# 1

# Ganymede through the Ages

MARTIN VOLWERK, KATRIN STEPHAN, ROLAND WAGNER, AND APURVA V. OZA

## 1.1 PROLOGUE

Ganymede is the third Galilean moon of Jupiter and the largest moon in the solar system (even larger than the planet Mercury). Through the history of humankind Ganymede has made a transition from a mythological figure to one of the most interesting objects in the solar system. In this chapter an overview will be given of the development of Ganymede through the various ages: from being a "prince abducted by a god" to being a "habitable colonized world."

Some of this may not be scientifically valid when it is dealing with the mythology around Jupiter and Ganymede in Section 1.2, and with science fiction views of Ganymede in Section 1.6. However, it is part of how Jupiter and Ganymede were and are seen.

The scientifically valid part starts with a discussion of the discovery of this moon in Section 1.3. The optical, ground-based studies of Ganymede including the early development of surface maps discussed in Section 1.4. Space-based observations and spacecraft flybys are discussed in Section 1.5, including the ever-increasing detailedness of images of the moon. The Galileo spacecraft results are only briefly mentioned, as those will be discussed further in the following chapters in this book.

Now please enjoy a trip through the ages covering the discovery and study of Ganymede.

## 1.2 THE MYTHOLOGY AGE

In many societies Jupiter, as a prominent bright wanderer across the skies, played an important part in their mythologies. Naturally, Ganymede, stemming from Greek mythology, is not mentioned in mythologies from other situations. Nevertheless, two other Jovian mythologies are also mentioned here.

### 1.2.1 Greek

Ganymede is a Greek mythological figure, mentioned for example in Homer's *Iliad*, and was the son of King Tros, the founder of Troy. He was acclaimed to be the most beautiful of mortal men:

> Now Erichthonius sired Tros, a lord of the Trojans, and Tros, in turn, had three distinguished sons: Ilus, Assaracus and Ganymede radiant as a god, and he was the handsomest mortal man on earth – and so the immortals, awestruck by his beauty, snatched him away to bear the cup of Zeus and pour out wine for all the deathless gods. (Fagles, 1990, p. 511)

Zeus (Jupiter) abducted him, disguised as an eagle, from Mount Ida near Troy (see Fig. 1.1), where Ganymede was herding a flock of sheep. Zeus carried him to Mount Olympus, where he then was made immortal and served as a cup bearer. King Tros did not go uncompensated for his loss and received fine horses from Zeus, which were delivered by Hermes (Mercury):

> "They are the very strain farseeing Zeus gave Tros, payment in full for stealing Ganymede, Tros's son: the purest, strongest breed of all the stallions under the dawn and light of day". (Fagles, 1990, p. 172)

Ganymede is also connected to the constellation Aquarius (Water Carrier), as according to some versions of the story Zeus placed Ganymede in the sky as the constellation Aquarius, next to the constellation Aquila (Eagle).

### 1.2.2 Chinese

In Chinese astronomy/astrology Jupiter is connected to the element wood (from the Chinese five elements philosophy) and to the Cyan Dragon (chinese: *qing* long), representing the east and spring. As one of the primary colours, cyan represents wood in Chinese philosophy, and Chinese astronomers found that Jupiter was a cyan planet in the skies.

Astronomers studied the heavens and Gan De (~400–340 BCE claimed to be the discoverer of Ganymede, see Section 1.3) and Shi Shen tabulated the orbits of the planets to high precision. Gan De writes in his "Treatise on Jupiter":

> "Every 12 years Jupiter returns to the same position in the sky; every 370 days it disappears in the fire of the Sun in the evening to the west, 30 days later it reappears in the morning to the east."

With the 12-year chronology in China, and the 12 signs of the Chinese zodiac, Jupiter was called "*Sui Xing*," star of the year. However, as its orbit is not exactly 12 years, an idealized Jupiter was entered "*Tai Sui*," the god of the year, who plays an important part in Taoism. With the 12 zodiacal signs and the 5 elements, there is a total of 60 Tai Suis. Interestingly, Tai Sui is a noble's god who only protects the emperor and kings. It is said that every year right under Tai Sui a meat-like growth can be found underground, being the incarnation of the god, which



https://doi.org/10.1017/9781108966474.002 Published online by Cambridge University Press

**Figure 1.1** Michelangelo's *Ganymede*. Copy after a lost original (1532) (*Wikimedia Commons* https://commons.wikimedia.org/wiki/File:Andr 37.jpg).

is taboo to dig up. Although it is also said to be a miraculous medicine that can cure all illnesses.

### 1.2.3 Vedic

The presence of Ganymede as one of Jupiter's abundant satellites may be present in Vedic cosmologies as far back as 800 BCE in the original astronomical text *Vedanga Jyotisha* of the ancient Indian subcontinent (Subbarayappa, 1989, p. 86). The Vedas state that Jupiter is *Brhaspati* (*spati* – *braha*: spirit – cosmic vastness) who is the guru (*ru* – *gu*: darkness – dispeller), or teacher, of all devas (gods) (Dalal, 2010).

The Ancient Indian mythology says that the devas would therefore orbit Brhaspati to gain *gnan* (cosmic knowledge), therefore although not explicitly mentioned as one of four bright satellites, Ganymede would indeed be one of 33 students (or satellites) seeking knowledge from Brhaspati.

Brhaspati as a planet is discussed more empirically from naked-eye observations at the turn of the common era in the texts *Aryabhatiya* (Aryabhata; 400 CE), *Romaka* (Latadeva; 500 CE), *Panch Siddhantika* (Varahamhira; 500 CE), *Khandakhadyaka* (Brahmagupta; 600 CE), and *Sidyadhivrddida* (Lalla, 700 CE). Consistent with European literature, no observational claim of a naked-eye detection of Ganymede is made, although speculation of *upagrahon* (satellites) is discussed in the context of Brhaspati as a continuation of the *Vedanga-Jyotisha*.

Thursday, from Proto-Germanic Thor's day (*thonaras daga*) is consistent across Indo-Germanic culture with Greek: *hemera Dios* (day of Zeus), Latin: *Jovis dies* (Jupiter day), and Hindi: *Guruvaar* (Guru/Brhaspati day).

## 1.3 THE DISCOVERY AGE

It is well known that early civilizations already studied the heavens and planets (see e.g. Kelley and Milone, 2011), sometimes with highly sophisticated techniques. For example, the ancient Babylonians used a "time-velocity" graph to calculate Jupiter's position, as found on cuneiform clay tables from 350 to 50 BCE (Ossendrijver, 2016).

Usually, it is accepted that the four large moons of Jupiter were discovered by Galileo after he obtained his first telescope from the Netherlands. However, there are some old Chinese sources that claim the discovery of Ganymede by a Chinese astronomer (Xi, 1981).

It is said that one of the earliest Chinese astronomers, Gan De, discovered Ganymede 2000 years before Galileo (Hughes, 1982). In the fourth century BCE Gan De studied the heavens, and in particular Jupiter (Chinese: *Sui Xing*, Year Star) and wrote two books on astronomy: *Sui Xing Jing* (*Treatise on Jupiter*) and *Tianwen Xingzhan* (*Astrological Prognostication*) in the "Warring States" period (475–221 BCE). Unfortunately, both books were lost, however, parts of them were incorporated in a later work by Qutan Xida (aka Gautama Siddha): *Kaiyuan Zhan Jing* (*The Kaiyuan Treatise on Astrology*) written between 718 and 726 CE (Xi, 1981). This work quotes from Gan De:

> "In the year of chan yan ... Jupiter was in (the Zodaical Division of) Zi, it rose in the morning and went under in the evening together with the Lunar Mansions Xunü, Xü and Wei (Aquarius). It was very large and bright. Apparently, there was a small reddish (*chi*) star appended (*fu*) to its side. This is called 'an alliance' (*'tong meng'*)."

In 1973 the Mawangdui Silk Texts were discovered in Changsha, Hunan (see e.g. Silbergeld, 1982) which contained copies of the works by Gan De and Shi Shen. They stem from before 168 BCE, the year that tomb number three at Mawangdui was sealed. Their writings were gathered under the name *Divination of Five Planets*, and record the motion of Jupiter, Saturn, Venus, and other planets in their orbits between 246 BC and 177 BC (Pankenier, 1992).

The question remains whether it is, indeed, possible to observe Ganymede with the naked eye. The French astronomer Flammarion wrote as a footnote in his book (Flammarion, 1880, p. 536):[1]

> Cette découverte de Galilée montre bien qu'avant lui on n'avait pas observé les satellites de Jupiter. Cependant, d'excellentes vues les ont quelquefois distingués à l'œil nu: cette observation constitue *la plus haute épreuve* que je connaisse pour juge de la portée de la vue humaine.
> This discovery of Galileo shows indeed that before him one had not observed the satellites of Jupiter. Nonetheless, excellent eyesights have sometimes distinguished them with the naked eye: this observation constitutes *the highest challenge* that I know to judge the reach of the human eyesight.

which does not appear in the later English translation by Gore [1907].

[1] https://gallica.bnf.fr/ark:/12148/bpt6k94887w.texteImage.

Admiral William H. Smyth writes (Smyth, 1844, p. 175):

> "Certain esprits fort express surprise that Galileo should have been so gratified by this discovery, since they hold that the satellites of Jupiter are often seen by the naked eye; and they cite the Apennines, and Etna, and the West Indies, and various other fine-climate places, as the spots where such a feat is frequently done."

