Jupiter

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Introduction

Starting from the Sun, Jupiter is the fifth planet of the Solar System. After the Moon and Venus, it is one of the brightest objects in the night sky. Composed mainly of hydrogen, its mass is more than twice that of all the other planets combined (>300 Earth Masses). Its diameter is approximately 140,000 km. Jupiter thus is considered the Giant of our planetary system. Jupiter also stands out from all the other planets for its impressive magnetic field, with no analogue in the solar system. With its satellite system, composed of four large moons (the Galilean satellites) and many smaller moons, it represents a miniaturized solar system. Rings are present in the inner part of the satellite systems, but they are very faint and composed of dust. Jupiter's main physical parameters are given in Table 1, while Table 2 lists space missions that have thus far visited the planet. Data provided by the recent NASA mission Juno have greatly improved our understanding of the planet's interior, atmosphere, auroral processes and magnetosphere. In the future, the ESA mission Jupiter Icy moons Explorer (JUICE, launch scheduled in 2022) and the NASA mission Europa Clipper (launch scheduled in 2023) will further investigate the planet and the Galilean satellites, with special focus on Europa and Ganymede.

The Interior of Jupiter

We are in a unique time to study the interior of the big giant in our solar system: Juno mission's extremely accurate gravity measurements (e.g. Iess et al., 2018) led to a radical change in our understanding of Jupiter's interior structure and deep atmospheric dynamics (Wahl et al., 2017; Guillot et al., 2018; Kaspi et al., 2018). Because the amount of heavy elements and their distribution in the interior of Jupiter are crucial constraints to understand how giant planets form, these results have a huge impact in our understanding of the solar system formation history.

Observational Constrains

The gravity field of Jupiter is estimated using its effect on the trajectory of the Juno spacecraft. The measurements are expressed by expanding the gravity field of Jupiter in Legendre polynomials, with the gravity harmonics Jn as the leading coefficients. The orbit of Juno was specially designed to have a larger sensitivity to these measurements, resulting in constraints one order of magnitude better than previous estimations (Bolton et al., 2017; Folkner et al., 2017; Table 3). In addition, the gravity data shows non-negligible odd gravity harmonics, the signature of a north-south asymmetry (Iess et al., 2018).

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Table 1 Data for Jupiter.

Mass (10^{24} kg)	1898.19
Volume (10^{10} km^3)	143,128
Equatorial radius (1 bar level) (km)	71,492
Polar radius (km)	66,854
Mean density (kg/m^3)	1326
Gravity (eq., 1 bar) (m/s^2)	24.79
Distance from the Sun Max	Max. 815,700,000 km (5.455 astronomical units a.u.) Mean 778,350,000 km (5.203 a.u.) Min. 740,900,000 km (4.951 a.u.)
Orbital period	11.86 years
Rotation period	9 h 55 m 29 s
Axial inclination	3.13°
Atmospheric composition (by volume)	*Major:* Molecular hydrogen (H_2): 86.00% Helium (He): 13.6% *Minor:* Methane (CH_4): 0.18%; Ammonia (NH_3): 0.07%; Water (H_2O): 0.05% (varies with pressure) *Aerosols:* Ammonia ice, water ice, ammonia hydrosulfide

Taylor FW, Atreya SK, Encrenaz T, et al. (2004) *The Composition of the Atmosphere of Jupiter*, F Bagenal, TE Dowling, and WB McKinnon (eds.), pp. 59–78. Available from https://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html

Table 2 Spacecraft that visited Jupiter.

Name	*Launch date*	*Encounter date*	*Nearest approach (km)*	*Comment*
Pioneer 10	2 March 1972	3 December 1973	131,400	Fly-by
Pioneer 11	5 April 1973	2 December 1974	46,400	Went on to Saturn
Voyager 1	5 September 1977	5 March 1979	150,000	Images of Jupiter and the Galileans. Went on to Saturn
Voyager 2	20 August 1977	9 July 1979	714,000	Complemented Voyager 1. Went on to Saturn, Uranus, Neptune
Galileo	18 October 1989	7 December 1995	Entry	Entry Orbiter and Entry Probe
Ulysses	6 October 1990	1st rendezvous 1992 2nd rendezvous 2004	119,091,456	Explore Sun's environment
Cassini	15 October 1997	30 December 2000	9,852,924	Flyby, went on to Saturn
New Horizon	19 October 2006	28 February 2007	2,300,000	Flyby, went on to outer solar system
Juno	5 August 2011	5 July 2016	4200	Currently orbiting Jupiter

Table 3 Observational constrains used in interior model calculations.

	Jupiter values by Juno
Temperature at 1 bar (K)	165 ± 4
Protosolar helium abundance	0.277 ± 0.006
J2 ($\times 10^{-6}$)	14696.572 ± 0.00467
J3 ($\times 10^{-6}$)[a]	-0.042 ± 0.0033
J4 ($\times 10^{-6}$)	-586.609 ± 0.0013
J5 ($\times 10^{-6}$)[a]	-0.069 ± 0.00267
J6 ($\times 10^{-6}$)	34.198 ± 0.003
J7 ($\times 10^{-6}$)[a]	0.124 ± 0.00567
J8 ($\times 10^{-6}$)[a]	-2.426 ± 0.0083
J9 ($\times 10^{-6}$)[a]	-0.106 ± 0.01467
J10 ($\times 10^{-6}$)[a]	0.172 ± 0.023

[a]There were no estimations of these gravity harmonics before Juno.

Jupiter has an observed depletion of helium in the atmosphere compared with the proto-solar abundance (Table 3), that is attributed to a helium phase transition or immiscibility of helium in hydrogen (Lorenzen et al., 2011). The helium forms droplets that rain down, causing a depletion of helium in the atmosphere and an overabundance in Jupiter's deeper interior. Regarding other species, Jupiter might be enriched in heavy elements ~3 times compared with the protosun.

Interior Models Assumptions

Several models have been published in recent decades that aim to explain the internal structure of Jupiter (e.g. Hubbard and Militzer, 2016; Debras and Chabrier, 2019). The problem has no unique solution and depends on parameters such as the rotation of the planet, the number of internal layers, the distribution of heavy elements, energy transport mechanisms, the level of atmospheric pressure at which helium settling occurs and the equation of state (e.g. Miguel et al., 2016). Some of the most recent equations of state for hydrogen include studies by Mazzola et al. (2018) and Chabrier et al., 2019 and references therein.

In the classical view, a giant planet is a small core surrounded by a homogeneous, convective envelope and rotates as a rigid body. This envelope is typically divided in two layers (Fig. 1, left panel), separated by the helium rain and hydrogen transition from molecular to metallic state.

Juno Mission and New Insights in Jupiter's Interior

The new remarkably accurate data of Jupiter's gravity field introduced further constraints that led to the development of new models for Jupiter's interior structure. In contrast to the classical view, these new results suggest that Jupiter's interior is not homogeneous: it might have a dilute core where the heavy elements are mixed within the hydrogen and helium envelope (Wahl et al., 2017; Guillot et al., 2018; Fig. 1, right panel). This new view of Jupiter's interior is backed up by calculations of the behavior of heavy elements in H—He mixtures (Soubiran and Militzer, 2016), by formation models that include the accretion of heavy elements (Lozovsky et al., 2017) and by evolution calculations (Vazan et al., 2018).

