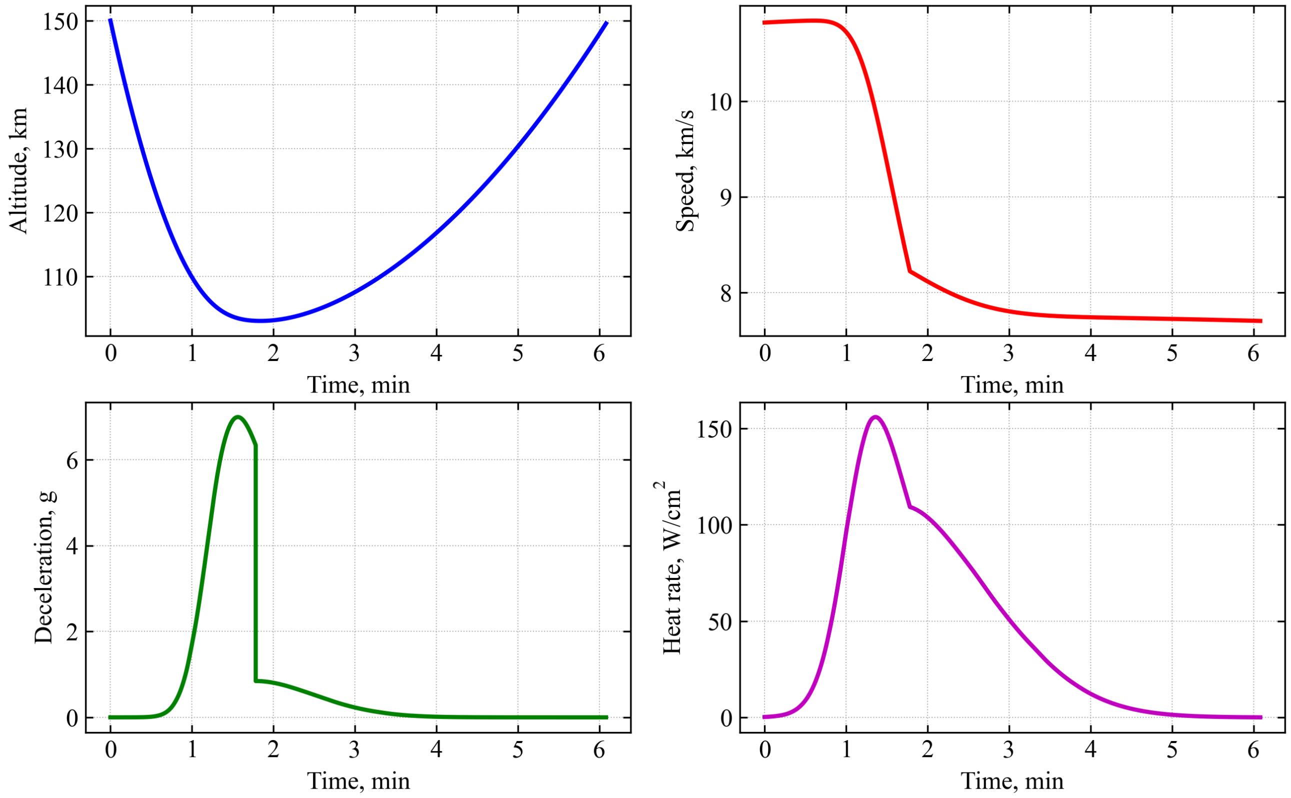

Fig. 3 Venus aerocapture design reference mission trajectory.

2. Earth

Aerocapture at Earth has been extensively studied since the 1980s for various technology demonstration missions such as the AFE, ST-7, and ST-9 flight opportunities, though none of them were eventually flown [8, 9]. The small spacecraft (under 200 kg) would launch as a secondary payload on a GTO mission, perform a burn to enter the atmosphere, and change its orbit from GTO to a smaller elliptic orbit [10]. The mission would demonstrate all aspects of drag modulation aerocapture, bring the technology to flight readiness with immediate applications to Mars and Venus missions. The proposed reference design uses the same vehicle design as for Venus and targets a 2000 km apoapsis. The entry speed is 10.6 km/s and the aerocapture corridor is [-4.87, -4.18] deg., with a width of 0.69 deg. Figure 4 shows the Earth aerocapture design reference trajectory. The peak deceleration is about 5g, and the peak stagnation point-heat rate is about 125 W/cm^2. The ΔV offered by the maneuver is 2300 m/s, and the periapsis raise ΔV is about 36 m/s.

