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Title: Salts and organics on Ganymede's surface from infrared observations by Juno/JIRAM

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Abstract:

The surface of Ganymede exhibits diversity in composition interpreted as indicative of geological age differences among dark and bright terrains. Observations from Galileo and Earth-based telescopes have revealed the presence of both water ice and non-ice material indicative of either endogenic or exogenic processes, or some combination. However, those observations attained a spatial resolution too coarse to reveal the surface composition at the local scale. Here we present high spatial resolution infrared spectra of Ganymede observed with the Jovian InfraRed Auroral Mapper (JIRAM) onboard the NASA Juno spacecraft during the close flyby that occurred on June 7th, 2021. We find that at a pixel resolution <1 km, the surface of Ganymede exhibits signatures diagnostic of hydrated sodium chloride, ammonium chloride and sodium/ammonium carbonate as well as organic compounds, possibly including aliphatic aldehydes. Carbon dioxide shows up mostly at trailing longitudes. The composition and spatial distribution of these salts and organics suggest that their origin is endogenic, resulting from the extrusion of subsurface brines whose chemistry reflects water-rock interaction inside Ganymede.

Main text:

Introduction

The surface composition of icy satellites, beyond the ubiquitous presence of water ice, is an outstanding question with important implications. The composition can provide clues to the origin and evolution of the body, and thus may set the stage for habitability. Subsurface liquid water oceans, when present, may interact with the icy surfaces above, directly bearing on ocean habitability and detection of possible tracers of extraterrestrial life. The simultaneous presence of endogenous and exogenous compounds creates challenges in probing the composition of the internal oceans thought to be present in "ocean worlds", especially in the Jovian system, i.e., Ganymede and Europa. Because Ganymede has a substantially thicker crust than Europa (e.g., refs. [1,2]), exchanges between its deeper interior and surface may not be responsible for its surface composition and thus may reflect exchange between the shallow crust and surface, or exogenous deposition.

Infrared observations of Ganymede returned by the Galileo *Near Infrared Mapping Spectrometer* (NIMS)[3] achieved broadly regional coverage at spatial resolution values of 100 to 150 km/px[4]. Those data suggested the presence of non-water-ice materials, specifically hydrated minerals revealed by asymmetries or distortions observed in the main absorption bands of water ice and differences in reflectance compared to that expected from pure ice[5]. Such spectral characteristics were associated primarily with dark terrains and were initially interpreted as salt minerals such as magnesium and sodium sulfate hydrates and evidence of endogenic processes. Similar processes were proposed to occur on Europa[6]. Recently, Earth-based spectroscopic observations achieving a spatial resolution of tens of km/px have suggested the presence of chlorinated salts as an alternative to the sulfate salts explanation for the distortions observed in the water ice bands on both Europa and Ganymede[7,8]. The reddish-brown colour associated with young geological features of Europa has been interpreted as due to irradiated sodium chloride[9]. Here, we use high spatial resolution infrared data from the Juno spacecraft's closest flyby of Ganymede to derive new constraints on the composition of Ganymede's surface.

Results

The JIRAM dataset. The *Jovian Infrared Auroral Mapper* (JIRAM)[10] onboard the NASA Juno spacecraft[11] combines a double L- and M-band infrared imager and a slit spectrometer covering the wavelength range between 2 and 5 µm with an average spectral sampling of 9 nm. The instantaneous field of view of the instrument is 238 µrad, giving a spatial resolution (pixel size) of ~2.38 km at 10,000 km.

On 7 June 2021, the spacecraft flew within ~1046 km of Ganymede's surface providing the opportunity for JIRAM to acquire five spectral slits and related infrared images on the satellite's dayside, shortly after closest approach[12] (Table 1). The nominal spatial resolution of the five JIRAM slits was <1 km, a factor of 3–5 times higher than the most resolved hyperspectral image previously acquired by Galileo/NIMS[4]. Observations with JIRAM during earlier orbits provided comparative spectra of much larger regions at a resolution of tens of km[13]. Correcting for straylight (Methods), the average spectral profile of Ganymede during the close flyby differs from previous JIRAM spectral profiles (Fig. 1 and Supplementary Figs. 1–3) and from those that Galileo/NIMS obtained in the past.

Several spectral features (*f*) emerge from the average spectrum measured by JIRAM (Fig. 1b). In ascending order of wavelengths, those with a good signal-to-noise ratio (see Methods) are seen at: 2.08 µm (*f1*), 2.54 µm (*f2*), 2.89 µm (*f3*), 3.00 µm (*f4*), 3.48 µm (*f5*), 3.58 µm (*f6*), 3.65 µm (*f7*), and 4.25 µm (*f8*). Further inflections and very to extremely weak absorption bands are noted at about 2.22 µm, 2.42 µm, 2.60 µm, 2.82 µm, 3.05 µm, 3.16 µm, 3.25 µm, and 3.38 µm.

Comparison with laboratory data. Here, we use Extended Data Table 1 along with the stacked plots in Supplementary Figs. 4–11 to investigate potential assignments for the spectral signatures observed by JIRAM based on numerous spectral endmembers measured in laboratory in the spectral range 2–5 µm. We discuss the spectral signatures in ascending wavelength order.

