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Paul Schenk
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Introduction

1.1 The revolutionary importance of the Galilean satellites

Watershed moments, upon which the fates of nations, continents, or peoples hinge, are rare in human history. The Battle of Salamis in 480 BC, the Battle of Zama in 202 BC (my sympathies are with Carthage), the defeat of the Moors by Charles Martel in AD 732, the Sack of Constantinople in 1204, the death of Ogedei Khan as his armies approached Wien (Vienna) in 1241, the coming of the Black Plague in the fourteenth century, and the Czar's and Kaiser's decision to mobilize in August 1914 come to mind.

In this year 2009, we approach the 400th anniversary of another of these watershed events: the discovery of Jupiter's four large Galilean satellites, Io, Europa, Ganymede and Callisto, in January 1610 by Italian scientist Galileo Galilei. Galileo, sometimes falsely credited with invention of the telescope, perfected the basic instrument and was the first to point one at the heavens in earnest. Importantly for Galileo, he was quick to understand the revolutionary import of what he saw. Every object he observed, starting with the Moon, followed by Venus and Jupiter, revealed fundamental truths hidden to the naked eye that profoundly altered our perception of how the Universe worked, and in turn our worldview of ourselves and our place as a species in the Universe. Other revolutions were to follow in astronomy, chief among them Edwin Hubble's discovery that spiral nebulae are in fact millions of island galaxies like our own in a vast Universe, but Galileo's revolution permanently broke our myopic anthropocentric view of our place in the Universe, although it would take a few centuries for this new view to finally permeate the collective mass consciousness (and in some minds it never has).

The four moons Galileo saw are binocular objects, and would be visible to the naked eye outside the glare of Jupiter itself. Although there are claims (for Chinese astronomer Gan De in 362 BC, for example) that those with exceptional sight can actually detect the brighter moons with

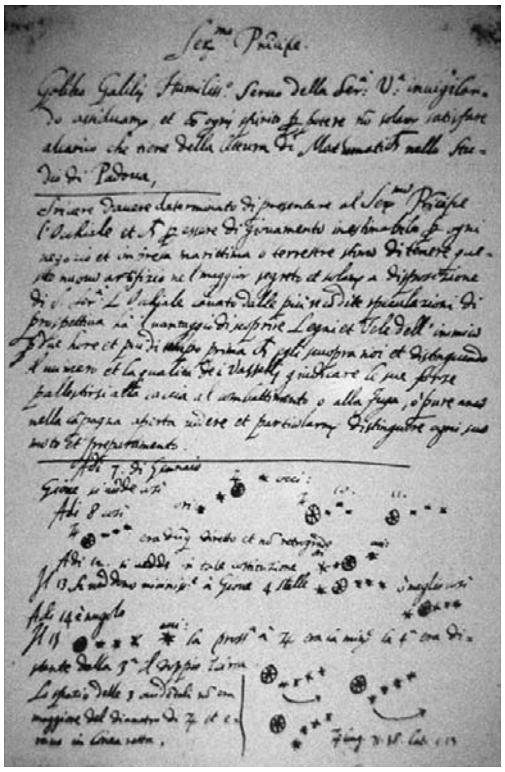

Figure 1.1 A page from Galileo's notes of his discovery of the Galilean satellites January 7, 1610. Jupiter is the large star and the four moons are the small shifting stars to either side. These are among the most valuable scientific documents in history. Credit: NASA.

the eye, their existence was inconceivable as December 1609 rolled to a close. Looking at Jupiter, Galileo saw three new "stars" in a line very close to the planet (Figure 1.1). After several days of observation, it was clear that there were in fact four new objects, and that they were all in orbit around Jupiter, not the Earth. Galileo's observations, and those of the Jovian moons in particular, thus gave a critical boost to the emerging Copernican Sun-centered worldview.