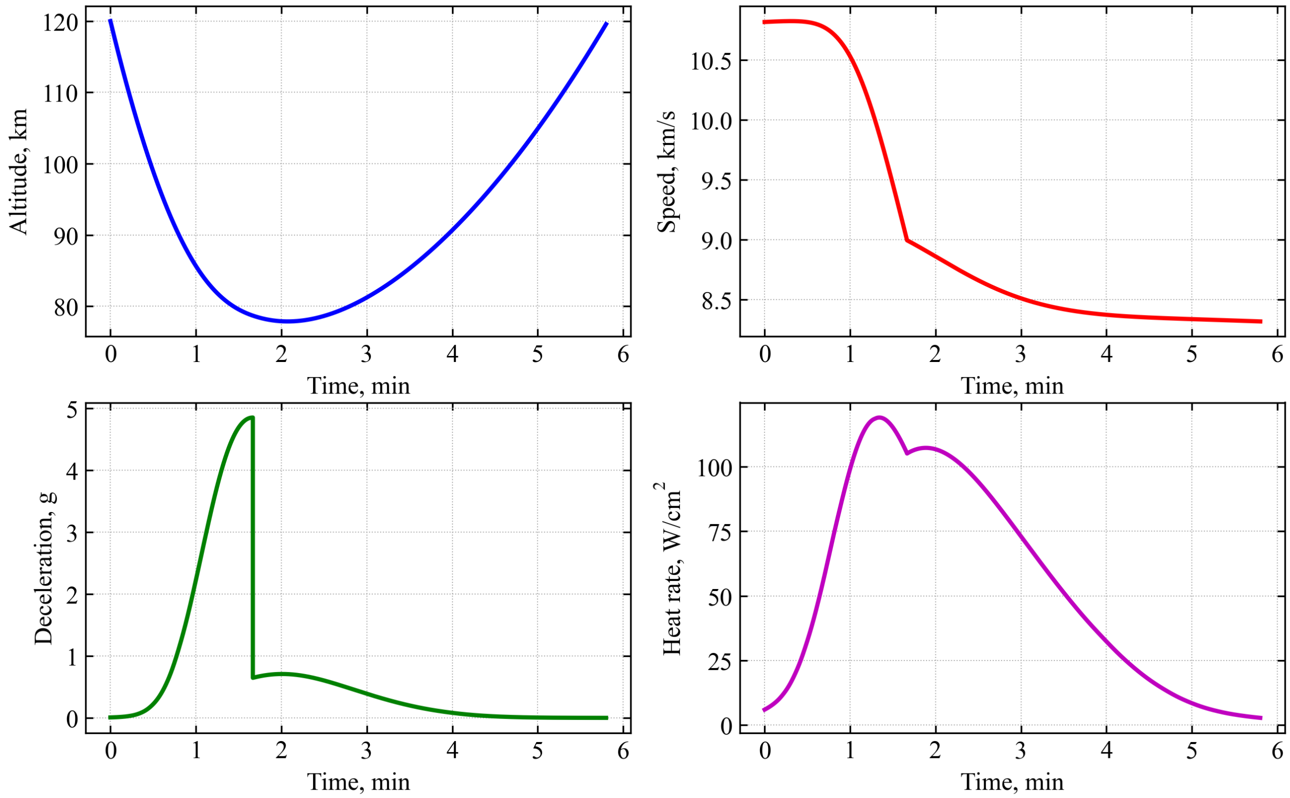

Fig. 4 Earth aerocapture design reference mission trajectory.

3. Mars

The thin Martian atmosphere presents a relatively benign aero-thermal environment for aerocapture, making it the most studied destination for aerocapture. More recently, drag modulation aerocapture has received renewed interest [11, 12]. The low gravity combined and the extended atmosphere makes it more attractive for aerocapture in terms of larger corridor width and lower heating rates compared to Earth and Venus. The low heating rates at Mars and the frequent launch opportunities make Mars an ideal candidate for a low-cost aerocapture technology demonstration outside of the Earth [13]. The reference design uses the same vehicle as for Venus and targets a 2000 km apoapsis altitude. The entry speed is 5.4 km/s and the aerocapture corridor is [-9.86, -8.78] deg., with a width of 1.09 deg. Figure 5 shows the Mars aerocapture design reference mission trajectory. The peak deceleration is about 2.5g, and the peak stagnation point-heat rate is about 20 W/cm^2. The ΔV offered by the maneuver is 1760 m/s, and the periapsis raise ΔV is about 33 m/s.