The *f1* band centred at 2.08 µm is not compatible with pure crystalline ice, whose absorption in that spectral region is centred at 2.02 µm, i.e., in the short-wavelength edge of the JIRAM sensitivity range. This indicates that ice is mixed with other compounds that have an absorption centred at this wavelength, such as NH_4Cl, $NaCl \cdot 2H_2O$, or bloedite, which is a hydrated sodium magnesium sulfate mineral ($Na_2Mg(SO_4)_2 \cdot 4H_2O$).

JIRAM observes very weak spectral signatures at 2.22 and 2.42 µm. The band at 2.22 µm, which does not show up in water ice, could be ascribed to NH_4Cl, NaCl, $MgCl_2 \cdot 6H_2O$, $NaHCO_3$, $Na_2CO_3 \cdot 2NaHCO_3 \cdot 3H_2O$ (trona), or $(NH_4)_2CO_3$. The inflection seen at 2.42 µm is consistent with $MgCl_2 \cdot 6H_2O$ and $MgSO_4 \cdot 6H_2O$. Nitrate salts have diagnostic absorptions around 2.06, 2.21, and 2.42 µm, which may overlap with water bands and whose exact position may vary depending on the cation in the nitrate salt[14]. However, they have much stronger bands beyond 2.5 µm, which do not show up in JIRAM spectra. Hydrated silica also exhibits absorption bands at 2.21–2.22 µm due to Al/Si–OH combination tones, with an additional, weak OH band at 2.42 µm possibly diagnostic of hydrous phyllosilicates such as smectites. On the other hand, $CaCl_2$ has two spectral signatures at 2.23 µm and 2.60 µm.

The weak *f2* band at 2.54 µm is a typical characteristic of hydrated chloride compounds such as $NaCl·2H_2O$, $CaCl_2·6H_2O$ and $MgCl_2·2H_2O$, of carbonates such as $NaHCO_3$, Na_2CO_3 and $CaCO_3$, and of the sulfate bloedite. Pure granular water ice displays a feature at 2.50 µm, especially for ultrafine to intermediate grain size. However, the position and shape of *f2* favors these contaminants over the case of pure ice.

The strong absorption *f3* seen at 2.89 µm is the fundamental O–H stretching transition active in water ice as well as in hydrated and hydroxylated minerals. In the hydrated salt minerals considered in Extended Data Table 1, the minimum of this band generally varies between 2.86 µm and 3.08 µm, with 2.89 µm being akin to $NaCl·2H_2O$ and $MgCl_2·6H_2O$.

The 3.00-µm *f4* band is compatible with Na_2SO_4 (weakly hydrated as measured in laboratory) and $(NH_4)_2SO_4$; although signatures at 3.01-µm and 3.16-µm could also be due to water adsorbed/bound in phyllosilicates[15]. NH_4-bearing phases display diagnostic absorptions in the range 3.01–3.08 µm[16]. The ν_3 absorption in NH_4 is variable and is likely related to the degree of hydrogen bonding of NH_4–H_2O complexes[17], which could explain the very weak signature seen by JIRAM at 3.05 µm. The reflectance peak around 3.10 µm is due to Fresnel reflection off the facets in water ice grains (e.g., ref [18]).

The *f5* band at 3.48 µm is compatible with carbonate salts such as $NaHCO_3$, Na_2CO_3, $CaCO_3$, and $(NH_4)_2CO_3$, but also with several organics. Similarly, the *f6* band at 3.58 µm could be matched by $CaCl_2$ and $CaCO_3$, but also by organics.

Among the salts of endogenous origin, chlorides are those that show a larger number of positive detections compared to the spectral signatures measured by JIRAM, including weak and very weak signatures, although Ca- and Mg-chlorides have substantially different profiles, especially beyond 3 µm, whereas $NaCl·2H_2O$ and NH_4Cl are more plausible. Within sulfate salts, Ca-, Na-, and NH_4-sulfates can be safely ruled out since they have substantially different spectral shapes both between 2.0 and 2.7 µm and beyond 3.5 µm. Bloedite appears to be the sulfate salt that best mimics the shape measured by JIRAM. Carbonates represent an intermediate case between chlorides and sulfates in terms of positive spectral detections, although Ca- and Na-carbonates should display a strong absorption close to 4 µm, unseen in JIRAM spectra, making $NaHCO_3$ or $(NH_4)_2CO_3$ more plausible options.

The overall 3.0–3.7 µm range is diagnostic of organics. The existence of organic compounds on Callisto and Ganymede had first been suggested based on a spectral signature at 3.4 µm detected in NIMS data, associated with the $–CH_3/CH_2$ stretch in aliphatic organics or in tholins[19,5]. The earlier more distant observations by Juno/JIRAM supported the finding of organics, but a concrete identification was not possible[13]. In the JIRAM dataset discussed here, an extremely weak signature shows up at 3.25 µm, within the 1σ instrumental noise. Aromatic hydrocarbons display a =C–H signature in the 3.22–3.33 µm range[20], which in principle might explain this feature. As for aliphatic alkane compounds, the $–CH_3$ (methyl) asymmetric stretch has a spectral counterpart in the range 3.36–3.39 µm, while the symmetric $–CH_3$ stretch has a counterpart in the 3.47–3.49 µm range[21]. Similarly, the asymmetric stretch $–CH_2$ (methylene) has a spectral counterpart at 3.40–3.45 µm while the symmetric stretch occurs at 3.49–3.52 µm[20]. A very weak band at 3.38 µm in the JIRAM average spectrum, at the limit of 1σ noise, suggests a methyl group is more likely to be present (or more abundant) than a methylene group. The weak *f7* 3.65-µm band could be due to aryl ($Ar–CH_3$) or alkyl (RCHO) groups[21,22]. The simultaneous presence of two features *f6* at 3.58 µm and *f7* at 3.65 µm could be indicative of aldehydic C–H vibrations, while the carbonyl group stretch C=O is beyond the wavelength range of JIRAM.