For more than a thousand years, it had been generally assumed that everything revolved around the Earth, which a casual observation of the heavens would imply. Copernicus helped relaunch the ancient Greek theory (by Aristarchus) of the Sun-centered (or heliocentric) Solar System in the early 1500s, but by the early 1600s the theory had received a decidedly ambivalent response. There were a few believers to be sure, but most had never heard of it, or remained unimpressed or uninterested. What Galileo saw on the Moon, Venus and Jupiter demonstrated that the celestial bodies are not immutable and that they do not all revolve around the Earth. (We now know that nothing is the center of anything, but the major point had been achieved.) Although it would be decades before the debate was won, mainly against yet another of the many reactionary responses from the conservative wing of the church to independent human thought, the first great astronomical revolution was now inevitable (and required only Kepler's "invention" of the elliptical orbit to be complete).

1.2 Post-discovery

A few years after Galileo's announcement in the *Sidereus Nuncius* (*Stellar Message*), German astronomer Simon Marius claimed to have discovered the four moons at about the same time. Today, Galileo is given credit, but it is Marius who is credited with the names by which we know these four moons, all named after Jove's indiscretionary loves in Greek mythology. These names did not enter common use till the twentieth century. Today, Marius and Galileo are both honored with names of large provinces on Ganymede.

The Galilean satellites then lay dormant in human thought for several centuries. True, they were useful for terrestrial longitude determination and for estimating the speed of light (based on eclipse timings). In the seventeenth century, Laplace explained the curious mathematical timing, or resonance, between the three inner moons in which their orbital periods are related by simple integers (this Laplace Resonance is named for him). The profound consequences of this orbital dance were not understood for another 200 years, however.

With the advent of "modern" telescopic instruments and techniques, the Jovian moons began to emerge as real planetary bodies. Still, by the dawn of the Space Age in the late 1950s, little was known about these worlds (Figure 1.2). *Pioneers* 10 and 11 were the first visitors to Jupiter a few years before (I listened to the hourly radio news summaries for word of *Pioneer* 10's successful launch). Although the imaging systems were "primitive," they did show a few fuzzy global features that can now be identified on our maps (Figure 1.3). Earth-bound observers saw dark "polar caps" on Io, bright caps on Ganymede and a dark equatorial band (or patches) on Europa. These features proved real, but most other apparent markings did not.

Spectroscopic observations found water ice on all the moons except Io, which also looked oddly yellowish. Instead, sodium clouds were found in Io's orbit. These scant facts lead to perhaps the best-known pre-*Voyager* speculation, which suggested that Io was covered by the salty deposits of a dried-up ocean. There was also the curious coordinated timing between Jupiter's radio emissions and Io's rotation period. By the mid 1970s, it was apparent something odd was going on in the Jupiter system.

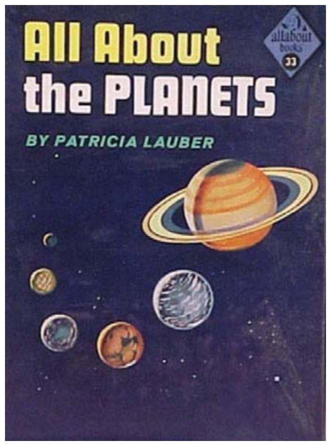

Figure 1.2 The Solar System was a relatively simple, sedate place as the Space Age dawned. Only one paragraph is granted the four Galilean satellites in this volume that once occupied my bookshelf, space enough to assert that Ganymede has canal-like lines, an obliquely prophetic statement as it turns out. (*All About the Planets*, P. Lauber, Random House, 1960.)

1.3 *Voyager* and *Galileo*: Global mapping begins

The Galilean satellites have launched another revolution in our own time, the importance of which is not yet fully manifest. This revolution began in 1979. Prior to spring that year, it was commonly assumed that the satellites orbiting the four giant outer planets were essentially relicts of planetary formation, perhaps even cold dead worlds. *Voyagers* 1 and 2 were the first to explore the Jovian system with what we would call modern scientific instruments, including high-definition television cameras. What they revealed fundamentally altered our perception of the Outer Solar System. All four moons proved to be unique planetary bodies, as these pages document. The monopoly of Mars on our imagination was broken.

