Revolutionizing Orbit Insertion with Active Magnetoshell Aerocapture

Charles Kelly and Akihisa Shimazu

University of Washington, Seattle, WA, 98195, USA

I. Introduction

Figure 1. Artist's depiction of a magnetoshell operating at Mars.[1]

One of the primary challenges facing Solar System exploration is that of entry, descent, and landing (EDL). NASA's long-term goals require getting massive payloads into stable orbits around distant bodies. Such feats demand huge Δv budgets that simply cannot be achieved using current propulsion technology. Today's probes are often limited to fly-by missions of little scientific value while large orbiters require years-long gravity assist maneuvers that render human passage impossible. It is therefore necessary for the future of space exploration to develop game-changing approaches to EDL that eliminate these restrictive mass and time requirements.

The use of electric propulsion (EP) for planetary entry can solve the first of the two issues with EDL, which is the restrictive mass requirement. Traditional EP devices operate at much higher efficiency than chemical propulsion solutions, which allow them to carry less propellant and therefore save mass. However, they come with a cost of significantly reduced thrust, which renders such devices only applicable for small probes or missions where time constraints are of no concern. Thus, traditional EP can not solve all of the problems with EDL.

Another technology that is often referenced to resolve the issues of EDL is aerocapture, a technique whereby a spacecraft uses the aerodynamic drag of a planetary atmosphere to decelerate from a hyperbolic injection trajectory to a stable orbit. Traditionally, this amounts to the use of a rigid shell[2] or an inflatable shield[3] to deflect the flow. Based on past trade studies, this method has been shown to produce a large advantage in cost and delivered mass to all eight Solar System destinations with atmospheres and is identified as the enabling technology for otherwise infeasible missions at Saturn, Jupiter, and Neptune.[4]

However, aerocapture is yet unrealized in a mission setting due to the significant risks that it introduces. Since the drag area is only on the order of the spacecraft's size, successful aerocapture relies on plunging deep into the atmosphere to achieve the necessary deceleration. This requires substantial thermal protection systems (TPS) to ensure that the high heat flux inherent to a hyperbolic entry does not destroy the spacecraft. Furthermore, aerocapture is highly susceptible to local atmospheric weather variations, as the drag surfaces cannot be controlled once they are built and launched. Thus, the benefits of aerocapture have often been overshadowed by the added risks, preventing such systems from being used for any real missions.

The concept proposed herein aims to improve aerocapture through the use of EP technology by replacing the hard-body decelerators with an air-breathing plasma propulsion device known as a magnetoshell. The magnetoshell takes the traditional plasma-based EP technology and operates it backwards to produce a drag force on a spacecraft during atmospheric entry. Instead of using on-board power to accelerate the on-board propellant to obtain thrust, the magnetoshell uses on-board power to capture and decelerate the atmospheric neutrals to obtain drag.

The neutral particles are captured by a sphere of low-beta dipole plasma external to the spacecraft. The deceleration is achieved through charge exchange (CEX) interactions between thermal ions in the magnetoshell with atmospheric neutrals. The fast and directed neutrals in the atmosphere are converted into ions and impart their momentum on the spacecraft through field line bending. In the process, thermal ions are converted into slow moving neutrals, in effect decelerating the atmospheric neutrals. Since the device uses the ambient neutrals as its propellant, it requires virtually no fuel on-board except for startup and sustainment. The only true requirement for this device is the on-board electric power.

There are several advantages to Magnetoshell Aerocapture (MAC) that position it as a revolutionary tool for interplanetary exploration. Aerocapture has been studied extensively as an application to deep space missions, but it has been never implemented because of the intense thermal loads. However, magnetoshells operate at much lower densities than traditionally conceived aerocapture systems because the dipole's collection radius can be made arbitrarily large. The benefit of this is two-fold: the frictional heat is dumped into the plasma rather than the spacecraft while the structural load on sensitive components like solar panels is kept to safe levels. This eliminates the need for heavy TPS and risky low-altitude trajectories. MAC can also attain variable force and instant on/off capability to mitigate uncertainties in the target atmosphere. As a result, MAC resolves the trade-offs between available orbit insertion techniques: it offers the dynamic control and diverse application of modern EP while providing the mission-enabling mass and cost benefits of aerocapture.

