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# 13 Abstract

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We performed spectral analyses on four serendipitous observations of Europa acquired by the 14 JIRAM instrument (Adriani et al., 2017) onboard the Juno mission. Due to the fixed orienta-15 tion of the spacecraft spin axis and orbital plane placed along terminator, Europa is observed at 16 approximately 90° phase angle from distances greater than 3.35E5 km resulting in a best spatial 17 resolution of 80 km/px. The one thousand spectra dataset returned to the ground offers a lim-18 ited coverage in longitude but an almost complete excursion in latitude from poles to equator. 19 With a 2 to 5  $\mu$ m spectral range and a sampling of about 10 nm/band, JIRAM reflectance spec-20 tra allow extraction of different spectral indicators suitable to characterize surface composition, 21 grain size distribution and temperature: the 2  $\mu$ m water ice band center appears on average 22 centered at 2.038  $\mu$ m as a result of the presence of both amorphous and crystalline ice phases 23 and non-ice materials. The reflectance level on the 2.4  $\mu$ m inflection should r is comparable to 24 the maximum absorption on the 2  $\mu$ m band pointing to the presence of non-ice materials, like 25 magnesium chlorinated or hydrated magnesium salts, mixed with water ice. Assuming water 26 ice as the principal endmember, we estimate the surface regolith grain size by comparing the 2 27

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 $\mu$ m band depth and the ratio between I/F at 3.63 and 2.27  $\mu$ m (*Filacchione et al.*, 2012). On 28 average, we measure values of 0.6 for the first and 0.1 for the latter: such values are compatible 29 with grain sizes in the range of tens to hundreds of microns. Despite the low signal-to-noise 30 beyond 2.7  $\mu$ m, due to the intrinsic low-reflectance of Europa's surface and very high phase 31 angle values occurring during the observations, JIRAM is able to measure the wavelength of 32 the reflectance peak around 3.6  $\mu$ m, which is a proxy of water ice temperature (*Filacchione* 33 et al., 2016a). In the dataset JIRAM has obtained the peak's maximum wavelength occurs at 34  $3.64 \ \mu m$  corresponding to a maximum diurnal temperature of 132 K. 35

<sup>36</sup> Keywords: Europa, Satellites, surfaces, Spectroscopy, Ices

### 37 1. Introduction

Despite the Galilean moons not being among the nominal scientific objectives of NASA's 38 Juno mission to Jupiter (Bolton and Connerney, 2017), JIRAM the Jovian InfraRed Auroral 39 Mapper (Adriani et al., 2017) was able to observe the surface of Europa during four opportu-40 nities. In the context of an overall program of "ocean worlds" exploration, the data returned 41 by JIRAM are valuable for better constraining the characteristics of the moon's surface in the 42 2-5  $\mu$ m spectral range. In the past, Europa's surface has been spectrally mapped at these 43 wavelengths only by three interplanetary missions. So far, Galileo/NIMS (Carlson et al., 1992) 44 has returned the more comprehensive dataset despite being limited to partial coverage of the 45 surface. These data have allowed mapping of the distribution of non-ice materials, mainly 46 identified as hydrated sulfuric acid, which appear more abundant on the trailing hemisphere 47 (Carlson et al., 2005) and hydrated salts (magnesium sulfates, sodium carbonates) associated 48 with the low-albedo areas (McCord et al., 1998, 1999). Also Cassini/VIMS (Brown et al., 49 2004) during its flyby of Jupiter in 2000 was able to perform limited observations of Europa's 50 surface at low spatial resolution in the 0.35-5.0 µm range (Brown et al., 2003; McCord et al., 51 2004). Similarly, LEISA spectrometer (*Reuter et al.*, 2008) on New Horizon has returned re-52

solved spectra of Europa's surface (Grundy et al., 2007) in the 1.2-2.5  $\mu$ m range. For the 53 future, Europa will be the target of NASA's Europa Clipper and ESA's Juice missions, both 54 planned to start their scientific investigations in the 2030 timeframe. These missions will have 55 aboard dedicated infrared mapping spectrometers covering the same spectral range of JIRAM: 56 Europa Clipper/MISE (Mapping Imaging Spectrometer for Europa, described in Blaney et al. 57 (2017)) and JUICE/MAJIS (Moon And Jupiter Imaging Spectrometer, detailed in Langevin 58 et al. (2014)). Since the 2-5  $\mu$ m spectral range is scarcely accessible from Earth-telescopes, 59 JIRAM data are of special value in providing an advanced look at the kind of spectra these 60 other mission will obtain. 61

A discussion of the current knowledge of Europa's surface spectral properties is given in section 2. Section 3 contains a description of the JIRAM instrument's architecture and operative mode necessary for a comprehension of Europa's observations which are detailed in section 4. After a description of the spectral indicators used to analyze JIRAM data (section 5), the main results relative to compositional properties (section 6), regolith grain size (section 7), water ice amorphization (section 8) and temperature retrieval (section 9) are exposed. A discussion about JIRAM results in the context of previous observations is given in section 10.

## <sup>69</sup> 2. Background

Europa is one of the four Galilean moons, the regular satellites of Jupiter named after Galileo Galilei who observed them for the first time on the night of January 7th 1610. With an average radius of 1560 km and a geometric albedo of 0.67 (*Buratti et al.*, 1983), Europa is the smallest and the brightest object among the four regular moons. The surface of Europa appears geologically young, with a crust made of water ice and nonice compounds floating above a subsurface liquid ocean (*Greenberg*, 2005).

