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Special Section:
Results from Juno's Flyby of Ganymede

Key Points:

- Juno passed Ganymede on 7 June 2021 at an altitude of approximately 1,000 km, the closest any spacecraft has come since the Galileo mission ended in 2003
- The path of Juno's trajectory allowed the spacecraft to pierce Ganymede's unique magnetosphere and map a swath of its surface and subsurface
- The geometry of the flyby is described for the close pass in June and a more distant pass (approximately 50,000 km) on 20 July 2021

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Juno's Close Encounter With Ganymede—An Overview

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Abstract The Juno spacecraft has been in orbit around Jupiter since 2016. Two flybys of Ganymede were executed in 2021, opportunities realized by evolution of Juno's polar orbit over the intervening 5 years. The geometry of the close flyby just prior to the 34th perijove pass by Jupiter brought the spacecraft inside Ganymede's unique magnetosphere. Juno's payload, designed to study Jupiter's magnetosphere, had ample dynamic range to study Ganymede's magnetosphere. The Juno radio system was used both for gravity measurements and for study of Ganymede's ionosphere. Remote sensing of Ganymede returned new results on geology, surface composition, and thermal properties of the surface and subsurface.

Plain Language Summary The evolution of Juno's orbit around Jupiter made it possible to execute a close and a distant flyby of Ganymede in 2021. The geometry of the close pass allowed Juno to enter Ganymede's unique magnetosphere. Juno's remote sensing instruments observed a significant area of Ganymede's surface and subsurface with higher resolution than Voyager or Galileo.

1. Introduction

Jupiter's moon Ganymede is the largest moon in the solar system and the only moon with its own intrinsic, permanent magnetic field that extends far beyond its surface to form a magnetosphere (Gurnett et al., 1996; Kivelson et al., 1996, 2002). The first missions to investigate Ganymede in detail were the Voyager flybys of Jupiter in 1979, and the Galileo mission, which orbited Jupiter from 1995 to 2003 and executed a series of six close Ganymede flybys (summarized by Volwerk et al., 2022). Key findings of these missions, combined with Earth-based observations from facilities such as Hubble and ALMA, are as follows.

Ganymede has a fully differentiated interior including a metallic core (Anderson et al., 1996; Hussmann et al., 2022). A subsurface liquid salt-water ocean forms a global layer, the top of which can be no more than 330 km below the icy surface (Kivelson et al., 1999; Saur et al., 2015, 2018). Ganymede is slightly larger and denser than, and forms a class with, the two other large solar system moons Callisto and Saturn's Titan. However, Ganymede's complex geologic history, which includes tectonic and/or volcanic production of grooved terrain well after the moon's formation, cutting through ancient heavily cratered terrain, shows a very different formation and evolution history than the other large moons (Schenk et al., 2022).

Ganymede's neutral molecular oxygen exosphere (Hall et al., 1998), sourced from sputtering, radiolysis, and sublimation of surface ice, is ionized by photo-ionization and electron impact on open field lines. O, H, and H_2O have also been detected (Barth et al., 1997; Hall et al., 1998; Roth et al., 2021, respectively). Hubble Space Telescope (HST) spectral images suggest oxygen auroral emissions are generated at or near the polar boundary between open and closed magnetic field lines (McGrath et al., 2013). The ionosphere is weak and transient—detected in some but not all of the earth occultations observed by the Galileo mission (Kliore, 1998).

Galileo near-infrared spectra showed that the composition of the satellite's surface is dominated by a mixture of water ice, trapped carbon dioxide and other species (Carlson et al., 1996). The ice particles form a thin layer of frost which, in the polar regions, shows a higher albedo in the visible part of the spectrum. It has been suggested (G. B. Hansen and McCord, 2004; Khurana et al., 2007) and bolstered by more recent datasets (Ligier et al., 2019;

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Mura et al., 2020) that this albedo difference may be due to the interaction of the magnetic field of Ganymede with the Jovian magnetosphere, which at least partially protects the surface regions between ±40° latitude from the impact of Jovian magnetospheric particles, while leaving the polar regions exposed to plasma bombardment (Paranicas et al., 2021).

