**The Mission Objectives (45s):**

-It could study the rock strata revealed in the walls of craters, to learn something about the

planet’s geologic history. It could even investigate cold traps on the Moon, in search of frozen water sequestered in the shadowed depths.

-The Axel family of rovers extends planetary mobility to steep and rugged terrains such as the interior of crater walls, pits, gullies, canyons, and crevasses**.**

<https://www-robotics.jpl.nasa.gov/how-we-do-it/systems/the-axel-rover/?fbclid=IwAR3TgO_RBfSNjlTKhK3zC9-EG-oshozg3kvCMUzPXY1jl1dKZunwUPi5nSg&view=default>

-Many interesting geological exploration targets exist in regions with steep and rough terrain,

such as impact crater walls, lava tube skylights, volcanic pit craters, chasms, graben, and fissures. Unfortunately, these places are often out of reach for traditional rover concepts. The Axel rover is a platform that can navigate difficult topography and steep slopes, allowing it to

carry a wide variety of instruments to a new array of target sites.

<https://www.hou.usra.edu/meetings/ipm2016/pdf/4122.pdf?fbclid=IwAR002KGWtsJZ_2x2OttPm4itMcInnNC8U4DM0YuhNfFpGDsKkahEa8ecbs8>

-The functionality of Axel rover would allow a mission to examine and characterize the lava layers exposed in the wall of a mare pit crater during abseil descent

<https://www.hou.usra.edu/meetings/ipm2016/pdf/4122.pdf?fbclid=IwAR002KGWtsJZ_2x2OttPm4itMcInnNC8U4DM0YuhNfFpGDsKkahEa8ecbs8>

- It could study the rock strata revealed in the walls of craters, to learn something about the

planet’s geologic history. It could even investigate cold traps on the Moon, in search of frozen water sequestered in the shadowed depths.

https://kiss.caltech.edu/final\_reports/Terrain\_final\_report.pdf

**Rover Design and Technology (60s):**

-Axels can be hosted on a fixed lander or a larger rover, or can themselves form a larger vehicle. An example of the latter is the DuAxel rover shown in Fig 2. This four-wheeled, Ackermann-steered vehicle is formed by docking two Axels to either side of a central module. The docking mechanisms allow the attached Axels to yaw and roll to enable mobility over undulated and rocky terrain. These mechanisms also enable DuAxel to lower itself to the ground on either side (a.k.a. a “kneel” maneuver) in order to deploy one or both Axels for exploring steeper terrains. Kneeling also serves as an anchor for deploying a single Axel but additional active anchoring is used depending on the terrain.

<https://www-robotics.jpl.nasa.gov/how-we-do-it/systems/the-axel-rover/?fbclid=IwAR3TgO_RBfSNjlTKhK3zC9-EG-oshozg3kvCMUzPXY1jl1dKZunwUPi5nSg&view=default>

-Designed to minimize complexity and increase robustness, the Axel rover uses a symmetrical design, which allows it to continue to operate in the event it flips over. It houses four primary actuators to control its two wheels, its boom, and an internal spool that carries hundreds of meters of tether. Secondary actuators are used to level wind the tether for repeated excursions as well as deploying instruments to the surface. Multiple instruments are housed inside its instrument bays within the wheel wells, which rotate independent of the wheels. Axel’s two-wheel design allows differential driving and flexible maneuvering without complex steering mechanisms. By coordinating the primary actuators, the rover can adjust its body pitch on slopes and orient different instruments along the rugged surface normal. The boom provides a reaction force for mobility on flatter terrains and provides a conduit for the tether to avoid entanglement. It also allows the rover to pitch/orient its body and instruments.

<https://www-robotics.jpl.nasa.gov/how-we-do-it/systems/the-axel-rover/?fbclid=IwAR3TgO_RBfSNjlTKhK3zC9-EG-oshozg3kvCMUzPXY1jl1dKZunwUPi5nSg&view=default>

The Axel rover consists of two wheels connected by a thick axle containing a winch and a tether [1]. Two Axels can be combined to form a “DuAxel”(Fig. 1), or one Axel can replace an axle on a more traditional rover body [1]. Over flat terrains (for example, from the landing site to the investigation area), Axelrover can traverse just like an ordinary rover.