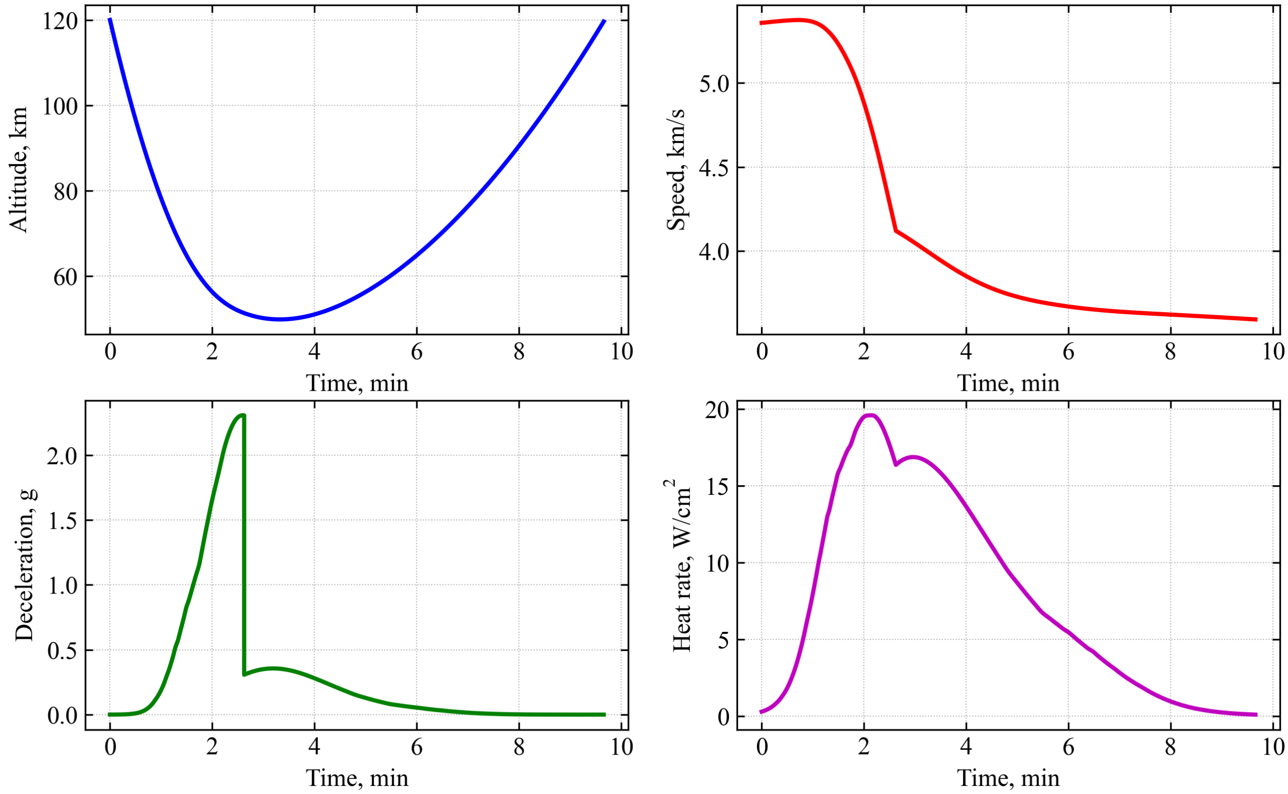

Fig. 5 Mars aerocapture design reference mission trajectory.

4. Titan

With its low-gravity and greatly extended atmosphere, Titan presents the most attractive destination for aerocapture in terms of the largest corridor width and the lowest heating rate [14, 15]. The benign environment makes both rigid aeroshells and deployable systems viable for aerocapture at Titan [16, 17]. The design reference mission for Titan drag modulation aerocapture uses a 12 m diameter vehicle with mass=5700 kg, β_1 = 30 kg/m^2, β_2/β_1 = 4.14 to deliver a 2600 kg orbiter to a 1700 km circular orbit. The entry speed is 7.3 km/s and the aerocapture corridor is [-37.3, -34.4] deg., with a width of 1.89 deg. Figure 6 shows the Titan aerocapture design reference mission trajectory. The peak deceleration is about 3.5g, and the peak stagnation point-heat rate is about 30 W/cm^2. The ΔV offered by the maneuver is 5750 m/s, and the periapsis raise ΔV is about 150 m/s. With the need for an orbiter around Titan following the Dragonfly mission, ADEPT drag modulation aerocapture has applications for a Titan orbiter which fits within New Frontiers [18, 19].

