Air and Space this Week

Item of the Week

THE GALILEO MISSION TO JUPITER

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October 18 is the 35th anniversary of the launch of the Jupiter-bound* Galileo *spacecraft *via STS-34, the Space Shuttle* Atlantis*. The spacecraft performed well, and the data acquired gave us a much better understanding of Jupiter and the Galilean Satellites, and it even became the first to show us asteroids up close.*

PRE-SPACEFLIGHT STUDY OF JUPITER

Jupiter is a bright object in the night sky. To the sky-watchers of the earliest 1600s, it was just one of the points of light that "wandered" amongst familiar groupings of stars in a complicated, but predictable, way. [BTW: The word "planet" is derived from the Greek for "wanderer."]

The telescope was invented in 1608, and it changed sky-watching forever.

The prevailing view of the Universe at that time was that The Earth Was The Center Of All Things and that celestial objects were "perfect." The sphere above us held the stars at a great distance, while the bright planets moved among them. Copernicus thought differently, and in 1543 published his famous book, *De Revolutionibus Orbium Ceolsestium*. He showed that there was an observational test on whether the heliocentric or geocentric system was accurate, and it involved the phases of Venus. When Galileo got his hands on one of the earliest telescopes, he immediately looked at three things: the phases of Venus, the Sun (by projection), and Jupiter.

Seeing that Venus, over a period of months, showed the full range of lunar-like phases convinced him of the validity of the Copernican model, since the geocentric model only allowed Venus to be seen as a crescent if at all. Seeing that the Sun had spots when it had been assumed to be celestially blemish-less was unnerving. And when he looked at Jupiter, a third negation of prevailing dogma was revealed. There were four small stars lined up around Jupiter, and they *moved*! A relatively-short period of nightly observations convinced Galileo that the small stars were actually objects that orbited Jupiter. If things orbited something other than the Earth, how could the Earth be the Center of All Things? Most unnerving, indeed!

Those four objects today are collectively known as the *Galilean Satellites*: Io, Europa, Ganymede, and Callisto.

Telescopes got better and better, and astronomers could see surface details the revealed Jupiter's thick, cloudy atmosphere festooned with giant storms, but not much detail about Jupiter's moons.

A much closer look was needed, and the transition from Project Apollo to beyond was created.

PIONEERS AND VOYAGERS

The usual sequence of planetary exploration is: observation from afar, fleeting observation from up close, continued detailed observation of the object, landing on the object, and finally, bringing a piece of the object back to Earth. Jupiter was being examined by Earth-bound telescopes during the Apollo era. A good next-step for NASA in the immediate post-Apollo years was to take the next step, and look at Jupiter briefly from close range. An existing line of spacecraft basic types, called "Pioneer," had already be developed and used for exploration. NASA opted to create two versions of Pioneer, numbers 10 and 11 in the series, and outfit them for the exploration of Jupiter and Saturn.

PIONEER 10

NASA was riding high in the 1969-1972 timeframe due to the successes of Apollo. But the Agency was contemporaneously planning for the future by building on the robotic exploration of the Moon that supported Apollo. "Mariner" was the first program to explore Venus and Mars, using a simple fly-by. Some failed, but *Mariner 2* successfully flew by Venus in 1962, ten years to the day before Gene Cernan made the last footprint (for now) on the Moon. Two others, *Mariner 4* and *Mariner 9*, were extremely successful at Mars.

Mariner spacecraft used solar power for operations. But NASA's plans were more ambitious; it developed two Pioneer-class spacecraft to fly-by the next two planets from the Sun, Jupiter and Saturn, both too far from the Sun for the solar panels of the day to provide sufficient power. Radioisotope Thermal Generators would be used, instead.

Pioneer 10 was launched on March 2, 1972, eight months before Apollo 17 astronauts left the surface of the Moon. This would be the first time NASA would attempt to venture through the asteroid "belt" and out to Jupiter. *Pioneer 10* lived up to its name. It pioneered the equipment and techniques that would allow sending spacecraft into the outer Solar System. It carried a camera and a total of 10 other scientific instruments, some of which were used during the journey to Jupiter, and others that were used during the fly-by.

Pioneer 10 flew by Jupiter on December 4, 1973, passing 81,000 miles above the cloud tops. Numerous images of Jupiter, Europa, Ganymede, and Callisto were returned to Earth, all of better quality than Earth-based telescopes could match. A lot of information about Jupiter's magnetic field and other characteristics were acquired, too.

