

Planetary Science Decadal Survey Community White Paper

Ganymede science questions and future exploration

Geoffrey C. Collins, *Wheaton College, Norton, Massachusetts*
gcollins@wheatoncollege.edu

Claudia J. Alexander, *Jet Propulsion Laboratory*
Edward B. Bierhaus, *Lockheed Martin*
Michael T. Bland, *Washington University in St. Louis*
Veronica J. Bray, *University of Arizona*
John F. Cooper, *NASA Goddard Space Flight Center*
Frank Crary, *Southwest Research Institute*
Andrew J. Dombard, *University of Illinois at Chicago*
Olivier Grasset, *University of Nantes*
Gary B. Hansen, *University of Washington*
Charles A. Hibbitts, *Johns Hopkins University Applied Physics Laboratory*
Terry A. Hurford, *NASA Goddard Space Flight Center*
Hauke Hussmann, *DLR, Berlin*
Krishan K. Khurana, *University of California, Los Angeles*
Michelle R. Kirchoff, *Southwest Research Institute*
Jean-Pierre Lebreton, *European Space Agency*
Melissa A. McGrath, *NASA Marshall Space Flight Center*
William B. McKinnon, *Washington University in St. Louis*
Jeffrey M. Moore, *NASA Ames Research Center*
Robert T. Pappalardo, *Jet Propulsion Laboratory*
G. Wesley Patterson, *Johns Hopkins University Applied Physics Laboratory*
Louise M. Prockter, *Johns Hopkins University Applied Physics Laboratory*
Kurt Retherford, *Southwest Research Institute*
James H. Roberts, *Johns Hopkins University Applied Physics Laboratory*
Paul M. Schenk, *Lunar and Planetary Institute*
David A. Senske, *Jet Propulsion Laboratory*
Adam P. Showman, *University of Arizona*
Katrin Stephan, *DLR, Berlin*
Federico Tosi, *Istituto Nazionale di Astrofisica, Rome*
Roland J. Wagner, *DLR, Berlin*

Introduction

Ganymede is a planet-sized (larger than Mercury) moon of Jupiter with unique characteristics, such as being the largest satellite in the solar system, the most centrally condensed solid body in the solar system, and the only solid body in the outer solar system known to possess an internally generated magnetic field. Its surface displays an array of geologic features spanning a wide range of ages, which record evidence of the internal evolution of a large icy satellite, dynamical interactions with the other Galilean satellites, and the evolution of the population of small bodies impacting the surfaces of the satellites. Understanding Ganymede's structure and history is an important key to understanding the Jupiter system, and large satellite systems around giant planets in general.

Exploration to date

Our current understanding of Ganymede is primarily based on eight flyby encounters: one by each Voyager spacecraft, and six by the Galileo spacecraft. Images at kilometer-scale resolution were obtained of subjovian and antijovian hemispheres during the Voyager encounters, with variable-quality Galileo imaging filling the gaps on the leading and trailing hemispheres at similar resolution. With the variation in imaging quality and viewing geometry, there is still about a third of the surface in which basic geological observations, such as the presence and orientation of tectonic grooves, cannot be made. A few small areas were imaged by Galileo at tens to hundreds of meters per pixel. These tantalizing images showed a very different surface than what was interpreted from Voyager images, and that much of the surface activity is forming features at the subkilometer scale. Mottled albedo in the dark terrain turned out to be a mix of either Callisto-like sublimation knobs or the bright walls of narrow, high-strain fault zones. The "grooves" in light terrain turned out to be long-wavelength undulations upon which a huge number of smaller normal faults have formed.

Global infrared spectral maps of major surface compounds were obtained by Galileo, and some minor volatile compounds were also detected. Spectral differences are partially related to Ganymede's geology, but the interaction of Ganymede's surface with the Jovian magnetosphere also plays a role. Current coverage is adequate to determine the broad latitudinal pattern of hydrated materials and grain size variations. However, only a few spectral measurements were done at high enough resolution to link spectra to individual geologic features.

Our understanding of Ganymede's atmosphere and auroral activity is based both on data from the ultraviolet spectrometer on Galileo and from Earth-based observatories.

