EPSC Abstracts,
Vol. 4, EPSC2009-572, 2009
European Planetary Science Congress,

Ganymede Colors

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Introduction. Ganymede, the largest moon in the solar system, was a prime target for observations by the SSI camera onboard the Galileo spacecraft. Despite the very limited data storage and downlink capacity of Galileo, a few global color observations of Ganymede were taken at different longitudes (*Tab. 1*), allowing an examination of the distribution of global and regional color units on this moon. The Galileo-SSI instrument [1] was an 8-bit CCD camera equipped with one "clear" and seven color filters sensitive at wavelengths between ~0.4 and ~1.0 µm. For satellite observations, violet (414 nm, VLT), green (559 nm, GRN), and 1-micron (990 nm, 1MC) filters were mainly used to obtain 3-color spectra. These allow the determination of surface-color units with respect to their spectral properties at near-UV or "short" wavelengths (wavelength range between ~0.4 and ~0.6 µm, "VLT/GRN") and near-IR or "long" wavelengths (between ~0.6 and ~1.0 µm, "1MC/GRN").

Ganymede colors. Ganymede shows a banded, latitude-dependent color structure which is partly independent of geologic units (*Fig. 1*). Its major surface component is water ice [2]. When observed with the SSI camera at the long wavelength (1MC/GRN) range, water-ice spectra would appear flat if the ice is fine-grained, or with a negative slope if coarse-grained [3]. Color measurements of the 1MC/GRN-color ratios on Ganymede show almost no negative slopes (*Fig. 2*), indicating that coarse-grained ice is rather rare on the surface. Areas with flat SSI spectra (and high albedo) should be covered by particularly pure water ice. Positive ("reddish") spectral slopes are indicative for non-ice impurities, candidates are D-type asteroid material and siliceous minerals, see [3] for a detailed discussion.

Within the near-UV wavelength range (VLT/GRN), *all* spectra show rather steep positive ("reddish") slopes (*Fig. 2*), indicating the global presence of a non-ice violet-absorbing material. Sulfur, with a steep spectral "red edge" between ~0.4 and ~0.5 µm [4] and possibly originating from the volcanically active moon Io, is a candidate material for the reddish spectra observed on all icy Galilean moons [3], but since sulfur has no diagnostic bands within the range of spaceborne spectrometers, its presence as the "violet absorber" on the Galilean moons remains to be proved.

From a global perspective, *five different color contrasts* are observed on Ganymede:

(1) Global geologic units: dark terrain ("regiones") vs. bright terrain ("grooved" or "sulci" terrain);
(2) Polar areas: bright, "white" polar frost vs. darker reddish high-latitude "frost" on the trailing side;
(3) Impact structures: bright craters (Osiris, Tros, ...) vs. dark craters (Khensu, Kittu, ...);
(4) Longitudinal pattern: trailing side (stronger violet absorber) vs. leading side (weaker abs.);
(5) Jovian/ Ganymede's magnetic fields: shielded areas (equatorial to mid) vs. unshielded areas (mid to high latitudes).

Dark and Bright Terrain. Brighter "grooved" and darker "regio" terrain are the two dominant global geologic units on Ganymede. The 1MC/GRN-color ratio image has a close-to-perfect correlation with these units (*Fig. 1C,F*), with the "regio" terrains showing steeper spectra, as expected for a higher non-ice material contamination. However, the VLT/GRN-color ratios only poorly matches the geologic units, indicating that the global "violet absorber" is relatively independent from the surface albedo and geology (*Fig. 1A,D*).

North-polar Terrain. The "whitish" frost cap is approximately ellipse-shaped and elongated towards the leading side with respect to the north pole (*Fig. 3, 4*). Its southern extension is partly determined by the underlying terrain, reaching

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lower latitudes over bright "bedrock" terrain like Xibalba Sulcus (cf. *Fig. 3*). Low-albedo areas (with higher surface temperatures at comparable latitudes) are "avoided" by the frost at mid latitudes; examples are Galileo or Perrine Regio. Redder and darker "frost" material is detected at high latitudes on the trailing side (*Fig. 3*). With rather reddish 1MC/GRN- (*Fig. 1F*), but unusually flat VLT/GRN-color ratios (*Fig. 1D*), the interpretation of this material as "reddish frost" is tentative, although NIMS data show deep water-ice absorptions here, consistent with the frost interpretation.

South-polar Terrain. The situation is similar to the north-polar area, except that the frost cap appears less opaque (cf. *Fig. 4*). Instead, it extends further towards the equator (*Fig. 1A*), presumably because of the wide absence of dark areas like Galileo Regio on the southern hemisphere.