Voyager acquired high-resolution images of all four satellites, but the politics of celestial dynamics, competing mission requirements, and a date with Saturn demanded that the *Voyagers* give Europa less attention than the other Galilean satellites. It required the focused and detailed

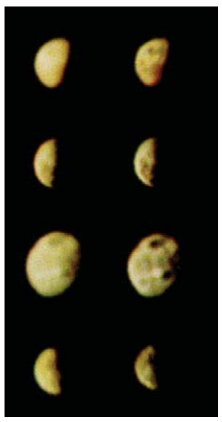

Figure 1.3 *Pioneer* 10 and 11 images of the Galilean satellites in 1973 and 1974 (from top to bottom: Io, Europa, Ganymede, and Callisto). These images have effective resolution of 200 to 400 kilometers. The right side versions have been heavily processed to enhance what little detail is present. Nowadays, the Hubble Space Telescope routinely acquires images with 10-fold improvement in resolution. Credit: NASA/Ames Research Center.

observations of another Galileo, in this case a robotic explorer launched from the human home world, to reveal the fundamental nature of this ice-covered moon, demonstrating that Europa most likely possesses an ocean of liquid water beneath its surface. This marks Europa as one of several objects in the Outer Solar System possessing liquid water, hydrocarbons (perhaps), and internal heat sources. Each is a required element of any potential habitat for life, as we understand such things. What really lies or grows (?) inside Europa is not yet known, but Europa leads an impressive group of active icy worlds, including Triton, Titan, Enceladus, and perhaps even Ganymede. Where this fundamental shift in thinking will take us in the next decades no one can say, at least until we return to Europa.

A total of eight spacecraft have visited the Jupiter system since 1972, the most recent in 2007. Of those carrying dedicated cameras, only three have passed within the confines of the Galilean satellites, and only one has lingered for more than a day (Appendix 4). These three spacecraft, the two *Voyagers* and *Galileo*, have changed our perceptions of these moons, yet no truly global mapping data sets exist for the Galilean satellites. The global mosaics presented here are cobbled together from hundreds of images taken by the *Voyager* and *Galileo* spacecraft during their flybys of these satellites, beginning in 1979 and resuming in 1996.

Voyagers' discoveries at Jupiter are spread throughout this *Atlas*, but the story began in 1966 as a simple concept to use Jupiter to accelerate a spacecraft towards the other outer planets. Although the concept of gravity assist was known, Ph.D. student Gary Flandro discovered the opportunity that became the germ of the *Voyager* project. *Voyager* started life as the Grand Tour, a fleet of four spacecraft to visit all five outer planets, including Pluto, during a grand alignment of planets that occurs only every 173 years or so. The budget was not awarded to fit this profile, so in 1972 four spacecraft became two, and five planets became two (plus two: Uranus and Neptune were optioned for *Voyager* 2 only if *Voyager* 1 succeeded at Jupiter and Saturn). Pluto was not physically within reach of either *Voyager* and only now is a spacecraft on its way to that remote orb.

The two *Voyagers* were targeted to observe opposite hemispheres of each satellite, but effective resolution seldom exceeded 1 km, and significant mapping gaps remained, especially on Io and Europa. Even before *Voyager* arrival, a follow-on mission, the Jupiter Orbiter Probe, was designed in the mid 1970s for a 1982 mission to capitalize on and complete the *Voyager* discoveries. Renamed *Galileo*, it would remain in Jupiter orbit for at least 2 years of extended studies of the planet and its moons.

It was *Galileo*'s mission during its repeatedly delayed grand orbital tour of Jupiter (later extended by four more years) to pass within a few hundred kilometers of Europa, Ganymede, and Callisto with a battery of remote sensing instruments. (Io was targeted for a close pass during the first orbit in 1995 but due to the extreme radiation environment, additional passes were awarded only after the primary mission had succeeded. A tape recorder anomaly caused the cancellation of these first high-resolution Io observations.) Among other investigations, *Galileo* was expected to essentially replace the partial *Voyager* maps with nearly global mapping at resolutions of a few hundred meters and acquire very high resolution images of high-priority targets at 10 to 100 meter resolutions. Information on interior structure and magnetic fields were acquired but compositional mapping was severely restricted. *Galileo* was never able to achieve more than a tiny fraction of its global mapping mission.