NASA managed to stay in contact with *Pioneer 10* until January 23, 2003, 30+ years after its Jupiter fly-by!

PIONEER 11

The *Pioneer 11* spacecraft was an almost-identical twin of *Pioneer 10*. It was launched over a year later, on April 6, 1973. NASA planned to get *Pioneer 11* not just to Jupiter, but also to use Jupiter's gravity to swing it toward Saturn. It successfully flew by both, Jupiter on December 3, 1974, and Saturn on September 1, 1979. It passed much more closely to Jupiter than its twin (only 26,400 miles), allowing for a better look overall and in particular, Jupiter's polar region. Its trajectory also allowed *Pioneer 11* to get images of Io. The Saturn fly-by was a resounding success, also, providing us with our first up-close look at Saturn and its rings. *Pioneer 11*'s last successful data transmission was on November 24, 1995.

VOYAGER!

NASA's curiosity was whetted significantly by the results from *Pioneers 10* and *11*. However, the Pioneer platform was not sufficient for a more detailed exploration of the outer Solar System, even using gravity assists. A bigger, more capable, spacecraft and the latest in instrument sophistication was needed. NASA had one such in mind, Voyager!

I've covered *Pioneer 11*, *Voyager 1*, and *Voyager 2* in a previous Item of the Week (https://www.airandspacethisweek.com/assets/pdfs/20210830 Two Accomplishments at Saturn.pdf), so I won't repeat the story of Ed Stone (https://www.airandspacethisweek.com/assets/pdfs/20240617 Ed Stone.pdf) and the amazing Voyagers here. But just the same, I'd like to bring a few points to your attention.

Orbital mechanics folks studying gravitational assists noticed a planetary alignment that could help them reach the outer Solar System more quickly and using less fuel than otherwise possible. The problem was that the alignment occurs only every 176 years, and the launch deadline for using it was imminent (1977). Congress would only fund a mission to Saturn, but NASA knew it was easier to secure funds for an extension of an already-successful mission than for a new one from scratch. The "Grand Tour" idea worked like a charm, and *Voyager 2*'s fly-bys of Uranus (January 24, 1986) and Neptune (August 25, 1989) are still our only close looks to date.

Voyager 2 was launched first (8/20/77 vs. 9/5/77), but *Voyager 1* would be on a slightly faster trajectory and would arrive first at Jupiter. Both would use Jupiter's gravity to fly onward to Saturn. A primary objective of the Project was to fly closely by Saturn's moon, Titan, to gather data and drop a probe into its atmosphere, since it is the only moon in the Solar System with an appreciable atmosphere. If *Voyager 1* failed at Titan, *Voyager 2*'s trajectory would be altered to make up for it, precluding any hope of a Grand Tour. *Voyager 1* accomplished its work at Titan successfully, clearing the way for *Voyager 2* to go on to Uranus and Neptune. It had turned out to be a coin-flip. The booster for *Voyager 1* underperformed a bit. It was OK to get *Voyager 1* to Saturn, but had the boosters been reversed, *Voyager 2* would not have had enough oomph to go past Saturn, even if *Voyager 1* had succeeded there.

Scientists modeling the gravitational environment of Jupiter and its larger moons realized after the mission was launched that Jupiter's innermost large moon, Io, was being subjected to strong gravitational tides, being pulled by both Jupiter and the next large moon further out, Europa. Their calculations showed that the tidal flexing could generate enough heat to melt Io's interior and cause considerable volcanic activity. Their paper detailing their prediction was printed less than a week before *Voyager 1* flew by Jupiter, close enough to get good images of Io. Eruption plumes from active volcanoes were there for all to see, a classic case of making an extraordinary claim and having extraordinary evidence come along conveniently. I call it the "Called Shot," a baseball term for a famous Babe Ruth homer in 1932. You can find out more about in the previous Item of the Week about Voyager (https://www.airandspacethisweek.com/assets/pdfs/20210830 Two Accomplishments at Saturn.pdf) and in this piece in the Archive (https://www.airandspacethisweek.com/assets/pdfs/Peale Cassen Reynolds Called Shot at Io.pdf).

Astonishingly, NASA is still in contact with both *Voyagers*, even though they detected and went through the heliopause some years ago!