Xi (1981) mentions that the Beijing Planetarium set up simulations and showed that people with good eyesight would be able to distinguish a 5.5 magnitude moon at an angular distance of 5 arcseconds from a 2 magnitude planet. Thus, seeing Ganymede and Callisto with the naked eye does seem possible.

Now look at the year 1608, in Middelburg, the Netherlands, where either Sacharias Janssen or Hans Lipperhey invented the telescope. The latter patented this instrument. In 1609 Galileo Galilei obtained his first telescope and presented it to the Doge of Venice as a tool for warfare. It was probably the British mathematician/mapmaker Thomas Harriot who first used the telescope to study the heavens (e.g. Roche, 1982), and made a map of the Moon and the first drawings of sunspots and thereby determined the rotation rate of the Sun.

In 1610, then, there is the *Annus Mirabilis*, when Galileo, in March, publishes his *Sidereus Nuncius* (the starry messenger) in which the surface of the Moon, the phases of Venus, and the four large moons of Jupiter are described (see Fig. 1.2). He named the Jovian moons *pianeti Meidici* after his the family who supported him financially, the Medicis.

There are, however, contemporaneous candidates for the discovery of the moons of Jupiter – for example, Simon Mayer (Marius), a student of Tycho Brahe and Johannes Kepler, who independently discovered the four moons. Putting up the timetable of the different discoveries by Galileo and Mayer shows that the latter may have preceded Galileo by a few days in discovering the revolution of the first three moons, but discovered the fourth moon nine days later than Galileo (Johnson, 1930; Pagnini, 1930). Another candidate who is mentioned is Thomas Harriot, who also studied the Jovian system, however this dating of the discovery before Galileo is based on an incorrect interpretation of a date in Harriot's calculations, which was an ephemeris date from Galileo and not an observation (Roche, 1982).

But then there still remains one puzzle: the Frieze in the main hall, Fresoc Casa Marta, Castelfranco Veneto and the painting *The Three Philosophers*, by Giorgio da Castelfranco (Giorgione), which date back to the first decade of the sixteenth century. In the frieze, Jupiter's orbit is portrayed with three concentric circles around the planet, which can be interpreted as the orbits of Io, Europa, and Ganymede. In *The Three Philosophers*, one of the men portrayed shows part of a document that he takes out of his pocket. A detailed analysis of this document shows that Jupiter and possibly the four largest moons are shown. If the interpretation of these two paintings is correct, this would mean that Giorgione would have known about the Galilean satellites about 105 years earlier than Galileo (Keim, 2009).

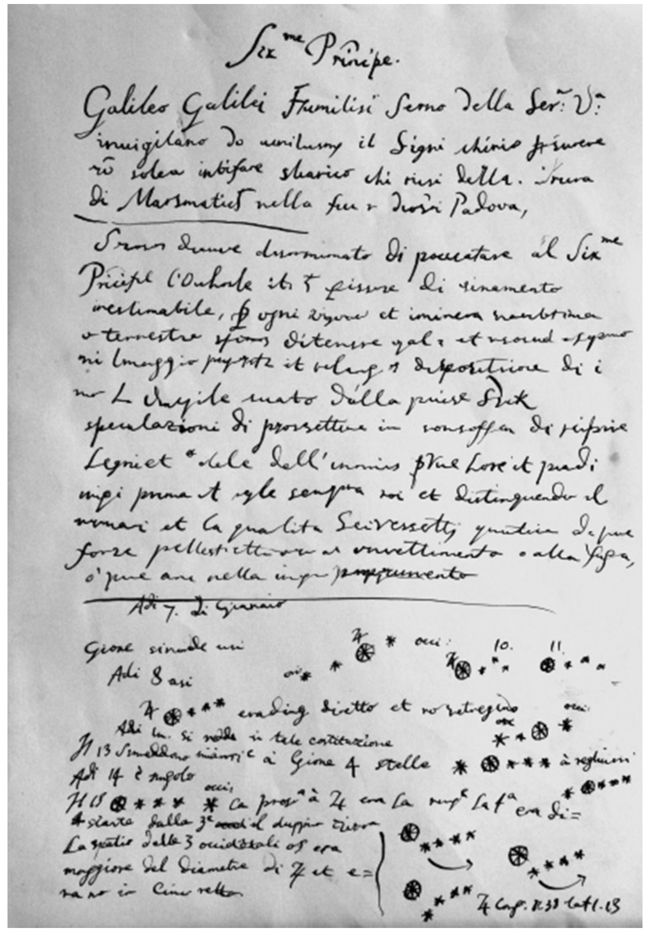

**Figure 1.2** Page from *Sidereus Nuncius* by Galileo, showing the four large moons of Jupiter. Credit: University of Michigan Special Collections Library.

## 1.4 THE TELESCOPE AGE

One of the earliest papers about Ganymede (in NASA's astrophysics data system, ADS) deals with a solar eclipse on Jupiter created by the shadow of the third satellite (Whitmell, 1896). See Fig. 1.3 for an image of Ganymede casting a shadow onto Jupiter. A calculation of the duration of such a solar eclipse is presented for a location $J$ at the equator of Jupiter and it is claimed that this point, which experiences a noon eclipse (of 41m duration), also experiences a forenoon and afternoon eclipse (both lasting 21.5m) when $J$ is at an angle of $58° \, 0' \, 56''$ with the Jupiter–Sun line at the beginning of the forenoon eclipse. Various other special eclipses are discussed. Of course this is a nice exercise of celestial mechanics and does not give any insights into Ganymede. However, the situation can also be reversed: Ganymede entering Jupiter's shadow.

### 1.4.1 Ganymede Entering and Exiting Jupiter's Shadow

Fedtke (1942) reports on observations of Ganymede entering the shadow of Jupiter, as seen through the 13″ refractor of the Königsberger Sternwarte on two different occasions. Using the time interval that it took to completely cover Ganymede, an estimated 10 and 9m, the diameter of the moon could be

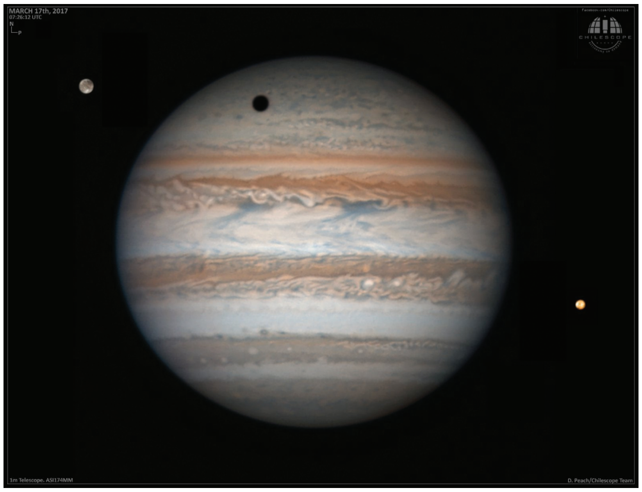

**Figure 1.3** Ganymede throwing a shadow on Jupiter. Image credit and copyright: Damian Peach, Chilescope.

determined as 6 400 and 5 800 km (official values: $R_G = 2\,634.1$ or $D_G = 5\,268.2$ km). These values contrast with earlier determinations of Ganymede's diameter by Barnard (1895), who used Filar micrometer measures of the diameters of the solar system bodies with the 36″ refractor at the Lick Observatory. Barnard (1895) found a diameter of 3 558±54 miles or 5 726±87 km from an average angular diameter of 1.521″, a value that falls well within diameter determinations between 1829 and 1894 which range from 1.488″ to 1.783″.

A satellite entering the shadow of its host will have less insolation and cool down. Murray and colleagues (1965) studied the 8–14 $\mu$m emissions from Ganymede, as well as the optical signal, as Ganymede entered the Jovian shadow on 1963 December 12. Observing the eclipse they found that the cooling or reheating of Ganymede's surface takes less than 15 minutes, with the bulk of the infrared emissions dropping off in less than 10 minutes. This made them conclude that the outermost few millimeters of Ganymede's surface have a thermal inertia as low as that of the Moon, and should be composed of "a fine dielectric powdered material devoid of any gas phase." They also state that it would be interesting to investigate if there is possibly a tenuous atmosphere at Ganymede.

Morrison and colleagues (1971) built further on these results, in which, for the first time, infrared (radiometric) observations at 20 $\mu$m wavelength with the, then-new Mauna Kea Observatory in Hawaii were presented. This work provided a more reliable measurement of the thermal inertia of Ganymede's surface than had previously been possible with observations only with a broadband filter at 8–14 $\mu$m wavelength. This work was later extended to the other Galilean satellites and Titan (Morrison et al., 1972).

**Intermission: Recollections of a Contemporary**

Dale Cruikshank narrates:

The discovery of ices on the Galilean satellites is usually credited to Gerard Kuiper. He was the pioneer infrared astronomer in the world, observing many stars and solar system bodies with the near-infrared spectrometer he built with infrared detectors that were developed during World War II and later declassified. He published an abstract in which it was stated that the reflectances of Europa and Ganymede "are most readily explained by assuming that II (Europa) and III (Ganymede) are covered by $H_2O$ snow" (Kuiper, 1957). However, there were no figures shown in this abstract. He also suggested that because Ganymede is darker than Europa, the snow on its surface might be contaminated with silicate dust.

In 1965, Moroz, who pioneered infrared astronomy in the USSR, published spectra of the Galilean satellites and interpreted the Ganymede spectrum as showing $H_2O$ ice. The 1965 paper in Russian was published in English in 1966 (Moroz, 1966).