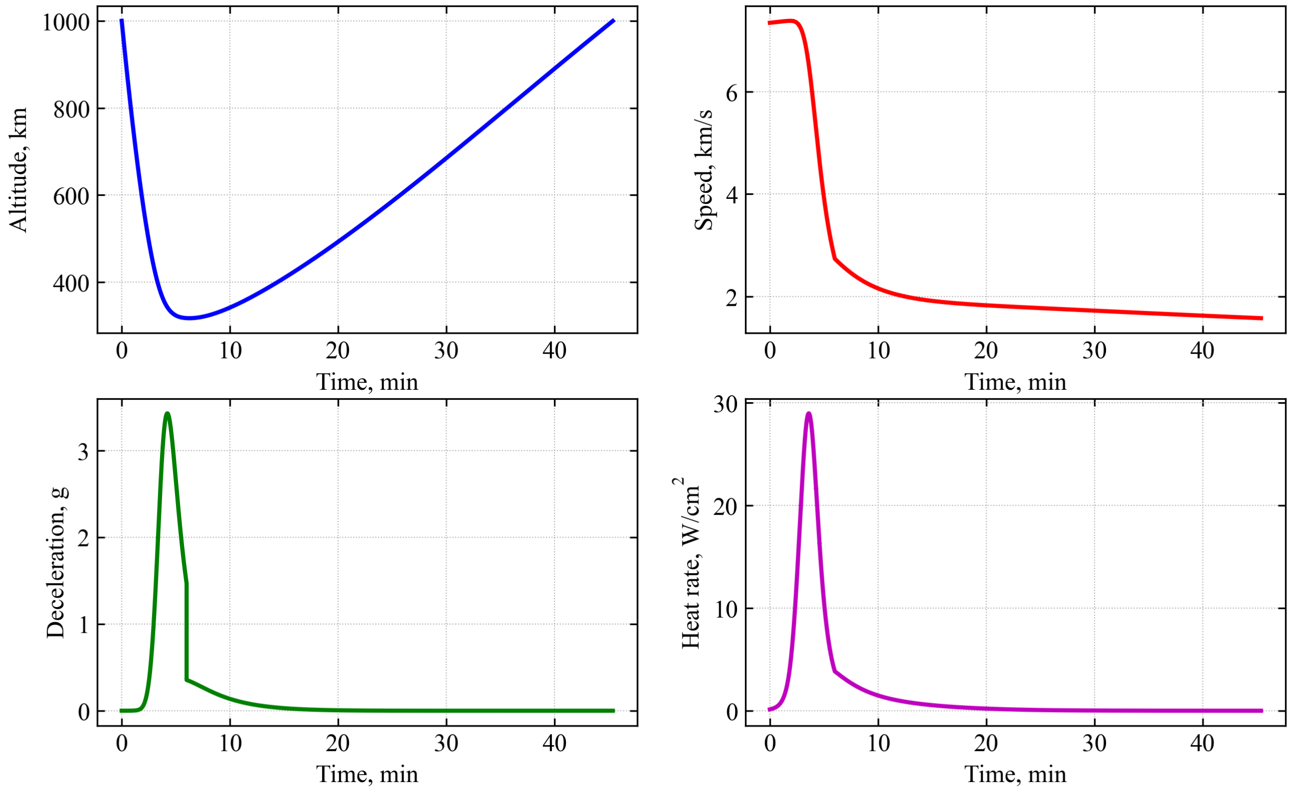

Fig. 6 Titan aerocapture design reference mission trajectory.

5. Uranus

Uranus' large heliocentric distance (19 AU) presents significant mission design challenges for orbit insertion. For cost and risk reasons, current baseline Uranus mission architectures do not use aerocapture [20, 21]. However, aerocapture can significantly increase the delivered mass to orbit and considerably reduce the flight time, and enable access to close-in orbits [22, 23]. The design reference mission uses an MSL derived aeroshell with m = 3200 kg, β =146 kg/m^2, L/D = 0.24 to deliver a 1400 kg orbiter + 300 kg atmospheric probe to a 4000 x 500,000 km orbit [24]. A high entry speed is chosen to maximize the available control authority with the low-L/D aeroshell. The entry speed is 29 km/s and the corridor is [-12.0, -11.0] deg., with a width of 1.00 deg. Figure 7 shows the reference bounding trajectories. The peak deceleration is in the range of 4–10g, and the peak stagnation point-heat rate is about 1400–2000 W/cm^2. The ΔV offered by the maneuver is 8900 m/s, and the periapsis raise ΔV is about 80 m/s. Compared to probes which enter steep, aerocapture requires shallow entry which results in large heat loads. The total heat load is 230 kJ/cm^2.