<https://www.hou.usra.edu/meetings/ipm2016/pdf/4122.pdf?fbclid=IwAR002KGWtsJZ_2x2OttPm4itMcInnNC8U4DM0YuhNfFpGDsKkahEa8ecbs8>

-Before moving again Axel can independently rotate its wheel well to access all of the other instruments in that wheel for collocated measurements of the same target [1]. The Axel wheel can also make a trench in the surface to expose fresh regolith to the instruments. The location of the instruments inside the wheel of the rover protects them from rocks, dust, and falling debris. In addition, whether used as an addition to a traditional rover, or as part of a DuAxel configuration, Axel could scout for interesting targets and collect samples to be carried back to heavier or bulkier instruments located on the main rover body.

<https://www.hou.usra.edu/meetings/ipm2016/pdf/4122.pdf?fbclid=IwAR002KGWtsJZ_2x2OttPm4itMcInnNC8U4DM0YuhNfFpGDsKkahEa8ecbs8>

- In addition, whether used as an addition to a traditional rover, or as part of a DuAxel configuration, Axel could scout for interesting targets and collect samples to be carried back to heavier or bulkier instruments located on the main rover body. Commercial off-the-shelf instruments that have been successfully integrated into the rover wheel payload space include a micro imager, a miniature spectrometer, and a thermal probe [1].

<https://www.hou.usra.edu/meetings/ipm2016/pdf/4122.pdf?fbclid=IwAR002KGWtsJZ_2x2OttPm4itMcInnNC8U4DM0YuhNfFpGDsKkahEa8ecbs8>

-To explore similar extreme terrains, the Jet Propulsion Laboratory (JPL) has developed the Axel rover in concert with the California Institute of Technology (Caltech). Axel is a minimally actuated tethered rover that can rappel down cliffs and into craters carrying science instruments. It has **four motors: one for each of its two wheels, one for the spool, and one for the arm** (Figure 2). To propel Axel forward, the arm pushes down on the ground in concert with the wheels. Axel’s body was designed to act like a winch to minimize tether abrasion; the tether starts out spooled around Axel’s body, and is payed out through the arm as Axel travels. To return to its starting position, Axel reels in the tether, using it as a climbing aid if necessary. This combination of four motors also allows the body to turn independently from the wheels. Thus, Axel can stop at any time on an ascent or descent to take pictures or measurements, as it is doing in Figure 3 and 4. Each wheel bears an instrument module, whose CAD model is shown in Figure 5. Up to four instruments can be mounted

on deployable panels inside the bay, such as a laser spectrometer, thermometer, and microscopic imager. Thanks to the independent motion of the body, any of these instruments can be deployed directly onto the planetary surface at any time.

Axel’s tether acts as both a mechanical support, and a conduit for power and communications. Thus, it can eschew bulky antennas, solar powers, and other power and communications systems; those functions are provided by its anchoring craft. Axel can be carried on another rover, to act as a mobile instrument. Additionally, two Axel rovers can be connected to form the DuAxel system. As shown in Figure 6, DuAxel is a four-wheeled rover comprised of two Axel rovers docked in a central module, which can carry an onboard power supply, antennas, and even additional cameras. DuAxel can travel long distances on relatively flat ground until it reaches a crater, at which point either or both Axels undock.