The new constraints provided by the Juno measurements also challenge the classic assumption of rigid body rotation. While the low order gravity harmonics (J2, J4, J6) are mostly affected by Jupiter's deep interior and shape, the high order harmonics (J8, J10) have a larger contribution coming from the atmosphere and can be used to constrain Jupiter's deep atmospheric flow and differential rotation. In Guillot et al. (2018) the authors used Juno's unprecedented measurements of Jupiter's high order *even* harmonics and estimations of the effect of differential rotation on J2 and J4, to constrain the extent of differential rotation in Jupiter's atmosphere and the depth where Jupiter starts rotating as a solid body. At the same time, Kaspi et al. (2018) used measurements of the *odd* gravity harmonics—which reflect asymmetries in the north and south hemispheres, only caused by atmospheric dynamics- to also estimate the extent of Jupiter's differential rotation. The result of these studies show that Jupiter has a differential rotation that extends down to ~3000 km (~4% of Jupiter radius) and beneath that climate-layer, the planet essentially rotates as a rigid body (Fig. 2). These results indicate that the weather layer of Jupiter is more massive and extends much deeper into the planet than expected and has important implications for improving our understanding of Jupiter's interior structure and, eventually, its origin.

Atmosphere

Composition and Vertical Structure

The first data on Jupiter's atmospheric composition were provided by spectroscopic studies of sunlight reflected by the planet in the visible and near-infrared wavelengths. Further information was added by radio, medium and far infrared and ultraviolet investigations. Molecular hydrogen is the most abundant gas (about 86% by volume), followed by helium (less than 14% by volume);

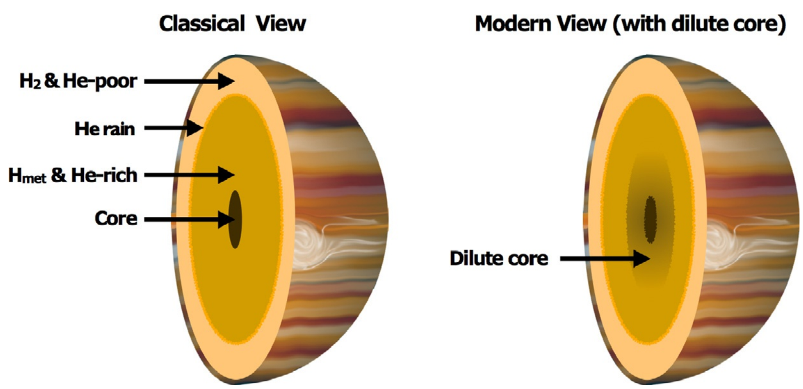

Fig. 1 Schematic view of Jupiter's interior.

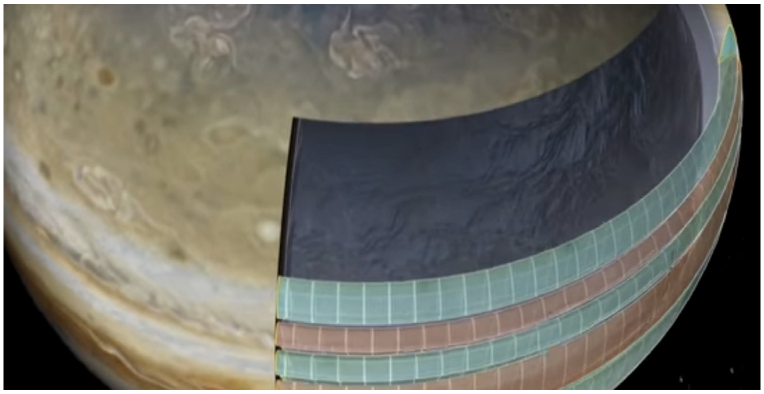

Fig. 2 Jupiter's zonal winds as shown schematically in the NASA press release of the papers Guillot, et al. (2018), Kaspi et al. (2018) and Iess et al. (2018). The bands and belts that extend up to 3000 km are shown in green and red, and the grey interior shows the rigid body behaviour of Jupiter's deep interior. Credits: NASA/JPL-Caltech.

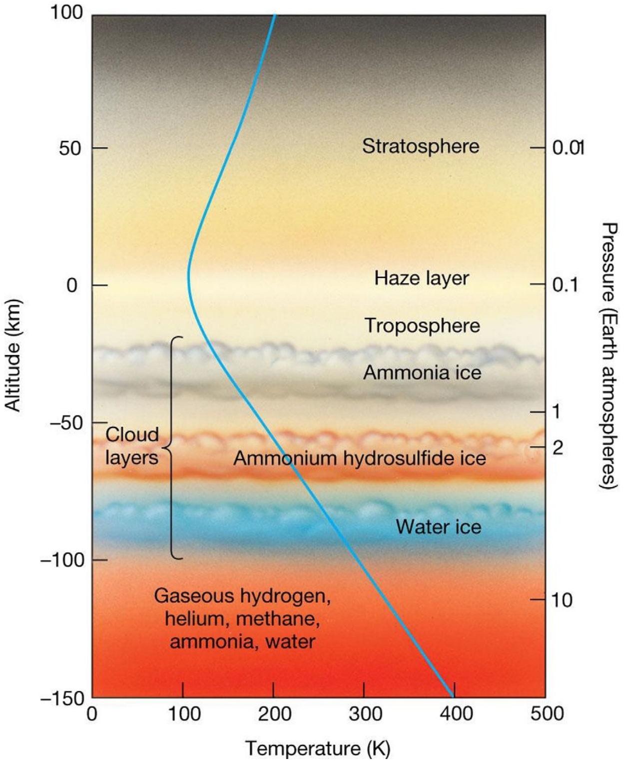

Fig. 3 Vertical structure of the Jupiter Stratosphere and Troposphere. © 2011 Pearson Education, Inc.

trace gases such us methane, ammonia, hydrogen sulfide and water vapor are also present (Table 1). Being a gaseous planet, Jupiter lacks a solid surface that can be used as a reference level for measuring the altitude. Thus the 0 km level is conventionally considered the top of the troposphere; clouds, confined by the convection occurring in the troposphere, are all located at negative altitudes (Fig. 3). The structure of the atmosphere is characterized by three main layers:

- a tropospheric haze created by photochemical reactions with temperature around 110 K;
- an ammonia cloud layer at a depth of about −40 km and with temperatures between 125 and 150 K; and
- an ammonium hydrosulfide cloud layer at a depth of about −80 km and temperatures around 200 K where at the base water ice can form.

Mid/Low Latitude Regions

Jupiter's atmosphere in the latitudes between about ±65 degrees shows several distinctive bands which are parallel to the equator (Fig. 4) and with alternating wind motions. They are characterized by different colors resulting from differences in the thickness and height of the ammonia ice clouds:

- lighter colored areas, called zones, are characterized by thicker clouds and high pressure, where the atmosphere rises;
- darker regions, called belts, are characterized by thinner clouds and low-pressure where air falls.

The bands are separated by winds that can reach speeds of up to more than 600 km/h.

Beneath the bands a very stable pattern of eastward and westward wind flows has been observed. It is usually referred to as Jupiter's zonal flow. Winds are faster in the equatorial regions in the easterly direction and around 20°N, reaching values >100 m/s (360 km/h). At higher latitudes, the alternating regions of westward and eastward winds show a flow speed decreasing towards the poles. As mentioned in the previous section (see also Fig. 2), recent results from the Juno mission have revealed that those jet streams extend down to a depth of thousands of kilometers beneath the cloud level, likely disappearing around –3000 km in a region of magnetic field dissipation (Kaspi et al., 2018). These jet streams involve about 1% of the Jupiter's mass.

The atmosphere of Jupiter is also dotted with ovals. These can be either cyclones or anticyclones, the former being low pressure storms where winds rotate in the same direction as the planet, the latter showing winds flowing around the storm in the direction opposite to those of the flow around regions of low pressure. The biggest oval is the Great Red Spot (GRS, Fig. 5A, but also visible in Fig. 4), an anticyclone first reported by the British scientist Robert Hooke in the mid-17th century. Since this first detection, it has persisted continuously with slight but visible changes in its shape. This well-known Jovian storm is in the Southern hemisphere and is larger than planet Earth. Most of the ovals are very bright in the visible spectrum and thus are called "white" (Figs. 4 and 5B). So far, the cloud morphology of the Jupiter's atmosphere, as well as the nature of the vortex features, such as the GRS and the white ovals, are not fully understood.