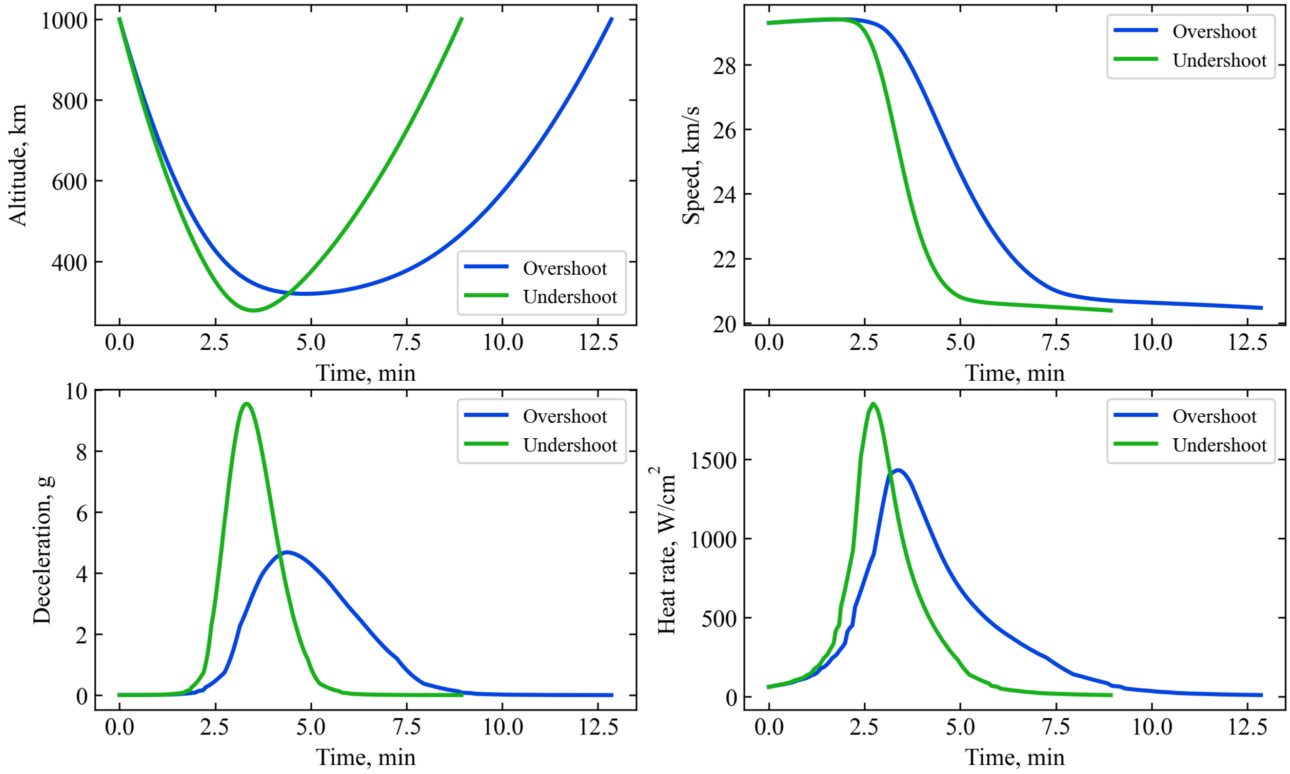

Fig. 7 Uranus aerocapture design reference mission trajectory.

6. Neptune

At a heliocentric distance of 30 AU, the ice giant Neptune presents an even greater challenge for orbiter spacecraft than Uranus [25]. Aerocapture at Neptune was extensively studied in the early 2000s using a mid-L/D vehicle to compensate for the large navigation and atmospheric uncertainties [26, 27]. However, since then it has become clear such a vehicle would not be available and attention has turned to using innovative techniques to leverage low-L/D aeroshells [28]. The proposed baseline design reference mission for Neptune aerocapture uses an MSL derived aeroshell with m = 3200 kg, β = 146 kg/m2, L/D =0.24 to deliver a 1400 kg orbiter + 300 kg atmospheric probe to a 4000 x 500,000 km orbit. As with Uranus, a high entry speed is chosen to maximize the control authority. The entry speed is 30 km/s and the aerocapture corridor is [-12.69, -11.88] deg., with a width of 0.80 deg. Figure 8 shows reference mission overshoot and undershoot bounding trajectories. The peak deceleration is in the range of 4–10g, and the peak stagnation point-heat rate is about 1700–2300 W/cm^2, which is within the capability of the PICA and HEEET TPS [29, 30]. The ΔV offered by the maneuver is 8080 m/s, and the periapsis raise ΔV is about 130 m/s.

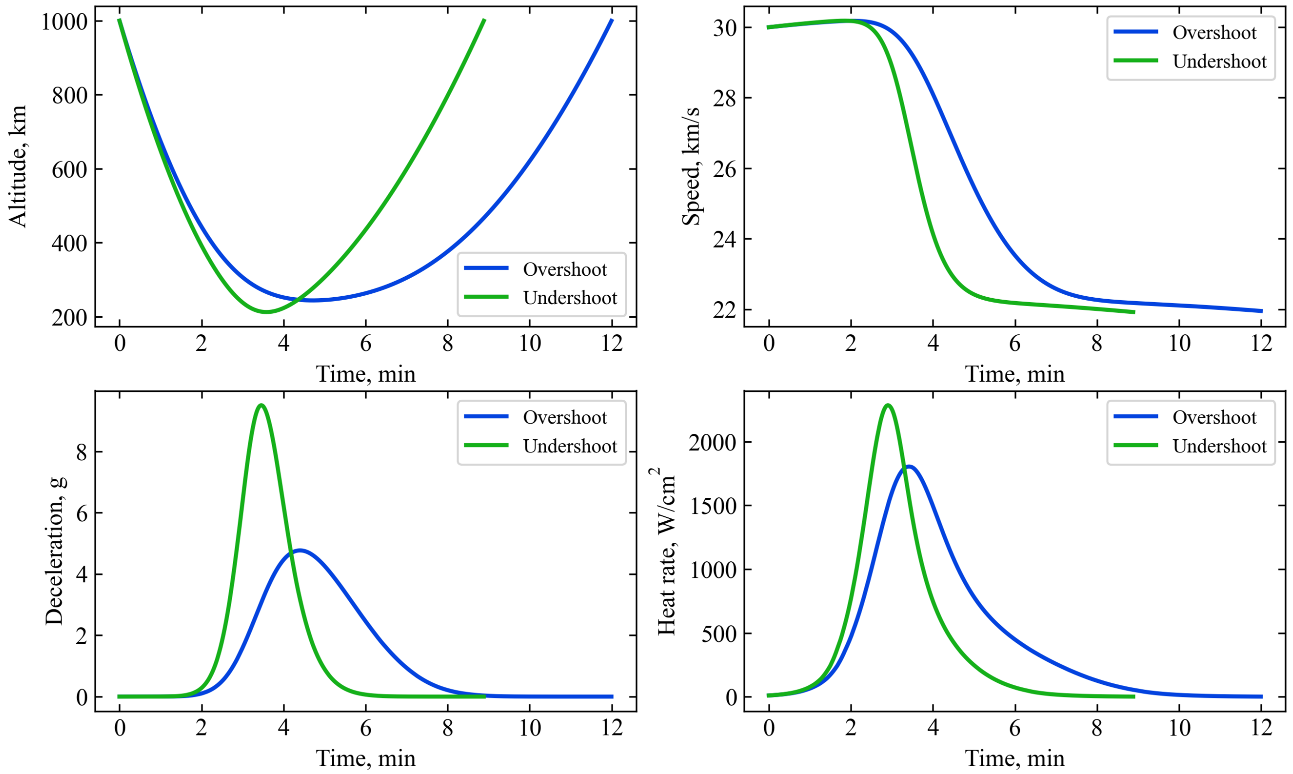

Fig. 8 Neptune aerocapture design reference mission trajectory.