As the attention of planetary astronomers was drawn to the Galilean satellites by subsequent work, it was always Kuiper who received credit for the discovery of $H_2O$ ice, although he had only published a brief verbal description. Moroz published spectra, and he was very upset and irritated that he did not get credit for the discovery. He expressed this to me during my one-and-a-half years of work with him in Moscow and Crimea, and subsequently in a letter after I returned to the United States.

Kuiper was apparently aware of this tension, and finally published his spectra in 1973 in the Communications of the Lunar and Planetary Laboratory (Kuiper, 1973). Kuiper died later that year. Moroz, who died in 2004, was never satisfied with the situation.

New observations of Ganymede with the infrared spectrometer of Moroz, conducted with the Shajn 2.6 m telescope at the Crimean Astrophysical Observatory confirmed the presence of $H_2O$ ice with higher quality data than Moroz had previously published. Ludmila Gromova, a graduate student at that time (who later married and published under the name Ludmila Zasova), and I, as a visiting American astronomer, together with Moroz published the results (Gromova et al., 1970).

In terms of physical studies of Ganymede, Morrison and colleagues (1971) built on the earlier work of Murray and colleagues (1965), which the authors cite, but for the first time this new work presented infrared (radiometric) observations at 20 $\mu$m wavelength. The ability to observe at 20 $\mu$m was unique to the then-new Mauna Kea Observatory in Hawaii (elevation 4.2 km), and this paper provided a more reliable measurement of the thermal inertia of Ganymede's surface than had previously been possible with observations only with a broadband filter at 8–14 $\mu$m wavelength.

The observations at 20 $\mu$m were extended to the other three Galilean satellites and Titan (Morrison et al., 1972).

### 1.4.2 Ganymede's atmosphere and Surface

After a successful discovery of an atmosphere on Io, Binder and Cruikshank (1964) used photometric measurement taken with the Kitt Peak 36″ telescope to search for an atmosphere on Europa and Ganymede. This is done through searching for an anomalous brightening of the moon after it comes out of eclipse, which can be caused by a frost layer on the surface or a haze over the surface created by a surface temperature drop. Binder and Cruikshank (1966) found at Europa (or JII) a brightness anomaly of $0.03 \pm 0.01$ magnitudes, which decayed in ~10 minutes. However, for Ganymede (or JIII) no brightening beyond 0.01 magnitudes was measured. This can be caused by the fact that it takes Ganymede longer, ~20 minutes, to exit the shadow of Jupiter and any frost or haze may have sublimed away before it can be noticed as an anomalous brightness.

The presence of (water) frost on the surfaces of the Galilean satellites had already been suggested by Kuiper (1952). Measuring the reflectivity of JII and JIII (Europa and Ganymede) Harris (1961) and Moroz (1966) found that it was lower at 2 $\mu$m than at 1 $\mu$m, something that is not uncommon for ices (see e.g. Kieffer, 1970).

Using the 60″ McMath telescope at Kitt Peak National Observatory, combined with a scanning Fourier spectrometer, Pilcher and colleagues (1972) measured the reflectivity of the Galilean moons for both the leading and trailing side. They found that the absorption bands in the reflected light, caused by the presence of water frost on the surface of JII and JIII, could be well established, where Ganymede had weaker absorption than Europa. When the geometric albedo of the water frost is assumed to be 0.5 and 0.35 for the underlying material (silicates) they arrive at a frost covering of ~70% of JII and 20–65% of JIII. For a detailed discussion of Ganymede's surface and hydrosphere see Chapters 11 (Ahrens et al.) and 12 (Kalousova et al.) in this book.

It took until 1972 before a successful measurement of Ganymede's atmosphere was made through an occultation of the star SAO 186800 on June 7. The observations showed nonabrupt immersions and emersions of the star, which means that there is a dimming atmosphere surrounding the moon. The surface pressure of the atmosphere was estimated to be greater than $10^{-3}$ mbar. Through these measurements, also the radius and average density of Ganymede could be determined as $5\,270^{+30}_{-200}$ km and $2.0^{+0.2}_{-0.03}$ g/cm$^{-3}$, respectively (Carlson et al., 1973).

Combining the results about the water frost on and the atmosphere of Ganymede, led Yung and McElroy (1977) to look at the possibility of an oxygen atmosphere at Ganymede. Water vapour can be dissociated through radiation at wavelengths below 2 800Å, and a series of reactions can take place in Ganymede's atmosphere, leading to the creation of $O_2$, which in turn can be photo-dissociated again into atomic oxygen that can escape into Jupiter's magnetosphere. They found that there can be an $O_2$ atmosphere around Ganymede with a surface pressure of $10^{-3}$ mbar, in agreement with the estimate above. A full discussion of Ganymede's tenuous atmosphere is given in Chapter 15 (Roth et al.) of this book.

After the Pioneer 10 and 11 missions to Jupiter in 1973 (see Section 1.5) interest in planetary satellites got a big push, as evidenced by the review papers by Morrison and Cruikshank (1974) and Mendis and Axford (1974). Sodium emissions from Io were discovered by Brown and Chaffee, Jr. (1974), and Trafton and colleagues (1974) showed that this was not just reflectance from the surface, but that there exists an extended cloud of sodium around Io. Lanzerotti and colleagues (1975) used the vertical spectrograph of the McMath solar telescope to scan the three innermost moons of Jupiter around the Na D I and II lines. They concluded that there was no significant evidence for emission from Ganymede.

Surface reflectance in the 0.5 to 5 $\mu$m range can be used to find the temperature of the icy surface of the moons. Using infrared observations of Ganymede, made with the 61″ Catalina Observatory telescope (Fink et al., 1973) and comparing the absorption bands in the reflectance with spectra obtained in the laboratory, Fink and Larson (1975) obtained a surface temperature for Ganymede of $103 \pm 10$ K. Clark and McCord (1980) studied spectra of Ganymede in the 0.65–2.5 $\mu$m band and concluded that the water absorption features are caused by free water on the surface, that is, not bound in minerals. And in a further study, comparing the spectra with laboratory reflectance studies of water frost, water ice, and water and mineral mixtures, Clark (1980) concluded that "the spectra of the icy Galilean satellites are characteristic of water ice (e.g., ice blocks or possibly very large ice crystals $\geq$ 1 cm) or frost on ice rather than pure water frost, and that the decrease in reflectance at visible wavelengths is caused by other mineral grains in the surface." See also Chapters 7 (Pappalardo et al.), 9 (Schenk et al.), 10 (Stephan et al.), and 11 (Ahrens et al.) in this book for more in-depth discussions on these topics.

### 1.4.3 Ganymede's Surface Maps

With the advancement of telescopes, it became possible to make images of the surface of Ganymede. Cassini, in 1665, claimed he could see markings on the Jovian satellites, although the crude telescopes of that time would actually render this impossible according to Schaeberle and Campbell (1891). Herschel (1797), in 1794–6, noticed brightness changes of the satellites and as this was periodic, he deduced that they rotate around their axis once per revolution (see also Chapter 3 (Stark et al.)). And in 1796, Schröter (1800) observed a dark marking, not unlike a shadow that a satellite would cast on the surface, on the northern hemisphere.

Some drawings with little detail of the surface of Ganymede were made by Schaeberle and Campbell (1891). Better results were obtained by William Pickering, using the Lowell observatory in 1894, who published a plate with 42 drawings of Ganymede at different longitudes, see Fig. 1.4(b) (Pickering, 1900).[2]

Camichel and Lyot (1943)[3] wrote about the difficulty of observing the surface of the Galilean satellites:

[2] http://cdsads.u-strasbg.fr/historical.html.

[3] Note that there are different references to this paper. This is the NASA-ADS reference. On the first page of this paper authorship is given to "MM. Camichel, Gentili et Lyot," and in other papers it is given to "MM. Lyot, Camichel et Gentili."

https://doi.org/10.1017/9781108966474.002 Published online by Cambridge University Press

> *En dehors des passages, les bonnes observations des satellites de Jupiter sont rares. Une seule série importante des dessins de longitudes divers avait été effectuée, en 1894, à l'Observatoire Lowell, par William H. Pickering.*
>
> Apart from the transits, good observations of the Jovian satellites are rare. One single, important series of drawings for different longitudes was carried out by William H. Pickering at the Lowell Observatory in 1894.

In 1941, observations at the Observatoire au Pic du Midi (Camichel and Lyot, 1943) revealed dark and bright patches on the surface of Ganymede. From the full set of observations a map was created showing a dark band along the equator and bright patches at the poles, see Fig. 1.4(f). Based on the recurrence of the observed structures they concluded that Ganymede rotates around an axis perpendicular to its orbital plane with a period practically equal to its revolutionary period. They also found that within a longitude window between 312° and 19° there exists a "vivid brightness" (*vive blancheur*) which does not rotate with the moon, and posed the question whether this is a deposit of highly volatile material that the solar radiation makes disappear.

One year later Danjon (1944) commented on the dearth of observations of the Jovian satellites and that it would be good to add some more in order to study these interesting objects, and presented a set of drawings of Ganymede's and Callisto's surfaces created in 1934. Danjon's observations show similar dark spots as presented by Camichel and Lyot (1943), with two prominent spots on the northern and one prominent spot on the southern hemisphere, see Fig. 1.4(g). Danjon (1944) also discusses the difference between his observations and those of Camichel and Lyot – some spots were not seen and some were at a different longitude. Commenting on the global map, Danjon writes:

> *Il me semble que MM. Lyot, Camichel et Gentili accentuent et schématisent un peut trop, dans le leur, les deux bandes parallèles à l'équateur de Ganymède, à 30° N. et S. Elles n'ont pas cette netteté géometrique sur leurs dessins et nous lisons du reste (page 57 de leur article) qu'elles sont interrompues. Il n'y a pas lieu, à mon avis, de voir là des véritable bandes.*
>
> It looks to me that Messrs. Lyot, Camichel and Gentili accentuate and schematize a bit too much, in their paper, the two parallel bands to Ganymede's equator at 30° N. and S. They do not have this geometrical sharpness as in their drawings and one reads later (page 57 in their paper) that they are interrupted. It is misplaced, in my opinion, to see real bands there.