II. Background

The unique feature of MAC is that the momentum imparted to the magnetoshell is primarily from the CEX collision process between the confined low beta dipole plasma and the incoming atmospheric neutrals during entry. While MAC has similarities to other magnetic sail concepts envisioned in the past (e.g. M2P2 concept by Winglee et al.[5] and Plasma MagnetoSphere concept by Slough[6]), utilizing atmospheric neutrals sets it apart. In these magnetic sails, the primary mechanism by which the spacecraft gains or loses momentum is through the interaction with external plasmas, usually in the form of solar wind. The fast moving plasma in the solar wind compresses the magnetosphere around the spacecraft and imparts momentum through complicated interactions similar to Earth's bow shock regions. These magnetic sail concepts are promising for interplanetary space propulsion, where the solar wind is abundant, but they are less suitable for EDL needs. The expected braking force that can be obtained from the planetary ionosphere is small due to its low plasma density.

Since the primary interaction between the confined plasma and the external environment is the ion-neutral CEX interaction, the magnetoshell can operate without any external plasma source, which makes it more suitable for EDL applications. Furthermore, it has been demonstrated by MSNW through a NIAC Phase I contract that the MAC system can be operated in a low beta plasma configuration,[1] as opposed to the high beta configuration required by the magnetic sails, which allows the confinement energy requirement to be smaller. Thus, MAC offers unique capabilities that have not been explored before.

Since both low beta dipole plasma physics and the charge exchange drag mechanism are important in the operation of MAC, the next few sections are devoted to these topics. The first section briefly discusses the low beta dipole configuration. The next two sections concern the CEX drag physics, with the first looking at a single particle picture and the second considering multi-particle effects.

A. Low beta Dipole Plasma Configuration

Plasma beta is the ratio of plasma pressure to the magnetic pressure and is an indication of the amount of energy stored in the plasma. In general, high beta plasma configurations require complicated machineries to sustain the high plasma current and magnetic field required to counter act the plasma pressure, which results in bulky and heavy confinement devices. In a low beta configuration, plasma develops a low current, thus it does not strongly perturb the magnetic field generated by the coils. The magnetic field profile of the magnetoshell can be approximated by that of a pure dipole with $B \sim 1/r^3$ radial dependence. The magnetoshell plasma density can also be approximated with $n(r) \sim 1/r^3$ dependence.

Magnetoshells can be operated in either high or low beta configurations, but low beta conditions are desirable since sustainment requirements are reduced. This allows magnetoshell confinement without large superconducting magnets, instead using regular resistive electromagnets. This allows for dynamic feedback control of the magnetoshell during entry for steering and added safety.

B. Charge Exchange Drag - Single Particle Picture

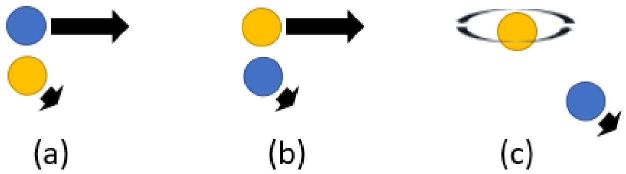

Figure 2. Illustration of CEX interaction inside magnetosphere. (a) A fast moving neutral particle (blue) approaches a thermal ion (yellow). (b) CEX interaction occurs, and charge is exchanged between the neutral and the ion. (c) The fast moving ion is confined by the magnetic field and gyrates, while the thermal neutral leaves the system.

The primary momentum-inducing mechanism of MAC is an ion-neutral charge exchange collision (CEX) interaction of the form

$$A + A^{+} \rightarrow A^{+} + A$$

where A is some molecular or atomic species, which depends on the atmospheric composition of the target planet. The charge exchange drag can be illustrated by considering an interaction between an ion confined inside a dipole field and an atmospheric neutral particle. In the frame of reference of the spacecraft, the confined ion has a random kinetic energy characterized by its temperature; the neutral has a directed kinetic energy, which depends on the spacecraft entry velocity and the neutral mass. We define the neutral velocity to be in the axial direction and the dipole field to be in the rz-plane, generated from an azimuthal ring current.

When the CEX interaction takes place between a thermal ion and a directed neutral, a thermal neutral and a directed ion are generated. The thermal neutral is no longer confined by the dipole field, thus it diffuses out of the dipole through random walks. The directed ion that is moving axially sees the radial component of the dipole field, and the motion of the ion is bent through the

$q\mathbf{v} \times \mathbf{B}$ force. As long as the gyroradius of the ion (r_i) is smaller than the size of the magnetoshell (L_0), the ion will eventually be confined in the dipole field, with net zero guiding center motion, transferring its axial momentum to the magnetic field line. The magnetic field line pulls on the coil to transfer the drag force to the spacecraft. In order for this process to occur, a lower limit on the dipole magnetic field is placed such that

$$\frac{r_i}{L_0} = \frac{mu}{qBL_0} < 1$$

where m is ion mass, u is the ion velocity, q is ion charge, and B is magnetic field. An illustrative figure on the CEX process is shown in Fig. 2.