Our understanding of Ganymede's magnetosphere prior to Juno's flyby is summarized in Jia and Kivelson (2021). Ganymede's magnetic field interacts dynamically with the ambient Jovian plasma and magnetic field. The opportunity to investigate Ganymede's unique magnetosphere in situ and its interaction with the Jovian magnetosphere with the modern Juno payload, has given us the most comprehensive close-range data set since those acquired by Galileo and Voyager (Table 1). Juno's close flyby of Ganymede occurred on 7 June 2021 with a more distant flyby on 20 July 2021.

2. Juno's Orbit Evolution

The Juno spacecraft, launched in 2011, went into orbit around Jupiter on 4 July 2016. The initial 53-day orbit was polar and elliptical, with apojove at an altitude of approximately 8,032,760 km and perijove at an altitude of 4,163 km (Bolton et al., 2017). The perijove (PJ) latitude at PJ1 was at approximately 3.8°N latitude. The orientation of the orbit ellipse was such that apojove was over the dawn terminator, perijove over the dusk terminator, and both nearly in the plane of the ecliptic. Jupiter's obliquity is just over 3°, thus the high inclination of Juno's orbit precluded any close flybys of the Galilean moons for almost the entire prime mission.

Juno's prime mission was designed to achieve 35 PJ passes, to map the Jovian magnetosphere with 11.25° longitudinal spacing. Over the 5 years of the primary mission, orbit evolution due to Jupiter's oblateness moved perijove northward and apojove southward as shown in Figure 1. Once the orbital distance of Juno at the equatorial plane crossing on the inbound leg of its orbit evolved inwards to the point that it reached the orbital distances of the Galilean satellites, opportunities became available to observe the moons up close. Trajectory timing was designed to encounter Ganymede when Juno crossed its orbit on PJ34 and PJ35. There are no more close Ganymede flybys in the remainder of the extended mission (EM) as the orbit continues to evolve.

3. Geometry of the Ganymede Flybys

3.1. PJ34 Ganymede Flyby

Juno flew by Ganymede on 7 June 2021 at a closest-approach (CA) altitude of 1,046 km over the leading hemisphere, about 14.8 hr before PJ34. The spacecraft approached Ganymede from the night side, went behind Ganymede as seen from the earth (achieving an earth occultation), passed through the moon's magnetosphere, then departed on the sunlit ∼sub-Jovian side. The trajectory with respect to Ganymede's magnetosphere is illustrated in Figure 2 and events are listed in Table 2.

As shown in Figure 3 remote sensing coverage began with an SRU image taken of territory lit by Jupiter-shine, on the night side of the terminator. UVS detected the aurora on both the nightside and dayside. MWR scanned the subsurface. JunoCam imaged the surface on the dayside. JIRAM collected five very high spatial resolution samples of different terrain types.

Table 3 lists the geometric parameters for the flyby.

3.2. PJ35 Ganymede Flyby

Juno made another more distant pass by Ganymede at approximately 50,000 km altitude on 20 July 2021, 15.4 hr before PJ35. At this distance the fields and particles instruments could study the environment at Ganymede's range from Jupiter, thus providing a point of reference for magnetospheric conditions without the presence of Ganymede. Comparisons to magnetospheric conditions on the PJ34 observations close to Ganymede help to establish how Ganymede affects conditions in Jupiter's magnetosphere.

The JIRAM, UVS and JunoCam imagers were able to gather data over territory not imaged in PJ34. Table 4 lists the flyby geometric parameters.

