# APPENDIX A



## WHY DID NESSP CHOOSE ICY WORLDS FOR THIS YEAR'S ROADS?

The icy worlds of our solar system present some tantalizing challenges for exploratory science. What lies beneath the icy surface? If there's water, could there be life? And will we need ice skates on our lander?

## WHAT ARE THE ICY WORLDS YOU WILL BE EXPLORING IN THIS CHALLENGE?

An "icy world" is defined as a body whose outer surface is composed mostly of water ice that's so cold it's as hard as rock on Earth. The interiors of the largest of these icy bodies may also have a global subsurface ocean of liquid water and a rocky inner core.

The most well-known icy moon is Jupiter's moon Europa; however, nearly all of the outer planets' moons are considered to be icy worlds. The surface below the dense atmosphere of Saturn's moon Titan is also composed of rock hard water ice and scientists think Titan also has an internal global water ocean. Another fascinating icy world is Triton, which has large plumes erupting from its complex surface.

Not all icy worlds are moons. The dwarf planets Pluto and Charon are both considered to be icy worlds, along with Ceres in the asteroid belt.

As you can see, there are many icy worlds. For this mission, we will be focusing on Jupiter's moon Europa, the target of NASA's upcoming Europa Clipper mission.

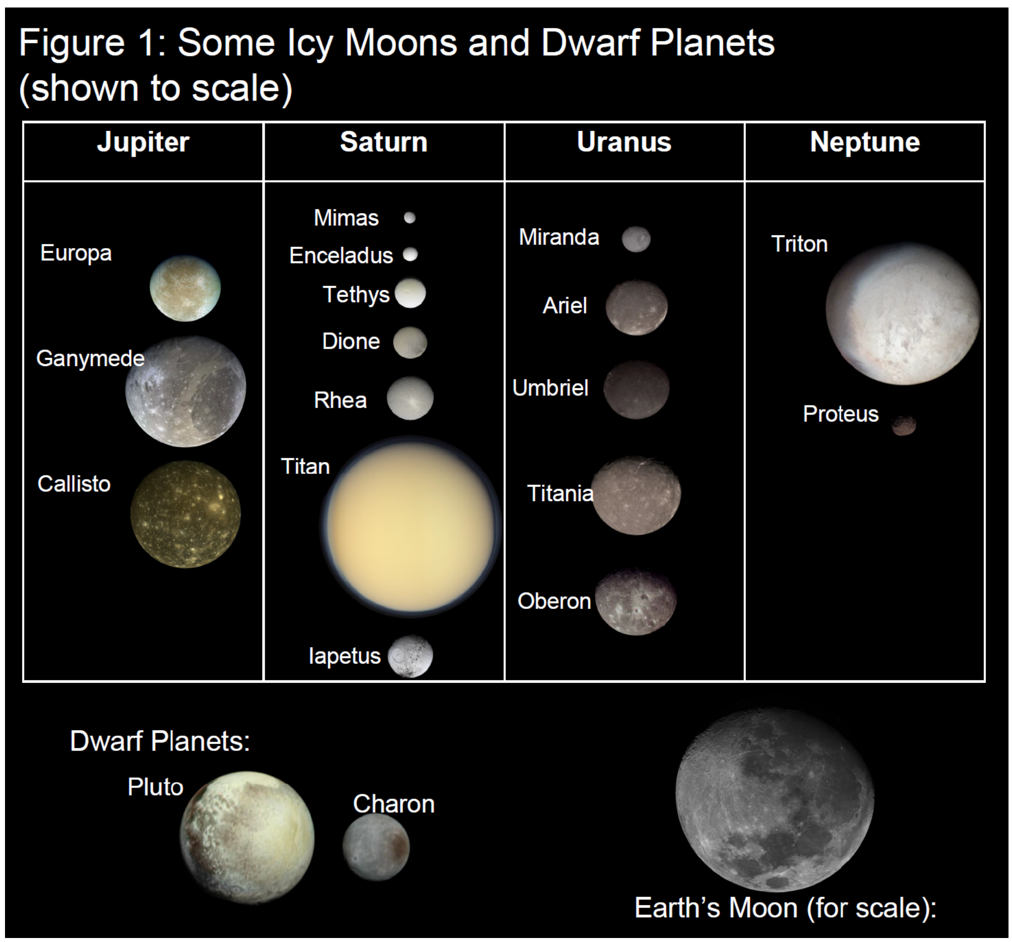


Figure 1: Some of the icy moons of the outer planets and dwarf planets Pluto and Charon. The moons, Pluto, and Charon are shown on the same scale as the Earth's moon, which is not an icy world but is provided for scale. (Adapted from montage by Emily Lakdawlla] with free use for educational purposes under the Creative Commons license. Original images: NASA/JPL)

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## WHY DO SCIENTISTS WANT EXPLORE THE ICY WORLDS OF OUR SOLAR SYSTEM?