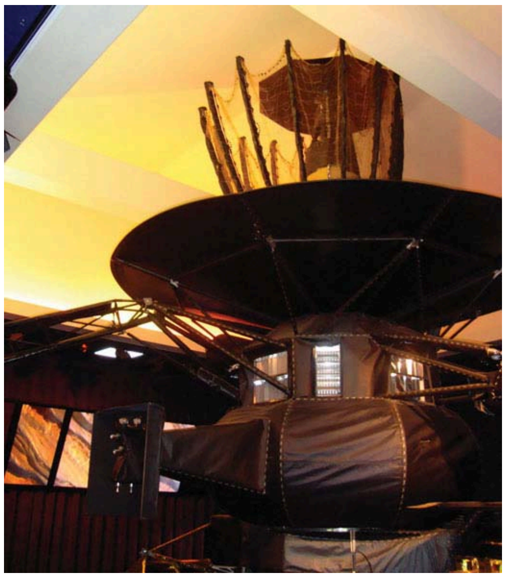

Figure 1.4 The *Galileo* engineering test model, on display at the Jet Propulsion Laboratory, Pasadena, CA. The wire mesh antenna at top is shown in its real-life jammed configuration.

The principal devil in this is the High-Gain Antenna, or HGA (Figure 1.4). The HGA onboard *Galileo* was designed to furl like an umbrella inside the Space Shuttle and be opened in space to provide the primary data link to Earth at 140000 bits per second. The additional delays incurred due to the *Challenger* accident weeks before the scheduled launch in 1986 had unforeseen consequences. After three more years on the ground and two years in space (furled to protect the gold-plated mesh from the Sun), the antenna refused to open properly for reasons that today remain obscure. The secondary antenna on *Galileo* could only transmit at roughly 10 to 20 bits per second, no better than during the first Mars mission back in 1965, when it took more than a month to transmit 22 small images back to Earth from Mars. After years of frustrated effort, the antenna remained unusable and *Galileo* would return only a tiny fraction of its intended data.

Once it was realized that the antenna would never work, JPL engineers did a superb job in teasing as much information from the probe as possible. Onboard and ground-based upgrades increased data transmission to ~150 bits per second by the time *Galileo* arrived in late 1995, an improvement but still crippling (compare this to your current cable or wireless capacity). The onboard tape recorder was also very limited, with a total capacity of only 115 megabytes, less than a CD-ROM. Using onboard data compression similar to JPEG, together with upgrades to receiving antennae, a valuable data set was obtained, including amazing high-resolution images of each satellite. Still, the imaging instruments had to share this downlink capacity with ten other instruments. The intense radiation environment at Jupiter also inflicted a toll on the spacecraft, requiring further engineering efforts to keep the machine operational. Towards the end of the mission, *Galileo* succeeded in obtaining its programmed objectives about as often as it failed. Despite the great success of all these efforts, the loss of potential data was staggering.

The science teams responsible for guiding *Galileo*'s tour of Jupiter faced a cruel choice: how best to use the sparse resources provided by the tiny backup antenna and recorder to achieve some of the original mission goals. Typical imaging results for any given Jupiter orbit during the original two-year prime mission (not including NIMS data) were only 150 to 180 images for Jupiter, its rings, and satellites, and quite a few of those were only partly returned. The allocation ratio for imaging increased slightly during the extended missions, which focused heavily on the new Europa and Io discoveries. With the exception of very limited success at Europa and Io, however, global mapping was sacrificed in favor of (reduced) high-resolution imaging (see Appendix 3). In fact, the global maps of Ganymede and Callisto are still heavily dominated by *Voyager* images, and the hemisphere of Io observed by *Voyager* 1 was never seen well by *Galileo* at all. As a result, the best resolution that can be sustained at global scales on any of these satellites is about 1 km, the resolution of all global and quadrangle maps in this *Atlas*.