Polar Regions

Before the arrival of the Juno mission the Jovian polar regions were poorly explored: they are not visible from Earth owing to Jupiter's low axial tilt, as well as only poorly investigated by previous missions because they did not venture far from Jupiter's equatorial plane. During the first perijiove, JunoCam observed the polar regions at a spatial scale of 50–70 km (Orton et al., 2017). As noted by previous missions such as Pioneer 11 and Cassini, Jupiter's atmosphere appears very different for latitudes poleward of about 65° N and S. Thanks to JunoCam images we have been able to discern several unexpected details (Fig. 6). East-west banded structures are not present there, whereas different types of discrete features are evident on a darker background (Orton et al., 2017):

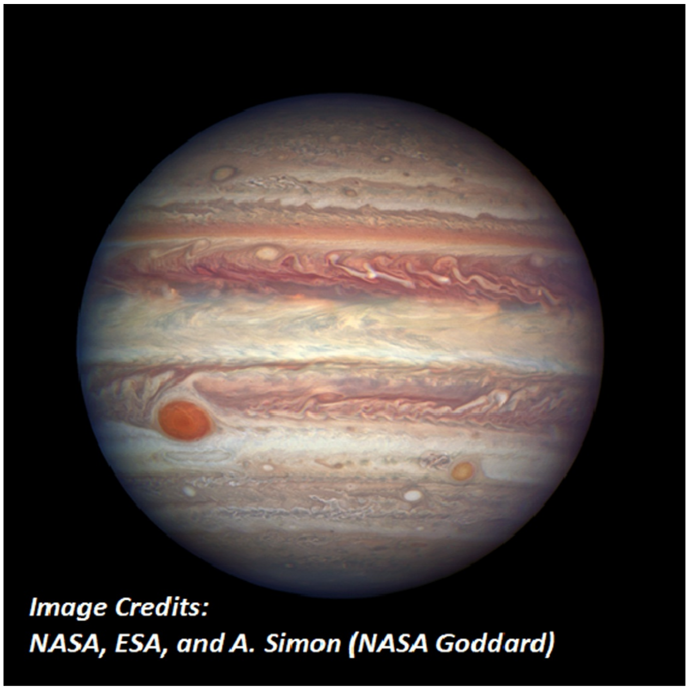

Fig. 4 Hubble Space Telescope photo of Jupiter taken on April 2017 when it was comparatively close to Earth (opposition), at a distance of 415 million miles. In this image the resolution is about 130 km/pixel. Credits: NASA, ESA, and Amy Simon (NASA Goddard). Image Courtesy of Amy Simon.

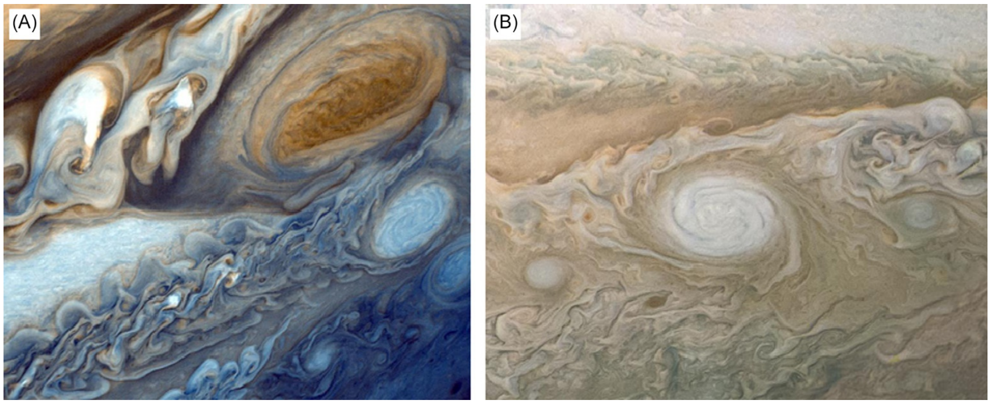

Fig. 5 Details of the Jupiter's Atmosphere. (a) The Great Red Spot imaged by the Camera on board Voyager 1. Image credits: NASA/JPL. (b) White oval in the south hemisphere image by Junocam. Image credits: NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill.

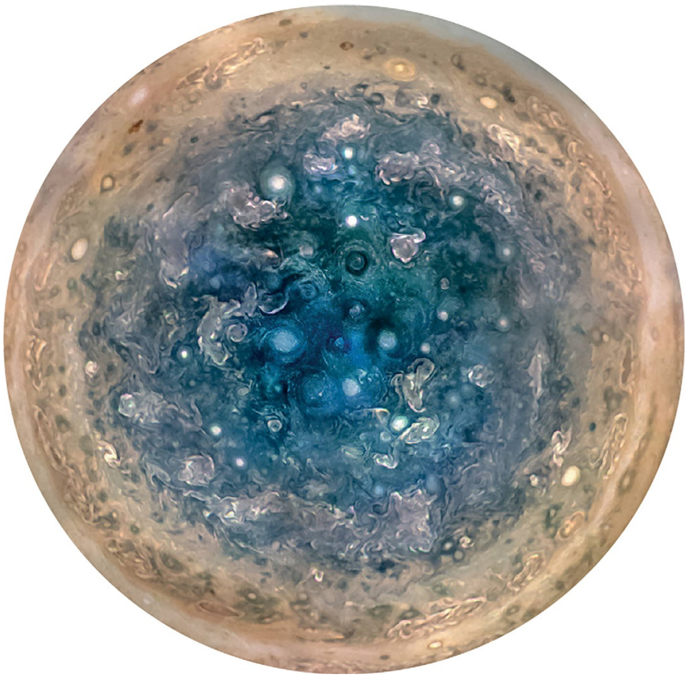

Fig. 6 Mosaics of Junocam images on the southern polar region. Credits: NASA/JPL-Caltech/SwRI/MSSS/Betsy Asher Hall/Gervasio Robles.

- several bright ovals with size ranging from 1400 km down to the Junocam resolution of about 50 km;
- amorphously shaped structures, referred to as "folded filamentary regions";
- narrow, elongated, leaner cloud features;
- high altitude clouds, above 58 ± 21 km the average background cloud level; and
- circumpolar cyclones.

Later Juno passages of the polar regions at closer proximity to the poles revealed unexpected details regarding the polar cyclones and their polygonal patterns (Adriani et al., 2018; Fig. 7).

Jupiter's configuration of polar cyclones is lacking on other planets, including Saturn's polar hexagonal features. Although migration of cyclones towards the pole might be expected, the processes that sustain Jupiter's polar cyclones without merging and their evolution to the observed configuration are poorly understood and under investigation.

