# 369 Research

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## 1 Background info on Ganymede (discovery, properties, etc)

Ganymede is a unique moon. It is large - bigger than Mercury and Pluto- and it is the ninth-largest object in the Solar System. Ganymede is the only moon (known) to have its own magnetic field. The Jovian satellite also has an atmosphere, and it is an icy world due to its thick icy crust. As well as this, the moon is tidally locked, meaning one side is always facing Jupiter.

Ganymede was discovered in 1610 by Galileo, using a telescope to observe what he thought were three stars near Jupiter. These three stars turned out to be Ganymede, Callisto, and a body that was a combination of light from both Io and Europa. The night after this, Io and Europa had moved and he later saw all four moons at once. A week after the original three-moon observation, Galileo predicted, correctly, that these bodies were orbiting Jupiter [1].

Many spacecraft have explored Ganymede: Pioneer 10 and 11, Voyager 1 and 2, Galileo, New Horizons, and Juno.

In the 1970s, Pioneer 10 and 11 approached Ganymede and returned the physical characteristics of the moon. The spacecraft's simple spin-scan imaging Imaging Photopolarimeter showed darker and brighter surface tracts on the satellite. The diversity and complexity of the surface were not known until the Voyager probes came along - their cameras were much more advanced.

The Voyager 1 and 2 probes approached Ganymede, in the late 1970s, in order to refine the size of Ganymede and found the moon was bigger than Titan, Mercury, and Pluto. Voyager 1 covered the closer half of Ganymede to Jupiter, and Voyager 2 covered the outer hemisphere. They revealed its grooved terrain, with Voyager 1 having a resolution of 1km/pixel, and Voyager 2 being much sharper, with 500m/pixel [2]. A large number of spectral images showed non-ice compounds on the surface. Unfortunately, some images taken from the probes were taken at a bad angle, which left large blank spots that physicists knew nothing about.

The Galileo spacecraft, launched in 1989, discovered Ganymede's magnetic field in 1996 by using its onboard plasma wave spectrometer - which measures changes in electromagnetic waves in Jupiter's environment - and magnetometer, which measured the strength and direction of the magnetic fields. The spacecraft captured whistler-mode emissions from Ganymede, which sound like static - that were caused by the magnetosphere [3]. These 'whistling' emissions exposed the strength of Ganymede's magnetic field and it can be inferred using characteristics of the whistling, that Ganymede's magnetic field strength must be at least 400nT. This is 4 times the magnetic field strength caused by Jupiter at the same distance, hence why Galileo proved that Ganymede has its own magnetic field. The Galileo probe had a much higher resolution than the Voyager probes, at ¡200m/pixel. This resolution returned samples of the terrain and surface features.

The New Horizons spacecraft observed Ganymede - in the early 2000s - from a far distance and topologically mapped the surface [4].

Juno, which completed a flyby of Ganymede in 2021, observed the surface in the greatest detail ever and spotted shimmering auroras stretching between Ganymede's poles and the equator. The spacecraft also revealed Ganymede's crater-saturated surface [5].

The Hubble space telescope, launched in 1990, found evidence that Ganymede had an underground ocean. It is believed that the thin oxygen atmosphere present on Ganymede is a result of the moon's underground ocean [6]. The presence of this ocean has been confirmed by readings taken by orbiters and through studies of how the moon's aurora behaves. An illustration is shown in figure 1, to show the interior composition of Ganymede.

## 2 Ganymede's Atmosphere

Ganymede's thin atmosphere is compromised of oxygen, O, $O_2$ and $O_3$, and a small amount of hydrogen. It is predicted that Ganymede's oxygen-rich atmosphere is emanating from the molecules on the icy surface of the moon being split into their hydrogen and oxygen counterparts through ultraviolet radiation. The hydrogen is expelled into space and the oxygen remains, forming the atmosphere. There is an ionosphere - a layer containing a high concentration of ions and free electrons - within the atmosphere [8]. It is believed that the ionosphere on Ganymede is composed of molecular oxygen at the polar regions of the moon, and atomic oxygen ions at low latitudes. Theories suggest the ionosphere should exist, as oxygen molecules are ionized by the impacts of the energetic electrons arising from the magnetosphere, and by ultraviolet rays radiated from