Do you think life could survive (or even thrive) in a dark salty ocean under miles of ice?

Scientists believe that Jupiter's moon Europa has a global ocean 10 to 15 miles (16 to 24 km) beneath its icy surface. Europa's ocean could be up to 100 miles (160 km) deep and contain twice as much water as all of the Earth's oceans combined. That's a lot of water, considering Europa has a diameter of only 1,940 miles (3,120 km), making it only a fraction of the size of Earth (with a diameter of 7,920 miles). In fact, many of the icy worlds in the solar system are what NASA calls "ocean worlds." These worlds are probably home to most of the liquid water in our solar system.

On Earth, where there is water there is life! Therefore, these watery, icy worlds are the perfect place to explore the limits of habitability in our solar system and beyond.

## YOU MIGHT BE WONDERING — WHY ARE THESE BODIES COMPOSED OF ICE INSTEAD OF ROCK LIKE THE EARTH?

To answer that question we have to go back about 4.5 billion years to the formation of our solar system.

Icy worlds formed outside what is known as the frost or snow line. This theoretical line occurred about 500 million miles, or approximately 5 astronomical units, from our young sun — almost the distance to Jupiter. Beyond the front line it was cold enough for water and other compounds like methane and ammonia to freeze into solids. Bodies like Saturn and Jupiter accumulated a large amount of material over their long orbits and became massive enough to capture light gasses like hydrogen and helium in their atmospheres. Scientists think that material that didn't go into making these gas giants formed the many icy moons that now orbit them.

Other icy bodies formed out of material orbiting the sun. Most of these bodies, like Pluto and Charon, are small and orbit in a region known as the Kuiper belt.

## BUT IF IT'S SO COLD OUT THERE, WHAT KEEPS THE LIQUID WATER OCEANS INSIDE ICY WORLDS FROM FREEZING?

Good question!

Most of the worlds that scientists think have liquid water oceans are moons of one of the gas giants, like Jupiter or Saturn. The strong gravitational force of the massive gas giants push and pull on the surface of the moons in a process known as tidal forcing.

We also experience tidal forces on Earth. Have you gone to the coast and explored a tide pool or built a sandcastle during low tide only to come back hours later to discover the same rocks and sand covered with water? It's the gravitational pull of our moon that causes the surface of the ocean to move up and down, periodically hiding and revealing stretches of shoreline.

As tidal forcing works on the icy moons it causes constant deformation of the surface and the interior of the icy moons, which in turn is the source of energy and heat that keeps the interior liquid. You can observe how forces produce heat at home by bending a paperclip back and forth. If you do it quickly enough (without breaking it!) you should feel the paper clip getting warm.

These tidal forces, as they break up or deform the surfaces of the icy worlds, also produce an interesting variety of surface features — which you'll see first-hand when you plan your mission to explore the map of Europa!

## THESE DARK, COLD, ICY WORLDS SEEM LIKE THEY'RE A PRETTY UNCOMFORTABLE PLACE TO LIVE, SO WHY DOES NASA THINK THEY MIGHT SUPPORT LIFE?

Earth has shown that life can survive and thrive in a wide variety of habitats. In fact, so far, scientists have found life on Earth everywhere liquid water exists.

That's right, if there's water there is life!

Some of you might have visited Yellowstone National Park and have been warned about getting too close to the boiling hot hydrothermal pools. Those pools aren't so good for human life, but extreme life forms called thermophiles love the heat! Scientists have even found life in near-freezing lakes in Antarctica, like Lake Whillans, where the water is shielded from the Sun by a half-mile of ice.

Why is water so essential to life as we know it? One very important reason is that it provides a liquid environment for our cells' working units, like proteins, to move about. It also dissolves nutrients for organisms to eat, transports important chemicals within living cells, and allows those cells to get rid of waste.