7. Performance Benefit

Figure 9 summarizes the performance benefit of aerocapture for the reference missions [31, 32]. For Venus and Earth, drag modulation aerocapture provides nearly a 100% increase in delivered mass to a 400 km circular orbit compared to purely propulsive insertion. At Mars, the performance benefit is smaller at about 17%, but still significant. At Titan, aerocapture provides a 600% increase in delivered mass to a 1700 km circular orbit. At Uranus, for the slow arrival trajectories aerocapture provides a 35% increase in delivered mass to a 4000 x 1M km orbit. At Neptune, for the slow arrival trajectories aerocapture provides a 43% increase in delivered mass to a 4000 x 500,000 km orbit. At Titan, Uranus, and Neptune, aerocapture is a mission enabling technology for orbit insertion from fast arrival trajectories. Outer planet missions stand to benefit the most from high C_3 trajectories[33], but also present inherent challenges due to the large atmospheric uncertainties [27].

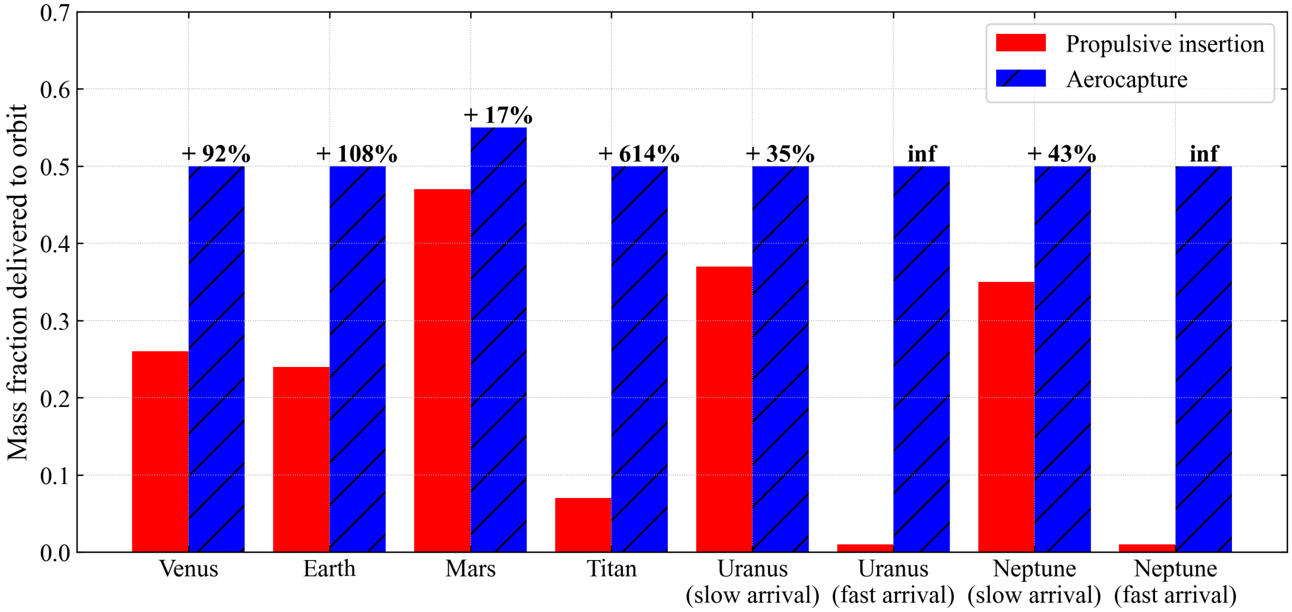

Fig. 9 Summary of the aerocapture performance benefit for future missions.

These results indicate that aerocapture offers substantial benefits to both small missions to Mars and Venus [34], as well as large strategic outer planet missions otherwise infeasible with propulsive insertion [35]. Rapid trade space exploration tools such as PLASMA can be used to further study trajectory and launch vehicle options using the reference design as a starting point [36], and for studies to select areas for technology investments towards future science missions [37, 38].

8. Summary

The study compiled a list of design reference missions for aerocapture at Venus, Earth, Mars, Titan, Uranus, and Neptune. These reference missions can provide an initial assessment of the feasibility of aerocapture for a proposed mission, and provide initial baseline values for more detailed system studies, The reference mission set provides a quick estimate of the entry conditions, control requirements, and aero-thermal loads for more detailed sub-system level architecture studies.

Data and Code Availability

The data and code used in the report are available online[*][†].