As only NASA can, with an assist from Ed Stone and everyone (still) involved with Voyager!

GALILEO

Four spacecraft had made successful fly-bys of Jupiter; now it was time to take the next step of planetary exploration, putting a spacecraft in orbit for long-term detailed study. What better name could there be for such a craft than "Galileo," a reflection of his discovery of the four satellites that collectively bear his name? The Galileo mission was envisioned as having two components: an orbiter that could provide detailed photographic and other data of Jupiter and the Galilean Satellites, and a separatable probe that could make measurements of Jupiter's upper atmosphere. Galileo would be primarily a NASA show, but West Germany supplied the propulsion module. One section of the spacecraft was held stable by celestial navigation, but another part used spin stabilization for instrumentation of the spacecraft's environment.

Galileo was launched from the Space Shuttle *Atlantis*, which lifted off on **October 18, 1989, 35 years ago this month**. *Galileo* was deployed the next day, and was sent Jupiter-ward by an Inertial Upper Stage rocket.

Sometimes one has to go one way to get to a destination in the other direction, and *Galileo* was a case in point. It would use three gravity assists to get to Jupiter economically, first one from Venus (2/10/90) and then two from Earth (12/8/90 and 12/8/92). Data were acquired from all three, providing new information about Venus, and giving all the instruments aboard a good test.

The instruments checked out just fine, but between the two fly-bys of the Earth a serious problem developed. The spacecraft was to deploy a 16'-diameter antenna for high-gain communications with Earth from Jupiter's distance (it wasn't needed while *Galileo* was in the inner Solar System). The antenna had 18 ribs, and three of them jammed when the deployment was attempted. The antenna could not be made to deploy fully, and its resulting claw-like shape seriously interfered with, but did not prevent, radio communications. NASA upgraded its Deep Space Network receiving facility and developed sophisticated data-compression software, an unplanned spin-off that subsequently found considerable use as in a variety of applications.

Both *Pioneers* and both *Voyagers* traversed the asteroid belt on their way to Jupiter. Unlike Hollywood's version, the real asteroid belt is mostly devoid of objects; none of the four previous spacecraft went anywhere near an asteroid. We'd never seen one up close, but *Galileo* trajectory planners were about to change all that. *Galileo* flew by asteroid 951 Gaspra on October 29, 1991. It is a rocky fragment formed by the collision that produced the Flora family of asteroids. Gaspra's exact position was not precisely known prior to the fly-by, which would have made up-close imaging impossible, but NASA developed a new optical navigation campaign while *Galileo* was *en route* (as only NASA can) that, when combined by a shotgun-like image mosaic tactic at closest approach, allowed a detailed look of an asteroid's surface for the first time.

Fancy trajectory work allowed *Galileo* to fly by another asteroid, 243 Ida, a significantly-larger object than Gaspra, on August 29, 1993. Ida had been discovered in 1884, and named for one of the infant Zeus' nurses on Crete. Ida, the daughter of Oceanus, was also the namesake for a wooded mountain on Crete. Mission scientists were astonished when pictures of Ida were found to show that it had a moon of its own, quickly named "Dactyl," in recognition of the Dactyls, mythological creatures that inhabited Mt. Ida, where they invented metalworking using fire. Today, we know of a number of asteroids with "moons."

Galileo was in a favorable position to observe the impact on Jupiter by the Shoemaker-Levy 9 comet in July, 1994. Quite a record for a spacecraft before reaching its destination!

The *Galileo descent probe* was separated from the main spacecraft on July 13, 1995. It would free-fall to Jupiter for the next five months. In late July, *Galileo* adjusted its trajectory with a burn of its main engine, arriving at Jupiter on December 7, 1995. During its orbit injection, it made a close pass of Europa and a very close pass of Io, enduring a radiation environment more than 25x that fatal to humans.

The descent probe hit the jovian atmosphere mere minutes after the orbiter's closest pass to Jupiter. The probe's high speed (47.4 km/sec) and the thickness of the upper atmosphere produced incredible temperatures, but the probe was protected using a heat shield developed from the type used on nuclear ballistic missiles. Decades later, new computational techniques showed that the shield was barely able to withstand the temperatures that were two times higher than that at the Sun's surface. Deceleration was heavy, from Mach 50 to Mach 1 in two minutes, after which the shield was jettisoned and a parachute deployed. The probe was able to radio data for almost an hour as it descended into the upper atmosphere. Its electronics finally failed at 150 °C when the ambient pressure was 22 bars.