The feature *f8* at 4.25 µm is the diagnostic signature of carbon dioxide (CO_2). Because free CO_2 ice has an absorption centred at 4.27 µm, the surface of Ganymede has complexed CO_2, namely CO_2 is mixed with something else in the uppermost mm-thick surface layer to produce the observed shift[23].

JIRAM data do not reveal, or are not decisive in revealing, any spectral signatures of exogenously produced compounds such as hydrogen peroxide or hydrated sulfuric acid (Supplementary Fig. 11). Both compounds were detected on Europa[24,25] and at high latitudes on Ganymede[8,26,27]; however, in the spectral range 2.0–2.5 µm where JIRAM data and laboratory spectra overlap, hydrated sulfuric acid has no diagnostic signatures. The strongest signatures of hydrogen peroxide in the near-infrared range 2–5 µm are due to the water solution; while the most diagnostic signature already observed on Europa, i.e., the one centred at 3.505 µm[24], is not detected on Ganymede beyond the JIRAM instrumental noise. Furthermore, the JIRAM spectra do not reveal signatures at 4.07 µm and 4.37 µm, diagnostic of sulfur dioxide (SO_2)[28,29]. SO_2 was convincingly identified on Europa and Callisto and has been suggested to be associated with implantation of magnetospheric S ions that originate from volcanic activity on Io[30].

Spectral unmixing is sub-optimal with JIRAM spectroscopic data obtained at Ganymede, and its results may be misleading (Methods, Supplementary Information). Evaluating the position of the spectral signatures and making comparisons with an ample number of meaningful laboratory spectra is a better approach in interpreting JIRAM data.

Mapping the JIRAM spectroscopic data. JIRAM spectral profiles reveal variability, due both to the changing illumination and observation conditions and to the different terrains sampled along the sequence (Fig. 2, Supplementary Fig. 12). JIRAM data spanned a narrow range of latitudes (10°N to 30°N) and a wider range of longitudes (-35°E to +40°E) in the sub-Jovian hemisphere, covering a variety of geological units such as grooved terrains, bright ejecta, and dark terrains (Supplementary Fig. 13). This area had not been covered by previous NIMS observations, except for slit 5 where the NIMS coverage had very coarse spatial resolution[4]. The maximum pixel resolution and consequently the least coverage is obtained in the first slit, while the following slits show a pixel resolution that progressively decreases with increasing coverage and distance from Ganymede. The spectral slits initially covered a branch of Phrygia Sulcus north of Tros crater (slit 1), mapped as old light subdued material[31], then moved from west to east covering a dark terrain unit classified as dark undivided material[31] (slit 2), then the bright ejecta of a small fresh crater mapped as young light grooved material[31] (slit 3), then another portion of Phrygia Sulcus northeast of Nanshe Catena, partly classified as dark cratered material and partly as intermediate light subdued material[31] (slit 4), and finally a larger area consisting of an intertwining of different terrains including dark cratered material, young light grooved material, and old/intermediate light subdued material[31] (slit 5).

Closeups of the JIRAM ground footprints reveal spatial variations in the strength of some absorption bands (Fig. 3, Fig. 4, Fig. 5, and Supplementary Fig. 14), allowing investigation of correlations with geological features and correlations among individual spectral signatures (Methods). While neither strong nor systematic correlations emerge between any pair of spectral signatures, within each JIRAM slit weak correlations and anticorrelations may arise between band depths, which are indicative of a variable degree of mixing between different species, such as water, salts and organics, in different terrains. The composition can vary according to the terrain type: a larger abundance of non-ice compounds is not necessarily found only in dark terrains but also in some grooved terrains, albeit with compositional differences between different grooves, suggesting that an endogenic process such as the extrusion of subsurface brines may determine the observed composition. The complexed CO_2 signature at 4.25 µm is weak in slits 1–3 covering leading longitudes, while it is stronger in slits 4 and 5 covering trailing longitudes (Fig. 2, Figs. 3–5). CO_2 hardly shows any correlation with other spectral signatures, except in slit 2 sampling a dark terrain, meaning that the distribution of CO_2 in the JIRAM coverage may not depend on the occurrence of other non-ice species considered here. Not all dark terrains appear equally enriched in CO_2, which is also consistent with a distribution controlled by geological processes[32].

Discussion

The composition observed by JIRAM on Ganymede at the local scale could be a mixture of $NaCl{\cdot}2H_2O$, NH_4Cl, $NaHCO_3$ or $(NH_4)_2CO_3$, and $Na_2Mg(SO_4)_2{\cdot}4H_2O$, presumably the solid residue of a deep ocean brine that reached the surface. The new higher resolution data also suggest the presence of the alkane methyl group $–CH_3$, possibly associated with aliphatic aldehydes. Aldehydes, which play an important role as prebiotic precursor molecules, have been found in carbonaceous chondrites[33] and potentially in Enceladus plume ice grains[34], and may result from liquid water activity[35]. Modelling indicates that Ganymede's low latitude/equatorial surface regions are shielded from electrons of energies up to approximately 40 MeV[36]. Those latitudes of the sub-Jovian/trailing hemisphere are shielded also from heavy ions of energies up to at least some hundreds of keV[37,38]. One therefore expects that the surface composition examined by JIRAM is minimally affected by radiation processing.