Of course, like you, life needs more than water to survive. Life also needs a source of energy and food. Earth has shown that life has found ways to utilize many sources of energy. Organisms even live around vents deep within our ocean, called black smokers. The organisms use nutrients and heat leaking from beneath the ocean floor to produce the energy. No sunlight required! Scientists think that the boundary between the liquid oceans and the rocky cores inside icy moons may have similar vents. If they do, these vents might provide enough energy and nutrients to support simple lifeforms.

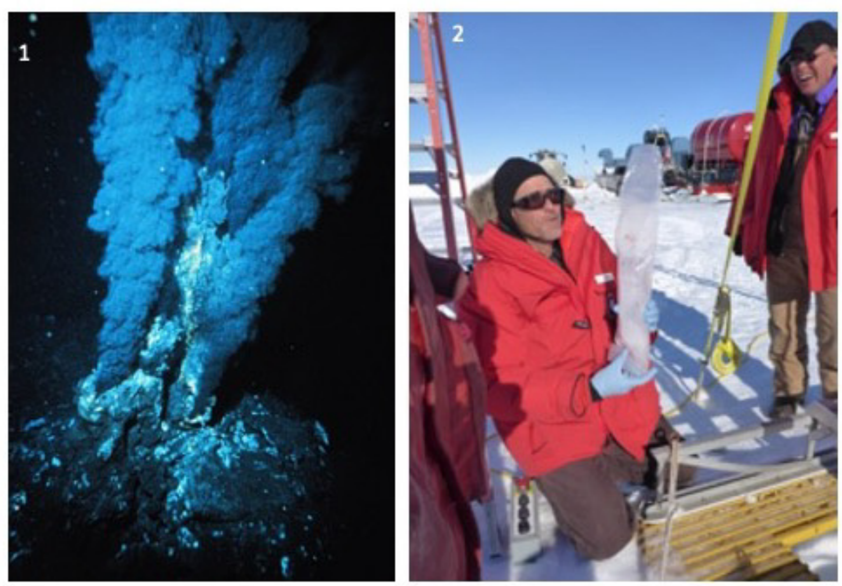

Figure 2: Scientists look for extreme life on Earth to try to understand where life might exist in the solar system and beyond. (1) This figure shows a black smoker on the dark surface below the Atlantic ocean. (2) This Shows a scientist examining an ice core produced when drilling a hole to so that robotic crafts could search for life in Lake Whillians. (images: (1) Wikimedia Commons (2) NASA/JPL).

## WHAT ARE NASA'S GOALS FOR EXPLORING ICY WORLDS?

Scientists come together every decade to produce a list of scientific goals that will drive how NASA missions explore our solar system. In 2019, these scientists determined the most important goals for the icy worlds are:

1. Determining which of the icy moons harbor liquid oceans
2. Characterizing the properties of those oceans
3. Conducting research both in space and on Earth to better understand how life might exist in a subsurface ocean

To achieve these goals, scientists are trying to better understand the energy sources within these bodies that allow global liquid oceans to exist. They are also working on techniques to remotely sense the properties of these oceans using measurements taken from orbiting spacecraft. Finally, scientists are designing lab experiments and searching the Earth for life in extreme environments to better understand the biology that might exist under the surface of these icy worlds.

Scientists are hard at work today, but did you know that the next two missions NASA plans to send to Europa and Titan won't arrive until 2030 or later? By then, you just might be ready to join these missions and help NASA achieve its objectives.