Lightening

Lightening is a common phenomenon in Jupiter's atmosphere, observed by Voyager, Voyager 2, Galileo and Cassini. It can be detected through night-side images in the visible range (Fig. 8) and by radio waves generated by lightening itself (whistler). Juno

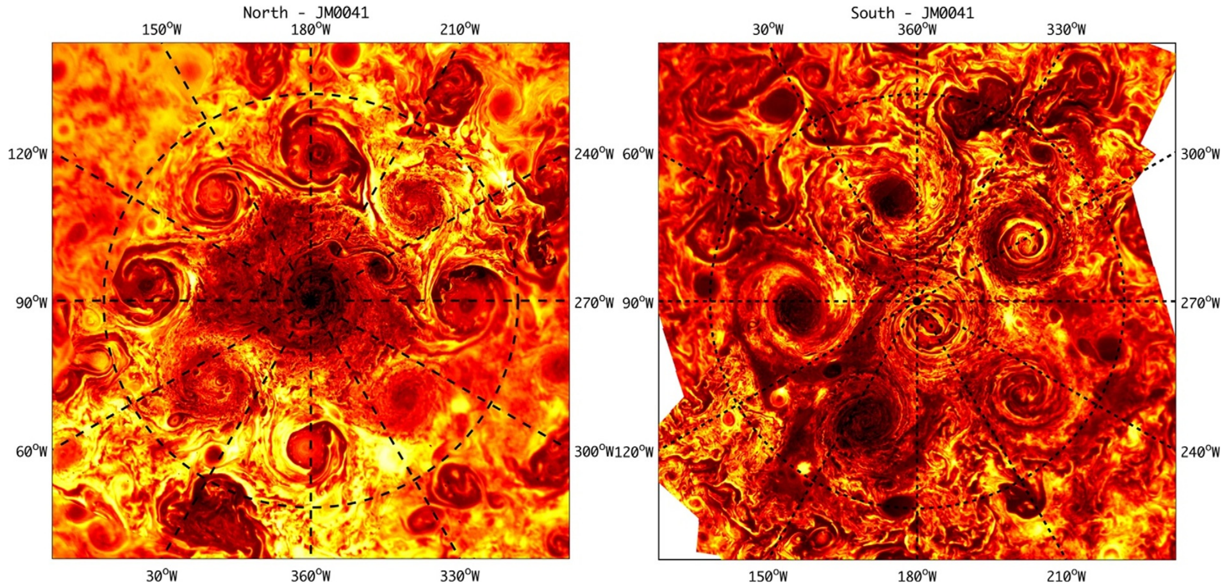

Fig. 7 JIRAM images of polar cyclones. Data from Adriani A, Mura Orton G, Hansen C, Altieri F, et al. (2018). Clusters of cyclones encircling Jupiter's poles. *Nature* 555: 256. doi: 10.1038/nature25491

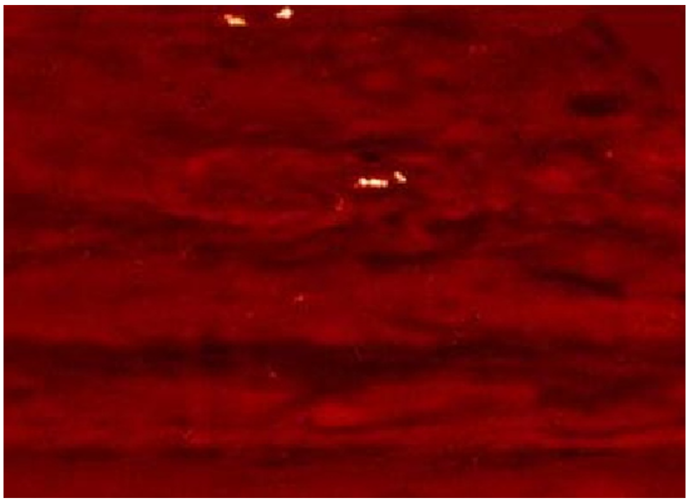

Fig. 8 Night lightening on Jupiter imaged by the Galileo spacecraft on December 1997. Credits: The Galileo Project, NASA.

MicroWave Radiometer (MWR) detected so far 377 lightning events from pole to pole, for the first-time showing analogies with terrestrial whistler (Brown et al., 2018). Juno found lightening to be prevalent in polar regions, especially in the north. On Jupiter, lightening is supposed to occur in the region of convective clouds where liquid water and water ice particles are both present, lightening strikes there are generated through a charge-separation process between liquid and ice.

Shoemaker-Levi 9 Impact

In 1994 at least 21 fragments of the comet Shoemaker-Levi 9 hit Jupiter from July 16 through July 22. It is thought that Jupiter captured the comet around 1929, while the impact was predicted in 1993. This event was followed by the Hubble Space Telescope (Fig. 9) and by several small telescopes. Indications of the collision lasted for about 2 years in the Jupiter's atmosphere. Data collected during the impact provided information about comet composition, high-altitude winds on Jupiter and the response of the magnetosphere induced by the change in the atmosphere following the impact. Moreover, it gave insights on planetary collisions in general.

Fig. 9 Dark spots in the Jupiter southern hemisphere showing the impact locations of the Comet Shoemaker-Levy 9 fragments collided with it in 1994. This image is from the Hubble and was acquired the last day of the impacts, on July 22, 1994. Credits: NASA/Hubble Space Telescope Comet Team.

Auroral Emissions

Auroral emissions arise from the impact of charged particles on the upper atmosphere. Because of the dipolar shape of the magnetic field, these charged particles originating from the magnetosphere are deflected towards the poles. In response to the precipitating plasma, the atmosphere emits radiation in different wavelengths. Voyager 1 and 2 spacecraft first detected the far UltraViolet (UV) aurora from both polar regions. Subsequently, infrared (IR) emissions from the H_3^+ ion were spectrally detected from the ground and then imaged near 3.4 μm. Finally, the visible Aurora of Jupiter was imaged from Galileo. At present, UV and IR high resolution images are collected from the Juno spacecraft, Fig. 10. While the UV and visible aurora are due to direct excitation of neutral atoms and molecules in the atmosphere, the IR auroral emission arises from a more complex interaction: precipitating electrons ionize the

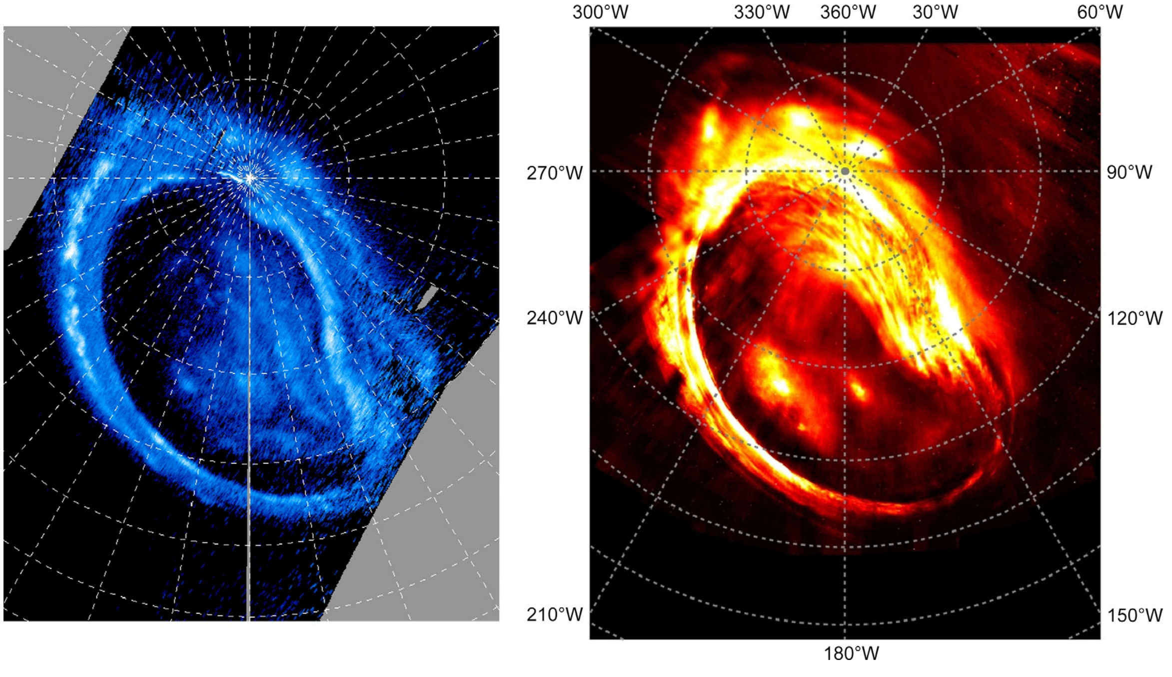

Fig. 10 Left Panel: Polar projection of the Northern aurora captured by the Juno-UVS imaging spectrograph during its perijove observations on August 27, 2016. Right Panel: same, for JIRAM. IR data. Data from Mura A, Adriani A, Connerney JPE, Bolton S, et al. (2018) Juno observations of spot structures and a split tail in Io-induced aurorae on Jupiter. *Science* 361: 6460.