C. Charge Exchange Drag - Multi-Particle Picture

While the CEX drag phenomenon is easy to illustrate in a single particle picture, additional collisional processes become important for the performance of the magnetoshell when an assembly of ion and neutral particles is considered. This section gives an overview of the requirements on the magnetoshell resulting from these multi-particle effects.

In order to ensure that charge exchange occurs in the magnetoshell, the mean free path of the charge exchange collision (λ_{cx}) must be smaller than the magnetoshell characteristic size, such that

$$\frac{L_0}{\lambda_{cx}} = L_0 n \sigma_{cx} > 1$$

where n is plasma number density and σ_{cx} is the CEX cross section. Thus, a lower limit for plasma density exists based on the magnetoshell size. There is also a weak dependence on the spacecraft entry velocity due to the relative collision energy dependence of the CEX cross section, but it can be largely neglected for typical entry velocities.

Although CEX collisions are necessary for the magnetoshell to function, secondary CEX reactions or elastic scattering can follow if the collision frequency between the neutrals and ions is too large, . This inhibits the ability of the produced ion to interact with the magnetic field long enough to change its axial momentum, leading to diminished momentum transfer to the magnetoshell. Thus, a limit is placed on an incoming neutral density (n_n) of the form

$$\frac{\lambda_{sc}}{r_i} = \frac{eB}{mn_n u \sigma_{sc}} > 1$$

where λ_{sc} is the mean free path of effective scattering collisions and σ_{sc} is effective cross section of both charge exchange and elastic scattering.

Another important collision in magnetoshells is ion-ion. The ion-ion collision enhances thermalization and reduces secondary collisions of the directed charge exchange-generated ions. Thus, from an ion thermalization standpoint, high plasma density is desired. However, high plasma density enhances recombination of the ion and electrons, which scales as $\sim n^2$ for a quasineutral system. Thus, the operating plasma density must be selected to limit recombination, which causes energy loss and thermal neutral production in the magnetoshell.

III. Research Status

While the MAC concept offers significant game-changing capabilities for EDL applications, it is still early in its development with a Technical Readiness Level (TRL) of 3, which renders it currently unusable for any real mission applications. However, major works are being done to move this technology from academia to commercial use. In this section, the current state of research on MAC is discussed to illustrate the path forward for MAC to change the future of in-space transportation.

A. Chamber Tests

In order to ensure that the ion-neutral CEX collision process that enables the operation of the magnetoshell is dominant, the effect of streaming neutrals on a tethered magnetoshell was experimentally tested as part of a NIAC Phase I project at MSNW.[1] A small magnetoshell was built and tested in the MSNW 2-meter vacuum chamber. The magnetoshell was designed with a modest dipole field of 500 Gs which is reasonable for mission scenarios. The supersonic streaming neutrals from the atmospheric entry was mimicked by a pulsed MPD thruster which generated a supersonic neutral/plasma mixture that impinged on the magnetoshell. The drag was measured on a specially developed dielectric torsional thrust stand. The magnetoshell demonstrated a relative drag of 1000 times the case without turning the magnetoshell on, confirming its drag-inducing characteristics.[1]

A follow-up experiment was performed at MSNW as part of an SBIR contract to develop a 6U-scale CubeSat and a plasma injection scheme to study the ability to use MAC technology in space[7] (see Fig. 4). Currently, a prototype 3U CubeSat is being produced in collaboration between MSNW and the Plasma Dynamics Laboratory at University of Washington under a NIAC Phase II contract to take a step towards flight demonstration and TRL 6. The details of the CubeSats are discussed later in this section.