Orbit insertion was completed about an hour after the probe's demise. The initial orbit was quite elliptical, but a series of thruster burns at opportune times made it more circular. The primary mission began, eventually comprising four fly-bys of Ganymede, three of Callisto, and three of Europa; each was 100-1000x closer than the closest fly-bys of the *Voyagers*.

Galileo was fulfilling all mission objectives, and remained in good condition, so NASA extended its mission three times. The principal object of study was Europa, which appeared to be covered by an iced-over liquid ocean. Tidal forces were affecting Europa's interior, much like but smaller than the tidal heating that made Io so volcanically active. For Europa to have a liquid ocean requires the presence of tidally-heated hot springs at its base. Such springs in deep-water locations on Earth invariably have abundant life. Hmmmm!

Galileo made 8 close passes by Europa during the mission extensions. Earlier missions had detected features (or lack thereof) that suggested a sub-ice ocean, and the close approaches supported that view strongly.

A short summary of the results of the Galileo Project include:

Jupiter is subject to powerful thunderstorms, with lightning strikes 1000x stronger than those on Earth.

Zones in the atmosphere beneath the cloud tops can be drier than expected, even free of clouds in places, but water vapor is still abundant.

A liquid sub-surface ocean has existed on Europa and likely exists today. Its fractured crust resembles that of pack ice on Earth, and one fracture, showing strike-slip movement, rivals the San Andreas Fault in size.

Galileo magnetic data suggests that Ganymede and Callisto also have, or at least once had, liquid (salt)water under their surfaces, too.

Europa, Io, and Ganymede have differentiated (iron-rich core overlain by a mantle of lighter material). Callisto is more uniform in composition.

Europa has a thin ionosphere, primarily oxygen; Ganymede has a thin atmosphere of hydrogen (which implies it is routinely replenished by some process).

Ganymede has a magnetic field. Like Europa, its surface shows abundant tectonic features.

Io is at least 100x more volcanically active than the Earth. Its volcanoes are hotter, too, than their terrestrial counterparts, suggesting that silicon-oxygen compounds are being erupted.

Jupiter's small ring system is formed from debris blasted off Jupiter's closest small moons by meteoric impact.

The Galileo Project was a complete success. *Galileo*'s final orbit was on September 21, 2003.

POST-*GALILEO*

Jupiter has been visited by a successful orbiter mission after *Galileo*, called *Juno*, now near the end of its tenure in Jupiter orbit (see second piece in the News: Solar System section below). The *Europa Clipper* is scheduled for launch this month. Its mission will be to investigate the frozen-over ocean-surfaced Europa that has the potential for harboring life. The *Lucy* spacecraft is presently *en route*, not to Jupiter but to six asteroids in Jupiter's orbit.

Saturn's first orbiter was a big success, too, a now-ended mission called *Cassini*.

Uranus and Neptune have yet to be revisited. However, *New Horizons* flew by Pluto in 2015, and is now exploring the Kuiper Belt region.

The post-*Galileo* missions named above are all worthy topics for a future Item of the Week, someday joining the *Cassini* and *New Horizons* missions in the Item archive: https://www.airandspacethisweek.com/assets/pdfs/20221010 Cassini Mission.pdf and https://www.airandspacethisweek.com/assets/pdfs/20210125 New Horizons - To Pluto and Beyond, with Style!.pdf .

RESOURCES

PIONEER 10* and *11

NSSDC: https://nssdc.gsfc.nasa.gov/planetary/pioneer10-11.html

NSSDC: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1972-012A

NSSDC: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1973-019A

NTRS: https://ntrs.nasa.gov/citations/20190002224

NASA: https://science.nasa.gov/mission/pioneer-10

NASA: https://science.nasa.gov/mission/pioneer-11

Mead, G.D., Special Editor, *Journal of Geophysical Research, Pioneer 10 Mission: Jupiter Encounter*, JGR volume 79, number 2, September 1, 1974

Fimmel, Richard O., et al., 1980, *Pioneer: First to Jupiter, Saturn, and Beyond*, NASA SP-446

Pioneer 10's Last Signal: https://nssdc.gsfc.nasa.gov/planetary/text/pion10_pr_20030225.txt