Other outer Solar System bodies have salts and organics identified as being of endogenic origin. This is most evident at Enceladus, where sodium salts (NaCl, $NaHCO_3$ and/or Na_2CO_3) were identified in plume material directly sampled by mass spectrometry[39]. A similar composition has also been found in the Cerealia Tholus dome at the centre of Occator crater on Ceres, where a mixture of $Na_2CO_3 \cdot H_2O$, $NaCl \cdot 2H_2O$, and NH_4Cl, was identified by spectroscopic remote sensing[40].

The ions in surface salts can provide insights into the origin and evolution of Ganymede, and help constrain the nature of subsurface liquid water. As on Earth, Enceladus, Europa and Ceres, the presence of Na at specific locations is indicative of interaction between liquid water and rocky material[39,9]. This interaction may have occurred early in Ganymede's history when accreted ice-rock mixtures experienced ice melting, and water and other primordial volatiles separated from rocks[41]. Water-rock interaction could have also occurred later if a subsurface ocean was in direct contact with Ganymede's rocky interior when the subsurface heat flow was larger than it is today, or during more recent times if high pressure ices existing beneath an ocean experienced melting at the surface of the rocky interior[42].

The presence of Cl in salts on Ganymede is easy to explain, as it is likely that Cl was present as a constituent in primordial rocks. Potential chondritic analogues (e.g., CI and CM chondrites) of Ganymede's initial rock component contain Cl in relatively high abundances[43], and rocky worlds (e.g., Io, Mars, Earth) have significant inventories of Cl[44]. During water-rock separation as described above, Cl would be leached from rock with high efficiency owing to its hydrophilic nature[45]. It is possible that Cl could have also been accreted as a constituent in primordial ices, such as hydrates of HCl or NH_4Cl formed from reaction of HCl with NH_3 in cometary ices.

The potential presence of NH_4-bearing salts suggests that Ganymede accreted icy materials that were cold enough to condense ammonia. Ultraviolet spectroscopy data obtained at Ganymede during the same Juno flyby are also consistent with an ammonia-like contaminant at low latitudes[46]. Ammonium salts are likely to be widespread among comets[47], and other planetary bodies located beyond the snow line (e.g., Ceres, Enceladus, Titan, Pluto) show evidence of NH_3 or NH_4^+-bearing materials[48-50]. Direct accretion of these species seems to provide the simplest explanation for the inferred presence of NH_4-bearing salts on Ganymede. A more complex and perhaps less likely origin scenario for NH_4^+ would involve hydrothermal processing of N in chondritic insoluble organic matter[51]. The viability of this hypothesis would depend on conditions being sufficiently reduced and not too hot in Ganymede's rocky interior (otherwise, N_2 would be generated instead[52]). Also, the apparent absence of nitrates may suggest limited oxidation of ammonium to nitrate if ammonium salts are present.

The origin of carbonate species (including surface CO_2 if endogenic) is likely to be analogous to that of the ammonium ion. That is, the most plausible scenario may involve accretion of volatile-bearing ices, containing CO_2 in this case. Observations of comets show that they contain even more CO_2 than NH_3[53]. Some chondrite parent bodies also accreted CO_2, as evidenced by the occurrence of enrichments of ^{13}C in carbonate minerals[54]. The case of a chondritic rock inheritance or one that reflects an additional cometary ice inheritance likely leads to accretion of CO_2 on Ganymede. This primordial CO_2 could then produce $NaHCO_3$ by rock weathering reactions (see above), or $(NH_4)_2CO_3$ could be produced by NH_3 reacting with CO_2 in melted primordial ices. Metamorphism of accreted organic matter mixed with hydrated and oxidized minerals in Ganymede's initial rocky interior could provide an alternative or complementary source of CO_2[55]. Certainly, high temperatures that favour carbon oxidation would have been reached; otherwise, Ganymede would not have a metal core[56].

Some of the tentatively identified salts are pH-sensitive, so their presence would constrain the pH of the source fluid. Modelling suggests that the source fluid would have been circumneutral to moderately alkaline (Methods). This inference suggests a balance between the acidity produced by volatiles (e.g., carbonic acid derived from CO_2) and the basicity that is inherent to silicate minerals. Extensive water-rock interaction could achieve such a balance, and would also be consistent with the presence of sodium salts as an independent indicator of aqueous alteration inside Ganymede.

The salt minerals and organic compounds spectroscopically identified by JIRAM on Ganymede, and their relationship with the geological characteristics of the explored area, suggest that these may be the result of extensive aqueous alteration of silicates that occurred at some point in the history of the satellite, perhaps combined with hydrothermal activity in its depths.

Methods

JIRAM data acquired at Ganymede during orbit 34. In Juno orbit 34, during the close flyby of Ganymede that occurred on 7 June 2021, JIRAM acquired a total of 6 images and 23 spectral slits. The spectral slits from #12 to #17 were acquired on the dayside of Ganymede (Supplementary Fig. 2). We discarded slit #12, i.e., the first dayside slit, due to poor (grazing) solar illumination resulting in very low signal-to-noise ratio (SNR), whereas the other five slits were retained for scientific analysis. In Table 1 and in the main text, for simplicity we refer to these five slits as: Slit 1, Slit 2, Slit 3, Slit 4, and Slit 5.
Each JIRAM slit is composed of 256 spectra, resulting in more than 1100 individual infrared spectra after filtering only data with favorable solar illumination and observation conditions (solar incidence angle and emission angle <75°) and ruling out data affected by permanent instrumental artifacts. This spectroscopic dataset had to first be corrected for straylight coming from Ganymede and entering the JIRAM instrument, which affects the wavelength range 2.0–3.8 μm by adding extra signal (see next subsection).