Impact Craters. The dark-ray crater Kittu (*Fig. 1 D,E*; *Fig. 4*) shows a rather flat spectral appearance throughout the SSI-wavelength range, which is very unusual for dark material on Ganymede. Because the surroundings of Kittu do not show this property, we propose that the Kittu-rays material originates from the impactor which might have been composed of C-type asteroid material. In contrast to Kittu, other craters like the dark-floor crater Khensu show the type of reddish spectra which is common on Ganymede.

Longitudinal Color Differences. A leading-/ trailing-side color dichotomy is measured within the shielded (equatorial) terrain, where the global "violet absorber" is stronger on the trailing side (*Fig. 4*).

Magnetospheric Influence. Ganymede's intrinsic magnetosphere is strong enough to shield the lower-latitude regions, but not the whole surface against the Jovian background field [5]. Subsequently, there exists a boundary on the northern and on the southern hemisphere of Ganymede where open (to the Jovian field) or closed field lines (from the Ganymede field) hit the surface. These "open/closed field-lines boundaries" are moving in conjunction with the Jupiter rotation and Ganymede's revolution around Jupiter. A correlation of the surface color with the magnetic field of Ganymede has been found [5] [6], presumably being responsible for the banded appearance of this satellite. The "global violet absorber" is stronger within the equatorial, shielded terrain than within mid-latitude to polar areas not shielded by Ganymede's own magnetic field (*Fig. 2*; *1C*; *3*) [6]. Khurana *et al.* [5] interpret this as a result of higher plasma-induced brightening in the polar and mid-latitude areas, compared to the equatorial terrains. Contrary to this, spectra of dark parts of the unshielded areas are redder than those of shielded terrain in the 1MC/GRN-color ratio, implying that charged particles from the Jovian environment also caused a reddening of the dark non-ice material on Ganymede.

References. [1] Belton, M.J.S. *et al.* (1992): The Galileo Solid-State Imaging Experiment. *Space Sci. Rev.* **60**, 413-455, doi: 10.1007/BF00216864. [2] Clark, R.N. (1980): Ganymede, Europa, Callisto, and Saturn's Rings: Compositional Analysis from Reflectance Spectroscopy. *Icarus* **44**, 388-409. [3] Denk, T. *et al.* (1998): Candidate Surface Materials of the Icy Galilean Satellites that Might be Distinguished by the Galileo-SSI Camera. *LPSC XXIX*, abstract 1676, http://www.lpi.usra.edu/meetings/LPSC98/pdf/1676.pdf. [4] Nash, D.B. *et al.* (1986): Io. In: *Satellites* (Burns, J.A., Matthews, M.S., eds.), Univ. Arizona Press, 629-688. [5] Khurana, K.K., *et al.* (2007): The origin of Ganymede's polar caps. *Icarus* **191**, 193-202, doi: 10.1016/j.icarus.2007.04.022. [6] Denk, T. *et al.* (1999): The Global Colors of Ganymede as Seen by Galileo SSI. LPSC XXX, abstract 1822, http://www.lpi.usra.edu/meetings/LPSC99/pdf/1822.pdf.

Tab. 1. Galileo-SSI global-color observation sequences of Ganymede.

Orbit	Filters	Spatial resolution	Sub-S/C center-lon.	Phase
C10	VGNmo	34 km/pxl	17°W	0.2°
G1	VGrNMO	13 km/pxl	155°W	30°
C30	ogv	8 km/pxl	251°W	30°
E14	VGO	18 km/pxl	306°W	10°
E6	VgnmO	14 km/pxl	323°W	37°

V=violet filter (VLT, 414 nm); G=green (GRN, 559 nm); R=red (RED, 664 nm); N=near-Infrared (NIR, 757 nm); M=methane 2 (MT2, 888 nm); O=one micron (1MC, 990 nm). Lower-case letters indicate images with gaps. The sub-S/C latitude was always ~0°N.

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Vol. 4, EPSC2009-572, 2009
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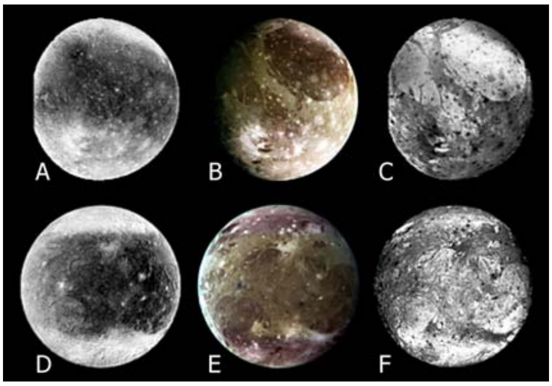