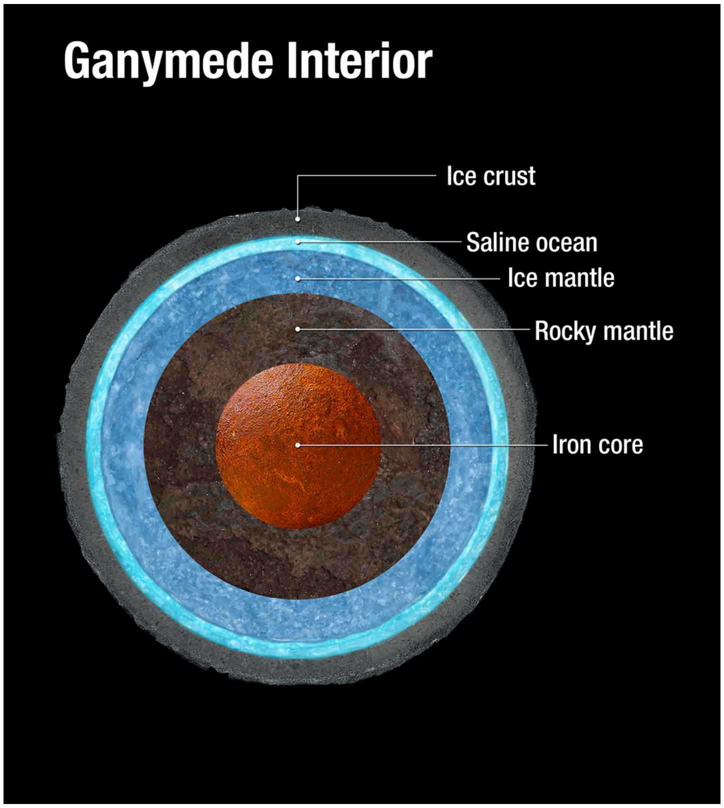


Figure 1: The figure shows the interior make-up of Ganymede, presenting the iron core, rocky mantle, icy mantle, saline underground ocean, and icy crust.
Source: NASA [7].

the Sun. Protons are absent in all regions of Ganymede's ionosphere [9]. The presence of Ganymede's atmosphere causes an effect called 'air-glow', where there is a faint emission of light as a result of the interaction between atomic oxygen and energetic particles. Air glow causes bright spots to appear on the polar regions, called polar auroras, due to the magnetic field.

# 3 Magnetic field on Ganymede

Magnetic fields are caused by convection in the molten iron core of a planet [10] (or in this case a moon). They occur due to radioactive decay and heat from the formation of matter, which transpire from collisions and compression of matter [11]. After thousands of years, the core becomes so hot that it reaches the melting point of iron - hence why there is a molten iron core. This core is illustrated in figure 1. For Ganymede, the matter used to form the satellite was (most likely) an accretion of dust and gas from the creation of Jupiter. It was much quicker at forming than other Jupiter moons as it was closer to the planet, where the dust and gas were denser [6]. Ganymede is so close to Jupiter that it is enclosed in the gas giant's magnetic field, however, Ganymede has its own magnetic field, due to its iron core, which was proven by the Galileo spacecraft. Convection within the liquid iron core, influenced by Jupiter's tidal forces, induces the magnetic field. Ganymede is the only moon known to have its own magnetic field, as magnetic fields are normally expected on planets, like Earth. As Ganymede has a magnetic field, it also has its own magnetosphere - an area of space around the moon dominated by the magnetic field. Closed field lines are present on Ganymede at a region below 30° latitude. Charged particles (such as electrons and ions) are trapped here, creating a radiation belt - a region surrounding the moon where charged particles accumulate due to the magnetic field. The main ion within the magnetosphere is singly-ionized oxygen.