Magnetosphere

Earth, Mercury, and Ganymede are the only solid bodies in the solar system known to possess internally generated magnetic fields. Ganymede's field is contained within Jupiter's strong field, creating a unique laboratory for studying magnetic reconnection and other magnetospheric interaction processes. Ganymede's time-varying magnetic field can be expressed as a superposition of a permanent dipole independent of Jupiter's magnetic field and an induced dipole driven by Jupiter's magnetosphere (Kivelson et al., 2002). While the fixed dipole portion of the field is likely generated within a fluid iron core, the details may be distinctly different from the Earth's dynamo.

At pressures < 14 GPa (i.e., in the regime of Ganymede's core), the eutectic melting temperature of Fe-FeS decreases with increasing pressure. As a result, unlike the Earth where the solid inner core grows by solidification of Fe at its surface, Fe snow may form near the core-mantle boundary of Ganymede and precipitate through the fluid outer core towards the solid inner core, and these convective motions possibly fuel Ganymede's dynamo (Hauck et al. 2006). The induced portion of the magnetic field indicates the presence of an electrically conducting layer at depth. A saline subsurface ocean is consistent with the observed response; however, a unique solution for the thickness and depth of such an ocean cannot be determined with present data. Future magnetometer measurements would constrain higher order terms in the magnetic field, which would help to distinguish among hypotheses for the mechanism of its generation.

Atmosphere and space weathering

The surfaces of the Galilean satellites are subjected to bombardment by energetic electrons and ions trapped in Jupiter's magnetosphere. These particle impacts can be destructive to surface materials, and cause radiolysis and sputtering. Ganymede's magnetosphere provides a unique environment in which to understand these processes, since the equatorial region is shielded by closed magnetic field lines, while the polar regions are connected to Jupiter's magnetic field lines. As a result, the energy flux due to charged particles is more than an order of magnitude lower at the equator than at the poles (Cooper et al. 2001). The surface boundary between the open and closed field lines is clearly visible in color images of Ganymede (Khurana et al., 2007), so there appears to be a strong effect on the surface composition/structure on either side of the boundary. Since surfaces on either side of this boundary started with the same composition, there is a unique opportunity to observe the same starting surface material under different weathering conditions. Understanding these radiolytic processes in greater detail will help us understand the nature of surface material modification on Europa, which receives an even higher radiation dose. It is also possible that the protected regions near Ganymede's equator could be a repository for long-term storage of plasma and impact ejecta material.

The plasma sputtering at Ganymede also produces a tenuous atmosphere dominated by molecular oxygen. Charged particle measurements indicate that there is an outflow of protons from Ganymede, implying ongoing gas production. The interaction of Jovian magnetospheric plasma with this tenuous neutral atmosphere excites emissions from atomic oxygen, which produces stunning auroral emissions at Ganymede. The morphology of the UV emissions has much more in common with those at Earth or Jupiter than with the other Galilean satellites, no doubt because Ganymede has its own magnetic field. There are many puzzling questions about the aurora on Ganymede, and we are currently unable to reproduce the observed morphology with any models currently available. Ganymede's tenuous atmosphere remains a largely unexplored repository that is likely to yield many clues about surface composition.

Dynamical interactions

With their orbital periods in a ratio of 1:2:4, the inner three Galilean moons, Io, Europa, and Ganymede are locked in the so-called Laplace resonance, but the history of this resonance remains unclear. Recent ground-based observations of the Galilean moons

and analysis of historical data suggest that the satellites evolve out of resonance, implying that Ganymede is receding from Jupiter (Lainey et al., 2009). Because the resonance forces the orbital eccentricities of the moons, the history of the resonance is strongly related to tidal heating in the satellites. The origin and evolution of the Laplace resonance thus contains fundamental information on the thermal history of Ganymede, which has implications for the presence of liquid water in Ganymede's interior as well as for the origin and persistence of its magnetic dynamo activity. Further ground-based campaigns combined with data from space missions will address the open question of the origin and evolution of the Laplace resonance. A primordial origin at the late stages of accretion (Greenberg 1987; Peale and Lee, 2002) is one possibility. Alternatively, the resonance may have formed by tidal evolution mainly controlled by the interaction of Jupiter and Io (Yoder 1979).