<sup>76</sup> Crossing through the surface are visible dark markings, called linea, and chaos terrains <sup>77</sup> generated by tidal movements below the ice shell with consequent resurfacing and exposure <sup>78</sup> of nonice materials. Infrared spectroscopic measurements have shown that europan nonice <sup>79</sup> material has similarities with magnesium salts (*McCord et al.*, 1998, 1999) and sulfuric acid-<sup>80</sup> rich compounds (*Carlson et al.*, 2005). The presence of salts is a clue to the presence of <sup>81</sup> environmental conditions favorable to life in the subsurface ocean (*Fanale et al.*, 2001; *Hand* <sup>82</sup> *et al.*, 2007) while sulfur-bearing compounds could result from radiolytic processes altering <sup>83</sup> endogenous materials (*Carlson et al.*, 1999b, 2002) or magnetospheric particles (*Dalton et al.*, <sup>84</sup> 2005, 2012).

Galileo/NIMS spectra evidence that water ice is distributed across Europa's surface in both 85 the crystalline and amorphous state (*Carlson et al.*, 2009). Crystalline ice forms in metastable 86 cubic lattice at temperature  $140 \le T \le 150$  K while disordered amorphous ice forms condense 87 at T  $\leq$  30K (high-density ice phase), T  $\leq$  100K (low-density ice phase) or at 100  $\leq$  T  $\leq$  140 K 88 (restrained phase). The latter can coexist with the crystalline cubic type when the temperature 89 is T  $\leq$  140 K (Jenniskens et al., 1998). With aging, these water ice types eventually mutate into 90 crystalline hexagonal ice with transformation rates that depend on temperature. Within the 91 range of temperatures observed on Europa's surface (minimum nocturnal T<76 K; maximum 92 diurnal T=132 K, Spencer et al. (1999)), one would expect that all amorphous ice would be 93 transformed into hexagonal ice in less than 20 years (*Jenniskens et al.*, 1998). 94

The crystalline and amorphous water ices can be recognized thanks to their different spectral 95 properties at infrared wavelengths. In particular, the crystalline form is characterized by the 96 presence of a secondary absorption at 1.65  $\mu$ m (missing in the amorphous ice) within the intense 97 1.5  $\mu$ m band, by the position of the 2.05  $\mu$ m band (shifted at 2.0  $\mu$ m in the amorphous ice) and 98 by the 3.1  $\mu$ m Fresnel's reflectance peak properties. The Fresnel's peak is a restrahlen feature 99 which occurs at wavelengths where the absorption is so strong that the medium reflects the 100 light like a metal. For water ice this feature appears broad and weak for the amorphous phase 101 while is narrower and structured like a triplet for cold crystalline ice (Hagen et al., 1981). 102

As said before, since the Europa's environmental temperature conditions do not allow the

survival of amorphous ice, additional mechanisms able to continuously refurbish it must be 104 acting. Amorphous ice can be formed by condensation of sublimated and sputtered molecules 105 and by irradiation from UV, electrons and ions. Many laboratory experiments have investigated 106 how the effects of different kind of radiations at different temperature ranges alter water ice 107 molecular structure (Moore and Hudson, 1992; Leto and Baratta, 2003; Baragiola, 2003; Leto 108 et al., 2005; Mastrapa and Brown., 2006). However, since the radiation is attenuated within 109 the medium, the resulting amorphization of the ice should occur only on a relatively shallow 110 surface layer. For electrons, for example, theoretical models show that radiation processing 111 occurs up to depths of 1 cm in mid and high latitude regions of Europa and up to 10-20 cm in 112 the radiation lenses centered on the apex of the leading and training hemispheres (Nordheim et 113 al., 2018). This effect must be kept in mind when spectral results are analyzed. The retrieval of 114 the water ice state from infrared spectral properties (k being the complex index of refraction) 115 is complicated because the absorption coefficient  $\alpha(\lambda) = 4\pi k(\lambda)/\lambda$  is wavelength-dependent 116 (Lynch, 2005). The optical skin depth,  $1/\alpha(\lambda)$ , which corresponds to unitary optical depth, 117  $\tau$ , is less than 1  $\mu$ m at the wavelength of the Fresnel's peak while at 2  $\mu$ m is less than 10 118 cm. This means that using these two wavelengths one is probing different depths within the 119 surface layer. A similar behavior is recognizable in Hansen and McCord (2004) work who have 120 exploited a simplified spectral modeling to map water ice forms across Europa's surface using 121 Galileo/NIMS data. Their findings show that crystalline water ice is able to fit the 1.5 and 122 2.0  $\mu$ m bands while amorphous ice is necessary to reproduce the spectral behavior observed on 123 the Fresnel's peak: the fact that amorphous ice is observed almost everywhere across Europa's 124 surface is a strong indication that the Fresnel's peak properties are easily altered by radiations 125 and thermal effects occurring in a very shallow water ice layer. Noteworthy, the Fresnel peak 126 is also influenced when water ice is contaminated by nonice materials, e.g. it is removed in 127 hydrated materials spectra (*Carlson et al.*, 2009). 128

New Horizon/LEISA has retrieved the 2  $\mu m$  water ice band depth and nonice material

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abundance maps which appear anti-correlated among them: the first is relatively constant, 130 between 35% to 60% in the regions less contaminated by nonice material, while the latter 131 reaches maximum abundance on the apex of the trailing hemisphere (Grundy et al., 2007). 132 While LEISA data are limited in coverage to regions at latitudes  $\leq +60^{\circ}$ , a better view of the 133 north polar regions has been achieved by Galileo/NIMS whose data show a water ice enrichment 134 across the north pole bright plains (Fanale et al., 1999). Galileo NIMS has also identified other 135 species like hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) by observing a faint absorption band at 3.5  $\mu$ m (*Carlson* 136 et al., 1999a), sulfur dioxide's 4.03  $\mu$ m feature (McCord et al., 1998; Carlson et al., 2009) and 137  $CO_2$  ice's 4.26  $\mu$ m band (Hansen and McCord, 2008). A further absorption at 3.78  $\mu$ m, possibly 138 associated to sulfur dioxide, has been observed by NIRSPEC on the Keck II telescope (Trumbo 139 et al., 2018). 140