H_2, which then recombine with neutral H_2 forming excited H_3^+ which finally emits in the IR. Local temperature and column density of H_3^+ can be derived from infrared spectra.

Polar aurorae are often diagnostic of plasma dynamics in the magnetosphere, and their detection in either the UV, or IR, or, hopefully both (see also Grodent et al., 2018), is a powerful tool in the development of our understanding of the magnetospheric processes. These can lead to auroral emission essentially via three mechanisms: (1) either wave-particle interactions accelerate and/or scatter particles into the loss cone (the part of the velocity distribution for which particles directly precipitate into the atmosphere), or (2) the plasma waves propagating along the magnetic field lines end up accelerating charged particles at high latitude (i.e. just above the auroral regions), or (3) large scale electric currents circulate along the field lines and accelerate the charges particles into the aurora through quasi-static electric fields at high latitude. It should be noted that these three mechanisms are not necessarily mutually exclusive, and several processes can take place at different locations along the same field lines, as recently evidenced by the Juno spacecraft (Mauk et al., 2018). In a system as large as the Jovian magnetosphere, several independent processes can simultaneously occur at different places for different reasons and the aurorae cannot be properly understood without distinguishing its various components.

Similar to the Earth aurorae, the most striking feature of the aurorae on Jupiter is an often incomplete and irregular ring of bright emissions surrounding the magnetic pole. However, these main emissions only account for about a third of the total power emitted by the aurorae in the ultraviolet wavelength (Grodent et al., 2018). Another third originates from poleward emission located inside the main emissions, while, at Earth, the region inside the oval is generally devoid of auroral emissions. The last third originates from outer emissions located equatorward of the main emission. This partition of the total power is only valid from a statistical point of view, as it varies from one observation to another. The poleward emissions are the ones that respond the most clearly to the solar wind, as they usually brighten when the solar wind dynamic pressure or the solar wind speed increase. The outer emissions on the other hand do not respond to the solar wind input, but rather vary as a function of internally driven reconfigurations of the middle magnetosphere. Between these two extremes, the main emission also brightens in response to solar wind intensifications, but some brightenings are not associated with any solar wind input.

Each of the three regions can be further sub-divided into specific features, some of which have been associated with specific phenomena. Four of them have been identified in the outer emissions: the satellite footprints, plasma injection signatures, secondary arcs, and diffuse emissions.

The presence of moon auroral footprints is one of the most interesting features of Jupiter's aurora. Magnetohydrodynamic waves, termed Alfven waves, stem from the motion of the satellites through the Jupiter co-rotating plasma. They travel down to Jupiter's ionosphere along the magnetic field lines and accelerate electrons as they proceed. Recent observations suggest that Callisto may have its footprint as well (Bhattacharyya et al., 2018). For each satellite, multiple spots that compose the footprint are often visible. This is believed to be the effect of (1) multiple reflections of the Alfven waves along the closed magnetic field line, where they cross sharp plasma density gradients, and (2) electrons beams accelerated along the magnetic field away from the planet in one hemisphere and precipitating in the opposite hemisphere. For each satellite, a long tail that follows the main spot is also observed. Recently, Mura et al. (2018) showed that each of these footprint features (multiple spots and tail) reveals a smaller-scale structure. In addition to the already-known secondary spot, the main footprint spot is followed by a series of regularly spaced secondary spots (Fig. 11). These are alternately displaced from the median track. The far tail of Io has a deeper structure as well: occasionally, the tail is formed of two separate parallel arcs, with a thicker, more intense and more turbulent poleward arc, and a thinner and fainter equatorward arc. Such small-scale features may be the signature of the presence of complex interactions.

Plasma injection signatures are the counterparts of hot and sparse plasma parcels injected from the outer magnetosphere into the middle magnetosphere. They appear as rather compact patches of auroral emissions. The occurrence rate of bright injection signatures increases during periods of intense volcanism at Io. Alternatively, diffuse emissions can also be found among the outer emissions and there have been associated with the strong pitch angle scattering stemming from the intense wave-particle interactions in the magnetospheric region where the mostly dipolar magnetic field lines become more stretched due to the current sheet.

The main emissions are generally associated with the current system that flows between the ionosphere and the current sheet and which accelerates azimuthally the magnetospheric plasma towards co-rotation with the magnetic field. In this co-rotation enforcement current system, the main emission is associated with the branch of the current loop that flows upward (i.e. away from the planet) along the magnetic field lines. It is the electrons accelerated downward, either through a quasi-static electric potential or through acceleration by Alfvén waves (Mauk et al., 2018), that create the bright ring of auroral emission called the main emissions. The size of the main emission appears to expand in response to intensified volcanic activity at Io. Moreover, these main emissions display clear variations in longitude, which appear fixed in local time. The dawn arc is generally thin, regular, and dimmer than the dusk flank, where the main emission often forms multiple bright and wide arcs. The pre-noon portion of the main emissions are generally the dimmest, forming a discontinuity in what would otherwise resemble a complete oval. The brightness variations on the main emissions mostly occur on timescales of several tens of minutes. However, pulsations with a 10-min period have also been reported and interpreted as the signature of ultra-low frequency (ULF) waves along the magnetic field lines connected to the middle magnetosphere. The dawn storms are also transient brightenings of the dawn arc of the main emission, which broadens and becomes very irregular in timescales of tens of minutes. The most powerful aurorae on Jupiter have been observed during a dawn storm event (Kimura et al., 2017).

The region located inside the main emissions is both the most complex and the least understood. It can be separated into three sub-regions, the dark region just inside the dawn arc of the main emission, the active region along the noon and dusk sides of the