In the early 1950s further observations of Ganymede were published in *The Strolling Astronomer*. Hare (1951) discusses several observations, for example by Cave (Fig. 1.4d), with smaller telescopes that all agree on brighter polar caps and possibly some darker structures near the equator.

Reese (1951) presented a drawing of Ganymede's surface that he based on observations by Brinckman, Cave, Cragg, Haas, Oberndorfer, and Sandner using telescopes with apertures of 4 to 12″. Assuming a tidally locked rotation of the moon and a zero longitude at superior conjunction, the result is shown in Fig. 1.4(i). This map seems to accord well around the equator with the one from Danjon (1944), but there is definitely less detail near the north and south pole.

Both (1952) praised the map by Reese for its details, but presented a new composite map created by Howe, Fig. 1.4(j), who used the three earlier maps Figs. 1.4(f)–(h), an unpublished map by Howe (1951), and drawings by Barnard and Antoniadi (undated), which is really a milestone in details. There are, of course, differences in the various maps, however, the dark band around the equator seems to be a common feature in all. Also, the two dark spots at longitude 160° to 220° latitude and 0° to 0° N and at 260° to 320° and latitude 0° to 60° N can probably be accepted as real (Both, 1952).

Further information on the surface of Ganymede is given in Chapters 7 (Pappalardo et al.) and 9 (Schenk et al.). The latest composite surface maps are shown in Appendix A (Roatsch et al.).

With the launch of satellites like Pioneer 10 and 11 (1972/73), Voyager 1 and 2 (1977), Galileo (1989), and the Hubble Space Telescope (HST) (1990), whole new windows opened for the exploration of Ganymede in the Space Age. However, the development of ground-based telescopes also continued, with larger and larger mirrors and of course adaptive optics (see e.g. Hart, 2010, and references therein). Dekany and colleagues (2013) show that images of Ganymede taken by the PALM-3000 telescope and the visible fast-frame imaging camera TMAS using adaptive optics, Fig. 1.5 (left) now obtain even better seeing than the HST, Fig. 1.5 (right).

## 1.5 THE SPACE AGE

### 1.5.1 The Pioneer Mission

In the beginning of the 70ies of the last century, the first spacecraft were sent to the Jupiter system in a time, when only 12 moons of the largest planet in the solar system were known. These two identical twin spacecrafts were termed Pioneer 10 and 11 (Pioneer F and G, originally Miles, 1973; Hall, 1975). Both had a mass of 258 kg and were equipped with 11 identical instruments, one additional instrument was added to Pioneer 11. Pioneer 10 and 11 were mainly designed for physical measurements, such as studies of cosmic rays, magnetospheric fields, temperatures, the solar wind, and the impact of small meteoroids and interplanetary dust particles, rather than imaging Jupiter and/or its satellites. Both spacecraft rotated several times per minute (at 4.8 rpm) around an axis aligned toward Earth, a configuration not well suited for imaging sensors. The imaging sensor aboard both Pioneer spacecraft is the imaging photopolarimeter (IPP) (Pellicori et al., 1973). It was preferentially used for imaging details and so far unknown features in the Jovian atmosphere.

[4] Reprinted from Murray [1975] with permission from Elsevier.

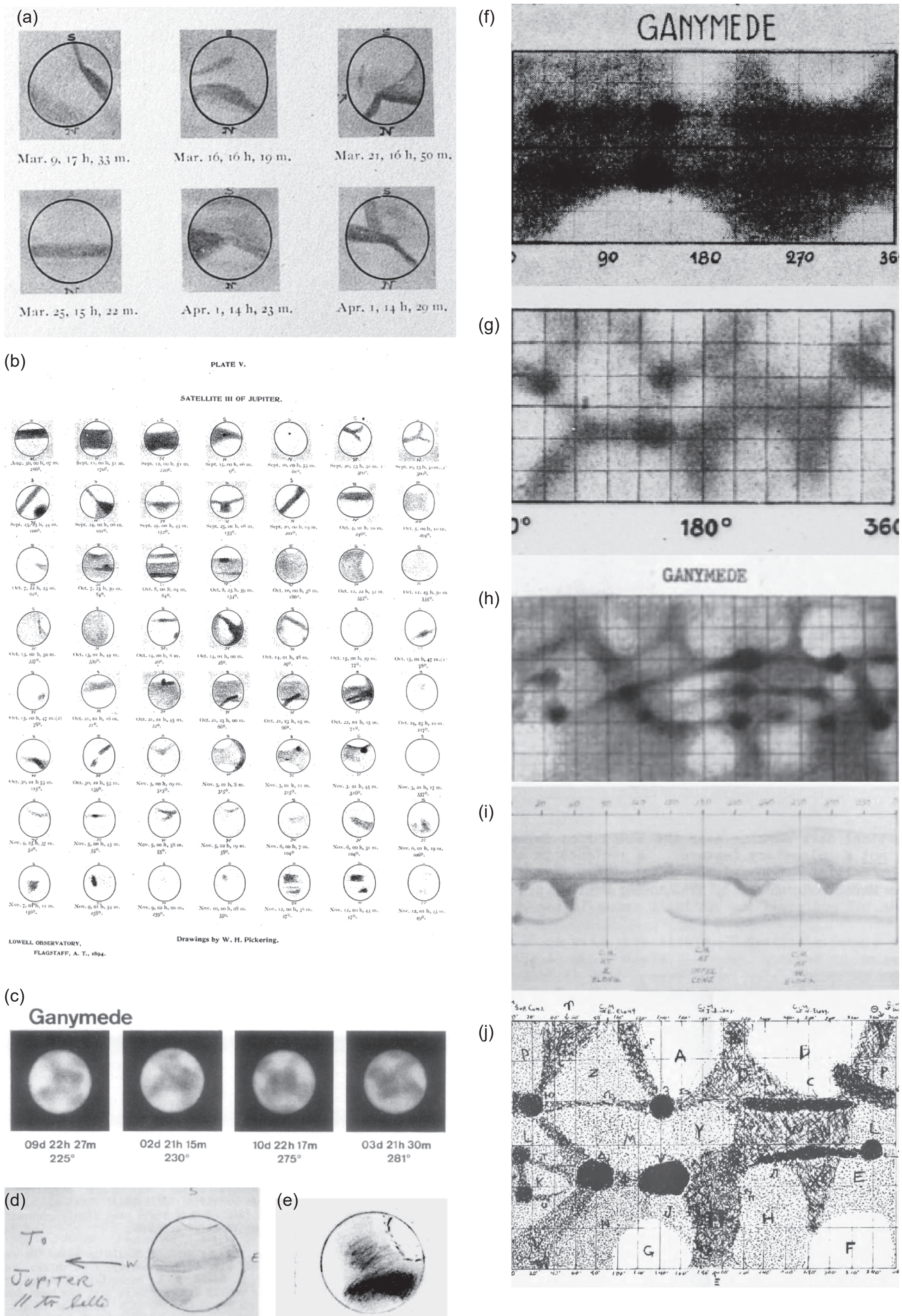


**Figure 1.4** Drawings (left) and historical maps (right) of Ganymede's surface. (a): Douglas, A.E. (2006). Drawings of Jupiter's third satellite. *Astronomische Nachrichten*. John Wiley and Sons. Lowell Observatory Archives. (b): Pickering (1900), (c): Murray (1975), reprinted from *Icarus*, 25(3). J.B. Murray, New observations of surface markings on Jupiter's satellites, 397–404, ©1975, with permission from Elsevier.[4] (d): Cave in Hare (1951), (e): Cruikshank (1963), (f): Camichel and Lyot (1943), (g): Danjon (1944), (h): Lyot (1953) (i): Reese (1951), (j): Howe in Both (1952). Note that in the maps on the right −90° latitude is at the top of the image.

https://doi.org/10.1017/9781108966474.002 Published online by Cambridge University Press