Interior

Galileo gravity measurements indicated that Ganymede's interior is highly differentiated, with a modeled internal structure consisting of a metallic core surrounded by a rocky mantle, in turn surrounded by a water ice layer 800-900 km thick. Analysis of the gravity data assumed that Ganymede is in hydrostatic equilibrium (Schubert et al., 2004), but the data also supports local deviations from equilibrium due to mass anomalies near the surface (Palguta et al., 2009). Confirmation of the interior state and mass anomalies on Ganymede will require the collection of gravity data from many more flybys, or ideally an orbiter.

As mentioned above, there is magnetic evidence that Ganymede probably contains an internal liquid water ocean with dissolved ions. The thickness of Ganymede's ice/water layer would mean such an ocean would be sandwiched between an upper floating shell of ice I and lower layers of higher density ice polymorphs. Such an ocean "sandwich" may be typical of most icy satellite oceans (Europa and Enceladus being notable exceptions), and the chemical evolution of such an ocean may be very different, as it is not in direct communication with a silicate layer.

Neighboring Callisto has almost the same mass and radius as Ganymede, but it appears to be only partially differentiated. The origin of this dichotomy remains a mystery, but there are several possibilities that have larger implications for the dynamics of the Jupiter system. One possibility is that Ganymede accreted with more energy than Callisto, starting in an initially molten state and differentiating immediately. Another possibility is that both bodies remained partially undifferentiated after accretion, but the completion of Ganymede's differentiation was thermally triggered by the late heavy bombardment (Barr and Canup, 2009) or by Ganymede's capture into the Laplace resonance with Europa and Io (Showman and Malhotra, 1997).

Surface geology

Heavily cratered dark terrain, which has similarities to the surface of Callisto, covers one third of the surface of Ganymede. The other two thirds of Ganymede has been resurfaced to form light terrain, much of which has been tectonically modified by structures known as "grooves." Whether the primary mode of resurfacing is tectonic or cryovolcanic is still an outstanding question. On one hand, no truly untectonized surfaces have been found in the limited high-resolution images of light terrain; all light terrain

displays at least some form of parallel lineaments cutting across the surface. High degrees of extensional tectonism in some areas has been shown to effectively erase the rims of impact craters (Pappalardo and Collins, 2005), but not all light terrain is tectonized to this extent. Smooth and topographically low areas seen in a high resolution stereo image (Schenk et al., 2001), coupled with local flow-like features are the best evidence so far for some form of cryovolcanism. On the other hand, the geometry of a similar smooth region on the other side of Ganymede suggests that it formed through crustal separation and spreading, much like bands on Europa (Head et al., 2002). The answers to these questions have implications for the amount of surface deformation and the role of liquid generation and transport processes within Ganymede's ice shell.

Grooves on Ganymede's surface form a global, interconnected network that records an intense period of activity at some point in the middle of Ganymede history. One possible explanation for this pulse of activity is that it is tied to Ganymede's capture into the Laplace orbital resonance with neighboring Europa and Io (Showman and Malhotra, 1997). Since Europa and Io have been resurfaced much more extensively and recently, Ganymede may be the only place that preserves evidence for the early history of this important gravitational interaction.

The presence of ancient dark terrain and the younger bright terrain provides a record of impact cratering throughout Ganymede's history and allows comparison of recent impact cratering into crusts that differ in compositional and thermal structure. The oldest of Ganymede's impact scars are the palimpsests, low-relief albedo features thought to have formed while the Ganymede crust was warmer and the ice depth to its putative sub-surface ocean was less. Their central smooth regions reflect either extensive impact melt pools or exposure of the sub-surface ocean as the result of the impactor fully penetrating the ice crust (Passey and Shoemaker, 1982). Palimpsests and other old crater forms in the dark terrain have little or no topographic relief due to significant viscous relaxation, indicating significantly higher heat flows in the past (Dombard and McKinnon, 2006).