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Format of the *Atlas*

Naturally enough, the *Atlas* proper is divided into four major parts, one for each satellite. Global maps at 1-kilometer resolution introduce each satellite. These are in cylindrical projection, in which latitude increases at a constant rate from pole to pole, and are reduced in scale to fit the page. These are followed by a set of five orthographic global maps from various perspectives (including leading and trailing hemispheres), simulating the views a passing astronaut might have. Following planetary mapping convention, each satellite is then divided into 15 quasirectangular maps of roughly equal size called *quadrangles* (Figure 2.1). These show the full 1-kilometer resolution detail of the global maps. These maps are named and numbered according to convention. For example, quadrangle “Je9” refers to “J”upiter satellite “E”uropa quadrangle “9.”

No two-dimensional map can fully represent a three-dimensional surface without distorting either feature sizes or shapes. The quadrangles come in three map projections. Polar maps are in polar stereographic projection. Equatorial maps are in mercator, while mid-latitude maps are in lambert conformal conic projection. All three projections are conformal in that they preserve shapes fairly well. None of these

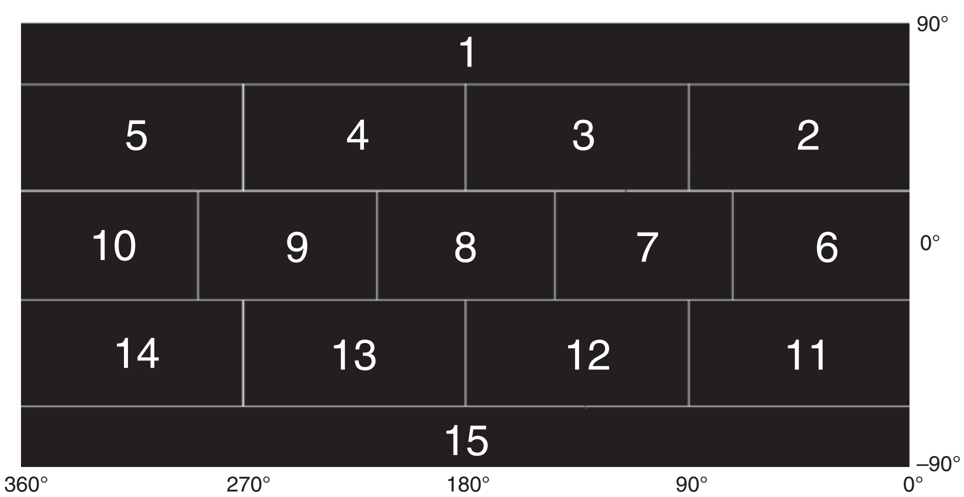

Figure 2.1 Index map showing global locations and dimensions of numbered quadrangle maps for each satellite. Each quadrangle as shown in the *Atlas* includes extra borders that overlap with neighboring maps by 2 degrees. This map is in simple cylindrical projection.

projections preserves areas, but each map size is sufficiently small that this distortion is minimized.

Following each quadrangle map, all *Galileo* and *Voyager* targeted high-resolution mosaics that occur within that quadrangle are presented. With a few exceptions, these are shown at their original resolution, which can vary between ~6 meters to roughly 500 meters (plus a few at up to 850 meters). The mosaics are in orthographic projection, but most are very small in area and map distortions are minimal. The mosaics are shown overlain on lower-resolution images to provide context. Collectively, these images cover less than 10% of the surfaces of these bodies. The locations of these targeted mosaics are shown on index maps for each satellite in Appendix 3.

The *Atlas* proper is followed by a discussion of the satellites as a planetary system and the relevance of future exploration. Appendices containing a glossary, a list of interesting related reading references, charts and data tables, and a gazetteer of feature names are in the final section.