Independent analyses of Europa's infrared spectra (Hansen and McCord, 2004; Dalton et al., 141 2012; Ligier et al., 2016) and polarimetric data (Poch et al., 2018) aiming to the retrieval of the 142 regolith grain size have shown a distribution within tens and hundreds of microns. The presence 143 of >100  $\mu$ m grains make the europan surface distinctively different with respect to other icy 144 satellites, like those of Saturn, in which very small grains dominate: according to Stephan et 145 al. (2010, 2012, 2016); Scipioni et al. (2017) the surfaces of the icy satellites of Saturn are 146 populated by submicron and micron (< 5  $\mu$ m) grains. Other authors (Verbiscer et al., 2006; 147 Filacchione et al., 2012; Ciarniello et al., 2011) have found larger grain size distributions (<148  $80 \ \mu m$ ) but still smaller than those on Europa. Similar discrepancies between grain sizes may 149 be due to the different spectral models employed in the retrieval as has been demonstrated by 150 published comparisons (Hansen, 2009; Shkuratov et al., 2012; Ciarniello et al., 2014). 151

<sup>152</sup> While ongoing or recent evolution is seen on all Galilean satellites surfaces, including the <sup>153</sup> resurfaced and chaos terrains on Europa, thermal sintering and bombardment of energetic <sup>154</sup> particles induced by the high Jovian temperatures and radiation environment might be the <sup>155</sup> cause of grain coalescence up to hundred of micron sizes. These effects are more important in the Jupiter's environment than at Saturn where temperature and radiation effects are much lower. Apart from this, Saturn's satellites orbiting within the E-ring boundaries are also affected by the deposition of fine grains from Enceladus' plume (*Porco et al.*, 2006) which contribute to replenish micron and submicron grains on their surfaces.

<sup>160</sup> When temperatures exceeds 100 K, such as on Europa's dayside, water ice grains have higher <sup>161</sup> mobility which would cause sintering, coalescence and growth (*Gundlach et al.*, 2018; *Häßner* <sup>162</sup> *et al.*, 2018). A similar mechanism is probable at the base of the formation of the larger grains <sup>163</sup> observed on Europa's surface but also in other water ice-rich environments, such as the surface <sup>164</sup> of comets (*Filacchione et al.*, 2016b).

# 165 3. JIRAM instrument

JIRAM is an advanced infrared imaging spectrometer and camera operating on board the 166 Juno mission specifically designed to observe Jupiter's atmosphere (Adriani et al., 2018) and 167 auroral emissions (Mura et al., 2018). The instrument shares a single telescope to feed a 2-168 5  $\mu$ m imaging spectrometer and a dual-band infrared camera through a beam splitter. The 169 spectrometer (SPE) spectral sampling is about 10 nm/band across a field of view (FOV) of 170 3.67°. A 2D HgCdTe detector is used to acquire a 256 samples by 336 bands frame. The imager 171 (IMG) relies on a push-frame design in which a single array detector observes the scene through 172 two filters in band L ( $\lambda$ =3.455  $\mu$ m,  $\Delta\lambda$ =0.29  $\mu$ m) and M ( $\lambda$ =4.780  $\mu$ m,  $\Delta\lambda$ =0.48  $\mu$ m). The L 173 band is optimized for the observation of Jupiter's auroral emissions caused by  $H_3^+$  emissions, 174 while the M band is devoted to observe the Jovian atmospheric thermal emission. Both L and 175 M channels have a field of view of  $6.2^{\circ} \times 1.8^{\circ}$  imaged by means of two adjacent  $432 \times 128$ 176 pixels areas arranged side by side on a 270 by 438 pixels detector. The instantaneous field of 177 view (IFOV) of both IMG and SPE channels is 250  $\mu$ rad/pixel resulting in a spatial resolution 178 of 250 km/pixel from one million km distance. The FOV of the SPE channel is co-located 179 within the IMG-M channel and oriented parallel to the spacecraft spin axis to optimize the 180

<sup>181</sup> coverage. Finally, the instrument uses a passive thermal design to reach cryogenic operating <sup>182</sup> temperatures: two external radiators are used to dissipate thermal loads necessary to maintain <sup>183</sup> the optical bench at T=130 K and the two detectors at T $\leq$ 85K. A comprehensive description <sup>184</sup> of the JIRAM instrument is given in *Adriani et al.* (2017).