Figure 3. Demonstration of drag on a magnetoshell in vacuum.[1]

Figure 4. 6U-scale magnetoshell operating in vacuum using Argon at 200 sccm, 300 W RF power, and 172 G field.[7]

B. Numerical Models

In order to commercialize the MAC concept, magnetoshell performance must be analyzed, requiring a deep understanding of the complicated ion-neutral collisional plasma physics. While reduced order analytical models are useful to understanding key parameters and scaling for the magnetoshell, the collisional plasma physics crucial for MAC are often too complicated for simple analytical solutions. Performing experimental tests can capture all of the relevant MAC physics, but typical vacuum chambers are limited in size and available neutral flow for a full test of the system. In-space testing is very expensive, and diagnostic capabilities are limited. On the other hand, while the numerical model has limited physics, it offers full diagnostic capability of the system and allows for isolation of certain physical processes for better understanding. Thus, a good numerical model that can capture the key MAC parameters is crucial in advancing the technology.

In the past, a simplified model of MAC with 2D cylindrical geometry has been used to obtain scaling and time-dependent performance.[1] The model has been used to explore the equilibration of the confined ions and electrons with the free-streaming neutrals due to collisional processes. In the model, a $\sim 1/r^3$ magnetic field profile was assumed with uniform chord temperature, density, and magnetic field. The model assumed local quasi-neutrality and Maxwellian equilibrium, and used Fokker-Planck relaxation rates, Bohm and classical diffusivity, and empirical cross sections to model plasma and neutral transport. The model showed that plasma density increased with ionization, and an equilibrium ion and electron temperature was obtained due to the free streaming neutrals. The model was successful to verify the drag-inducing result from the vacuum test.

Currently, there are two numerical models being developed to better model MAC physics. The first is a simplified 2D hybrid fluid-particle model to obtain steady-state understanding of the MAC configuration, assuming fluid plasma and particle neutrals. Since free-streaming neutrals are in the kinetic regime, this model hopes to capture kinetic effects that are missing in the fluid models. The second is a modification of a 2D Hall-MHD code called Cygnus to obtain full 2D fluid understanding of the confined dipole plasma. Cygnus was originally developed to study FRC formation, translation, merging, and compression, and it offers plasma-circuit coupling and a simplified neutral model with fully stationary neutrals. It is currently being updated to model the interaction between energetic streaming neutrals and stationary plasma in a low beta dipole configuration to better represent MAC conditions.

C. CubeSat Flight Demonstration

One of the greatest obstacles to the MAC research is laboratory testing. While small scale tests have been conducted in the past to demonstrate the concept, there remains an inherent difficulty in testing the magnetoshell in operational conditions due to its large scale and requisite high neutral velocity. No vacuum chamber in existence can accommodate the size of the magnetoshell and its required neutral flow. Thus, the only way to validate the technology is to actually test it in space. However, without flight heritage, it is unlikely for MAC to be used in a real mission to test its capabilities.

In order to overcome this issue, a CubeSat flight demonstration is planned, which allows relatively inexpensive testing of the MAC concept in a true obit entry environment. Due to its small size, the CubeSat architecture allows for great flexibility in launch opportunities and cost. At the same time, the CubeSat is large enough to install a MAC system and to demonstrate the magnetoshell based drag generation. In such a flight demo, the magnetoshell would be activated several times on orbit to test the orbit-lowering effect each time. The mission lifetime is short with an end goal of deorbiting the spacecraft.

A CubeSat mission architecture and hardware configuration has been designed, and work is underway to build a prototype unit for a ground-testing campaign. The goal of this campaign is to demonstrate the full functionality of the mechanical systems, plasma injection scheme, and magnetic dipole system. A vacuum chamber test is planned with the prototype to test the magnetoshell as a self-contained unit, which is a substantial improvement over previous tethered vacuum tests of the device. Such a test will demonstrate wireless actuation of subsystems, activate the magnetoshell at full-scale with on-board propellant feed, and take dipole plasma measurements for empirical data sets to be used in analytic modeling. These tests will advance the MAC technology to TRL 4 and will develop the CubeSat for orbital testing. The current design of the final flight ready version of the CubeSat is shown in Figure 5.

To design the CubeSat orbital demonstration mission, several factors were considered. First, it must be a secondary payload on a launch vehicle that regularly accepts CubeSats. This limits the CubeSat to an ISS release, which constrains the apogee altitude to 400 km and requires a nominal seven day coast period after release to distance itself from all other payloads. Since MAC will ultimately be used for hyperbolic entries, maximum eccentricity is desired. This eccentricity can be achieved if the CubeSat is released en-route to the ISS by the Cygnus cargo craft into a 400x220 km orbit.