Removal of straylight from JIRAM spectroscopic data. JIRAM data acquired soon after the science data discussed in this paper (i.e., spectral slit #18 taken at UTC 16:59:57) had Ganymede outside the field of view (FoV) and looked at the sky background, and as such should represent only the thermal background signal of the JIRAM spectrometer. On the contrary, a substantial extra signal shows up at short wavelengths, with a flat shape in uncalibrated (raw) data between 2.0 and 3.5 μm, which is different from the usual shape that is seen in other JIRAM slits of Ganymede as observed by JIRAM (Supplementary Fig. 1). Since this was not observed in any other JIRAM spectral data of the Galilean satellites and all other JIRAM functional parameters were nominal, we deduce that this extra signal is straylight. This straylight did not appear in previous observations of Jupiter or its satellites, which were not as close as this Ganymede flyby, suggesting that the distance from the target and the peculiar geometry of the flyby were largely responsible for its occurrence.
The flat shape of the straylight between 2.0 and 3.5 μm can be explained by signal coming from the dayside of Ganymede that entered the JIRAM spectrometer's box and reached the

focal plane without being dispersed by the grating. A junction between two segments of an order-sorting filter placed on top of the focal plane, whose spectral counterpart is centred at ~3.8 µm[10], provides a very effective rejection to this straylight, which is not detected between 4.0 and 5.0 µm.

Among the possible ways of removing the straylight, we preferred using raw data, rather than calibrating the straylight itself and then removing it from the calibrated spectra, as the latter approach induces spurious signatures due to the instrument transfer function. Therefore, we fitted the straylight of slit #18, averaged over all 256 spatial pixels (*samples*), with a sigmoid function (Supplementary Fig. 1). However, since the intensity of straylight changes over time as a consequence of Juno/JIRAM moving with respect to Ganymede, prior to removal the straylight spectrum needs to be further corrected for a normalizing factor, whose value changes from slit #13 to slit #17.

The JIRAM L-band imaging subsystem (measuring spectral radiance integrated from 3.3 µm to 3.6 µm) took images of the surface of Ganymede at the same time as the JIRAM spectrometer. The L-band imager has 432 columns (*samples*) and 128 rows (*lines*). Samples/columns from 87 to 342 are located just above the spectrometer slit (with an angular separation of about 0.1° between the slit and the L-filter border). Because the spatial resolution of these acquisitions is high, we can safely assume that the L-band imager (lines 1–128, samples 87–342, 256 samples in all) and the spectrometer slit (256 samples) receive the same physical signal, when integrated over a ~3.5° region that is much larger than the angular separation between them. In Supplementary Fig. 2 we show, for each acquisition, the difference between the radiance integrated from 3.3 to 3.6 µm using the spectrometer (R_S) and the radiance collected by the L-band imager (R_L), averaged over the pixels defined above.

For each acquisition and for each spectrum in the slit, we then subtract a straylight spectrum equal to $k \cdot R_N$ from the acquired data, where R_N is the calibrated sigmoid function, best fitting the average straylight in raw data, and k is the difference between R_S and R_L as presented in Supplementary Fig. 2.

Finally, once the spurious signal radiance has been subtracted individually from each of the five spectral slits acquired by JIRAM, the resulting average spectral profile of Ganymede displays a change both in the absolute level of the continuum at the short wavelengths, and in the spectral slope between 2.8 and 3.7 µm (Supplementary Fig. 3).

Computation of uncertainties in I/F spectral profiles. The error bars in Fig. 1b and Fig. 2 come from the in-flight Noise Equivalent Spectral Radiance (NESR) calculated on the sky background observed by the JIRAM spectrometer along with Ganymede observations. Here, we calculated the NESR profile as the standard deviation of the spectral radiance in the sky background pixels of slit #18, i.e., the first slit that had Ganymede outside the FoV soon after acquiring the science data. A standard error of the mean (SEM) for the NESR can be obtained by assuming that, while averaging over a population of N samples (in our case, N independent spectra of Ganymede), the uncertainty decreases with the square root of N, where N varies from one observation to another (159 spectra/pixels for slit 1, 241 for slits 2, 3 and 4, and 237 spectra/pixels for slit 5, or 1179 spectra/pixels for the entire dataset shown in Fig. 1b). Finally, for each spectral profile, the NESR SEM is converted into I/F units by dividing it by the solar radiance scaled by the heliocentric distance at the time of the observation (5.051 AU). Consistent with previous works based on JIRAM spectroscopic data, to this end we referred to the high-resolution MODTRAN extraterrestrial solar spectrum[58], convolved for the response of the individual spectral channels of the JIRAM spectrometer[59].