Table 1
Juno's Payload

Instrument name	Description	Ganymede science
Gravity	Doppler Radio Science (Asmar et al., 2017)	Ganymede gravity field and ionosphere
Mag	Dual Fluxgate Magnetometers (Connerney et al., 2017)	Ganymede's dynamo field and magnetic field structure in Ganymede's magnetosphere
MWR	Microwave Radiometer (Janssen et al., 2017)	Subsurface properties
JEDI	Energetic Particle Detectors (Mauk et al., 2017)	Energetic charged particle flux and composition in Ganymede's magnetosphere
JADE	Plasma Particle Detectors (McComas et al., 2017)	Plasma electron and ion distributions; ion composition in Ganymede's magnetosphere
Waves	Radio and Plasma Waves (Kurth et al., 2017)	Radio emissions from, and plasma waves in, Ganymede's magnetosphere
UVS	Ultraviolet Imaging Spectrograph (Gladstone et al., 2017)	Ganymede's aurora and surface albedo
JIRAM	Infrared Imaging Spectrometer (Adriani et al., 2017)	High resolution surface composition
JunoCam	Visible Color Imager (C. J. Hansen et al., 2017)	Day-side images for surface geomorphology
SRU	Stellar Reference Unit (Becker et al., 2017)	Night-side image illuminated by Jupiter-shine for surface geomorphology
ASC	Advanced Stellar Compass (Connerney et al., 2017)	Energetic electron detection in the Jovian environment

4. Science Results Summary

4.1. Interior Structure

Tracking data from Juno's radio subsystem are combined with datasets from the Galileo mission, allowing an update to the gravity field of Ganymede. The degree-2 gravity field is consistent with a body in hydrostatic equilibrium, while degree >2 signal hints at localized nonhydrostatic features (Palguta et al., 2006). Including explicitly the effect of nonhydrostatic gravity provides a more realistic assessment of the error in Ganymede's moment of inertia. The larger derived error allows for a larger variation in the densities of internal layers as compared to Anderson et al. (1996) (Gomez Casajus et al., 2022).

4.2. Surface and Subsurface Properties

Juno examined the surface of Ganymede from microwave to ultraviolet wavelengths. The subsurface mapped by MWR shows variation vertically and horizontally in thermophysical properties, from warmer ancient dark terrain to the very cold crater Tros (Brown, 2022). JIRAM data were obtained with pixel resolution <1 km/px on both the leading and trailing side, sampling grooved terrain, dark terrains, and fresh crater ejecta. Spectroscopic data show

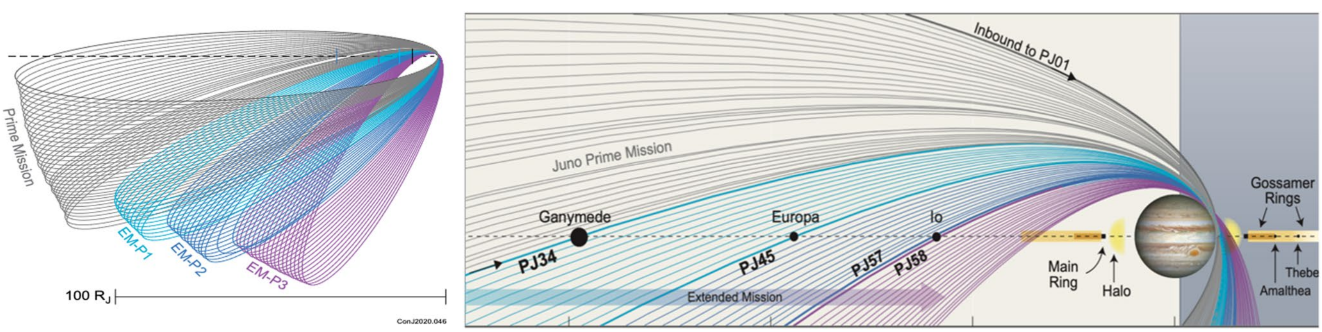

Figure 1. Left panel. The Juno orbit petal has been evolving due to the oblateness of Jupiter, such that perijove is moving north and apojove is moving south. The prime mission orbit period was 53 days; in the extended mission the orbital period has decreased to 43 days (phase P1), will shrink to 38 days after the close Europa flyby (P2) and finally to 33 days (P3) due to the effect of the moons' gravity on the close flybys. Right panel. In 2021 the inbound leg of Juno's orbit crossed the orbit of Ganymede, with the opportunity to observe Ganymede at an altitude of 1,046 km prior to PJ34, and at an altitude of approximately 50,000 km prior to PJ35.