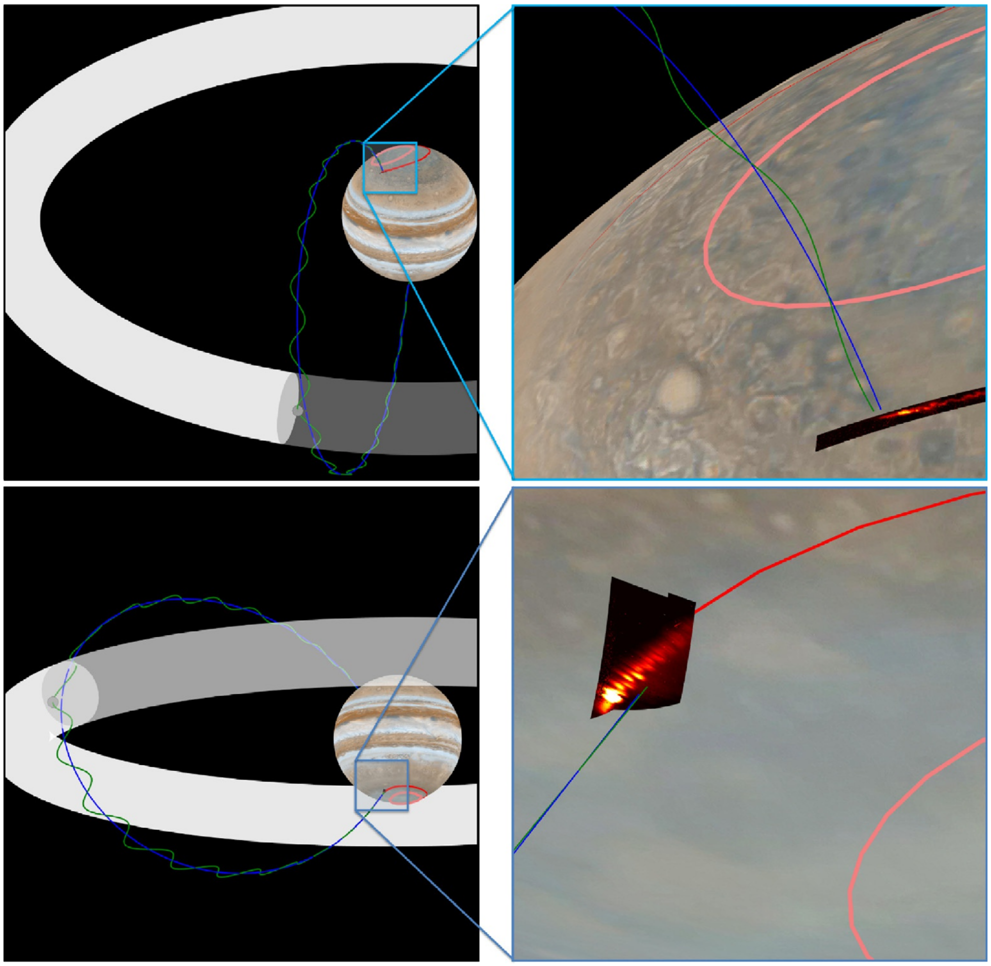

Fig. 11 Left Upper Panel: schematic illustration of the interaction between Io and the magnetosphere of Jupiter for the northern polar region. The Fig. shows Io, the Io plasma torus (gray, simplified and not to scale), an unperturbed magnetic field line (blue), an Alfvén wave (green, shape is simplified and not to scale), the main IFP and the footprint tail (red), the main auroral arc (orange). Right Upper Panel: same picture, zoomed to the region of Io footprint, and with infrared data overplotted. Right Bottom Panel: schematic illustration of the interaction between Io and the magnetosphere of Jupiter on the southern polar region. Right Bottom Panel: a zoom showing the infrared data. Data from Mura A, Adriani A, Connerney JPE, Bolton S, et al. (2018) Juno observations of spot structures and a split tail in Io-induced aurorae on Jupiter. *Science* 361: 6460.

main emissions and the swirl region in the polar-most section. The dark region is typically devoid of UV emissions, but is regularly populated by transient spots called polar dawn spots. Especially during periods of solar wind intensifications, the main emission forks into several arcs penetrating into the active region, making the delineation between the two regions unclear. In addition to these relatively stable arcs, the brightest emissions in Jupiter's aurora are found in the active region, where they appear as sporadic flares, sometimes isolated and sometimes appearing quasi-periodically (Bonfond et al., 2016). Either at the boundary between the active region or in the active region, straight filaments of emission, essentially aligned with the Sun direction can also be found. Finally, the swirl region is the locus of chaotic and dim patches of emissions.

Jupiter's Magnetosphere

Simply put, a magnetosphere is a region of space around a planet that is controlled by its magnetic field and plasma environment. In contrast to its name, a magnetosphere is not exactly spherical. This is due to the constant stream of plasma that flows away from our Sun and fills the solar system. This plasma, or "solar wind," interacts with the planetary magnetic field by compressing it on the sunward side and forming a long tail on the anti-sunward side. There are two categories of magnetospheres: the solar wind driven and the internal/rotationally driven magnetosphere. Earth's magnetosphere is an example of the former. The solar wind provides much of the plasma and energy found in Earth's space environment. In contrast, Jupiter is an example of the internal/rotationally driven magnetosphere. Jupiter's large size and fast rotation rate provide much of the bulk energy to the plasma whereas the dominant source of the plasma is provided by Jupiter's active moon, Io. Jupiter's large magnetosphere is host to a rich and diverse set of plasma physics phenomena. For example, Jupiter has the most intense radiation belts and the brightest aurorae in the solar system, its satellite Io is geologically active and fills the region with sulfur dioxide, there are large scale impulsive events, i.e., injections, that transport vast amounts of energy and mass within the system and more. In this brief review, we discuss some of the physical phenomena observed at Jupiter and the latest scientific work that is advancing our understanding. A detailed review of Jupiter's magnetospheric configuration and dynamics can be found in the Khurana et al. and Krupp et al. chapters of the Jupiter text book edited by Bagenal et al. (2004) (see Further Reading).

Jupiter's magnetosphere is typically categorized into three spatial regions: the inner (<10 Jovian radii (R_J)), middle (10–40 R_J) and outer (>40 R_J) regions, Fig. 12. Physical processes prevalent at different radii are the basis for these assigned distances; however, it should be noted that all three regions are coupled. For example, the inner region comprises the satellites Io and Europa and the intense radiation belts. As mentioned previously, Io is the primary source of plasma supplying Jupiter's magnetosphere with roughly ~1 ton/s. This plasma consists primarily of sulfur and oxygen ions with various charge states (Clark et al., 2016) and forms a torus that extends from near Io (5.2 R_J) out past Europa to ~10 R_J. The plasma torus is further characterized by a dense plasma that has a "cold" inner region confined to the centrifugal equator and "warm" outer region with a large-scale height. Additional plasma is sourced by Europa, Jupiter's atmosphere, and the solar wind. The plasma in this region is bound to Jupiter's strong magnetic field and corotates with the planet's fast rotation rate.

Jupiter's radiation belts are regions of space near the planet that are comprised of intense and very energetic ions and electrons. They were first discovered as radio emissions observed from Earth and later in situ with the Pioneer and Voyager flyby missions. They occupy radial distances between 2 R_J and extend near the orbital region of Europa. The nature of particle acceleration is still a mystery today, but it is thought that electric fields facilitate in the energization of the plasma as it moves inward towards Jupiter. The Juno mission is providing new details on both the high-latitude portions and the region very close to the planet, which have been largely unexplored. Juno discovered that an inner radiation belt resides inside the halo rings of Jupiter (Kollmann et al., 2017). The mechanism of its formation and maintenance is largely unknown and is being continuously observed by Juno. Additionally, the high-latitude radiation belt intensities observed by Jupiter appear to be lower than physics-based model predictions (e.g., Soria-Santacruz et al., 2016). Understanding how particles are accelerated to form Jupiter's intense radiation belts is a big open question in space physics.

The co-rotating plasma generated near Io beings to lag in Jupiter's middle magnetosphere. This lagging effect has a profound impact on Jupiter's global system. Radial and azimuthal current systems are generated as a result. The radial current system tries to maintain co-rotation and in turn magnetic field-aligned potentials are generated near Jupiter's auroral region that accelerate particles into its atmosphere generating the main auroral emissions. Azimuthal currents are generated near Jupiter's equatorial plane. The currents are large enough to significantly perturb Jupiter's equatorial magnetic field. These strong currents coupled with the weaker planetary magnetic field act to form a highly stretched magnetic field configuration, both in the radial and in the azimuthal