<https://kiss.caltech.edu/final_reports/Terrain_final_report.pdf>

-But one of the key features that we developed for the scientist, for Laura and her colleagues, is providing a lot of volume for instrument access. So inside the wheels, you see these cylindrical, these cylinders where we can put up to four instruments on either side.

https://www.youtube.com/watch?v=kdv\_V8Hu9kw&ab\_channel=KISSCaltech

**Challenges of Interplanetary Travel (45s)**

-Axel co-locates its stereo cameras, sensors, actuators, electronics, power components, and payloads inside a single enclosure, which provides robustness against environmental extremes and simplifies thermal management. Its sensor suite and onboard software enable autonomous tethered navigation on slopes.

https://www-robotics.jpl.nasa.gov/how-we-do-it/systems/the-axel-rover/?fbclid=IwAR3TgO\_RBfSNjlTKhK3zC9-EG-oshozg3kvCMUzPXY1jl1dKZunwUPi5nSg&view=default

**Landing and Deployment (45s)**

**Scientific Discoveries (60s)**

Moon Diver: A Sample Axel Mission Concept

The lunar mare basalt deposits serve as natural probes into the lunar interior. Recent images returned by the Kaguya and Lunar Reconnaissance Orbiter missions have revealed the presence of deep mare pits containing meter-scale layer stratigraphy exposed in their walls ([2- Such an exposure would offer a wealth of information about the compositional, petrologic, and emplacement conditions of the mare basalts through time. While normal rovers would not be able to reach these layers, the functionality of Axel rover would allow a

mission to examine and characterize the lava layers exposed in the wall of a mare pit crater during abseil descent [Fig. 3; 5]. Mineralogy (provided by a VIS/NIR spectrometer), texture (provided by a microimager), elemental chemistry (provided by an X-ray spectrometer), and age (provided by a mass spectrometer situated on the main rover body) would reveal the evolution of the mare lavas through the section. Axel’s onboard cameras

could record layer thicknesses and document the presence and characteristics of intervening regolith layers.

Once on the floor of the pit, the Axel rover could continue to explore. If the pit opened into a lava tube or other subsurface void, the rover could attempt to negotiate the floor up to the length of its tether (currently 250-300 m, potentially up to 1 km; [1]). After exploring the pit, the rover could reel itself back up the wall and either continue roving across the surface or rappel down a different side of the pit. https://www.hou.usra.edu/meetings/ipm2016/pdf/4122.pdf?fbclid=IwAR002KGWtsJZ\_2x2OttPm4itMcInnNC8U4DM0YuhNfFpGDsKkahEa8ecbs8

**Future Implications (45s)**

The Axel rover provides enhanced mobility which would enable it to land, rove to a pit, cave, cliff, or slope, approach the science targets, explore with a suite of high-priority science instruments, and exit, all with existing or highly developed technologies. This approach would revolutionize our capability to carry diverse instruments to many previously inaccessible terrains on a variety of planetary bodies.

<https://www.hou.usra.edu/meetings/ipm2016/pdf/4122.pdf?fbclid=IwAR002KGWtsJZ_2x2OttPm4itMcInnNC8U4DM0YuhNfFpGDsKkahEa8ecbs8>

**Questions & Answers:**

1/ how are they gonna make sure the wires don't break from either stress or other sharp debris that it goes on to ?

2/What failsafe is there for keeping that tether from getting snagged up in rocks? That is a lot of tech to get stuck like a lure in a tree millions of miles away?

1-2/ First of all, we use onboard terrain assessment and orbital imagery to determine paths and rover configurations around obstacles to prevent snagging (e.g., if we see a crack that presents a hazard we will navigate and lay the tether in a way that minimizes the snag risk,

2) The rover can use its center boom to lift the tether out of a snag if it happens even on steep terrain,

3) A permanent snag only limits the rovers ability to return to upslope so we could easily continue exploring down the crater or slope without an issue,

4) DuAxel is a redundant system that could either deploy a second Axel for exploring an interesting area or we could outfit the docking mechanism with a spare wheel that would allow the remaining rover and central module to drive off to a new site like a tractor trailer.

**The rugged electromechanical tether is just 0.2" in diameter with an abrasion shield for rocks and high strength fibers that can resist up to 1000 lbs of force. We've tested the tether on lunar simulant material and it can withstand 1000s of cycles of abrasion and even sharp bends around knife-edge rocks while still transmitting power and data over internal wires.**