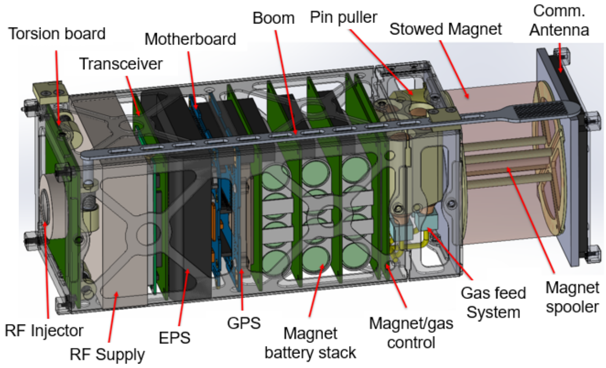

Figure 5. Subsystem layout of MAC CubeSat.

Second, enough time must be allotted for the magnetoshell batteries to recharge. The power system was designed to allow for 800 seconds of magnetoshell activation at perigee. In order to allow enough time for a battery recharge with 2x margin, two days of coast period between activations is required. With a design goal of up to five activations of the magnetoshell before completely de-orbiting the CubeSat, the mission is expected to last 17.5 days after release. The expected flight profile generated from orbit simulations in Copernicus is shown in Figure 6.

One of the most important factors in the CubeSat mission design is for the results to be measurable and conclusive. Due to the difficulty of measuring Δv and orbit period changes, a GPS sensor is included on-board to relay the altitude of the CubeSat to ground stations. The achieved altitude change after the activation of the magnetoshell is the design metric of success. The comparison of the orbit data with the simulated result will assess the accuracy of the current understanding of MAC and will further the design for future applications.

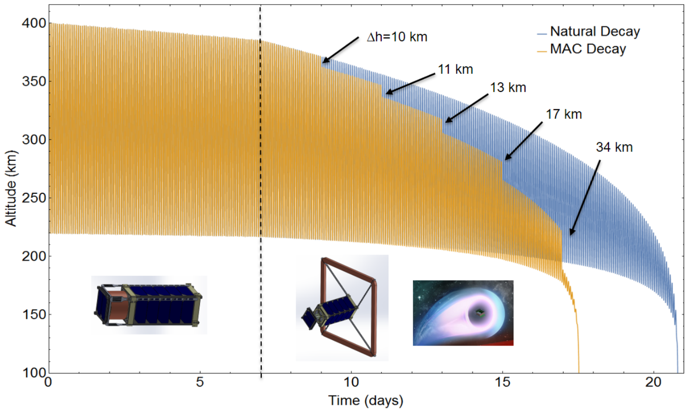

Figure 6. Mission profile for MAC CubeSat. The coil is deployed after seven days, increasing the decay rate. The magnetoshell is activated for 800 s every two days. Lifetime is 17.5 days, compared to 20.8 for the nominal orbit.

D. Technology Development Plan

To mature MAC to the mid–high TRL range, a series of demonstrations and incremental applications will be performed. The sub-kW CubeSat de-orbit flight to be completed within three years will achieve TRL 6. Pending successful demonstration in an orbital environment, a full-scale test will be deployed to characterize a realistic magnetoshell on the scale of 5 m in size, 10 kW power level, and 1.5 kN of force. Further application in the next ten years will see an ISS payload returned using a magnetoshell, bringing MAC to TRL 8. This will position it well for immediate use in Mars cargo delivery, as NASA intends to apply aerocapture technologies without the need to flight-qualify them in the Martian atmosphere.[8] Due to the scalability of the magnetoshell subsystem, this roadmap is easily achievable within a decade of mastering the associated engineering challenges.

IV. Future of Space Exploration with MAC

MAC has the potential to change the face of interplanetary science by delivering larger and faster payloads to key destinations. In order to explore its role in meeting long-term exploration goals, system-level designs have been executed[1,7] applying MAC to manned and robotic spacecraft architectures. These missions, along with the CubeSat flight, showcase the robust scalability of the magnetoshell as an orbit insertion technology.

The mission studies used NASA's orbit simulation code Copernicus to generate orbit transfer and atmospheric injection trajectories. The requisite decelerating force F for capture was found by inputting an effective area A and altitude-dependent density data ρ for the planetary atmosphere to Copernicus and propagating drag according to

$$F = \frac{1}{2}\rho u^2 C_d A$$

using a generic drag coefficient $C_d = 2.2$. Once the desired effective area is found, the dipole parameters are determined from scaling relations. The magnet size R_m and field strength B_0 are dictated by

$$R_d = \frac{\lambda_{cx}(B_0, R_m)}{\pi}$$

where R_d is the dipole collection radius (effective area). Subsequent constraints such as coil mass, power, and temperature can be similarly determined from preceding constraints. The process is iterative and lands on a solution that is feasible within the magnetoshell parameter space for a given atmosphere. A sample aerocapture trajectory in Copernicus at Neptune is shown in Figure 7.