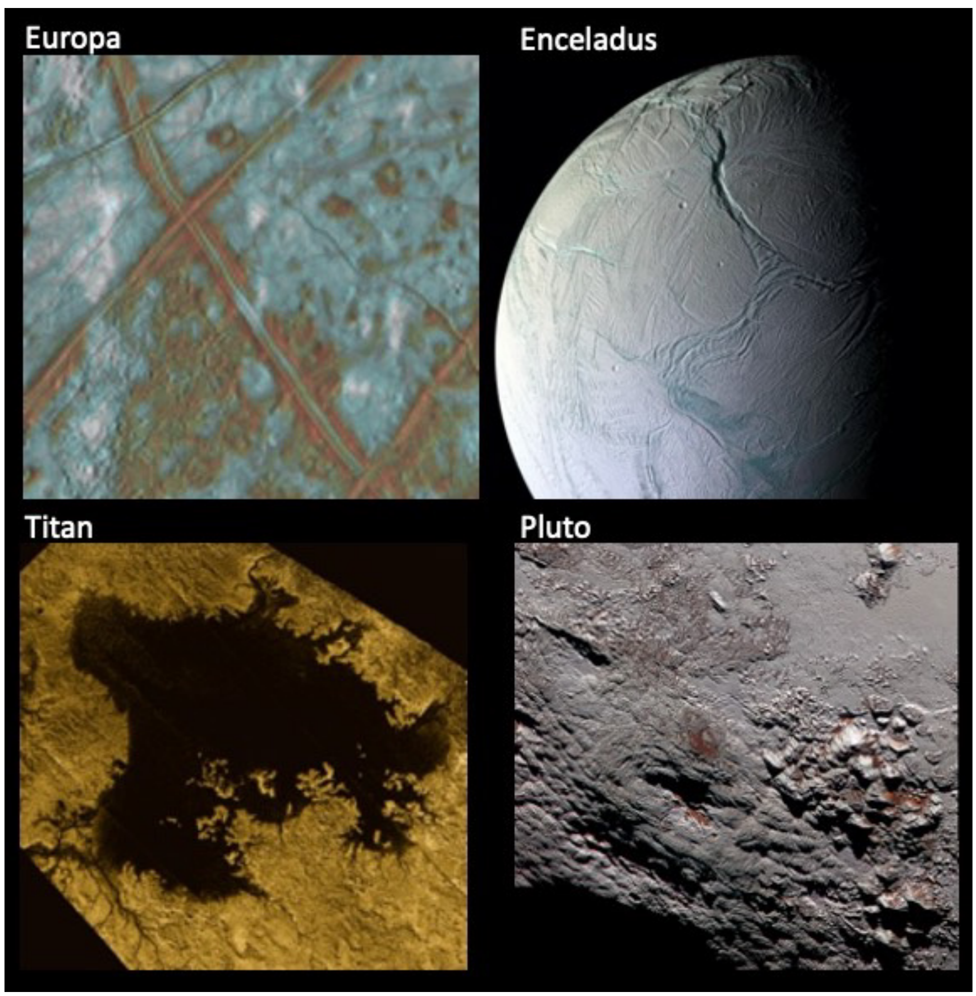


Figure 3: The complex surfaces of some of the icy worlds imaged by the Galileo (Europa), Cassini (Enceladus and Titan), and New Horizons (Pluto) spacecraft. (images: NASA/JPL)

## PAST MISSIONS TO THE ICY WORLDS

Although Galileo Galilei first discovered Jupiter's four largest moons (Io, Europa, Ganymede, and Callisto) in 1610, we knew little about the icy bodies in the outer solar system until the early 1970s when the Pioneer and Voyager probes returned images of their surfaces. These probes discovered that the icy bodies of the outer solar system are diverse and complex, both puzzling and exciting scientists. On Europa, images showed a fractured terrain that made it appear as the surface periodically broke into pieces, shifted, and re-froze. Titan, a moon of Saturn, had a thick, orange, dense atmosphere that prevented the spacecraft from peering at its surface. Neptune's moon Triton had icy lava flows and active plumes that launched material nearly 5 miles (8 km) above the surface. In the course of a few years, the solar system became a much more interesting place.

Next up was the Galileo spacecraft, which orbited Jupiter for over 7 years (1995–2003) and took higher-resolution images. It also made multiple flybys of each of Jupiter's large icy moons. The Galileo spacecraft discovered Europa's subsurface ocean using a technique called magnetic induction. It also detected Ganymede's magnetic field and got a close-up view of the powerful volcanic activity on Io.

From 2005 to 2017, the Cassini mission provided similar data at Saturn. During its first Titan flyby, Cassini released the Huygens probe which sent back the first images of Titan's surface as it slowly descended through the dense atmosphere. Later in the mission, Cassini used radio waves to remotely observe many liquid lakes on the northern and southern poles of Titan. Another exciting discovery of the Cassini mission was the detection and direct sampling of plumes coming out of the south pole of the small white inner moon Enceladus.