Computation of band depths and associated uncertainties. For each of the eight spectral signatures highlighted in Fig. 1b, the calculation of the band depths is performed by first removing the spectral continuum by means of a linear fit between the shoulders of the bands, and then evaluating the depth according to (ref. [60]) as: BD = (R_C - R_B) / R_C, where R_B and R_C are respectively the reflectance at the band centre and the reflectance of the spectral continuum at the band centre. To calculate the uncertainty associated with the band depth of the main spectral signatures displayed in the average spectrum of Fig. 1b, we considered the mean in-flight noise in units of I/F discussed in the previous subsection and we applied the error propagation to calculate the absolute uncertainty ΔBD associated with a given band depth (that is, the uncertainty associated with the ratio R_B / R_C, given by R_B / R_C multiplied by the sum of the relative errors on R_B and R_C), and hence the ratio between band depth and associated uncertainty. The value of this ratio can be used to discriminate between "strong" and "weak" absorption bands. Details about these parameters are specified in Supplementary Table 1.

Plots of different material categories. In Supplementary Figs. 4–11 we show stacked plots in the 2–5 μm range for the categories of endogenous compounds: water ice, chlorides, carbonates, sulfates, nitrates, and phyllosilicates (smectites). We also show a stacked plot for organics and for some exogenous products displaying diagnostic features in the near infrared range. In each stacked plot, we compare the average spectral profile of Ganymede as measured by JIRAM in I/F units with the reflectance profiles of different compounds measured in the laboratory, after convolution for the JIRAM spectral resolution[59]. Measurements at cryogenic temperatures, if available, were preferred over room temperatures. When multiple grain sizes were available, we chose coarse-grained compounds because at the low latitudes investigated by JIRAM, water ice is coarse-grained[4,26]. The black, thick dashed lines mark the wavelength positions of the main absorptions revealed by JIRAM (located at: 2.08 μm, 2.54 μm, 2.89 μm, 3.00 μm, 3.48 μm, 3.58 μm, 3.65 μm, and 4.25 μm), while thinner goldenrod dashed lines mark the positions of weaker features (at 2.22 μm, 2.42 μm, 2.60 μm, 2.82 μm, 3.05 μm, 3.16 μm, 3.25 μm, and 3.38 μm).

Spectral unmixing. We applied linear spectral unmixing to the JIRAM data, both to the global average spectrum of Ganymede and separately for each of the five slits covering different terrain types, using two consolidated approaches: Fully Constrained Least Squares (FCLS), and Markov chain Monte Carlo (MCMC). FCLS is a linear minimization algorithm[61]. MCMC is a statistical sampling method that uses Markov chains to generate samples from a desired probability distribution[62].
We first set up a library from laboratory spectral profiles of compounds relevant to the surface composition of Ganymede, as found in literature (Supplementary Table 2). All profiles were convolved to match the JIRAM spectral resolution[59]. We initially applied FCLS modelling to individual categories of compounds (i.e., chlorides, sulfates, carbonates, nitrates, smectites, organics, and exogenic species), to evaluate which compound within each category provides a best fit (i.e., the minimum chi-square value) to JIRAM data in the 2.0–3.7 μm region shortward of the filter gap. We then considered the best candidate in each category and rerun the model using a mixture made up of all the best candidates. Coarse-grained water ice is always included among the spectral endmembers. Two synthetic,

spectrally flat endmembers with constant value of 1.0 and 0.0 (respectively tagged "white" and "black") are used to model the albedo, as done in other recent works (e.g., ref. [26]). In a second step, we applied MCMC to validate the results obtained with FCLS. Here, to facilitate numerical convergence in a reasonable processing time, we enforced a spectral correlation length of 20 nm, which means that different wavelengths are highly correlated at this spectral scale (corresponding to roughly two JIRAM spectral channels). Results are displayed in Supplementary Fig. 15.

The general observation is that, although these unmixing models can properly fit the spectral continuum, they can hardly reproduce specific weak and/or narrow spectral signatures. Furthermore, no substantial percentages of water ice are needed to return a good fit, because several hydrates mimic the spectral profile of water ice in the region between 2 and 3 μm. When using MCMC, the coefficients of the linear combination associated with hydrated sulfuric acid are substantially higher than in the case of FCLS; but the best fit in general improves by excluding this compound, for which no reflectance spectral profiles measured in laboratory exist longward of 2.5 μm.

Reconstruction of geometric information for JIRAM spectroscopic data. The computation of geometric information for JIRAM data is usually obtained by means of the SPICE toolkit[63]. However, in this specific close Ganymede flyby, the SPICE-derived geometric information shows substantial deviations from the observed data, which are due to the large relative speed of the spacecraft and are highlighted by known surface features or by an offset in the limb profile of Ganymede. Hence, to improve the SPICE-based geometric information for JIRAM, we applied a limb fitting technique similar to that used in (ref. [13]). First, geometric information for JunoCam optical images (*106xx-Metadata.json*, with *xx* from 29 to 32) was computed using SPICE, then the geometric values were adjusted by fitting the limb of Ganymede. By comparing the location and shape of surface features observed in JunoCam images with those observed in JIRAM images, we derived the geometric information of JIRAM spectral data consequently, because the relative alignment of the JIRAM spectrometer and the JIRAM double imager is known with very high accuracy (< 1 pixel[59]). To take smearing into account, the geometric information concerning the latitude and longitude of JIRAM spectroscopic data is calculated not only for the pixel centre but also for the four corners of each pixel, both at the beginning and at the end of the exposure. This way, for each pixel we obtain a projected trapezoid that represents the effective area covered during the exposure time.