A set back of this research is that the cause of the magnetic field on Ganymede is not concrete - it is only theorised that it is due to the dynamo action within the moon's core. This speculation comes from the fact that other bodies that have the same metallic core as Ganymede don't have magnetospheres, and that Ganymede's core is so small that it should have cooled sufficiently, so that fluid motions are no longer possible. There are other theories for the reason that Ganymede has a magnetic field.

### 3.1 Underground Ocean

Ganymede's underground ocean affects the magnetic field because it interacts with Jupiter's magnetic field. As the Jovian satellite is embedded within Jupiter's magnetic field, when Jupiter's magnetic field changes, the aurora seen on Ganymede also changes, in a rocking motion. By studying this 'rocking' motion, physicists determined that there was a saline liquid in the structure of Ganymede - as the aurora rocked less than half of the amount that it would if there was no salty ocean present [12]. Figure 2 presents the difference in rocking.

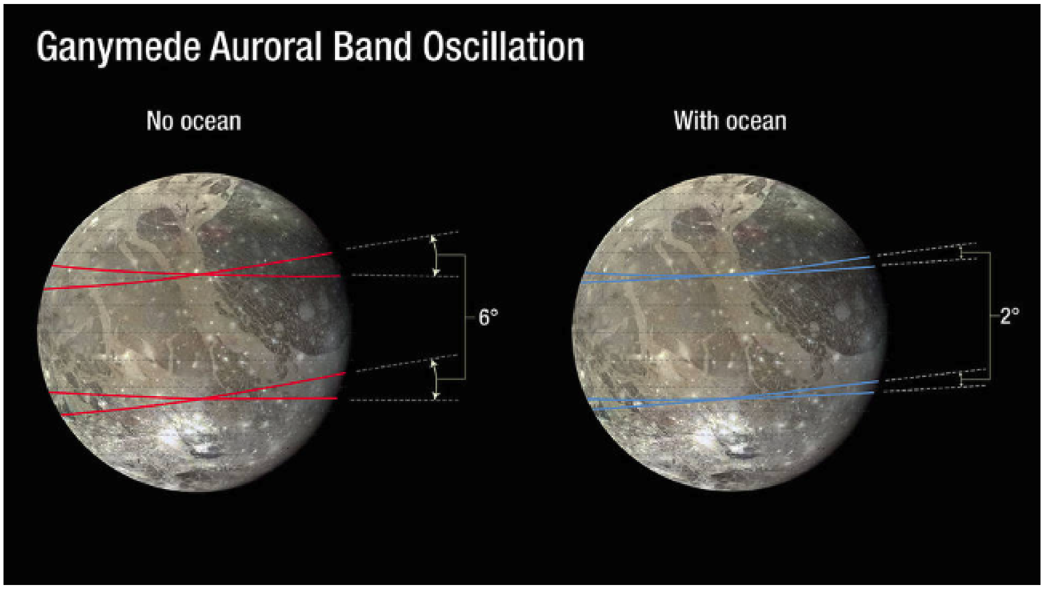


Figure 2: The figure plots the difference in the amount of rocking that the moon would encounter with and without the saline ocean.
Source: NASA [12]

### 3.2 Aurora

Ganymede's magnetic field causes auroras that circle the moon's poles. This is because the field directs plasma, which is an electrically charged gas, from Jupiter, which collects at the poles.

### 3.3 Magnetic Moments

The magnetic dipole present on the moon is at a tilted angle with respect to Ganymede's rotational axis, causing the magnetic moment to travel directly opposite Jupiter's magnetic moment. This dipole moment is twice as strong at the poles of Ganymede than around the equator.

## 4 Surface Features on Ganymede

Spacecraft such as Pioneer 10 and 11, Voyager 1 and 2, New Horizons, Galileo, and Juno all completed at least one flyby of Ganymede and collected data on the surface features - along with many other features.

Ganymede's surface is composed of equal parts of rocky material and water ice and has two types of terrain - dark regions, which are old and full of impact craters, and young, light regions, where the terrain is molded due to tectonic-plate movement from tidal heating from being situated so close to Jupiter [13]. The light terrain has cross-cutting lanes and a grooved surface. These light and dark terrains are visible through the satellite's thin polar caps. The origin of these polar caps is due to plasma bombardment turning the ice brighter. There was also a strong correlation between the polar cap boundary and Ganymede's magnetic field boundaries.