As Ganymede's heat flow lessened over the course of its history, and the depth to its sub-surface ocean increased, the craters forming in its surface have begun to resemble more recognizable crater forms seen on terrestrial bodies. The reduction in heat flow also reduced the rate of viscous relaxation, allowing better preservation of the original crater morphology. The similar surface gravity of Ganymede and the Earth's moon allows direct comparison of crater morphology on these compositionally dissimilar bodies (e.g. Schenk, 2002; Bray et al., 2008). Studies of the variation in crater morphology between Ganymede's dark terrain, bright terrain and the Earth's moon thus allow us to develop our understanding of the cratering process in rock, ice, and ice-rock mixes. Comparisons with craters on Europa help us to understand and separate out the effect of layering of a stiff lithosphere over a fluid layer at some depth within the target body.

The variation in heat flow over Ganymede's history has changed the thickness of the mechanical lithosphere over time, allowing the formation of both pristine and relaxed craters, and both Europa-like spreading bands and large imbricate normal fault sets. Thus Ganymede can serve as a bridge between thick-lithosphere geologic features that are more easily interpretable from terrestrial experience, and the more difficult to interpret thin-lithosphere features found on places like Europa and the south pole of Enceladus.

Surface Composition

Spectral measurements of Ganymede's surface have revealed common compositional characteristics with both Europa and Callisto. High-resolution spectra of Ganymede show absorption bands interpreted to be hydrated salt minerals (McCord et al., 2001), very similar to the possible hydrated salts found on Europa. This implies that some briny liquid has modified the surface, possibly erupted from the subsurface. High-resolution spectra of Ganymede also show several Callisto-like absorption bands between 3.4 and 4.6 microns that are interpreted to be evidence for SO₂, CO₂, H₂S, and C-H bonds in tholins (McCord et al., 1997). The source of the organic material could be formed *in situ* from radiolysis and chemical reactions within the contaminated icy crust, and from exogenic material falling onto Ganymede's surface. Unlike Callisto, the CO₂ on Ganymede is distributed around the globe and is not correlated with impact craters, but is instead predominantly found in dark terrain (Hibbitts et al., 2003).

It has been inferred from spectra of Ganymede's water absorptions that ice particles are generally smaller on the leading hemisphere than on the trailing hemisphere and towards the equator (Calvin et al., 1995). This is probably the result of micrometeorite gardening, combined sputtering effects on the trailing side. Sputtered ice particles easily reach the cold polar regions along Ganymede's field lines, and form a thin layer of frost. Moreover, Hansen and McCord (2004) pointed out that although there is a general trend from more crystalline ice at low latitudes to more amorphous ice in the polar regions (as might be expected due to greater radiation exposure at the poles), local conditions produce large variations in this trend.

The trailing hemisphere of Ganymede, like the trailing hemispheres of the other satellites, is more exposed to irradiation by particles trapped in the Jovian magnetic field. Both ozone (Noll et al., 1996) and molecular oxygen (Spencer et al., 1995; Calvin et al. 1996) have been detected in UV and visible spectra of the trailing hemisphere of Ganymede (Hendrix et al. 1999). Both of these species are trapped within the ice, and probably originate from ionic bombardment of the icy surface.

Summary of outstanding science questions

- How is Ganymede's intrinsic magnetic field generated? How long has it persisted?
- Does Ganymede have a liquid water ocean? How has the size of this ocean varied over time? What impurities cause the induced magnetic field? What is the composition and biological potential of the ocean?
- Did Ganymede differentiate near the time of accretion, or did it differentiate later in solar system history? What was the trigger that caused the different interior states of Ganymede and Callisto?
- Is Ganymede's thermal history characterized by monotonic decline, or did Ganymede experience a pulse of tidal heating? Did entrance into the Laplace resonance affect Ganymede's internal evolution?
- What caused the formation of grooved terrain on Ganymede? Is it linked to a pulse of tidal heating?
- What is the age of grooved terrain? How extended was its formation period?
- What are the relative roles of tectonism and volcanism in shaping bright grooved terrain? Is bright terrain composed of thick cryovolcanic deposits? What are the topographic relationships between dark and light terrains?