To finally map JIRAM data, we considered for each spectral slit a grid with fixed angular resolution matching the nominal pixel resolution, ranging from 0.31 km/px (slit 1) to 0.61 km/px (slit 5). Starting from the knowledge of the individual JIRAM ground footprints/trapezoids, we sum all band depth values falling within a given angular bin, then we average those data keeping track of the overall redundancy. This approach ultimately allows us to properly map each of the five JIRAM spectral slits despite the variable spatial resolution.

Correlation coefficients for pairs of band depths. To evaluate potential correlations in surface composition as observed by JIRAM, we calculated correlation coefficients between the depths of the eight main spectral features shown in Fig. 1b. Since JIRAM's spectral slits sample different terrain types, to properly evaluate correlations arising among different spectral signatures we have produced one correlation matrix for each slit, in order to highlight different behaviors from one region to another, rather than mixing all BD values together (Supplementary Tables 3). In all slits, no systematic correlations arise between any pair of spectral signatures, which could point to systematic instrumental artifacts/residuals.

Geochemical interpretations of inferred salt compositions.

We performed thermodynamic calculations using the code SUPCRTBL[64] to quantify how relative abundances in the CO_2–HCO_3^-–CO_3^{2-} and NH_4^+–NH_3 systems would change as a function of pH. These calculations are approximate because they correspond to 0°C and 1 bar, and ionic strength effects are neglected. The source fluid may actually chemical speciate as a brine that is at sub-zero temperatures prior to salt deposition. However, we consider our simplified systems to be appropriate given the nature of the current observational data (i.e., inferred presence of a few salts rather than detailed concentration information). Also, a low pressure is appropriate for the source fluid when it is in the shallow subsurface prior to extrusion. We hold an agnostic view as to how the source fluid that is considered here could relate to a salty water ocean that resides inside Ganymede[2].

Supplementary Fig. 16 quantifies the pH dependence of the speciation of ammonia and carbonate species. This figure allows us to constrain the pH that would be consistent with the composition of salts inferred from JIRAM data. Supplementary Table 4 provides suggested constraints on pH for the indicated salt to have a "significant" abundance. Significance is treated subjectively here based on Supplementary Fig. 16, as the observational data are qualitative with regards to how they constrain aqueous chemistry. Nevertheless, pH operates over a log scale, which helps to mitigate this type of uncertainty. It is not straightforward to interpret Supplementary Fig. 16 for $(NH_4)_2CO_3$ because the figure treats the two speciation systems separately, while they are clearly linked in the case of this compound. We clarified this issue by performing a coupled speciation calculation for $(NH_4)_2CO_3$ using The Geochemist's Workbench, and obtained a pH of ~10.

We conclude that a salt assemblage on Ganymede's surface that includes significant $NaHCO_3$ should have a source fluid pH between ~6 and ~11, while an alternative assemblage containing a significant amount of $(NH_4)_2CO_3$ would probably require a pH close to 10. Both endmembers would be consistent with the coexistence of NH_4Cl and $NaCl{\cdot}2H_2O$. It appears that the source fluid would have been circumneutral to moderately alkaline. This inference suggests a balance between the acidity produced by volatiles (e.g., carbonic acid derived from CO_2) and the basicity that is inherent to silicate minerals.

Data availability

The JIRAM dataset used for our analysis is publicly available at the Juno Archive at the Planetary Atmospheres Node (https://pds-atmospheres.nmsu.edu/PDS/data/PDS4/juno_jiram_bundle/data_calibrated/orbit34/). The filenames of JIRAM spectroscopic data of Ganymede are listed in Table 1. Source data are provided with this paper (ref. [65]).

Code availability

The computer code used to produce I/F spectral profiles of Ganymede and to compute band depths is a direct implementation of the procedures described in the Methods. Spectral unmixing with FCLS was carried out using PySptools, available at: https://pysptools.sourceforge.io/. Spectral unmixing with MCMC is a direct implementation of the algorithm[63]. The computer code used to model the chemical speciation of NH_3 and CO_2 is a direct implementation of the SUPCRTBL code[64].

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Author contributions

F.T. led the analysis and interpretation of JIRAM data, writing major sections of the Main Text and Methods. A. Mura is the Team Leader of the JIRAM instrument; he derived geometric information for JIRAM data, provided correction for straylight, and wrote part of the Methods. A. Cofano searched laboratory spectra available in the literature and relevant for the JIRAM spectral range, highlighting the spectral matches in Extended Data Table 1, and performed spectral unmixing. F.Z. mapped the JIRAM data and contributed to the interpretation. C.R.G. wrote part of the Discussion and of the Methods. M.C. and G.P. contributed to the discussion of the results. J.I.L. and C.P. contributed to data interpretation. R.S. and A. Cicchetti managed the operations of the JIRAM instrument. R.N. was responsible for the JIRAM calibration pipeline. All authors contributed to the discussion of the results and helped with the manuscript preparation.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at [DOI to be added by the production team]

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Table 1. JIRAM spectral slits and geometric circumstances. For each of the five spectral slits used in this work, we list the PDS filename, acquisition time at mid-exposure, and some geometric information such as altitude over the surface, nominal pixel resolution, phase angle, solar incidence angle, emission angle, and local solar time. The five slits were acquired in a two-minute period and in the altitude range 1317–2558 km above the surface, yielding unprecedented nominal pixel resolution values between 0.31 and 0.61 km (mean value 0.45 km). The effective spatial resolution is affected by smearing in the along-track direction. However, this does not coincide with the slit's major axis, so that adjacent pixels observe quite different areas.