A major challenge for any imaging instrument onboard a spinning spacecraft is the com-185 pensation of the rotation during the period of time necessary to acquire an image. In the case 186 of Juno, the spacecraft is a spin axis-stabilized platform with an angular rotation of about 2 187 r.p.m.  $(12^{\circ}/s)$  placed on highly elliptical, 53.5 day-long, polar orbits around Jupiter (*Bolton*) 188 and Connerney, 2017). Due to operational constraints, JIRAM can operate only in a limited 189 period of time, spanning between -13 to +2 hours around perijovian passage (occurring at 190 4.200 km above the top of Jupiter's clouds), when the relative velocity of the spacecraft with 191 respect to Jupiter reaches values as high as 60 km/s. JIRAM is able to counter-compensate 192 the spacecraft's rotation by means of a controlled de-spinning mirror placed at the entrance 193 of the telescope. The mirror rotation axis is oriented parallel to the spacecraft rotation axis. 194 During acquisition, the de-spinning mirror is commanded to rotate with an angular velocity 195 equal and opposite to the spacecraft one. The spacecraft angular velocity and clock (relative 196 to the condition of nadir pointing on Jupiter) is determined by the onboard attitude control 197 and transmitted to the JIRAM instrument at every spacecraft rotation. The mirror parameters 198 (angular offset, timing and angular velocity) as well as the acquisition parameters of the SPE 199 and IMG channels (timing, integration times, operative modes) are commanded to capture 200 scientific targets when transiting through the instrumental FOV. Thanks to this architecture 201 it is possible to freeze the scene within the FOV for a maximum time of 1.2 s. for each 30 s. 202 long spacecraft rotation. During each rotation JIRAM can acquire one hyperspectral slit in 203 the 2-5  $\mu$ m spectral range with the SPE channel and one image in L and/or M band with the 204 IMG channel. However, while JIRAM-SPE is in principle able to build in time hyperspectral 205 images, in practice it cannot operate in imaging mode, because the time resolution necessary 206

to acquire consecutive adjacent slits is far beyond the possibilities of the onboard attitude and timing system due to the fast dynamics of the Juno's spacecraft. A description of JIRAM science planning and commanding activities is given in *Noschese et al.* (under review).

Since the spacecraft's on board attitude system has been designed and optimized to allow 210 scientific observations of Jupiter but not of the Galilean satellites, which are not among the 211 objectives of the Juno mission, the acquisition of Europa's spectra are particularly challeng-212 ing. One of the major difficulties encountered is the timing of the observations because the 213 onboard attitude system has been designed to provide the clock of the nadir-pointing condition 214 during each spacecraft rotation only for Jupiter and not for the satellites. This means that to 215 observe them is necessary to compute a priori the time and angle offsets (including margins) 216 to command JIRAM acquisitions. Despite these limitations, JIRAM team has exploited the 217 instrument capabilities far beyond the nominal science cases in order to observe the Galilean 218 moons, resulting in the acquisition of the serendipitous dataset of Europa presented in the next 219 section 4. 220

#### **4.** Dataset and calibration

JIRAM has successfully observed Europa's surface during Juno's orbits #2 (August 2nd-3th 222 2016), #8 (September 1st 2017), #9 (October 25th 2017) and #11 (February 8th 2018) when 223 Europa's orbital position was crossing Juno's orbital plane. The resulting dataset is listed in 224 Table 1. The duration of the acquisitions, grouped into sessions, is driven by the time necessary 225 to observe a transit of Europa within the JIRAM-SPE field of view. The spectrometer's data 226 show Europa's disk crossing the length of the slit from one side to the other. In each session 227 JIRAM has acquired consecutive images and spectra taken once every 30 s, i.e. every spacecraft 228 rotation. Due to the limitations explained in section 3, it was impossible to acquire connected 229 slits to build hyperspectral images; instead they are randomly dispersed across the surface. 230 The geometric parameters for each observation reported in Table 1 are derived from trajectory-231

Session	Latitu	de (deg)	Longit	ude (deg)	Incide	ence (deg)	Emiss	ion (deg)	Phase	(deg)	Resolution	# spectra
Orbit-Date-Time	min	max	min	max	min	max	min	max	min	max	(km/pix)	
JM0002_160802_213108	22.3	27.0	133.0	144.7	88.1	98.6	27.3	29.3	86.2	86.2	1809	19
JM0002_160803_010100	0.5	66.4	75.7	217.3	14.5	151.9	10.8	83.4	87.3	87.3	1781	19
JM0081_170901_105708	20.6	24.0	37.4	40.8	28.5	28.5	73.4	73.4	91.5	91.5	88	4
JM0081_170901_110210	2.2	87.5	7.1	288.7	19.8	94.8	21.9	85.8	91.4	91.6	87	3
JM0081_170901_110711	2.0	82.2	12.7	357.6	28.1	160.8	16.7	78.2	91.3	91.7	87	8
JM0081_170901_111213	-3.6	79.3	9.9	358.7	23.6	162.6	15.5	83.7	91.4	91.9	86	9
JM0081_170901_111715	1.8	74.4	0.8	351.7	22.6	169.0	12.1	88.4	91.5	92.0	85	10
JM0081_170901_112216	7.0	72.7	3.9	356.4	25.3	169.5	11.4	82.4	91.7	92.1	84	8
JM0081_170901_112718	3.9	67.9	0.2	354.0	22.5	162.7	11.0	84.7	91.8	92.3	84	9
JM0081_170901_113219	-11.8	67.1	1.5	357.4	22.0	169.7	5.1	85.1	91.9	92.4	83	7
JM0081_170901_113651	4.8	77.8	3.9	352.5	30.3	158.7	23.9	76.1	92.1	92.6	83	12
JM0081_170901_114152	5.3	75.1	1.0	351.4	28.5	162.9	22.3	85.8	92.2	92.7	82	10
JM0081_170901_114654	2.8	67.8	4.8	359.1	27.6	169.8	16.7	86.4	92.4	92.8	81	9
JM0081_170901_115156	7.9	67.8	3.1	357.1	30.4	161.8	17.5	85.4	92.5	93.0	81	14
JM0081_170901_115657	10.5	63.8	4.0	359.5	28.0	165.3	13.4	78.5	92.7	93.1	81	10
JM0081_170901_120159	6.9	67.5	1.3	357.0	27.5	174.0	10.7	82.6	92.8	93.3	80	7
JM0081_170901_120700	9.2	68.7	0.4	356.2	72.5	172.3	10.6	80.2	93.0	93.3	80	4
JM0091_171025_000341	-8.4	-0.4	36.4	44.2	32.1	39.9	61.4	72.3	87.8	87.9	135	6
JM0091_171025_001317	-89.2	17.7	0.4	358.4	15.6	159.9	12.5	86.9	88.2	88.8	135	24
JM0091_171025_002324	-87.0	25.9	4.2	358.8	7.18	156.4	2.5	87.6	89.6	90.0	135	15
JM0091_171025_003331	-81.2	17.2	1.5	356.4	28.8	161.3	5.6	80.8	91.0	91.3	136	11
JM0111_180208_054729	-80.0	-14.3	1.2	356.9	46.0	152.1	31.1	86.7	84.5	85.3	186	42
JM0111_180208_055735	-84.3	-19.4	0.4	358.8	37.2	151.6	26.8	85.1	85.2	86.0	186	46
JM0111_180208_060741	-85.8	-13.8	1.8	359.3	37.4	155.1	24.2	88.4	86.0	86.7	187	27
JM0111_180208_061717	-89.3	-9.6	1.8	359.7	31.1	156.8	21.1	88.2	86.6	87.4	188	51
JM0111_180208_062723	-88.9	-17.8	0.4	359.8	38.7	158.2	19.9	81.6	87.4	88.1	188	36