Pioneer 11 Ends Operations: https://nssdc.gsfc.nasa.gov/planetary/text/pioneer-11_endops.txt

The Planetary Society: https://science.nasa.gov/mission/pioneer-11

NASM: https://airandspace.si.edu/collection-objects/pioneer-10-11/nasm_A19770451000

VOYAGER

NSSDC (Voyager Project): https://nssdc.gsfc.nasa.gov/planetary/voyager.html

NSSDC (*Voyager 1*): https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1977-084A

NSSDC (*Voyager 2*): https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1977-076A

Science@NASA (*Voyager 1*): https://science.nasa.gov/mission/voyager/voyager-1

Science@NASA (*Voyager 2*): https://science.nasa.gov/mission/voyager/voyager-2

Voyager Missions to Jupiter, 1981, a volume of reprints from the Journal of Geophysical Research, volume 86, number A10, September 30, 1981

Old Data, New Discovery: https://www.nasa.gov/missions/voyager-program/revisiting-decades-old-voyager-2-data-scientists-find-one-more-secret

GALILEO

NSSDC Orbiter: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1989-084B

NSSDC Probe: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1989-084E

NASA Science: https://science.nasa.gov/mission/galileo

JPL: https://www.jpl.nasa.gov/missions/galileo

Yates, C.M., et al., 1985, *Galileo: Exploration of Jupiter's System*, NASA SP-479

Meltzer, Michael, 2007, *Mission to Jupiter: A History of the Galileo Project*, NASA History Division, NASA SP-2007-4231

Galileo Data Still Useful: https://www.nasa.gov/solar-system/old-data-new-tricks-fresh-results-from-nasas-galileo-spacecraft-20-years-on

Fact Sheet: file:///C:/Users/dr_pa/Dropbox/Downloads/galileo.pdf

JUNO

NSSDC: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2011-040A

NASA Science: https://science.nasa.gov/mission/juno

JPL: https://www.jpl.nasa.gov/missions/juno

NASA Fact Sheet: https://science.nasa.gov/resource/fact-sheet-juno

NASA 10 Things: https://science.nasa.gov/missions/juno/10-things-two-years-of-juno-at-jupiter

Southwest Research Institute: https://www.missionjuno.swri.edu

Wikipedia: https://en.wikipedia.org/wiki/Juno_(spacecraft)

EUROPA CLIPPER

NSSDC: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=EUROPA-CL

NASA Science: https://science.nasa.gov/mission/europa-clipper

JPL: https://www.jpl.nasa.gov/missions/europa-clipper

Mission: https://europa.nasa.gov/spacecraft/meet-europa-clipper

Press Kit: https://www.jpl.nasa.gov/press-kits/europa-clipper

Wikipedia: https://en.wikipedia.org/wiki/Europa_Clipper

LUCY

NSSDC: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2021-093A

NASA: https://science.nasa.gov/mission/lucy

Southwest Research Institute: https://lucy.swri.edu

NASA SVS: Designing *Lucy*'s Path: https://svs.gsfc.nasa.gov/13948

Wikipedia: https://en.wikipedia.org/wiki/Lucy_(spacecraft)

CASSINI/HUYGENS

A+StW Item of the Week: https://www.airandspacethisweek.com/assets/pdfs/20221010 Cassini Mission.pdf

NSSDC (*Cassini*): https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1997-061A

NSSDC (*Huygens*): https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1997-061C

NASA Science: https://science.nasa.gov/mission/cassini

Science@NASA: https://science.nasa.gov/mission/cassini/about-the-mission

"Grand Finale": https://solarsystem.nasa.gov/missions/cassini-hds/mission/grand-finale/why-cassini-mattered

Wikipedia: https://en.wikipedia.org/wiki/Cassini–Huygens

NEW HORIZONS

NSSDC: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2006-001A

APL: https://pluto.jhuapl.edu

NASA: https://www.nasa.gov/missions/new-horizons/exploring-the-unexplored-new-horizons-mission-to-pluto

NASA Blog: https://blogs.nasa.gov/pluto

Science@NASA: https://science.nasa.gov/mission/pluto-exploration

Wikipedia: https://en.wikipedia.org/wiki/New_Horizons

Musical Tribute by Sir Brian May of *Queen*: https://www.youtube.com/watch?v=j3Jm5POCAj8

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