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[*] https://github.com/athulpg007/arXiv-paper-notebooks/tree/master/arXiv%3A2308.10384%20-%20design-reference-missions-notebooks

[†] https://github.com/athulpg007/arXiv-paper-notebooks/tree/master/arXiv%3A2309.0943%20-%20performance-analysis-notebooks

References

[1] Lichtenstein, J. H., “Some Considerations on the Use of Atmospheric Braking for a Transfer Into a Martian Orbit,” Tech. Rep. NASA TN D-2837, NASA Langley Research Center, Hampton, VA, 1965. URL `https://ntrs.nasa.gov/api/citations/19650016654/downloads/19650016654.pdf`.

[2] Cruz, M., “The Aerocapture Vehicle Mission Design Concept,” *Conference on Advanced Technology for Future Space Systems*, Hampton, VA, 1979. doi:10.2514/6.1979-893.

[3] Girija, A. P., “Aerocapture: A Historical Review and Bibliometric Data Analysis from 1980 to 2023,” *arXiv preprint arXiv:2307.01437*, 2023. doi:10.48550/arXiv.2307.01437.

[4] Girija, A. P., “A Systems Framework and Analysis Tool for Rapid Conceptual Design of Aerocapture Missions,” Ph.D. thesis, Purdue University Graduate School, 2021. doi:10.25394/PGS.14903349.v1.

[5] Craig, S., and Lyne, J. E., “Parametric Study of Aerocapture for Missions to Venus,” *Journal of Spacecraft and Rockets*, Vol. 42, No. 6, 2005, pp. 1035–1038. doi:10.2514/1.2589.

[6] Girija, A. P., “Comparative Study of Planetary Atmospheres and Implications for Atmospheric Entry Missions,” *arXiv preprint arXiv:2307.16277*, 2023. doi:10.48550/arXiv.2307.16277.

[7] Girija, A. P., “Photon Spacecraft and Aerocapture: Enabling Small Low-Circular Orbiters at Mars and Venus,” *arXiv preprint arXiv:2310.00891*, 2023. doi:10.48550/arXiv.2310.00891.

[8] Hall, J., “An Overview of the ST-7 Aerocapture Flight Test Experiment,” *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Monterey, CA, 2002. doi:10.2514/6.2002-4621.

[9] Carpenter, R., “Aeroasist Flight Experiment: Mission Overview,” Tech. rep., Texas Space Grant Consortium, 1992. URL `http://www.tsgc.utexas.edu/archive/PDF/AeroassistFlightExp.pdf`.

[10] Werner, M. S., and Braun, R. D., “Mission Design and Performance Analysis of a Smallsat Aerocapture Flight Test,” *Journal of Spacecraft and Rockets*, Vol. 56, No. 6, 2019, pp. 1704–1713. doi:10.2514/1.A33997.

[11] Falcone, G., Williams, J., and Putnam, Z., "Assessment of Aerocapture for Orbit Insertion of Small Satellites at Mars," *Journal of Spacecraft and Rockets*, Vol. 56, No. 6, 2019, pp. 1689–1703. doi:10.2514/1.A34444.

[12] Peng, Y.-m., Xu, B., Fang, B.-d., and Lei, H.-l., "Analytical Predictor-Corrector Guidance Algorithm Based on Drag Modulation Flight Control System for Mars Aerocapture," *International Journal of Aerospace Engineering*, Vol. 2018, 2018. doi:10.1155/2018/5907981.

[13] Girija, A. P., "A Low Cost Mars Aerocapture Technology Demonstrator," *arXiv preprint arXiv:2307.11378*, 2023. doi:10.48550/arXiv.2307.11378.

[14] Lockwood, M. K., Queen, E. M., Way, D. W., Powell, R. W., Edquist, K., Starr, B. W., Hollis, B. R., Zoby, E. V., Hrinda, G. A., and Bailey, R. W., "Aerocapture Systems Analysis for a Titan Mission," Tech. Rep. NASA/TM-2006-214273, NASA Langley Research Center, 2006. URL `https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060007561.pdf`.

[15] Nixon, C. A., Kirchman, F., Esper, J., Folta, D., and Mashiku, A., "Aerocapture Design Study for a Titan Polar Orbiter," *2016 IEEE Aerospace Conference*, IEEE, Big Sky, MT, 2016, pp. 1–16. doi:10.1109/AERO.2016.7500825.

[16] Girija, A. P., "A Survey of the Design Trade Space for Atmospheric Entry, Descent, and Landing Missions," *arXiv preprint arXiv:2308.03238*, 2023. doi:10.48550/arXiv.2308.03238.

[17] Girija, A. P., "Planetary Entry Probe Dataset: Analysis and Rules of Thumb for Future Missions," *arXiv preprint arXiv:2308.07005*, 2023. doi:10.48550/arXiv.2308.07005.

[18] Spilker, T. R., "Significant Science at Titan and Neptune from Aerocaptured Missions," *Planetary and Space Science*, Vol. 53, No. 5, 2005, pp. 606–616. doi:10.1016/j.pss.2004.12.003.

[19] Girija, A. P., "ADEPT Drag Modulation Aerocapture: Applications for Future Titan Exploration," *arXiv preprint arXiv:2306.10412*, 2023. doi:10.48550/arXiv.2306.10412.