Table 1: List of Europa's JIRAM-SPE observations and geometry parameters.

reconstructed SPICE kernels (Acton, 1996). All Europa observations are acquired with the 232 maximum integration time of 1.2 s. Noteworthy, attitude-reconstructed SPICE kernels for the 233 Juno mission do not include spacecraft's nutation and precession effects, resulting in further 234 uncertainty in the retrieval of the instrumental FOV position on Europa's surface. In addition, 235 JIRAM-IMG has collected multiple images covering the entire disk of Europa (see Fig. 2) 236 for an example) at the same time of the SPE acquisitions. Within the JIRAM dataset the 237 minimum and maximum altitude of Juno from Europa ranges between 3.3E5 km and 7.6E6 238 km corresponding to spatial resolution between 80 and 1809 km/pixel, respectively. Due to the 239 characteristics of Juno's trajectory, Europa is always observed by JIRAM with a solar phase 240 angle of approximately  $90^{\circ}$ . 241

<sup>242</sup> The aforementioned limitations in retrieving georeferenced data prevent us from producing

maps with accurate locations of JIRAM-SPE pixels. Thus, our results are discussed in terms 243 of localization across wide sectors of Europa's surface, being only capable of identifying the 244 position of the illuminated pixels at hemispheric scale. The regions of the surface visible from 245 Juno at the time of JIRAM acquisitions are reported in Fig. 1. The observations taken during 246 orbits JM0002-JM0081 contain data collected above the northern hemisphere while the second 247 two (JM0091-JM0111) are mainly taken above the southern regions. During orbit JM0002 248 JIRAM has achieved a good coverage above the northern/antijovian hemisphere despite those 249 data being limited by the worst spatial resolution of the dataset (1781-1809 km/pixel). The 250 northern/jovian hemisphere together with a portion of the trailing hemisphere are both covered 251 during orbit JM0081 with the best spatial resolution of the dataset (80-88 km/pixel). The 252 coverage achieved during orbits JM0091-JM0111 is limited around lon=0° from the equatorial 253 regions to the south pole with spatial resolution of 135-188 km/pixel. 254

The raw signal of each JIRAM acquisition is corrected pixel by pixel for the instrument 255 background and detector's dark current noises measured on a deep sky field with the same 256 integration time of the science data. The onboard software operates automatically the sub-257 traction of the noises before the data are transmitted on-ground (Adriani et al., 2017). With 258 respect to the standard JIRAM calibration pipeline that produces data calibrated in units of 259 spectral radiance, the SPE data are further processed to: 1) remove the non-linear readout 260 noise (high frequency noise between odd and even spectral bands) introduced by the detector's 261 multiplexer (*Filacchione et al.*, 2007); 2) to convert radiance into I/F units. The odd-even 262 effect is removed by applying the following correction on the spectral radiance R measured at 263 band b: 264

$$R_c(b) = \frac{R(b) + \frac{R(b-1) + R(b+1)}{2}}{2} \tag{1}$$

The resulting corrected radiance,  $R_c$ , is used to derive the I/F at wavelength  $\lambda$ :

$$\frac{I}{F}(\lambda) = \frac{4\pi D^2 R_c(\lambda)}{SI(\lambda)} \tag{2}$$



Figure 1: Europa's surface coverage on the JIRAM-SPE dataset shown on a cylindrical map of the satellite. The fraction of the surface containing the positions of JIRAM's slit projections during orbits JM0002 (rendered in blue color), JM0081 (green), JM0091 (orange) and JM0111 (purple) is shown. The base map is derived from Voyager and Galileo images (by Björn Jonsson, available from http://www.mmedia.is/bjj/).

where  $SI(\lambda)$  is the solar irradiance measured at 1 AU (*Kurucz*, 1994) and D is Europa's heliocentric distance (in AU) at the time of the observation.

With the scope to optimize the spectral analysis, we have filtered Europa's spectra by selecting only the ones having  $I/F(2.227 \ \mu m) \ge 0.01$ . This selection allows to remove lowsignal spectra like the ones across limb or terminator where JIRAM pixels are only partially filled. As a result of this filtering, the initial dataset of about one thousand I/F spectra is reduced to 419 spectra shown as a spectrogram in Fig. 2. The spectrogram shows the I/F spectra available for each observation is reported in Table 1. Europa's spectrogram appears highly uniform, showing the intense water ice absorptions at 2  $\mu$ m and at 2.8-2.9  $\mu$ m on each spectrum. At wavelengths longer than 3  $\mu$ m the I/F is in general noisier than at shorter wavelengths due to the intrinsic low reflectance of the surface and worse instrumental sensitivity.