2.1 Nomenclature

All names for features on these satellites are taken from the official International Astronomical Union sanctioned listing of names (see Appendix 5), which resides at the US Geological Survey website in Flagstaff, AZ. They are complete as of 2008. Aside from craters and active plume sites, each name includes a Latin-derived descriptor term (e.g., Maasaw *Patera* for caldera, Cadmus *Linea* for linear markings or bands, Tiamat *Sulcus* for parallel grooves and ridges, Memphis *Facula* and Castalia *Macula* for bright and dark spots, etc.) related to the type of geologic feature involved (see the USGS Planetary Nomenclature website for definitions). Proper names of Ionian features relate to the Io myth, but mostly to volcanic, fire or thunder gods, as appropriate. Those on Ganymede and Callisto are related to Mesopotamia and Egypt, and on Callisto with Nordic legend. Those on Europa are related to the myths of Europa and also to Celtic mythology and place names. On all maps, feature names are labeled to the right of the center of that feature, except when such placement would obscure other interesting features or run off the edge of the map. If the feature is ambiguous, a small dot is used to highlight its identification.

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Making the maps

3.1 Image calibration and quality

Assembling the global maps shown here required the production of and combining of image mosaics from numerous observations by *Voyager* and *Galileo* obtained over periods of years. Before making a true global map, the images must be calibrated to remove background features inherent to the cameras. Unusual characteristics of both *Voyager* and *Galileo* cameras and the nature of each mission plan also affect the location and quality of these images, characteristics that must be taken into account during calibration and global map construction.

3.1.1 *Voyager*

The *Voyager* vidicon tube (old-style television) imagers were designed in the late 1960s and used an electron beam to read out the image data. Although robust and relatively stable, the *Voyager* cameras suffered from problems typical of vidicon cameras. On occasion, the upper left corner of the image was anomalously bright. This unpredictable phenomenon is not accounted for in standard calibration tools, and the corner must be either deleted or smoothed. Near Io, the radiation environment created a temporary background surge in the detector, occasionally saturating bright parts of the image. This can be corrected by knowing the timing and intensity of the exposure anomaly.

The most difficult problem relating to *Voyager* vidicon images is a general distortion due to bending of the electron-scanning beam. This distortion can be corrected using 220 or so 3- to 4-pixel-wide fiducial marks (reseaux) etched across the vidicon chip (and whose true positions are relatively well known). The correction is most severe and sometimes unstable near the edges, where the image sometimes remains slightly distorted. Fortunately, there is sufficient overlap in most *Voyager* mapping mosaics that we can delete the outer 40 or so pixels from the images, except in rare cases where no other imaging exists.

Also, the *Voyager* reseaux themselves represent permanent "dead" areas, amounting to a few percent of the total image. These black spots are usually filled by blurring data from neighboring pixels. For this *Atlas*, these areas were nulled out wherever possible. Valid data from adjacent or lower-resolution images were allowed to fill these holes.

Both *Voyager* encounters with Jupiter were highly successful, except for a timing offset on *Voyager* 1 between camera exposure and slewing of the camera to the next target. Triggered by high radiation before the first satellite encounter, this caused the smearing of some of the best images of Io, Ganymede and Callisto. Overlap of adjacent clean frames covers much of this loss, but for some areas we must rely on lower-resolution approach images.

3.1.2 *Galileo* SSI

Galileo's high-resolution imaging camera (solid-state imager or SSI) used the first CCD imaging system selected to fly in deep space. Built in the late 1970s, the *Galileo* CCD was then relatively new technology. Although much more stable against distortion and intensity flare than the *Voyager* vidicon cameras, the *Galileo* cameras were not without adversity. Late in the mission, images occasionally exhibited strange random square artifacts 6 or 8 pixels wide, which must be removed. Also, if bright surface features saturated or overexposed parts of the CCD, the photon charges on those pixels leaked downward into neighboring pixels, causing bright streaks across part of the scene, a phenomenon known as "bleeding" or "icicles" (an effect not seen in modern CCDs). This is usually most evident in images with highly contrasting bright and dark terrains, such as on Callisto and parts of Ganymede.

Jupiter's intense radiation resulted in a number of anomalies, the most important of which was sensitivity to radiation-induced noise in images of Io and occasionally Europa. This came in the form of random brightened pixels towards the bottom of some images, resembling shaken salt. Oddly, the highest-resolution images acquired near Io itself tended to be less affected than context images acquired a few thousand kilometers further away.

Project engineers were kept very busy keeping the spacecraft operating properly in the unforgiving high-radiation environment of Jupiter's