Slit #	Filename	UTC Time	Altitude (km)	JIRAM nominal pixel res (km)	Phase angle (deg)	Solar incidence angle (deg)	Emission angle (deg)	Local solar time (h)
1	JIR_SPE_RDR_2021158T165730_V01.DAT	2021-06-07T16:57:26	1316.5	0.313	83.4-79.9	73.9-75.6	10.3-5.5	7.2-7.1
2	JIR_SPE_RDR_2021158T165800_V01.DAT	2021-06-07T16:57:56	1551.2	0.369	83.3-79.8	61.9-64.1	22.7-17.2	8.1-8.0
3	JIR_SPE_RDR_2021158T165830_V01.DAT	2021-06-07T16:58:27	1843.2	0.438	83.2-79.6	48.9-52.0	36.5-30.1	9.1-8.9
4	JIR_SPE_RDR_2021158T165900_V01.DAT	2021-06-07T16:58:57	2181.9	0.519	82.6-79.1	34.4-39.1	50.3-42.0	10.2-9.9
5	JIR_SPE_RDR_2021158T165930_V01.DAT	2021-06-07T16:59:27	2558.2	0.608	82.3-78.9	14.3-23.1	75.7-59.8	11.9-11.1

Figure Legends/Captions

Figure 1. Average spectral profile of Ganymede as observed by Juno/JIRAM. a, Average spectral profiles of Ganymede, in units of calibrated radiance factor (I/F), obtained by JIRAM in several flybys where spectroscopic data of good quality could be achieved. A different colour corresponds to a different average spectrum and a different Juno orbit. In all cases, data were filtered in such a way as to retain only those pixels with a solar illumination angle and an emission angle less than 75°, to increase the signal-to-noise ratio. The gap at 3.8 µm corresponds to a permanent artifact[10]. All the spectral profiles show a prominent absorption at ~2.9 µm, which is the main signature of water, as well as a weaker absorption at 4.25 µm due to CO_2. **b**, Detail of the average profile obtained in orbit 34 on 7 June 2021 with error bars, and vertical dashed lines highlighting the position of the main spectral signatures. Data are presented as mean values of 1179 pixels +/- standard error of the mean (SEM) measured on the sky background during the same observing sequence (Methods). The upper right inset is a closeup of the organics' region between 3.0 and 3.7 µm, where dashed brown boxes highlight regions diagnostic of aromatic, aliphatic, and aldehyde compounds, respectively.

Figure 2. Spectral variability in JIRAM data. Average spectral profiles of Ganymede measured in five separate JIRAM slits. Data are presented as mean values of 159, 241, 241, 241 and 237 pixels, respectively +/- SEM measured on the sky background during the same observing sequence (Methods). Each plot in the left column is named after a terrain unit described in the main text and shown in Supplementary Fig. 13. In the right column, we show images acquired simultaneously with the JIRAM M-band imaging subsystem, where the colour code is related to the brightness temperature computed at 4.78 µm. The images are all 432×128 pixels in size. The *x*-axis ("sample") identifies the column index while the *y*-axis ("line") identifies the row index. Although smeared, the JIRAM images display geologic features in the observed scene, which can explain the variability observed in the spectroscopic data.

Figure 3. Spatial distribution of band strengths in grooved terrains. Closeups of the ground footprints of JIRAM spectral slits 1 (left column) and 4 (right column), covering different grooved terrains. From top to bottom, each panel displays the depth of selected spectral features: 2.08 µm, 2.54 µm, 2.89 µm, 3.48 µm, and 4.25 µm. The labels on the axes express east longitude (*x*-axis) and north latitude (*y*-axis). Smearing is accounted for in projecting the ground footprints (Methods). The colours in the projected footprints highlight variability in the observed scene, linked to the composition of the terrains that JIRAM investigated. To allow correlation with geologic features, a JunoCam optical image is used as a background in slit 1 (~1 km/px) (Supplementary Data), while the Voyager+Galileo optical basemap (1 km/px)[57] is used in slit 4. A scale bar indicates the size of the observed features. To emphasize band depth values, different stretches are applied in the colorbars of slit 1 and slit 2. The full set of projections for the band depths of all 8 spectral signatures is shown in Supplementary Fig. 14.

Figure 4. Spatial distribution of band strengths in dark and bright terrains. Closeups of the ground footprints of JIRAM spectral slits 2 (left column) and 3 (right column), covering a dark terrain and the bright ejecta of a fresh crater, respectively. The meaning of the panels in terms of band depths, the coordinate system and the projection method are the same as in Figure 3. To allow correlation with geologic features, JunoCam optical images are used as a background (~1 km/px) (Supplementary Data). For each row of panels, the same colorbar applies. The full set of projections for the band depths of all 8 spectral signatures is shown in Supplementary Fig. 14.

Figure 5. Spatial distribution of band strengths in multiple terrains. Closeups of the ground footprints of JIRAM spectral slit 5, covering multiple terrain types including dark terrains and grooved terrains. The meaning of the panels in terms of band depths, the coordinate system and the projection method are the same as in Figure 3 and Figure 4. To allow correlation with geologic features, the Voyager+Galileo optical basemap (1 km/px)[57] is used. The full set of projections for the band depths of all 8 spectral signatures is shown in Supplementary Fig. 14.

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