[20] Jarmak, S., Leonard, E., Akins, A., Dahl, E., Cremons, D., Cofield, S., Curtis, A., Dong, C., Dunham, E., Journaux, B., et al., "QUEST: A New Frontiers Uranus orbiter mission

New Frontiers-class Uranus Orbiter: Exploring the feasibility of achieving multidisciplinary science with a mid-scale mission concept study," *Acta Astronautica*, Vol. 170, 2020, pp. 6–26. doi:10.1016/j.actaastro.2020.01.030.

[21] Cohen, I., Beddingfield, C., Chancia, R., DiBraccio, G., Hedman, M., MacKenzie, S., Mauk, B., Sayanagi, K., Soderlund, K., Turtle, E., et al., "New Frontiers-class Uranus Orbiter: Exploring the feasibility of achieving multidisciplinary science with a mid-scale mission," *Bulletin of the American Astronomical Society*, Vol. 53, No. 4, 2021, p. 323. doi:https://doi.org/10.3847/25c2cfeb.262fe20d.

[22] Girija, A. P., "Aerocapture Enabled Fast Uranus Orbiter Missions," *arXiv preprint arXiv:2310.14514*, 2023. doi:10.48550/arXiv.2310.14514.

[23] Iorio, L., Girija, A. P., and Durante, D., "One EURO for Uranus: the Elliptical Uranian Relativity Orbiter mission," *Monthly Notices of the Royal Astronomical Society*, Vol. 523, No. 3, 2023, pp. 3595–3614. doi:10.1093/mnras/stad1446.

[24] Girija, A. P., "A Flagship-class Uranus Orbiter and Probe mission concept using aerocapture," *Acta Astronautica*, Vol. 202, 2023, pp. 104–118. doi:10.1016/j.actaastro.2022.10.005.

[25] National Academies of Sciences, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*, National Academies Press, 2022.

[26] Lockwood, M. K., Edquist, K. T., Starr, B. R., Hollis, B. R., Hrinda, G. A., Bailey, R. W., Hall, J. L., Spilker, T. R., Noca, M. A., O'Kongo, N., et al., "Aerocapture Systems Analysis for a Neptune Mission," Tech. Rep. NASA/TM-2006-214300, NASA Langley Research Center, 2006. URL `https://ntrs.nasa.gov/api/citations/20060012088/downloads/20060012088.pdf`.

[27] Girija, A. P., "Comparative Study of Planetary Atmospheric Uncertainties and Design Rules for Aerocapture Missions," *arXiv preprint arXiv:2310.10067*, 2023. doi:10.48550/arXiv.2310.10067.

[28] Girija, A. P., "Comparison of Lift and Drag Modulation Control for Ice Giant Aerocapture Missions," *arXiv preprint arXiv:2309.13812*, 2023. doi:10.48550/arXiv.2309.13812.

[29] Spilker, T. R., "Enabling technologies for ice giant exploration," *Philosophical Transactions of the Royal Society A*, Vol. 378, No. 2187, 2020, p. 20190488. doi:10.1098/rsta.2019.0488.

[30] Girija, A. P., "Thermal Protection System Requirements for Future Planetary Entry and Aerocapture Missions," *arXiv preprint arXiv:2309.01938*, 2023. doi:10.48550/arXiv.2309.01938.

[31] Hall, J. L., Noca, M. A., and Bailey, R. W., "Cost-Benefit Analysis of the Aerocapture Mission Set," *Journal of Spacecraft and Rockets*, Vol. 42, No. 2, 2005, pp. 309–320. doi:10.2514/1.4118.

[32] Girija, A. P., "Performance Benefit of Aerocapture for the Design Reference Mission Set," *arXiv preprint arXiv:2309.09438*, 2023. doi:10.48550/arXiv.2309.09438.

[33] Girija, A. P., "Launch Vehicle High-Energy Performance Dataset," *arXiv preprint arXiv:2310.05994*, 2023. doi:10.48550/arXiv.2310.05994.

[34] Mercer, C., "Small Satellite Missions for Planetary Science," *15th NASA Venus Exploration and Analysis Group Meeting*, VEXAG, Laurel, MD, November 14–16, 2017.

[35] Ingersoll, A. P., and Spilker, T. R., "A Neptune Orbiter with Probes Mission with Aerocapture Orbit Insertion," *Progress in Astronautics and Aeronautics: NASA Space Science Vision Missions*, Vol. 224, 2008, pp. 81–113. doi:10.2514/5.9781600866920.0081.0114.

[36] Girija, A. P., "Planetary Science Mission Architecture (PLASMA) Exploration Tool: Pilot Phase Study Report," *Engineering Archive*, 2023. doi:10.31224/4454.

[37] Girija, A. P., "Technology Recommendations for Enabling Future Planetary Science Missions with Aerocapture," *Engineering Archive*, 2023. doi:10.31224/4520.

[38] Mercer, C., "Aerocapture for the Outer Planets," IPPW, Williamsburg, VA, 2024. URL `https://ntrs.nasa.gov/citations/20240008851`.