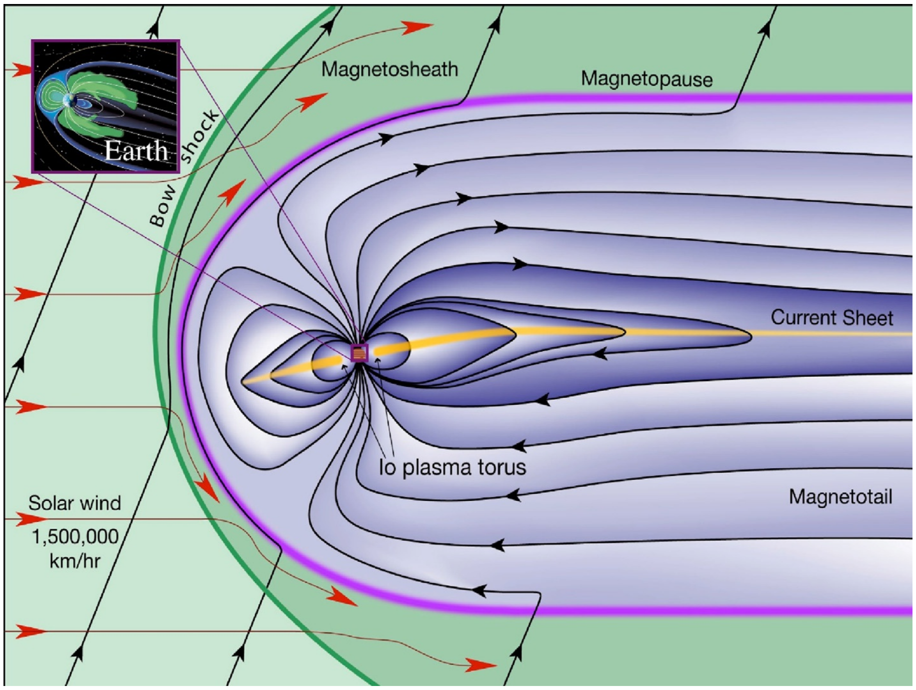

Fig. 12 Illustration of Jupiter's magnetospheric configuration and size comparison to Earth's magnetosphere. Credits: Fran Bagenal and Steve Bartlett (http://lasp.colorado.edu/home /mop/resources/graphics/graphics/)

direction. Additionally, the plasma temperature in this region is heated to ~10 keV, some 100 times more than the inner magnetosphere. This process is not well understood.

Beyond the middle magnetospheric region, the co-rotating plasma lags significantly and the magnetic field becomes weaker, therefore most of the energy density is stored in the particles. The current sheet that formed in the middle magnetosphere is still present in this region and extends all the way out to the magnetopause, the boundary between Jupiter's magnetic field and the solar wind. Its half thickness in the outer region is ~2 R_J. Outside of the current sheet are the lobe regions, which are generally characterized by very low plasma densities. In the dayside or sunward side of the magnetosphere, the magnetopause is very dynamic and can move inward and outward in response to solar wind conditions. In the nightside outer magnetosphere there are magnetotail current systems that exacerbate the stretching and form a long tails that can extend all the way to Saturn's orbit. Processes in the tail region play an important role in shedding the plasma generated in the inner magnetosphere. One process is magnetic reconnection. Unlike Earth, where magnetic reconnection is driven by the solar wind, on Jupiter it is driven by the planet's fast rotation. A theoretical framework showed magnetic field topological changes in the tail region resulting from the requirement that the observed plasma transitions from co-rotational to radial outwards. Reconnection is considered as one way to shed iogenic material downtail and out of the Jupiter system. Galileo provided evidence of tail reconnection (e.g., Vogt et al., 2014) at distances of ~70–100 R_J. Later the New Horizons spacecraft flew down-tail of Juptier's magnetosphere and observed iogenic and jovian plasma moving anti-sunward as far away as 2500 jovian radii, thus confirming the idea that reconnection plays a role in shedding plasma. Juno initially crossed the magnetopause dozens of time during its first orbits and discovered that particles can easily leak out of Jupiter's magnetosphere (Mauk et al., 2019). Juno also found circumstantial evidence for magnetic reconnection occurring near the boundary, a process that is poorly understood at Jupiter (Ebert et al., 2017).

Moons

Jupiter has 79 confirmed moons. Table 4 lists some physical parameters for satellites over 9 km in diameter. The largest moons, Io, Europa, Ganymede and Callisto (Fig. 13), are also known as the Galilean satellites, being first observed by the astronomer Galileo Galilei in 1610; they are also some of the most interesting objects in the solar system, each of them standing out for a peculiar characteristic.

Io: This is the inner moon of the Galilean satellites and is the most active body in the solar system in terms of volcanism. Io's surface is very young and no impact craters (shaping the oldest terrains in the solar system) are still evident. Volcanic activity is caused by tidal heating: due to orbital resonances between Io, Europa and Ganymede, Io's orbit is eccentric, and the satellite undergoes periodic deformations. Materials ejected by Io's volcanoes are spread along its orbit, generating a torus. Several lava-flows and lava lakes are present, with surface mean temperatures of the lavas about1600 K. The surface is characterized by yellow, orange, red and black areas. Sulfur dioxide has been detected in the eruption gas emissions. Io is one of the most colorful bodies in the solar

Table 4 Satellites of Jupiter with diameter ≥9 km.

Satellite	*Mean distance from Jupiter (km)*	*Orbital period, days*	*Diameter, km (equator)*	*Density (water = 1)*	*Orbital eccentricity*	*Orbital inclination*
Small inner satellites						
Metis	128,100	0.294	60	2.8	0.001	0.021
Adrastea	128,900	0.300	26	2(doubtful)	0.002	0.027
Amaithea	181,100	0.489	262	1.8	0.003	0.389
Thebe	221,900	0.674	110	1.5	0.018	0.070
Galileans						
Io	421,000	1.769	3660	3.6	0.004	0.036
Europa	671,100	3.551	3130	3.0	0.009	0.470
Ganymede	1,070,400	7.154	5268	1.9	0.002	0.195
Callisto	1,882,700	16.689	4821	1.1	0.007	0.281
Outer prograde satellites						
Themisto	7,507,000	130.0	9	2 (doubtful)	0.242	43.08
Leda	11,165,000	240.0	16	2.7	0.264	27.46
Himalia	11,461,000	250.6	186	2.8	0.162	27.50
Lysithea	11,717,000	259.2	38	3.1	0.212	28.30
Elara	11,741,000	259.6	78	3.3	0.217	26.63
Outer retrograde satellites						
Ananke	21,276,000	610.5	28	2.7	0.244	148.9
Carme	23,404,000	702.3	48	2.8	0.253	164.9
Pasiphae	23,624,000	708.0	58	2.9	0.109	151.4
Sinope	23,939,000	724.5	38	3.4	0.250	158.1

Moore P (2005) *Solar System/Jupiter, Saturn and Their Moons* (2nd edn), pp. 282–289.