Fig. 1. False-color (filters 1MC, GRN, and VLT; **B**, **E**), short-wavelength color ratio (VLT/GRN; **A**, **D**), and long-wavelength color-ratio (1MC/GRN; **C**, **F**) images of Ganymede. Top row (**A**, **B**, **C**): data from the Galileo G1 orbit (anti-Jovian and leading side); bottom row (**D**, **E**, **F**): from the E14 orbit (trailing and sub-Jupiter side). North is up. See also *Tab. 1* for details on SSI filters and observation geometries. – **A** and **D** show the banded, latitude-dependent color structure of Ganymede. – The large dark terrain on the northern hemisphere in **B** is Galileo Regio. The northern open/closed field-lines boundary clearly divides the color properties within this area (**C**). – The bright spot left of the image center in **D** (dark spot in **E**) is the spectrally unusual crater Kittu.

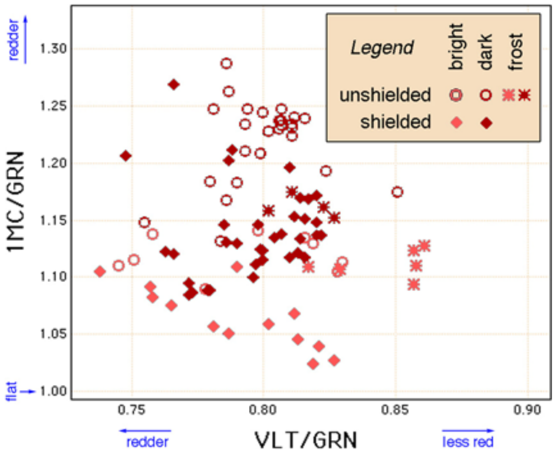

Fig 2. Color-ratio diagram from Ganymede G1 data. Each dot represents a normalized 3-color spectrum from a small part of the surface. The symbols indicate different terrain units. – No spectrum shows a negative slope. The color differences between shielded and unshielded areas, esp. in the long-wavelength (1MC/GRN) range, are obvious.

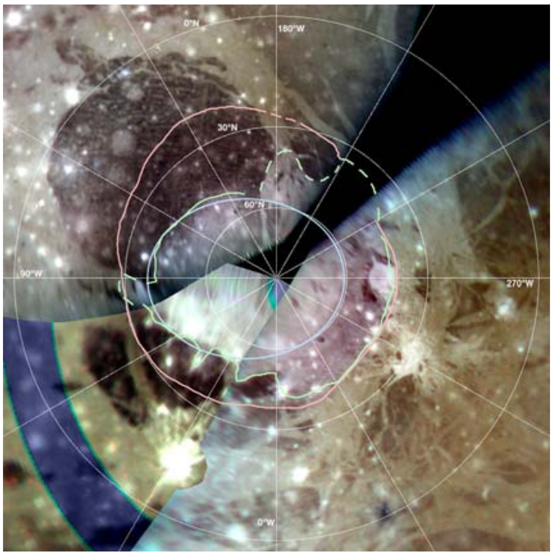

Fig 3. Stereographic projection of Ganymede's northern hemisphere (1MC, GRN, VLT filters for rgb). The north pole is at image center, the outer white circle marks the equator, the leading side is towards left, Jupiter towards bottom. G1 data are at upper left, C10 data at lower left, E14 data at lower right. The green line marks the boundary of the polar frost (whitish and reddish); its most southward extension down to ~30°N is in Xibalba Sulcus on the leading side. The blue ellipse marks the approximate extension of the whitish frost. The red line marks the 1MC/GRN color-ratio boundary. It is virtually identical to the northern open/closed field-lines boundary of the magnetosphere.

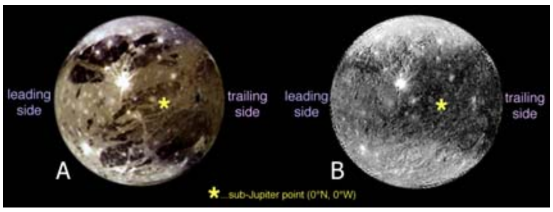

Fig 4. Sub-Saturn hemisphere of Ganymede (C10 data near 0° phase); **A**: NIR, GRN, VLT false-color image; **B**: VLT/GRN-color ratio. North is up. – The polar caps (inclined towards the leading side) can be clearly seen, and the more reddish color of the trailing side is also obvious. The bright spot near the center is bright ejecta from crater Tros (11°N, 27°W). Dark-ray crater Kittu (0°N, 335°W) is to the right of the sub-Jupiter point. The dark area on the upper left is Perrine Regio.