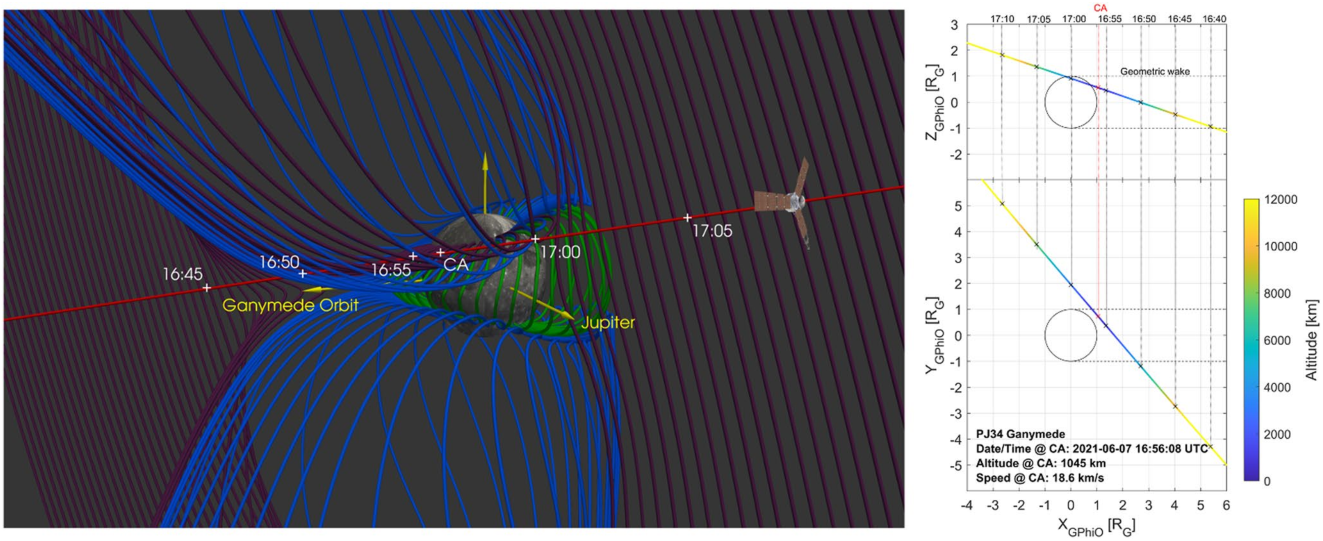

Figure 2. Left Panel. Juno pierced Ganymede's magnetosphere, moving from the left to the right, at times indicated on the red trajectory line. Ganymede's closed field lines are shown in green, with open field lines connecting Ganymede to Jupiter in blue. Jovian field lines not connected to Ganymede, black, are distorted by the presence of the Ganymede field (Duling et al., 2022). Right panel. Juno's trajectory shown in the Cartesian GPhiO coordinates defined as: the primary axis $\hat{Z}$ is parallel to Jupiter's rotation axis in the northward sense, the secondary axis $\hat{Y}$ is along the Ganymede-Jupiter direction, and the $\hat{X}$ axis completing the right-handed coordinate system and in the plasma corotation direction; Ganymede's radius (R_G) = 2631.2 km.

a wealth of information, with variable distribution of specific categories of mineral salts and possibly organic compounds. The analysis of JIRAM spectroscopic data suggests that Ganymede's surface composition at low latitudes is complex and likely endogenous in nature, with perhaps limited alteration by space weathering. Visible images from the SRU and JunoCam reveal detail at higher resolution, in stereo, and with better quality in the imaged region than the best of the existing Voyager and Galileo coverage, enabling improvements to the geologic and topographic maps (Becker et al., 2022; Ravine et al., 2022). Albedo mapped at ultraviolet wavelengths shows latitudinal trends in composition and ice grain size (Molyneux et al., 2022). Sputtering rates to evaluate energetic particle weathering of Ganymede's surface have been computed (Paranicas et al., 2022).