Figure 2: Europa's dataset spectrogram from JIRAM-SPE. Spectral axis is shown along the horizontal axis. The 419 observations listed in Table 1 are stacked along the vertical axis (observation number and Juno's orbits boundaries are shown on the left and right, respectively). The noise visible around 3.80  $\mu$ m on all spectra is a residual caused by the instrumental order sorting filters junction. The I/F spectra shown in the next Fig. 3-central panel correspond to spectra #1-19 visible on the top of the spectrogram.

From the spectrogram is possible to retrieve single I/F spectra as horizontal profiles. As

an example, the median I/F of Europa derived from 19 spectra selected from the first session 279 of the dataset (observation JM0002\_160802\_213108) is shown in Fig. 3-top panel. The single 280 I/F spectra used to compute the median spectrum are reported in the central panel. The 281 instrumental noise affecting JIRAM data is computed by comparing the measured spectral 282 radiance with respect to the noise-equivalent spectral radiance (NESR). The NESR gives the 283 minimum spectral radiance in  $W/(m^2 \ \mu m \ sr)$  corresponding to 1 DN as measured by the 284 instrument at operative temperature conditions. The JIRAM NESR shown in Fig. 3-bottom 285 panel is defined as: 286

$$NESR = \frac{STDEV(D(\lambda) + B(\lambda))}{Resp(\lambda)}$$
(3)

where  $D(\lambda)$  is the dark current,  $B(\lambda)$  is the background signal (equivalent to the sky) and 287  $Resp(\lambda)$  is the instrument responsivity at wavelength ( $\lambda$ ). These quantities are averages com-288 puted along the slit on all spatial samples. The determination of the instrument's responsivity is 289 detailed in Adriani et al. (2017). The instrumental noise shown in Fig. 3 is computed from the 290 ratio between Europa's median radiance and NESR. The noise on the I/F spectra is negligible 291 between 2 and 2.7  $\mu$ m where the Europa's flux is high and the instrument NESR is minimum. 292 On the contrary, the noise progressively increases at longer wavelengths where Europa's flux is 293 low and instrument sensitivity is worse. 294

A direct comparison of JIRAM and Galileo/NIMS data is complicated by the sparseness 295 and spatial resolution of the available datasets. In Fig. 3-top panel we compare a JIRAM obser-296 vation at high latitudes with a similar I/F spectrum by NIMS averaged above the north polar 297 region (Hansen, G., personal communication, 2003). NIMS data are selected from Galileo's 298 orbit G1 and include the north pole and bright limb (around  $lon=330^{\circ}$ ). Differently from 299 JIRAM observations, NIMS data were acquired at lower phase angle ( $\approx 31^{\circ}$ ), with incidence 300 angles varying from  $4^{\circ}$  to  $84^{\circ}$  and with emission angles from  $3^{\circ}$  to  $84^{\circ}$ . While the two spectra 301 are remarkably similar between 2.227 and 2.7  $\mu$ m, the 2  $\mu$ m water ice band appears stronger 302 in JIRAM than on NIMS spectrum. This could be a consequence of the different phase angle 303

between the two datasets (31° for NIMS, 90° for JIRAM) but we cannot exclude intrinsic dif-304 ferences between the composition of the two areas observed by JIRAM and NIMS since they 305 do not match exactly. Both theoretical studies (Hapke, 1993; Ciarniello et al., 2014) and ob-306 servations of icy surfaces (Filacchione et al., 2014, 2016a) have shown how the intensity of the 307 infrared bands depends on phase angle. This is consequence of the fact that the efficiency of the 308 multiple scattering, on which depends the intensity of the continuum level, is driven by phase 309 angle and surface roughness. Conversely, the intensity of the absorption features is driven by 310 the single scattering which is much less sensitive to illumination condition changes. From the 311 theory of phase function described in *Gradie and Veverka* (1986) is known that the band depth 312 decreases at low and at high phases, while it is almost constant across a wide range of phases, 313 typically between 30°-40° and 100°-120° (depending on composition and grain size). In this 314 range of phase angles the single scattering regime dominates throughout the entire absorption 315 band. Conversely, at low phase angles ( $<30^{\circ}-40^{\circ}$ ) the band depth decreases because the mul-316 tiple scattering becomes predominant on the continuum, where albedo is higher but it is less 317 effective at the band center where albedo is low and single scattering continue to prevail (Hapke. 318 1993). At high phase angles  $(>100^{\circ}-120^{\circ})$ , forward/multiple scattering prevails again on the 319 continuum resulting in a significative decrease of the band depth. Due to the higher phase 320 angle, JIRAM observations are therefore much less affected by multiple scattering than NIMS. 321 Similar considerations are valid also to explain the higher I/F observed at longer wavelengths 322 in the NIMS spectrum with respect to JIRAM's. Finally, a spectral shift of about 30 nm is 323 seen between the two spectra: the position of the 2  $\mu$ m band minimum, the peak at 2.227  $\mu$ m 324 and the feature at 2.541  $\mu$ m appear shifted towards shorter wavelengths on NIMS spectrum. 325 This shift is probably caused or by the low spectral sampling mode used in this specific NIMS 326 observation or by a different nonice fraction between the two datasets. 327

Since single spectra are frequently marred by spikes caused by the harsh radiation environment and by the low SNR long wards 2.7  $\mu$ m (see Fig. 3-central panel), we compute median I/F spectra grouping all single spectra taken during the four orbits JM0002, JM0081, JM0091,
JM0111 (Fig. 4). Taking advantage of the wide excursion in latitude covered by the JIRAM
dataset (Fig. 1 and Table 1) during these orbits, different areas of Europa's surface can be
compared among them by means of the following spectral characteristics:

- 1. the shape of the 2  $\mu$ m water ice band around its minimum is broader on northern hemisphere (orbits JM0002 and JM0081) than of the southern hemisphere observations (orbits JM0081 and JM0111);
- 2. the intensity of the continuum level at 2.541  $\mu$ m decreases moving from northern to southern hemisphere data. Also the sharpness of the inflection around 2.541  $\mu$ m follows a similar trend;

340 3. the intensity of the 3.1  $\mu$ m peak is fainter on the northern hemisphere data while becomes 341 more intense on the southern hemisphere spectra;

- 4. conversely, the broad continuum peak at 3.5-3.6  $\mu$ m is stronger than the 3.1  $\mu$ m feature on spectra taken during orbits JM0002, JM0081 and JM0091 while it is less intense on JM0111 data;
- 5. JM0002 median I/F spectrum shows a faint absorption band centered at 3.5  $\mu$ m compatible with a similar feature first detected by Galileo/NIMS (*Carlson et al.*, 1999a) and assigned to hydrogen peroxide ( $H_2O_2$ ). However, this feature is not recognizable in the rest of the JIRAM dataset suggesting or a  $H_2O_2$  distribution preferentially localized within the area observed during JM0002 (northern/antijovian hemisphere) or a spurious detection.

<sup>351</sup> The implications of these spectral characteristics is discussed next.

# **5.** Spectral Indicators

Starting from the characteristics and variability of the JIRAM spectral dataset we have discussed in the previous section, a set of six spectral indicators is employed to describe the <sup>355</sup> physical state and composition of Europa's surface. These indicators are the same previously
<sup>356</sup> used and validated for the analysis of Saturn's ice satellites and rings data acquired by VIMS on
<sup>357</sup> Cassini (*Filacchione et al.*, 2007, 2010, 2012, 2016a) and are applicable, with some precautions,
<sup>358</sup> also for Europa, water ice being one of the principal spectral endmembers:

1. 2  $\mu$ m band center wavelength,  $\lambda_{BC}(2 \ \mu$ m), is used as a proxy of the water ice amorphous/crystalline state and of the non-ice material composition;

<sup>361</sup> 2. 2  $\mu$ m band depth, BD(2  $\mu$ m), is a proxy of water ice and non-ice material abundance, <sup>362</sup> and regolith grain size distribution.

363 3. Ratio I/F(2.541  $\mu$ m) / I/F(2.020  $\mu$ m) is a proxy of the abundance of the non ice material;

4. Ratio I/F(3.100  $\mu$ m) / I/F(2.847  $\mu$ m) is another proxy of the surficial water ice amorphous/crystalline state;

5. Ratio I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) is a proxy of water ice grain size;

6. Wavelength of the I/F peak around 3.6  $\mu$ m,  $\lambda$ (3.6  $\mu$ m), is a proxy of water ice temperature.

The wavelengths used to define these indicators are marked in Fig. 3. Unfortunately, because the JIRAM spectral range starts from 2.0  $\mu$ m, it is not possible to resolve the short-wavelength wing of the water ice band but only its minimum. As a consequence, we derive the  $\lambda_{BC}(2 \ \mu\text{m})$ by fitting JIRAM data in the 2.0-2.2  $\mu$ m with a 3<sup>rd</sup>-degree fit. The  $I/F_{min}$  corresponding to the  $\lambda_{BC}(2 \ \mu\text{m})$  is then used to compute the BD(2  $\mu$ m) as

$$BD(2\ \mu m) = 1 - \frac{I/F_{min}}{I/F(2.227\ \mu m)} \tag{4}$$

We remark that the spectral indicators we are using are calibrated with respect to pure water ice grains. In presence of nonice materials mixed with water ice, both the absorption bands and continuum properties will change. For this reason in the following we are using the spectral indicators as "proxy" of water ice grain properties, water ice being the dominant endmember of Europa's surface and where water ice does not dominate, these proxies should be taken with caution. We are using a similar approach because JIRAM spectral range is limited in the 2-5  $\mu$ m where is not possible to unambiguously retrieve nonice material composition. To achieve this it is necessary to explore Europa's surface with a more wide spectral range, including visible and near infrared wavelengths where diagnostic features are located, and with a much higher spatial resolution to better resolve nonice material endmembers. In the next sections a discussion of the results obtained from the analysis of the spectral indicators derived from each spectrum of the dataset is given.

### 385 6. Composition

The possibility of inferring Europa's surface composition is limited by JIRAM's 2-5  $\mu$ m 386 spectral range, which has been optimized to study Jupiter's atmosphere (Adriani et al., 2018) 387 and auroral emissions (Mura et al., 2018). The lack of the VIS-NIR range makes JIRAM much 388 less diagnostic of a comprehensive characterization of ice surface composition. Within these 389 limits, JIRAM data are however valuable because they offer spatial coverage above both polar 390 regions, albeit at coarse spatial resolution, which were largely unexplored by previous missions 391 and are unaccessible from Earth-based observations. The JIRAM median I/F spectra (Fig. 3-392 4) are dominated by the presence of the intense 2.0 and 3.0  $\mu$ m water ice bands. The water ice 393 Fresnel's peak at 3.1  $\mu$ m appears to be low-contrast across the entire dataset. JIRAM spectra 394 show similarities with synthetic spectra of water ice simulated by means of Hapke (1993) theory 395 following the method described in *Raponi et al.* (2016). The spectral simulations are performed 396 using crystalline water ice optical constants measured at 130 K (Mastrapa et al., 2008, 2009) 397 assuming a phase function p(g)=0.5 (*Clark et al.*, 2012) and a phase angle  $g=90^{\circ}$  in order to 398 match JIRAM observational conditions. The resulting reflectance spectra for nine grain sizes 399 between 10  $\mu$ m and 1 cm are shown in Fig. 5-left panel. Laboratory reflectance spectra of three 400 frozen eutectic chlorine salts (MgCl<sub>2</sub>, NaCl, KCl) measured at T=-30°C (Hanley et al., 2014) 401 are reported for comparison in Fig. 5-right panel. Shirley et al. (2010) have retrieved the surface 402 composition of different units finding that ridged plains are compatible with ternary mixtures 403