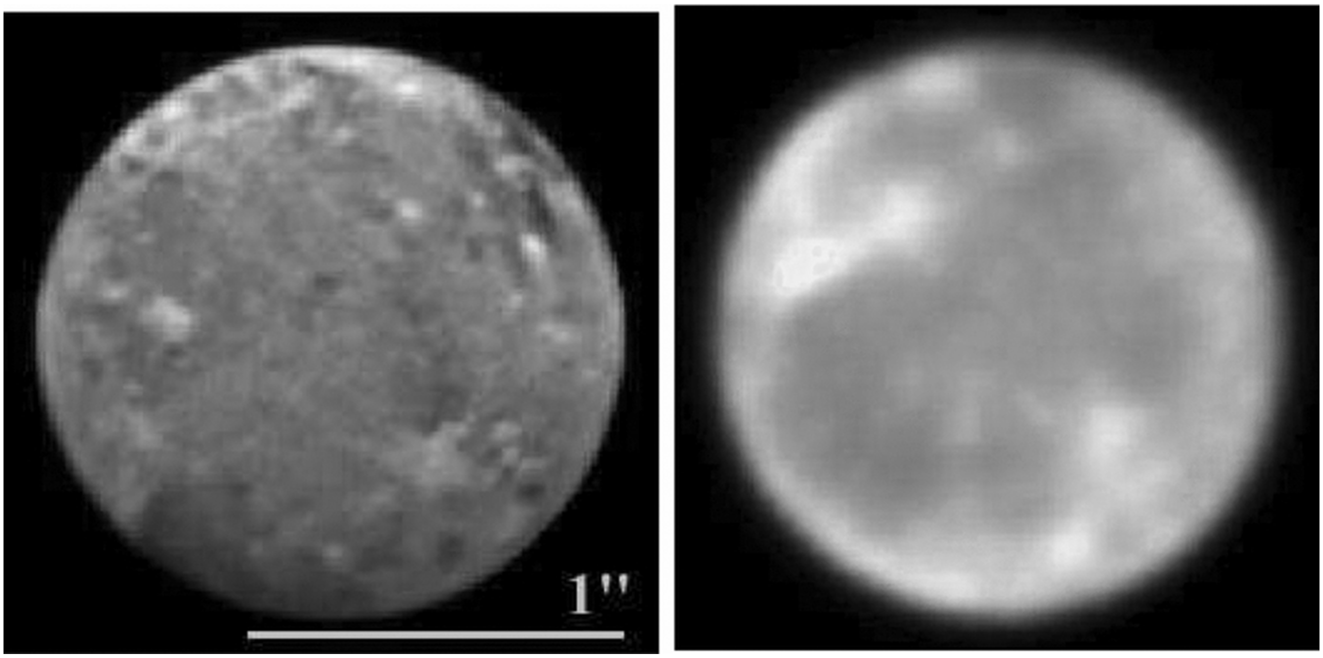


**Figure 1.5** Left: PALM-3000 and TMAS false-color image of Ganymede using the Johnson-Cousins BRI filters. The pixel sampling is ~35 km in this image. Right: Hubble Space Telescope false-color image of Ganymede for comparison (NASA image). Figure taken from Dekany and colleagues (2013), a color version can be obtained from the online journal.

Pioneer 10 was launched on 1972 March 2 and provided a series of "firsts": the first spacecraft to fly beyond Mars, the first spacecraft to fly through the main asteroid belt, and the first one to reach the orbit of Jupiter and to continue further into the outer solar system. Pioneer 10 proved for the first time that spacecraft can safely travel through the asteroid belt without being damaged. Only a comparably small number of hits by dust particles were recorded during this passage between July 1972 and February 1973. During its closest approach to Jupiter on 1973 December 4, Pioneer 10 passed the cloud tops at a distance of 130 354 km. The IPP instrument took ~500 images of the Jovian atmosphere at a spatial resolution of ~300 km/pxl. It also took the first images of the three icy Galilean satellites Callisto, Ganymede, and Europa, at that time providing the clearest images of dark and bright surface features on these bodies (see Gehrels, 1977). However, the spatial resolution was not good enough for detailed geoscientific investigations (see Fig. 1.6) compared to standards of more recent missions. The last signal from Pioneer 10 was received on 2003 January 23, from a distance of 12.23 billion km from Earth. The current distance of Pioneer 10 is 18.9 billion km. The spacecraft is heading towards $\alpha$ Tau (Aldebaran), which it will pass in ~2 million years.

Pioneer 11 was launched on 1973 April 6, and passed Jupiter closer than Pioneer 10, at a distance of 42 828 km above the atmosphere. After the flyby, Pioneer 11 continued its journey to Saturn, which it flew by on 1979 September 1, in a year which had seen the first successful flybys of the two Voyager spacecraft at Jupiter. The decision was made by NASA to end the mission on 1995 September 30. Final contact from the spacecraft was received two months later, on 1995 November 24. Pioneer 11 is heading out of the solar system in a direction opposite to that of Pioneer 10. The spacecraft is currently in constellation Scutum and will pass a K-type dwarf star, within 0.8 light years, in 928 000 years. Its current distance (2023 January) is 19.7 billion km from Earth.

### 1.5.2 The Voyager Mission

In the late 1960s, NASA conceived an Outer Planets Grand Tour to the four large planets Jupiter, Saturn, Uranus, Neptune, as well as to Pluto, the latter at that time still listed as a planet (e.g. Bagenal et al., 2004). The plan was to launch two spacecraft in 1976–7 to reach Jupiter, Saturn, and Pluto, and another dual launch in 1979 to reach Jupiter, Uranus, and Neptune, using gravity assist at each of the four large planets. Constraints in budget severely affected NASA's space program in the early 1970s, however, and the ambitious Grand Tour was cancelled. Then, a modified cheaper mission was redesigned with two Mariner-based spacecraft only, termed Mariner Jupiter Saturn, which eventually became Voyager 1 and 2 in 1977. Due to a planetary alignment of the four large planets, which takes place only once every 176 years, it was possible to send at least Voyager 2 on to Uranus and Neptune, meaning that most of the task of the cancelled Grand Tour could be fulfilled.

The two Voyager spacecraft were identical, each with a mass of 825 kg spacecraft and 11 scientific instruments aboard (Bagenal et al., 2004). Among the 11 scientific instruments, the Voyager Imaging Experiment (ISS) consisted of a wide angle (WA) and a narrow angle (NA) Vidicon camera (Smith et al., 1977). The task of the ISS instrument was to perform detailed investigations of atmospheric features of Jupiter and Saturn, of the rings of Saturn, and imaging of the surfaces of the major Jovian and Saturnian satellites at spatial resolutions of 1 km/pxl or higher (Smith et al., 1977), as shown in Fig. 1.6.

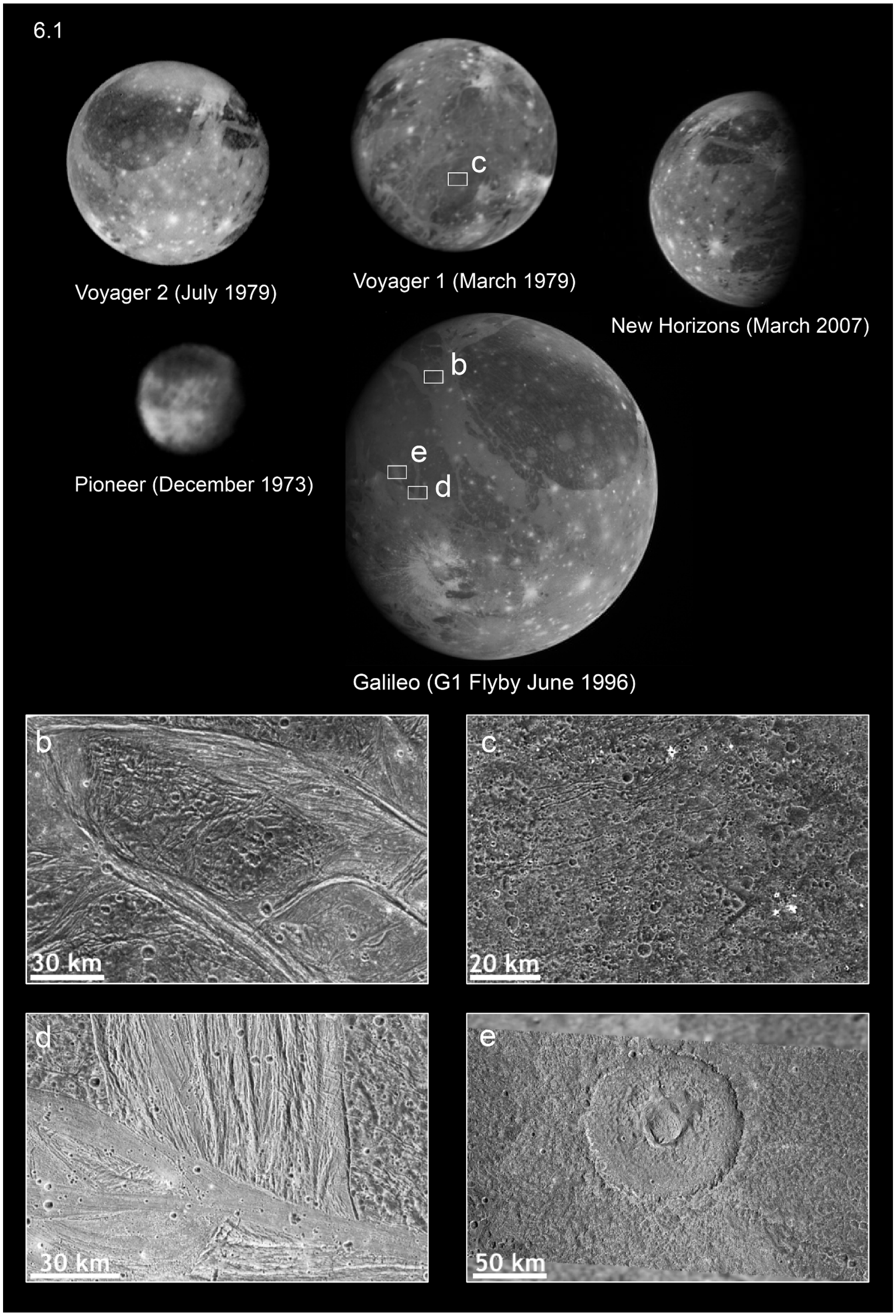


**Figure 1.6** Global and detailed views of Ganymede, imaged in various missions to Jupiter and beyond. (a) Global views from the Voyager flybys in 1979; the narrow angle (NA) Vidicon camera aboard Voyager 2 imaged the anti-Jovian hemisphere, the NA camera aboard Voyager 1 the sub-Jovian hemisphere. The large approximately circular dark area is Galileo Regio. The anti-Jovian hemisphere, with the dark terrain of Galileo Regio, was also captured by the photo-polarimeter aboard Pioneer 10 during its flyby in December 1973, which provided the first images of Ganymede and the other Galilean satellites ever taken. These images are about a factor 100 less in spatial resolution compared to global Voyager images. On its cruise to Pluto, the New Horizons spacecraft passed Jupiter and its satellites in March 2007, imaging the leading hemisphere of Ganymede with the LORRI camera. (b–e) Global and detailed images from the Galileo mission (1995–2003). In the first Ganymede flyby (G1) of its orbital tour, the Galileo solid-state camera (SSI) imaged the anti-Jovian hemisphere. Detailed images from Ganymede's major terrain types at higher resolutions (order of 150–500 m/xl) were taken during further close flybys of the Galileo orbiter (see chapters on geology and stratigraphy in this volume). (b) Older, densely cratered dark terrain and younger, bright, tectonically resurfaced terrain (orbit G2). (c) Dark terrain of Nicholson Regio (orbit G28). (d) Tectonic resurfacing in bright terrain of Erech Sulcus (orbit G8). (e) Central pit crater Melkart (orbit G8). The locations of these detailed views are indicated by the labeled rectangles in the global views. Due to the differences in resolution, the sizes of the rectangles do not exactly render the areas shown in the four detailed panels