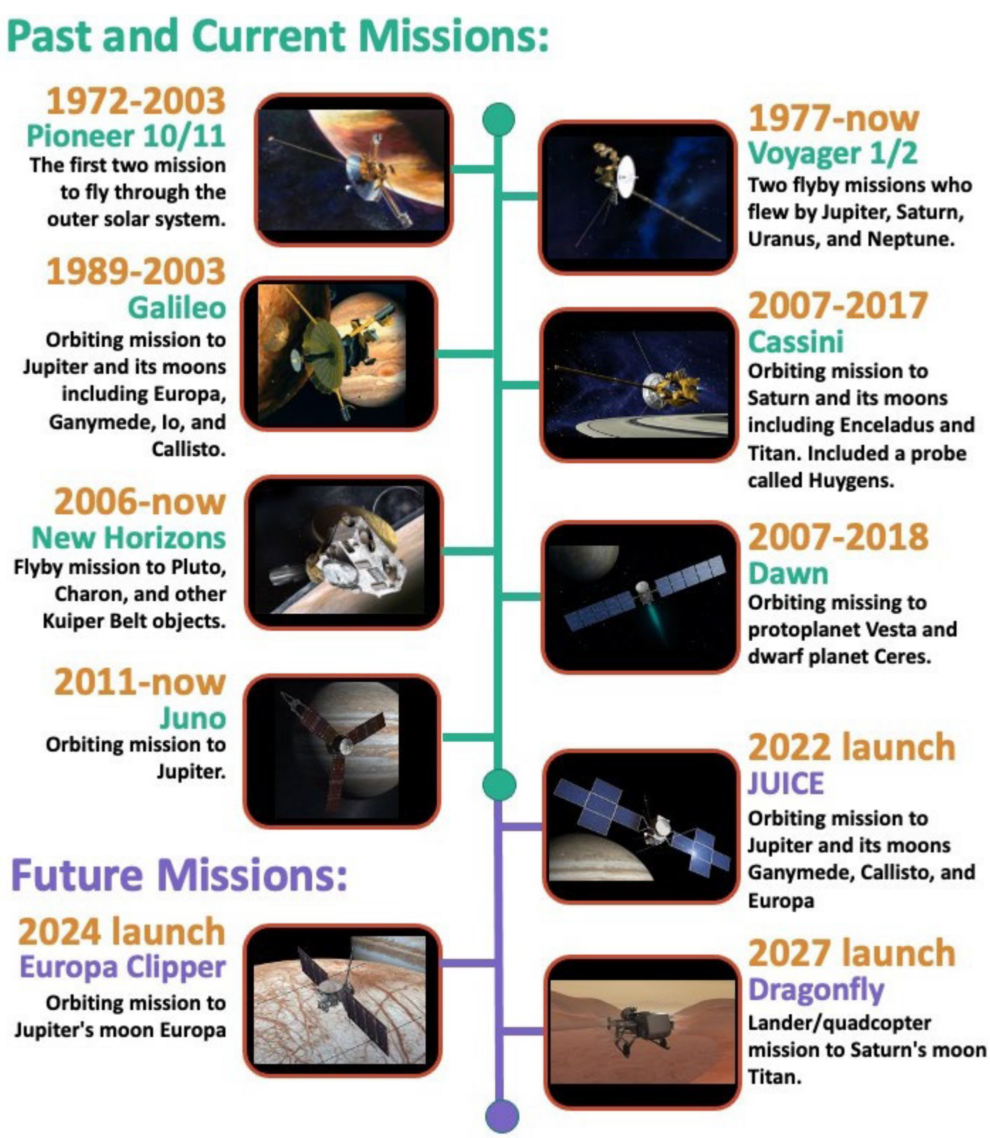


Figure 4: A timeline of past, current, and future missions to the icy worlds in our solar system. (spacecraft images: NASA/JPL and ESA)

In 2015, New Horizons became the first spacecraft to take close-up images of Pluto's surface. The spacecraft was moving so fast when it reached far-away Pluto it could only quickly zip by. Despite this, New Horizons provided amazing high-resolution imagery of nearly all of Pluto's surface and directly measured the properties of its atmosphere. Again, scientists were blown away by the unexpected. Pluto's cold surface was shown to be as complex as any other icy body with intense light and dark color variation and tall mountain ridges. Pluto's atmosphere was also much denser than scientists previously thought.

Around the same time, the spacecraft Dawn went into orbit around Ceres, a dwarf planet in the asteroid belt between Jupiter and Mars. Unlike many of the icy worlds we have discussed so far, Ceres' surface is a mixture of rock and ice because it orbits much closer to the Sun. Dawn discovered Ceres has a unique surface that is heavily cratered but also speckled with salty bright spots.