- Is any part of Ganymede's surface still geologically active today?
- What can the wide variety of impact crater morphologies and relaxation states tell us about the thermal history of Ganymede?
- What causes gravity anomalies on Ganymede? What is the link between gravity and topography?
- How does the epoch of dark terrain formation compare to Callisto's early geological history? Is dark terrain primordial?
- What does the distribution of craters on Ganymede tell us about the evolution of the impactor population in the Jovian system through time?
- How variable is the composition and layering of the ice shell? Does dark terrain contain enough silicate material to affect the ice strength?
- What non-ice compounds occur on Ganymede's surface? How is their distribution related to surface geology?
- How is Ganymede's surface altered by space weathering? What is the role of Ganymede's magnetic field in shielding the surface?
- What is the spatial and temporal structure of Ganymede's atmosphere, and what clues does it hold about the surface and interior evolution of Ganymede?
- What controls the unusual morphology of Ganymede's auroral emissions?

Future exploration of Ganymede

Further exploration of Ganymede by an orbiting spacecraft was recognized as a priority item in the 2003 NRC decadal survey. The Europa Jupiter System Mission currently planned by ESA and NASA includes a European spacecraft (the Jupiter Ganymede Orbiter) that would orbit Ganymede after exploration of the Jupiter system. (see also "Science of the Europa Jupiter System Mission" white paper by Pappalardo et al.) This mission would go a long way toward solving the outstanding science questions listed above, by studying:

- Ganymede's magnetosphere, and its interaction with the Jovian magnetosphere. This will address questions about the origin of Ganymede's magnetosphere, processes in the coupled magnetospheres, the atmosphere, and the internal ocean.
- Ganymede's interior through gravity and topography measurements. This will address questions about the tidal response of the ocean, the origin of gravity anomalies, and the thermal evolution through changes in deformation of the mechanical lithosphere in response to loads.
- Ganymede's surface through remote sensing campaigns at many wavelengths, at high resolution, and with global coverage. This will address questions about the composition of Ganymede's surface, the origin of grooved terrain, and the population of impact craters.
- Ganymede's near subsurface through electromagnetic sounding. This will address questions about bulk properties of the lithosphere, the existence of a regolith layer, and the role of cryovolcanism in resurfacing bright terrain.

We strongly endorse the science objectives and proposed implementation of the Europa Jupiter System Mission, which includes as a key element the ESA Jupiter Ganymede Orbiter, and we recommend that the decadal survey give its full support to this joint mission.