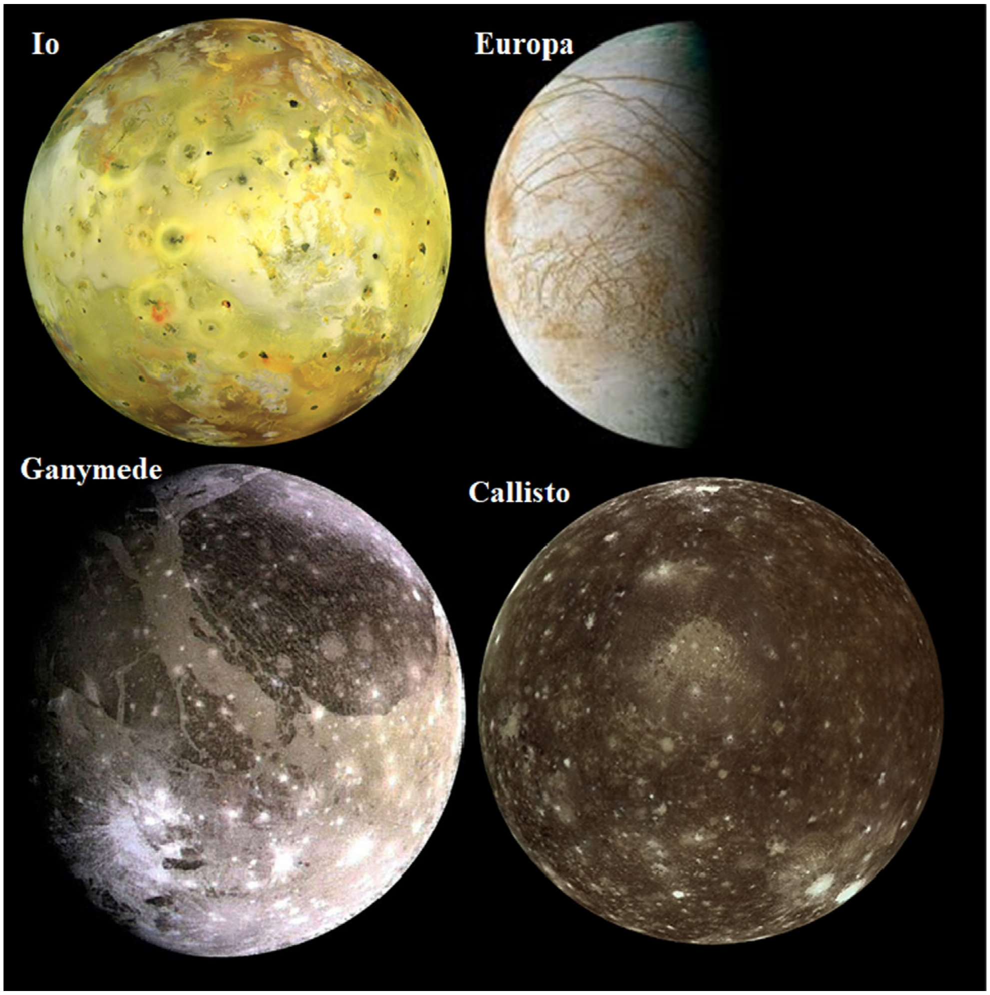

Fig. 13 The Galilean satellites (relative sizes not to scale). Left Upper Panel: Io color mosaic image from the near-infrared, green and violet filters of the camera on board the NASA Galileo spacecraft. This image should simulate what a human eye would see. Image credit: NASA/JPL/University of Arizona. Right Upper Panel: An image of Europa taken by the Galileo spacecraft, credits NASA/JPL/Ted Stryk. Left Bottom Panel: Ganymede, image credits: NASA/JPL/Galileo probe. Right Bottom Panel: Callisto. Image credits NASA/JPL/Ted Stryk.

system. The first volcano was observed by the Voyager spacecraft; so far, more than 150 volcanoes have been identified. One of them, named Loki, is considered the strongest volcano in the Solar System, emitting more heat than all the active volcanoes on the Earth combined.

Europa: This is the smallest moon among the Galilean satellites, but the most interesting in terms of potentiality of being habitable. With a rocky mantle submerged beneath 100 km of water, and surface ice heavily processed by Jovian radiation, the energy and ingredients required for life may be present in abundance. Europa's surface is also very young and very different from that of Ganymede or Callisto, although all three bodies are covered by ice. Moreover, the surface is very smooth, indicating that resurfacing by outflow of water from subsurface is taking place all over the moon. The entire satellite is crisscrossed with bright and dark stripes, as well as curvilinear ridges and grooves. A variety of mechanisms on geologically short timescales provide evidence of exchange occurring between the ocean and surface. Complex areas of brownish-red material may have been sourced from the water layer within the moon, arising from geologic processes that involve melting of the ice shell. Active cryovolcanism has been considered as a transport mechanism, which would result in recent deposition onto the surface from liquid reservoirs below. Evidence for plumes of water on Europa has been also observed.

Ganymede: This is the largest satellite in the Solar System (larger than the planet Mercury), but indeed not so massive: its mean density is less than that of water. Ganymede is characterized by a tenuous atmosphere and a marked magnetic field that causes auroras in the polar regions. Ganymede's internal structure consists of three main layers. An inner core of metallic iron (which generates the magnetic field), a spherical shell of rock (mantle) surrounding the core, and an external shell mainly consisting of ice surrounding the rock shell and the core. The ice shell is thought to be very thick, perhaps 800 km. The icy surface shows two main types of terrains: i) very ancient, thickly cratered dark regions and ii) younger light regions, marked with an extensive array of ridges and grooves. There is evidence of ancient tectonic activity. Large craters on Ganymede appear shallower and flatter than comparably sized craters on the Moon and Mercury, suggesting that adjustment of the icy surface took place there.

Callisto: This is the outermost of the Galilean satellites and the one with the deepest cratered and oldest surface, with two main ringed plains: Valhalla and Asgard. The surface is thought to be 4 billion years old, with no indication of significant geologic activity in the past. Smaller and less dense than Ganymede, it is composed by ice and rocks, but its internal structure is less constrained than that of the other Galilean moons. A thin atmosphere of carbon dioxide surrounds the satellite. A salty ocean as on Europa, but deeper inside the globe, has been predicted for Callisto. This places Callisto on the list of possible words where life could exist in our solar system beyond the Earth. The presence of a salty ocean has been hypnotized because Callisto shows a weak magnetic field, induced by Jupiter's field, which should raise by a conducting layer in the interior but its density does not justify a metallic core as for Ganymede.

Rings

Hints of Jupiter's rings were found by Pioner 11 in 1975 but their presence was confirmed by long exposure images obtained NASA's Voyager 1 spacecraft 5 years later. The ring system extends from about 1–4 R_J, thus between Jupiter and Io (at ~6 R_J). The inner irregular satellites Metis, Adrastea, Amalthea, and Thebe are embedded within the rings and they act as both sources and sinks for ring materials. Three main components characterize Jupiter's rings: (i) a pair of tenuous rings confined between Thebe and Amalthea with a unique "gossamer" morphology, this is the faintest component; (ii) a flat (full-width-at-half-maximum thickness between 30 and 100 km), main ring 6500 km wide around Adrastea and Metis; and (iii) an halo near the inner edge of the main ring with a thickness that rapidly grows up to 20,000 km. Unlike Saturn, Jupiter's rings are very faint and composed of small, dark particles of dust.

Open Questions and Future Investigations

The remarkable data obtained from the Juno mission has changed our view of the interior of Jupiter. Nevertheless, many unsolved questions remain. One of the remaining challenges is the development of a better comprehension of the dilute core and how it affects the internal structure of Jupiter. We also need to keep improving our knowledge of the equations of the state of hydrogen, helium, and mixtures (with ices and rocks), which have an important role in increasing our understanding of the deep internal structure of the big giant. Another important piece of the puzzle is to link the information we are obtaining from the magnetic field and atmosphere with the internal structure of the planet to get a deeper understanding of the complex processes happening in the boundary between the deep interior and Jupiter's atmosphere. Modelers face major challenges in attempting to explain Jupiter's atmospheric band structure, wind fields, polar vortex dynamics, as well as formation and persistence of the storms, even though the Juno missions collected data with unprecedented details.

The system formed by Jupiter's magentosphere and aurorae is vast and complex, and improving our knowledge of the processes at play will enhance our ability to understand our solar system and other distant worlds.

Spacecraft missions such as Pioneer, Voyager, Galileo, Cassini, New Horizons and Juno have provided us with many discoveries even beyond our imagination. The JUICE and Europa Clipper spacecrafts are the next space missions to visit Jupiter. They are planned to launch in the early-to-mid-2020s with arrival dates around 2030. These missions will provide key clues in understanding Jupiter's atmosphere, auroral processes, the interaction between planet and its bigger satellites as well as the three-dimensional structure of its magnetosphere. Moreover, they will explore the Galilean moons at an unprecedented level of detail, in particular Europa and Ganymede, to better assess the potential habitability of ocean words with implications also for the occurrence of life outside the Solar System.

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