A. Earth–Moon

The Earth–Moon system is a critical proving ground in NASA's roadmap to understanding and colonizing the Solar System. MAC can be used in a variety of local missions, enabling a safe method for deep space crew return,[9] sample return,[10] and asteroid capture. An Earth injection from L2 was simulated that places a 2000 kg payload into LEO. The magnetoshell system was only 900 kg and achieved 3.1 km/s of Δv by inflating to a 25 meter radius over 13 passes. Such a system is safe for the Orion capsule due to the low heat flux inherent to MAC and is easily achievable with current launch vehicle technology. Additionally, It would significantly increase the scientific value of an ARM-style mission by enabling near-Earth operations on a full-size asteroid rather than a small piece.

B. Mars

MAC can play a vital role in developing sustainable transport to Mars as NASA ramps up the effort to set human feet on the planet. DRA 5.0 already calls for aerocapture as a necessary technology in delivering cargo, while it requires all-propulsion architectures for the crewed components due to safety concerns. For cargo delivery, the 20 MT aeroshells can be replaced with a 1 MT magnetoshell to achieve orbit insertion–this reduces the IMLEO mass of the cargo mission by 80 MT. Using low-risk MAC for the crewed mission shows even greater savings; IMLEO mass is reduced by 224 MT and saves almost $2 billion in launch costs. In addition to DRA 5.0, some forward-thinking architectures like Mars Trucks[11] and the Evolvable Mars Campaign[12] call for aerocapture as an enabling requirement, and MAC can easily replace the aerocapture requirement in these. Another benefit of using MAC to transport manned cargo is transit time. Since the magnetoshell can scale to handle much larger entry velocities than traditional propulsion, direct trajectories can be taken that cut exposure to deep-space radiation by many factors. Thus, MAC serves both as a safer, lighter drop-in replacement of the aerocapture in existing Mars architectures and also as an enabler of new mission architectures that were not possible with present day technologies. Indeed, MAC takes a giant leap towards making sustainable avenues to Mars realistic.

C. Neptune and Beyond

Little is understood about the furthest planet in the Solar System. Much effort has been put into designing probes that would explore Neptune,[13–15] yet no probe has been sent because it is prohibitively expensive for little science return. However, analysis has shown that aerocapture is the enabling technology for visiting the gas giant, increasing delivered mass by 800%.[4] Using only a 2 meter radius magnetoshell in place of kinetic decelerators increases the payload mass by a further 75%. Using MAC improves such a mission by a full order of magnitude, turning it from an impossibility into a trivial probe. Similar missions employing aerocapture at Venus[16, 17] and Titan[18, 19] would see great returns from the use of MAC. In this way, MAC is truly a game-changing technology that unlocks many missions without the need for far-future launch and propulsion capabilities.

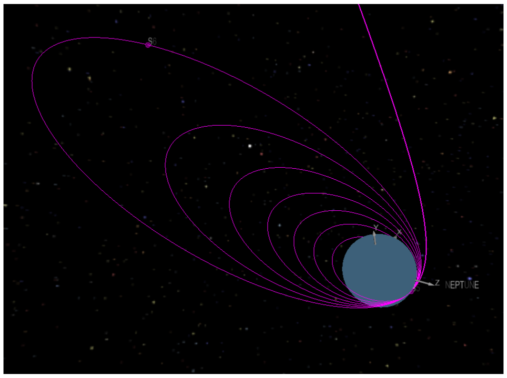

Figure 7. Example Neptune aerocapture simulation in Copernicus.

V. Conclusion

MAC is a promising EP-based technology that will enable mission designs unrealizable with current aerocapture or propulsive techniques. The ability to rapidly decelerate in a controlled manner upon entry to the target planet is critical for shorter, more flexible, and safer missions while reducing the fuel cost typically associated with orbit insertion. Though MAC is low-TRL still, there is a solid plan to develop, validate, and flight-test the technology for commercial and scientific use. It has the potential to be as ubiquitous as solar-electric rocket propulsion in developing sustainable methods for interplanetary travel. MAC will guide massive freight into stable orbits around Mars, catch manned ships zooming along rapid transfers through deep space, and deliver probes to the far reaches of the Solar System.

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