Voyager 2 was launched first, on 1977 August 20, followed by the launch of Voyager 1 on 1977 September 5. During the Jupiter encounter of Voyager 1 on March 5, 1979 and of Voyager 2 on July 9, 1979, the ISS instrument returned spectacular images not only from Jupiter but especially from the surfaces of the four Galilean satellites Io, Europa, Ganymede, and Callisto, and also of the smaller satellite Amalthea (Smith et al., 1979a, b). The trajectories of the two Voyager spacecraft were chosen such that different hemispheres of the satellites could be imaged during different flybys. Voyager 1 captured the sub-Jovian hemisphere of Ganymede, Voyager 2 the hemisphere facing away from Jupiter. Like Pioneer, the Voyager encounters at Jupiter provided some discovery "firsts" not anticipated prior to Voyager: (1) a faint Jupiter ring; (2) two previously unknown satellites (Metis and Thebe); (3) intense, tidal-driven active volcanism on the innermost Galilean satellite Io; (4) two different terrain types on Ganymede, dark and bright regions; (5) dark densely cratered icy surfaces on Ganymede and Callisto; (6) widespread tectonic features in the bright terrain on Ganymede and on Europa; and (7) surface features suggesting ice volcanism (cryovolcanism) on Europa and, to a lesser degree, on Ganymede (Smith et al., 1979a, b). Subsequent to the two Jupiter encounters, more spectacular images were returned from Saturn by Voyager 1 (1980 November 12) and 2 (1981 August 25), and by Voyager 2 from Uranus (1986 January 24) and Neptune (1989 August 25).

Since 1990 January 1, the Voyager mission has been named the Voyager Interstellar Mission. As of January 2023 Voyager 1 is 159.3 AU or 23.8 billion km from Earth and the farthest-distant man-made object. It is moving into the direction of star AC + 79 3888, also known as Gliese 445, in the Camelopardalis constellation, which it will pass within 1.6 light years in ~40 000 years. Voyager 1 is expected to be out of power in about 2025. Voyager 2 is (as of January 2021) 126.8 AU or 18.9 billion kilometers away from Earth and will pass star Ross 248 within 1.7 light years in ~40 000 years, and Sirius within 4.3 light years in 296 000 years.

### 1.5.3 The Galileo Mission and Beyond

Most of the knowledge we have about Ganymede today results from NASA's Galileo mission. In 1995, the Galileo spacecraft entered orbit around Jupiter and absolved four close encounters with Ganymede during the primary mission (1995 to 1997). During first flybys, radio-science and other data revealed that Ganymede had a fully differentiated interior with a core, a silicate mantle, and an ice crust (Anderson et al., 1996). The plasma wave experiment and magnetometer data gave evidence of an internally generated magnetic field forming a magnetosphere around Ganymede (Kivelson et al., 2002, and Chapters 13 (Christensen et al.) and 14 (Kivelson et al.) of this book). For the first time, Galileo acquired a large number of UV spectra of Ganymede's surface showing that Ganymede has an extended hydrogen exosphere, $SO_2$ and $O_3$ in the surface material through magnetospheric alteration (Hendrix et al., 1999). In addition, near-infrared hyperspectral images (Carlson et al., 1996) enabled for the first time the combined investigation of the satellite's surface composition with geology as seen in Galileo SSI images and revealed the presence of several non-ice compounds on the surface of Ganymede including also radiolytic products of the interaction between Ganymede's surface and magnetosphere (McCord et al., 1998, and Chapters 10 (Stephan) and 15 (Galli et al.)).

Galileo's Europa Mission (GEM) ran from 1997 December 8 to 1999 December 31. Its science objectives were not limited to Europa, but also included analyses of the other satellites, as well as of Jovian fields and particles and atmospheric characteristics. Galileo's Millennium Mission (GMM) ran first from January 2000 through March 2001 and was then extended until the end of mission operations in January 2003. The GMM conducted additional investigations into the dynamics of Ganymede's unique magnetosphere. Galileo's closest approach to Ganymede coincided with that of the Cassini spacecraft, which passed Jupiter in December 2000 within 10 million km in order to pick up speed through a gravity assist on its way to the Saturnian system. Joint Galileo–Cassini observations revealed solar wind effects and magnetospheric dynamics. High-resolution Ganymede images were also taken. Magnetometer field measurements suggest that a salty water layer exists between Ganymede's ice shell and a deep layer of a high-pressure polymorph of ice (Kivelson et al., 2002, and Chapter 14 (Kivelson et al.)). Galileo met its demise in September 2003, when, by design, its trajectory took it on a collision course toward Jupiter and it burned up in the planet's atmosphere.

On its way to Pluto and Charon, the New Horizons spacecraft observed Jupiter's icy satellites, Europa and Ganymede, during its flyby in 2007 and recorded topographic and compositional mapping at visible and infrared wavelengths and that could not be observed properly during the Galileo mission of Ganymede's Jupiter-facing hemisphere (Grundy et al., 2007). The most recent observations of Ganymede's polar regions were made in December 2019, when the Juno spacecraft flew by Ganymede during its 24th orbit of Jupiter at a range between 97,680 to 109,439 kilometers (60,696 to 68,002 miles) (Mura et al., 2020). Juno will continue to observe the Jovian system with multiple rendezvous planned for Ganymede, Europa, and Io through its just extended mission through September 2025, or until the spacecraft's end of life.

In addition to the spacecraft missions, observations by the HST had a major impact on Ganymede science, particularly through UV imaging and spectroscopy. Launched in 1990, HST was placed into orbit around Earth outside the distortion of Earth's atmosphere at about 547 kilometers (340 miles) above the planet's surface and is still in operation with the ability to record images at ultraviolet to near-infrared wavelengths. HST made critical measurements of Ganymede's atmosphere (also Chapter 16 (Roth et al.)) showing that Ganymede also exhibits auroral emission, first observed by Hall et al. (1998) with the Goddard High Resolution Spectrograph (GHRS) on board the HST. These observations constrained the fluxes and spectral shapes of the OI 1356 Å and OI 1304 Å emission lines, which imply a molecular oxygen atmosphere with a column density in the range of $(1–10) \times 10^{14}$ $cm^{-2}$ (Hall et al., 1998).

The line shape of the OI 1356 Å emission is consistent with the radiation being emitted from two circumpolar auroral ovals situated in the north and south polar regions of Ganymede (see also Chapter 18 (Gunell et al.)). Subsequent spatially and spectrally resolved HST observations with the Space Telescope Imaging Spectrograph (STIS) clearly demonstrate the existence of two auroral ovals around Ganymede's magnetic north and south poles as shown in the work of Feldman et al. (2000) and McGrath et al. (2013). In March 2015, using Hubble to study the motion of its aurorae during a time span from 1998 to 2007, the researchers determined that a large saltwater ocean was helping to suppress the interaction between Jupiter's magnetic field and that of Ganymede. The ocean is estimated to be 100 km (60 miles) deep, trapped beneath a 150 km (90 miles) ice crust (Saur et al., 2015).

## 1.6 THE SCIENCE FICTION AGE

The human exploration of Ganymede has already advanced much further in science fiction, as is to be expected. Human colonization, native Ganymedians and surface conditions that vary from icy, to sub-arctic periodially flooded by tidal action, to being volcanically active and jungle covered, are some of the ideas presented. A short, incomplete discussion of science fiction literature and movies dealing with Ganymede is presented below. The actual status of Ganymede'a habitability is discussed by Chela-Flores in Chapter 20 of this book.

### 1.6.1 Books

One of the first stories involving Ganymede is the 1938 short story "*Tidal Moon*" by Stanley and Helen Weinbaum, in which, in 2083, human companies are collecting "cree" that is grown by Ganymede's natives, the Nympus, a red moss that turns blue due to the ammonia in Ganymede's atmosphere. On Earth it is used as a combined anaesthetic and medicine. Although it was already known that the moon was tidally locked in its orbit (see Section 1.4.3) in this story the moon has a 6 month rotational period with a sub-arctic climate and large bodies of water. Every three months each part of Ganymede's surface is flooded because of Jupiter's tidal force and only the human settlement "Hydropole" at the south pole stays dry.

The books will be categorized here into two, sometimes overlapping, groups: Ganymede with indigenous inhabitants and Ganymede as a human colony, sometimes used for agriculture.