4.3. Exosphere, Ionosphere, Aurora

The ionosphere was probed by observing Juno's radio signal as the spacecraft disappeared behind Ganymede as seen from the Earth, and electron density in the ionosphere was determined (Buccino et al., 2022). The UVS mapped emissions from Ganymede's aurora that mark the boundary of the open and closed field lines of Ganymede's magnetosphere. This data set constrains models of Ganymede's magnetosphere (Greathouse et al., 2022). Data obtained from Hubble Space Telescope at the time of Juno's encounter reveal the coupling of the brightness of the aurora to Jupiter's plasma sheet (Saur et al., 2022).

Table 2
Geometric and Magnetospheric Events

2021 June 7 hh:mm UTC	Altitude	Event
16:40	15,636	Earth occultation ingress
Approximately 16:42	13,474	Entry into wake region
16:50	5,115	Magnetosphere entry: Transition from field lines connected Jupiter-Jupiter to Jupiter-Ganymede field lines
16:53	2,439	Earth occultation egress
16:56	1,049	Closest approach
16:57	1,166	Night–day boundary crossing (radial projection from surface)
Approximately 17:01	3,890	Outbound magnetopause boundary crossing

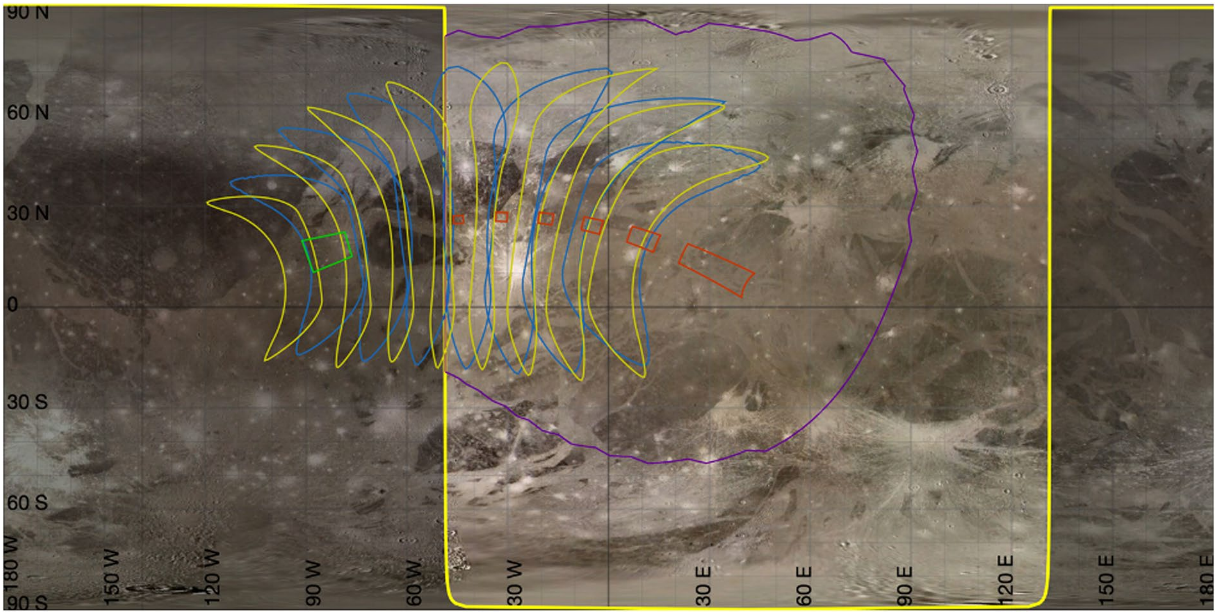

Figure 3. Remote sensing coverage began with the SRU image on the nightside illuminated by Jupiter-shine, outlined in green. Yellow and blue wedges outline the MWR surface coverage for channels 3 and 1, respectively. The red boxes outline the locations of the high resolution JIRAM surface samples. JunoCam surface images covered the area outlined in purple. The thick yellow line shows the location of the terminator.