References

- Barr, A. C., and Canup, R. M. (2009). Constraints on early solar system dynamical evolution from the interior states of Ganymede and Callisto. EPSC Abstracts, 646.
- Bray, V. J., Collins, G. S., Morgan, J. V., and Schenk, P. M. (2008). The effect of target properties on crater morphology: Comparison of central peak craters on the Moon and Ganymede. *Meteoritics and Planet. Sci.* **43**, 1979-1992.
- Calvin, W. M., Clark, R. N., Brown, R. H., and Spencer, J. R. (1995). Spectra of the icy Galilean satellites from 0.2 to 5 μ m: A compilation, new observations, and a recent summary. *J. Geophys. Res.* **100**, 19041-19048.
- Calvin, W. M., Johnson, R. E., and Spencer, J. R. (1996). O₂ on Ganymede: Spectral characteristics and plasma formation mechanisms. *Geophys. Res. Lett.* **23**, 673-676.
- Cooper, J. F., Johnson, R. E., Mauk, B. H., Garrett, H. B., and Gehrels, N. (2001). Energetic ion and electron irradiation of the icy Galilean satellites. *Icarus* **149**, 133-159.
- Dombard, A. J., and McKinnon, W. B. (2006). Elastoviscoplastic relaxation of impact crater topography with application to Ganymede and Callisto. *J. Geophys. Res.* **111**, E01001.
- Greenberg, R. (1987). Galilean Satellites – Evolutionary paths in deep resonance. *Icarus* **70**, 334-347.
- Hansen, G. B., and McCord, T. B. (2004). Amorphous and crystalline ice on the Galilean satellites: A balance between thermal and radiolytic processes. *J. Geophys. Res.* **109**, doi: 10.1029/2003JE002149.
- Hauck, S. A., II, Aurnou, J. M., and Dombard, A. J. (2006). Sulfur's impact on core evolution and magnetic field generation on Ganymede. *J. Geophys. Res.* **111**, E09008.
- Head, J. W., Pappalardo, R. T., Collins, G. C., Belton, M. J. S., Giese, B., Wagner, R., Breneman, H. H., Spaun, N. A., Nixon, B., Neukum, G., and Moore, J. (2002). Evidence for Europa-like resurfacing styles on Ganymede. *Geophys. Res. Lett.* **29**, 2151.
- 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.
- Hibbitts, C. A., Pappalardo, R. T., Hansen, G. B., and McCord, T. B. (2003). Carbon dioxide on Ganymede. *J. Geophys. Res.* **108**, doi:10.1029/2002JE001956.
- Khurana, K. K., Pappalardo, R. T., Murphy, N., and Denk, T. (2007). The origin of Ganymede's polar caps. *Icarus* **191**, 193-202.
- Kivelson, M. G., Khurana, K. K., and Volwerk, M. (2002). The permanent and inductive magnetic moments of Ganymede. *Icarus* **157**, 507-522.
- Lainey, V., Arlot, J.-E., Karatekin, O., and VanHoolst, T. (2009). Strong tidal dissipation in Jupiter and Io from astrometric observations. *Nature* **459**, 957 – 959.
- McCord, T. B., Carlson, R., Smythe, W., Hansen, G., Clark, R., Hibbitts, C., Fanale, F., Granahan, J., Segura, M., Matson, D., Johnson, T., and Martin, P. (1997). Organics and other molecules in the surfaces of Callisto and Ganymede. *Science* **278**, 271-275.
- McCord, T. B., Hansen, G. B., and Hibbitts, C. A. (2001). Hydrated salt minerals on Ganymede's surface: Evidence of an ocean below. *Science* **292**, 1523-1525.
- Noll, K. S., Johnson, R. E., Lane, A. L., Domingue, D. L., and Weaver, H. A. (1996). Detection of ozone on Ganymede. *Science* **273**, 341-343.
- Palguta, J., Schubert, G., Zhang, K., and Anderson, J. D. (2009). Constraints on the location, magnitude, and dimensions of Ganymede's mass anomalies. *Icarus* **201**, 615-625.
- Pappalardo, R. T., and Collins, G. C. (2005). Strained craters on Ganymede. *J. Struct. Geol.* **27**, 827-838.
- Passey, Q. R. and Shoemaker, E. M. (1982). Craters and basins on Ganymede and Callisto: Morphological indicators of crustal evolution. In *Satellites of Jupiter*, D. Morrison, ed., Univ. of AZ Press, 340-378.
- Peale, S. J. and Lee, M.H. (2002). A primordial origin of the Laplace relation among the Galilean satellites. *Science* **298**, 593-597.
- Schenk, P. M. (2002). Thickness constraints on the icy shells of the Galilean satellites from a comparison of crater shapes. *Nature* **417**, 419-421.
- Schenk, P. M., McKinnon, W. B., Gwynn, D., and Moore, J. M. (2001). Flooding of Ganymede's bright terrains by low-viscosity water-ice lavas. *Nature* **410**, 57-60.
- Schubert, G., Anderson, J. D., Spohn, T., and McKinnon, W. B. (2004). Interior composition, structure and dynamics of the Galilean Satellites. In *Jupiter: The Planet, Satellites and Magnetosphere*. Bagenal, F., T.E. Dowling, W.B. McKinnon (eds), Cambridge University Press, 281-306.
- Showman, A.P. and Malhotra, R. (1997). Tidal evolution into the Laplace resonance and the resurfacing of Ganymede. *Icarus* **127**, 93-111.
- Spencer, J. R., Calvin, W. M., and Person, M. J. (1995). CCD spectra of the Galilean satellites: Molecular oxygen on Ganymede. *J. Geophys. Res.* **100**, 19049-19056.
- Yoder C.F. (1979). How tidal heating in Io drives the Galilean orbital resonance locks. *Nature* **279**, 767-770.