#### *1.6.1.1 Indigenous Inhabitants*

As in *Tidal Moon*, Ganymede has indigenous inhabitants in Isaac Asimov's "*Christmas on Ganymede*" (1941) called the "Ossies" because they resemble OstricheS, who are used as a working force for mining for example wolframite. Introducing the Ossies to Santa Claus causes problems for the human colonists and the mining company.

Not all Ganymedians are collaborating with human visitors. In "*The Counterfeit Man*," a short story by Alan E. Nourse (1963) shapeshifting malicious aliens get onboard the spacecraft returning from Ganymede to Earth, taking over (at least) the captain of the ship after landing on Earth. In Philip K. Dick's "*The Ganymede Takeover*" (1967) the Earth is taken over by Ganymedian worm-like creatures.

Not always are the indigenous inhabitants from Ganymede. In Isaac Asimov's short stories "*Not Final!*" (1940) and "*Victory Unintentional*" (1942) human colonists get into conflicts with the inhabitants of Jupiter. Whereas, in "*The Gentle Giants of Ganymede*" by James P. Hogan (1978) a crashed spacecraft is discovered in which members of an alien race are found, who actually come from a distroyed planet between Mars and Jupiter.

#### *1.6.1.2 Human Colony*

In Robert Heinlein's novels Ganymede is often mentioned to be a human colony. In "*Farmer in the Sky*" (1953) there is an agricultural colony, and in "*I Will Fear No Evil*" (1970) a commission proposes to terraform Ganymede. Also in Poul Anderson's "*The Snows of Ganymede*" terraformers are sent to this moon to survey its possibilities, only to be thwarted by an already existing human colony.

After the Earth is devastated by war, the protagonists in "*The Ganymede Club*" (1995) by Charles Sheffield, try to solve a mystery/conspiracy on Ganymede. Therapist Lola Belman meets a patient whose past is a mystery, and finds a dangerous group will stop at nothing to keep Lola from exploring the past and discovering their existence.

In the book/TV series *The Expanse* by James S. A. Corey, Ganymede is colonized and used both as a mining and an agricultural resource. "*Caliban's War*" (2012) describes that on the surface of Ganymede there are agricultural domes on the surface which are illuminated by mirrors in space.

The most rigorous colonization of Ganymede takes place in "*The Marriage of the Living Dark*" (1997), the last book in the "*Chung Kuo*" series by David Wingrove. All Galilean moons are turned into spaceships and leave the solar system for most nearby stars. This way they flee from the warring factions on the Earth where the Chinese great experiment, the Ten Thousand Year Empire of the Han, has failed.

### 1.6.2 Movies and TV

Ganymede also gets used in TV series and movies As mentioned above, it plays an important part in the book/TV series *The Expanse* (2015–present).

The German (TV) movie *Operation Ganymed* shows the return of remaining astronauts after their multiyear mission to the Jovian system, where they found primitive life on Ganymede. However, they return to a (postnuclear war?) desolate Earth.

On Ganymede a ship was buried under the surface by "the Shadows" in the TV series *Babylon 5* (1993–1999). It was dug up in the episode *Messages from Earth* (1996) leading to dire consequences in the constantly further developing Shadow War.

In the Australian children's science fiction drama *Escape from Jupiter* (1994–95) and its sequel *Return to Jupiter* (1996) Ganymede is home of the parents of the protagonists and a mining colony.

The BBC TV series *Red Dwarf* (1988–present) had Ganymede terraformed and apparently it is one of the more fancy of the Galilean moon colonies.

## 1.7 EPILOGUE

This is the end of the time travel through the discovery and study of Ganymede. From a mythological figure, it has developed to one of the most interesting objects in our solar system.

A moon with an internal magnetic field (see Chapters 13 (Christensen et al.) and 14 (Kivelson et al.)), with possibly a liquid water layer between two ice layers (Chapter 12 (Kalousova et al.)) embedded in and interacting with the greater Jovian magnetosphere (Chapters 15 (Galli et al.), 18 (Gunell et al.) and 19 (Bonfond et al.)). This is the perfect target for a new space mission: JUICE (Grasset et al., 2013), which was launched on 14 April 2023.

This chapter should have given the reader a taste of what was, and for deeper immersion into the study of Ganymede the following chapters in this book are recommended.

## ACKNOWLEDGMENTS

Part of this work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

## REFERENCES

Anderson, J. D., Lau, E. L., Sjogren, W. L., Schubert, G. and Moore, W. B. (1996), 'Gravitational constraints on the internal structure of Ganymede', *Nature* **384**, 541–543.

Anderson, P. (1958), *The Snows of Ganymede*, ACE Books, Double Novel Books D-303, New York, USA.

Asimov, I. (October 1941), Not Final, in: Astounding Science Fiction, Stanley Schmidt, USA.

Asimov, I. (January 1942), Christmas on Ganymede, in: Startling Stories, Ned Pines' Standard Magazines, USA.

Asimov, I. (August 1942), Victory Unintentional, in: Super Science Stories, Popular Publications, USA.

Bagenal, F., Dowling, T. E. and McKinnon, W. B. (2004), *Jupiter: The Planet, Satellites and Magnetosphere*, Cambridge University Press, Cambridge.

Barnard, E. E. (1895), 'Filar micrometer measures of the diameters of the four bright satellites of Jupiter, made with the 36-inch equatorial of the Lick Observatory', *Mon. Not. R. Astron. Soc.* **55**, 382–391.

Binder, A. B. and Cruikshank, D. P. (1964), 'Evidence for an atmosphere on Io', *Icarus* **3**, 299–305.

Binder, A. B. and Cruikshank, D. P. (1966), 'Photometric search for atmospheres on Europa and Ganymede', *Icarus* **5**, 7–9.

Both, E. E. (1952), 'Jupiter's satellite Ganymede in 1951–52', *The Strolling Astronomer* **6**, 78–81.

Brown, R. A. and Chaffee, Jr., F. H. (1974), 'High-resolution spectra of sodium emission from Io', *Astrophys. J.* **187**, L125–L126.

Camichel, H. and Lyot, B. (1943), 'Observations planetaire au Pic du Midi, en 1941', *L'Astronomie* **57**, 49–60.

Carlson, R., Smythe, W., Baines, K. et al. (1996), 'Near-infrared spectroscopy and spectral mapping of Jupiter and the Galilean satellites: Results from Galileo's initial orbit', *Science* **274**, 385–388.

Carlson, R. W., Bhattacharyya, J. C., Smith, B. A. et al. (1973), 'An atmosphere on Ganymede from its occultation of SAO 186800 on 7 June 1972', *Science* **182**, 53–55.

Clark, R. N. (1980), 'Ganymede, Europa, Callisto, and Saturn's rings: Compositional analysis from reflectance spectroscopy', *Icarus* **44**, 388–409.

Clark, R. N. and McCord, T. B. (1980), 'The Galilean satellites: New near-infrared spectral reflectance measurements (0.65–2.5 $\mu$m) and a 0.325-5 $\mu$m summary', *Icarus* **41**, 323–339.

Dalal, R. (2010), *Hinduism: An Alphabetical Guide*, Penguin, India.

Danjon, A. (1944), 'Les satellites de Jupiter', *L'Astronomie* **58**, 33–36.

Dekany, R., Roberts, J., Burruss, R. et al. (2013), 'PALM-3000: Exoplanet adaptive optics for the 5 m Hale telescope', *Astrophys. J.* **776**.

Dick, P. K. (1967), *The Ganymede Takeover*, Ace Books, New York, USA, ISBN: 9780727816870.

Douglass, A. E. (1897), 'Drawings of Jupiter's third satellite', *Astron. Nachr.* **143**, 411–414.

Fagles, R. (1990), *Homer: The Iliad*, Penguin, London.

Fedtke, C. (1942), 'Jupitermond iii (Ganymede)', *Astron. Nachr.* **273**, 6.

Feldman, P. D., McGrath, M. A., Strobel, D. F. et al. (2000), 'HST/STIS ultraviolet imaging of polar aurora on Ganymede', *Astrophys. J.* **535**, 1085–1090.

Fink, U. and Larson, H. P. (1975), 'Temperature dependence of the water-ice spectrum between 1 and 4 microns: Application to Europa, Ganymede and Saturn's Rings', *Icarus* **24**, 411–420.

Fink, U., Dekkers, N. H. and Larson, H. P. (1973), 'Infrared spectra of the Galilean satellites of Jupiter', *Astrophys. J.* **79–179**, L155–L159.

Flammarion, C. (1880), *Astronomie Populaire*, C. Marpon et E. Flammarion, Paris.

Gehrels, T. (1977), *Jupiter*, University of Arizona Press, Arizona.

Grasset, O., Dougherty, M. K., Coustenis, A. et al. (2013), 'JUpiter ICy moons Explorer (JUICE): An ESA mission to orbit Ganymede and to characterise the Jupiter system', *Planet. Space Sci.* **78**, 1–21.

Gromova, L., Moroz, V. I. and Cruikshank, D. P. (1970), 'Spectrum of Ganymede in the region 1–1.7 $\mu$', *Astron. Tsirk.* **569**, 6–8.

Grundy, W. M., Buratti, B. J., Cheng, A. F. et al. (2007), 'New Horizons mapping of Europa and Ganymede', *Science* **318**, 234–237.

Hall, C. F. (1975), 'Pioneer 10 and Pioneer 11', *Science* **188**, 445–446.

Hall, D. T., Feldman, P. D., McGrath, M. A. and Strobel, D. F. (1998), 'The far-ultraviolet oxygen airglow of Europa and Ganymede', *Astrophys. J.* **499**, 475–481.