4.4. Ganymede's Magnetosphere Structure and Dynamics

An incursion into Ganymede's magnetosphere was detected by Juno's fields and particles package. Entry into Ganymede's sphere of influence was marked by a magnetic field rotation at approximately 16:42 indicating a transition from Jovian to Ganymedian magnetic regimes. Juno's flight across Ganymede's leading hemisphere brought access to the wake region, before reaching its closest approach at approximately 16:56 and finally exiting the magnetosphere at ∼17:01, marked by a field rotation once again (Weber et al., 2022). The average magnetic

Table 3
PJ34 Ganymede Closest Approach

PJ34 Ganymede encounter	
Time of closest approach	7 June 2021 16:56 UTC
Altitude	1,046 km
Subspacecraft latitude	23.6°N
Subspacecraft longitude	56.8°W
Subsolar latitude	0.06°N
Subsolar longitude	318°W
Phase angle	98°
Sun-Jupiter-Ganymede angle	136°
Juno speed with respect to Ganymede	18.57 km/s
Jupiter centrifugal latitude (Phipps & Bagenal, 2021)[a]	1.8°S
Jupiter System III west longitude	302°W

Note. All parameters are with respect to Ganymede unless otherwise noted.
[a]The centrifugal equator is the plane to which the magnetospheric plasma is confined, geometrically defined as the loci of points where each magnetic field line is at its farthest distance from Jupiter's spin axis.

Table 4
PJ35 Ganymede Closest Approach

PJ35 Ganymede encounter	
Time of c/a	20 July 2021 16:48 UTC
Altitude	50,109 km
Subspacecraft latitude	22.5°S
Subspacecraft longitude	237.4°W
Phase angle	80.9°
Jupiter centrifugal latitude	0.4°N
Juno speed with respect to Ganymede	17.9 km/s

Note. All parameters are with respect to Ganymede unless otherwise noted.

field conditions outside Ganymede's magnetosphere are described by Vogt et al. (2022). The fields and particles profiles in Ganymede's magnetosphere were characterized:

- Plasma ions and electrons: The ion composition near Ganymede is very different from the local plasma environment. H_2^+ and H_3^+ ions were detected inside Ganymede's magnetosphere and outside in the wake region. The presence of H_2^+ and H_3^+ is a strong indicator that the composition is dominated by water products from Ganymede's surface (Allegrini et al., 2022). Observation of heated, streaming electrons near Ganymede's magnetopause was consistent with magnetic reconnection (Ebert et al., 2022; Valek et al., 2022).
- Energetic charged particles: Similar flux levels on polar Ganymede field lines to those in the surrounding region were found (Paranicas et al., 2022). Ganymede causes a relative decrease in high energy electron flux that is central to and symmetrical about Ganymede's position (Clark et al., 2022; Kollman et al., 2022).
- Radio and plasma wave: Radio emissions were detected, likely originating from Ganymede's magnetosphere. Various plasma wave modes and instabilities have been identified, namely, whistler modes, electron cyclotron harmonics, and upper hybrid bands. The latter emissions allowed for the inference of the local electron density profile, revealing a day-night asymmetry in variability (Kurth et al., 2022).
- Magnetic field: Updated best-fit spherical harmonics of Ganymede's internal magnetic field reveal a very dominant dipole moment, with quadrupole moments that are over an order of magnitude weaker (Weber et al., 2022). The detection of flux ropes and non-zero magnetic field normal component across the ram-side magnetopause was consistent with magnetic reconnection (Duling et al., 2022; Romanelli et al., 2022).

5. Conclusions

Important new observations have clarified long-standing puzzles from the Galileo epoch and generated new questions to guide the upcoming JUICE and Clipper missions. Juno will continue its program of comparative studies of the Galilean satellites with close flybys of Europa on 29 September 2022 (PJ45), and Io on 30 December 2023 (PJ57) and 3 February 2024 (PJ58), which will further advance our understanding of Jupiter's diverse retinue of large satellites.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All Juno data are archived in the NASA Planetary Data System (PDS) at https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO and https://pds-ppi.igpp.ucla.edu/mission/JUNO.

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