### 4.1 Weathering on Ganymede

The surface on Ganymede is very asymmetric. These variations are correlated to its magnetic field, in which Jupiter's magnetosphere plasma is directed along the closed field lines and collides with the poles of the moon - hence why the poles are so bright and the equatorial region is not as affected by space weather. The poles of Ganymede are so bright as ice is affected by radiating particles, due to the moon's magnetic field.

## 4.2 Dark Terrain

Dark terrain makes up for around 1/3 of Ganymede's surface and based on measured crater densities, of which there are many in the dark sections of Ganymede, the terrain is estimated to be over 4 billion years old [14]. This is nearly the same age as Jupiter, and as Ganymede is thought to have been created at around the same time as Jupiter, the dark terrain, therefore, holds information for the processes that have affected the moon since it was created. This dark description comes from the fact that the ice in these regions contains clay and organic materials [4], which are thought to have been left behind by impacts. This fits well with our description of dark terrain (impact craters are far more abundant in these regions). The dark terrain on the satellite hosts many trenches, called furrows, which are around 10km wide and occur in sets [15] and are one of Ganymede's most recognizable structures. The Galileo spacecraft revealed the dark terrain is heterogeneous - compromised of a mix of structure/material - where the pole-facing slopes are brighter than the Sun-facing slopes, hinting there is the deposition of ice [16].

## 4.3 Light Terrain

Light terrain is believed to be tectonic in nature, takes up 2/3 of Ganymede's surface, and is a result of tidal heating events (the repeated deformation of a body due to gravitational waves of another body) because of Jupiter. Tidal heating could have exhausted the lithosphere (the solid, outer part of the moon), causing cracks and deforming the once-dark terrain. High-resolution images, taken from the Galileo spacecraft, prove the existence of the tectonic, grooved light terrain. Another cause for the light terrain may be cryovolcanoes - a volcano that erupts with ice, water, and other materials instead of molten rock and ash - erupting water onto the surface. Calderas are volcanic craters created by these volcanoes.

## 4.4 Cryovolcanoes

There are four theorized steps to how the cryovolcanoes cause light terrain: dark terrain tectonism, tectonic resurfacing, volcanic resurfacing, and cross-cutting sulci. Dark terrain tectonism includes the movement of tectonic plates in the dark terrain regions, which happens due to Jupiter's strong gravitational waves, where furrows are created. Tectonic resurfacing regards the misshaped surface, allowing for volcanic resurfacing, where the eruption of water or ice floods a graben (a pit in the land, similar to a valley) and resurfaces the dark terrain to create a smooth, light terrain. Cross-cutting sulci form when cryovolcanoes erupt non-parallel to previous resurfacing and cause cross-cutting surfaces. This is one of the main characteristics of light terrain.

# 5 Reference explanation

[1] - Translation of Galileo's Sidereus Nunicus, which was like a journal where Galileo wrote all of his observations.
[2] - NASA website with great detail on the Voyager probes.
[3] - A paper illustrating some results from Galileo's flyby of Ganymede, and proving the existence of a magnetic field.
[4] - Physics site with a lot of detail about Ganymede.
[5] - A page exploring the Juno flyby of Ganymede.
[6] - Nasa website talking about Ganymede's structure, magnetic field, orbit, formation, surface, atmosphere, and magnetosphere.
[7] - NASA website, showing images and discoveries of Ganymede from the Hubble Space Telescope.
[8] - A paper all about the atmosphere of Ganymede.
[9] - A paper on the ionosphere of Ganymede.
[10] - A paper talking about magnetic fields in planets - can be transferable for Ganymede as it has the same mag field as a planet would.
[11] - National Geographic website stating how iron cores are formed.
[12] - Website explaining the presence of the underwater salt ocean on Ganymede.
[13] - A website stating some basic facts about Ganymede.
[14] - A book with lots of detail about the surface features of Ganymede.
[15] - An article about imagine completed by Voyager 2.
[16] - Article about the geology of Ganymede.

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