Hare, E. E. (1951), 'Jupiter 1950 report no. 4', *The Strolling Astronomer* **5**, 8–10.

Harris, D, Pholometry and Colorimetry of Planets and Moons, in G. P. Kuiper and B. M. Middlehurst, eds., 'Planets and Satellites', University of Chicago Press, Chicago, USA, 272–342

Hart, M. (2010), 'Recent advances in astronomical adaptive optics', *Appl. Optics* **49**, D17–D29.

Heinlein, R. (1953). *Farmer in the Sky*, Charles Scribner's Sons, New York, USA, ISBN: 0345324382.

Heinlein, R. (1970). *I Will Fear No Evil*, G. P. Putnam's Sons, New York, USA, ISBN: 978-0441359172.

Hendrix, A. R., Barth, C. A. and Hord, C. W. (1999), 'Ganymede's ozone-like absorber: Observations by the Galileo ultraviolet spectrometer', *J. Geophys. Res.* **104**, 14169–14178.

Herschel, W. (1797), 'Observations of the Changeable Brightness of the Satellites of Jupiter, and of the Variation in Their Apparent Magnitudes; With a Determination of the Time of Their Rotatory Motions on Their Axes. To Which is Added, a Measure of the Diameter of the Second Satellite, and an Estimate of the Comparative Size of All the Four', *Phil. Trans. Royal Soc. London* **87**, 332–352.

Hogan, J. P. (1978), *The Gentle Giants of Ganymede*, Random House Publishing Group, New York, USA, ISBN: 0345323270.

Hughes, D. W. (1982), 'Was Galileo 2,000 years too late?', *Nature* **269**, 199.

James S. E. Corey, Caliban's War, publisher: Orbit, London, UK, ISBN: 9781841499918, 2012

Johnson, J. H. (1930), 'The discovery of the first four satellites of Jupiter', *J. Brit. Astron. Assoc.* **41**, 164–171.

Keim, F. (2009), *Die Entdeckung der Jupitermonde 105 Jahren vor Galileo Galilei*, Peter Lang, Frankfurt.

Kelley, D. H. and Milone, E. F. (2011), *Exploring Ancient Skies*, Springer, New York.

Kieffer, H. (1970), 'Spectral reflectance of $CO_2$-$H_2O$ frosts', *J. Geophys. Res.* **75**, 501–509.

Kivelson, M. G., Khurana, K. K. and Volwerk, M. (2002), 'The permanent and inductive magnetic moments of Ganymede', *Icarus* **157**, 507–522.

Kuiper, G. P. (1952), *The Atmospheres of the Earth and Planets*, University of Chicago Press, Chicago.

Kuiper, G. P. (1957), 'Infrared observations of planets and satellites', *Astron. J.* **62**, 245.

Kuiper, G. P. (1973), 'Comments on the Galilean satellites', *Comm. LPL* **10**, 28–34.

Lanzerotti, L. J., Robbins, M. F., Tolk, N. H. and Neff, S. H. (1975), 'Scans of Io, Europa, and Ganymede in the NaD region', *Astron. Soc. Pacific* **87**, 449–453.

Lyot, B. (1953), 'L'aspect des planètes au Pic du Midi dans une lunette de 60 cm d'ouverture', *L'Astronomie* **67**, 3–20.

McCord, T. B., Hansen, G. B., Clark, R. N. et al. (1998), 'Non-water-ice constituents in the surface material of the icy Galilean satellites from the Galileo near-infrared mapping spectrometer investigation', *J. Geophys. Res.* **103**, 8603–8626.

McGrath, M. A., Jia, X., Retherford, K. et al. (2013), 'Aurora on Ganymede', *J. Geophys. Res.* **118**, 2043–2054.

Mendis, D. A. and Axford, W. I. (1974), 'Satellites and magnetospheres of the outer planets', *Ann. Rev. Earth Planet. Sci.* **2**, 419–474.

Miles, H. (1973), 'Jupiter probe – Pioneer 10', *J. Brit. Astron. Ass.* **83**, 192–195.

Moroz, V. I. (1966), 'Infrared spectrophotometry of the Moon and the Galilean satellites of Jupiter', *Sov. Astron.* **9**, 999–1006.

Morrison, D. and Cruikshank, D. P. (1974), 'Physical properties of the natural satellites', *Space Sci. Rev.* **15**, 641–739.

Morrison, D., Cruikshank, D. P. and Murphy, R. E. (1972), 'Temperatures of Titan and the Galilean satellites at 20 microns', *Astrophys. J.* **173**, L143–L146.

Morrison, D., Cruikshank, D. P., Martin, T. Z., Berry, J. C. and Shipley, J. P. (1971), 'Thermal inertia of Ganymede from 20-micron eclipse radiometry', *Astrophys. J. Lett.* **167**, L107–L111.

Mura, A., Adriani, A., Sordini, R. et al. (2020), 'Infrared observations of Ganymede from the Jovian infrared auroral mapper on Juno', *J. Geophys. Res.* **125**.

Murray, B. C., Wastphal, J. A. and Wildey, R. L. (1965), 'The eclipse cooling of Ganymede', *Astrophys. J.* **141**, 1590–1592.

Murray, J. B. (1975), 'New observations of surface markings on Jupiter's satellites', *Icarus* **25**, 397–404.

Nourse, A. E. (1967), *The Counterfeit Man*, Scholastic Book Services, USA. ISBN: 0999129031.

Ossendrijver, M. (2016), 'Ancient Babylonian astronomers calculated Jupiter's position from the area under a time-velocity graph', *Science* **351**, 482–484.

Pagnini, P. (1930), 'Galileo and Simon Mayer', *J. Brit. Astron. Assoc.* **41**, 415–422.

Pankenier, D. W. (1992), 'The bamboo annals revisited: Problems of method in using the chronicle as a source for the chronology of early Zhou. Part 2: The congruent mandate chronology in Yi Zhou shu', *Bull. School Orient. Afric. Studies* **55**, 498–510.

Pellicori, S. F., Russell, E. E. and Watts, L. A. (1973), 'Pioneer imaging photopolarimeter optical system', *Appl. Optics* **12**, 1246–1358.

Pickering, W. H. (1900), 'Satellite III', in P. Lowell, ed., "Annals of the Lowell Observatory, Vol. II", Cambridge University Press, Cambridge, pp. 101–126.

Pilcher, C. B., Ridgway, S. T. and McCord, T. B. (1972), 'Galilean satellites: Identification of water frost', *Science* **178**, 1087–1089.

Reese, E. J. (1951), 'Map of Ganymede in 1949', *The Strolling Astronomer* **5**, 1.

Roche, J. J. (1982), 'Harriot, Galileo, and Jupiter's satellites', *Arch. Int. Hist. Sci.* **32**, 9–51.

Saur, J., Duling, S., Roth, L. et al. (2015), 'The search for a subsurface ocean in Ganymede with Hubble Space Telescope observations of its auroral ovals', *J. Geophys. Res.* **120**, 1715–1737.

Schaeberle, J. M. and Campbell, W. W. (1891), 'Observations of markings of Jupiter's third satellite', *Astron. Soc. Pacific* **3**, 359–365.

Schröter (1800), 'Beobachtungen des Saturns, dessen ring und trabanten; des Uranus und des Jupiters, sammt deren trabanten etc. mit einem 10 füssigen Dollond un 13 und 27 füssigen Reflector', *Astron. Jahrbuch für das Jahr 1800* 166–175.

Sheffield, C. (1995). *The Ganymede Club*, Tom Doherty Associates, New York, USA. ISBN: 0312856628.

Silbergeld, J. (1982), 'Mawangdui, excavated materials, and transmitted texts: A cautionary note', *Early China* **8**, 79–92.

Smith, B. A., Briggs, G. A., Danielson, G. E. et al. (1977), 'Voyager imaging experiment', *Space Sci. Rev.* **21**, 103–127.

Smith, B. A., Soderblom, L. A., Beebe, R. et al. (1979a), 'The Galilean satellites and Jupiter: Voyager 2 imaging science results', *Science* **206**, 927–950.

Smith, B. A., Soderblom, L. A., Johnson, T. V. et al. (1979b), 'The Jupiter system through the eyes of Voyager 1', *Science* **204**, 951–957.

Smyth, W. H. (1844), *A Cycle of Celestial Objects, Vol. 1*, J. W. Parker, London.

Subbarayappa, B. V. (1989), 'Indian astronomy: An historical perspective', in S. K. Biswas, D. C. V. Mallik and C. V. Vishveshwara, eds., Cosmic Perspectives, Cambridge University Press, Cambridge, pp. 25–40.

Trafton, L., Parkinson, T. and Macy, Jr., W. (1974), 'The spatial extent of sodium emission around Io', *Astrophys. J.* **190**, L85–L89.

Weinbaum, G. S. and Weinbaum, H. (1938), *Tidal Moon*, in: Thrilling Wonder Stories, Ned Pines' Standard Magazines, USA.

Whitmell, C. T. (1896), 'Solar eclipses on Jupiter due to the third satellite (Ganymede)', *J. Brit. Aston. Ass.* **6**, 424–426.

Wingrove, D. (1997), *The Marriage of the Living Dark*, Doubleday Canada Limited, Toronto, Canada. ISBN: 0385257368.

Xi, Z. (1981), 'The sighting of Jupiter's satellite by Gan De 2000 years before Galileo', *Chin. Astron. Astrophys.* **5**, 242–243.

Yung, Y. L. and McElroy, M. B. (1977), 'Stability of an oxygen atmosphere on Ganymede', *Icarus* **30**, 97–103.