<sup>404</sup> of water ice (46%), hydrated sulfuric acid (27%) and hydrated salts (27%) while smooth low <sup>405</sup> albedo plains are made of hydrated salts (62%), hydrated sulfuric acid (27%) and water ice <sup>406</sup> (10%).

Apart from the variability caused by the grain size, that we will discuss in the next section, 407 pure water ice is not able to fully reproduce Europa's data: this is particularly evident when 408 comparing the intensity of the reflectance in the 2  $\mu$ m band absorption with the inflection of the 409 continuum at 2.5  $\mu$ m. Other than large cm-sized grains, the ratio I/F(2.541  $\mu$ m) / I/F(2.020 410  $\mu$ m) is always positive and much larger than 1 on water ice synthetic spectra (Fig. 5-left panel). 411 This is the typical case observed in Saturn's ice satellites and rings spectra (*Filacchione et al.*, 412 2012) where water ice is the dominant endmember. Conversely, in Europa spectra this ratio is 413 systematically lower and distributed with an average value of about 1 in the JIRAM dataset 414 (Fig. 6). To reproduce a similar behavior it is necessary to introduce additional endmembers, 415 such as chlorinated salts, hydrated sulfates, sulfate brines, and hydrated sulfuric acid, which 416 are able to reduce the reflectance at 2.5  $\mu$ m to the same value of the 2  $\mu$ m band (Fig. 5-right 417 panel). 418

<sup>419</sup> Moving from orbit JM0002 to JM0111 a decreasing trend is observed in the ratio series: <sup>420</sup> observations acquired in the northern hemisphere and equatorial areas during orbits JM0002 <sup>421</sup> (blue points) and JM0081 (green) are those with the larger ratio value ( $\approx$ 1.15 to 1.25), indi-<sup>422</sup> cating a lower abundance of contaminant. The maximum amount of contaminant is measured <sup>423</sup> across the southern hemisphere and equatorial region observed during orbits JM0091 (orange) <sup>424</sup> and #11 (magenta sector) where the average ratio is  $\approx$ 1.

# 425 7. Grain size

The dimension of pure water ice regolith grains can be derived from the measurement of the I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) ratio and from the BD(2  $\mu$ m). The values of these spectral indicators as a function of the grain size is calibrated starting from the synthetic water ice

Grain size	$\frac{I/F(3.630 \ \mu m)}{I/F(2.227 \ \mu m)}$	$BD(2 \ \mu m)$
$10 \ \mu m$	0.31	0.50
$30 \ \mu m$	0.15	0.69
$50 \ \mu { m m}$	0.10	0.77
$80 \ \mu m$	0.07	0.84
$100 \ \mu m$	0.05	0.86
$200~\mu{\rm m}$	0.03	0.93
0.2 cm	0.15	0.90
0.5 cm	0.54	0.64

Table 2: Reference values of I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) ratio and BD(2  $\mu$ m) as function of grain size for water ice. Values are derived from synthetic spectra computed at phase 90° and temperature T=130 K shown in Fig. 5-left panel.

<sup>429</sup> spectra shown in Fig. 5-left panel and tabulated in Table 2.

As shown in Fig. 7-top panel, the I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) ratio is almost constant across the entire JIRAM dataset and is dispersed with a median value of 0.079 which, according to Table 2, is compatible with grain sizes of 50-80  $\mu$ m and  $\approx$ 0.5 cm. The BD(2  $\mu$ m) distribution (Fig. 7-bottom panel) shows a small decrease moving from northern to southern latitudes, which could indicate a prevalence of smaller grains on the latter. The dataset has a median value of 0.60 which is compatible with small 10-30  $\mu$ m or large 0.5 cm grain sizes.

The I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) ratio and BD(2  $\mu$ m) values we have measured on the JIRAM dataset are compatible with both tens of microns and fraction of centimeter grains sizes. A similar degeneracy is due to the trend characterizing the two indicators as a function of the grain size (Fig. 8-left panel). Theoretical points are in fact aligned along two parallel branches converging on the inversion point placed at BD(2  $\mu$ m)=0.93 that corresponds to 200  $\mu$ m grain size. Two almost parallel branches describe the small (tens to hundred of microns) and large (fraction of centimeter) grains at lower band depths: the former are placed along lower I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) ratio values, the latter at higher values. The majority of JIRAM data (Fig. 8-right panel) are distributed along the lower branch pointing to small (<200  $\mu$ m) grain sizes, but a fraction of them is along the upper branch, which implies compatibility with large (>200  $\mu$ m) grain sizes.

Thanks to the availability of two spectral indicators which rely on the properties of the scattering of the continuum (the I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) ratio) and on the strength of the absorption (the 2  $\mu$ m band depth), we can conclude that the size distribution on the surface of Europa is dominated by grains tens to hundreds of microns in size with a possible smaller fraction of millimeters size grains.

We need to interpret these results with caution: on the one hand the presence of non ice 452 materials can significantly change the values of the spectral indicators which in our analysis are 453 based on pure water ice composition. The fact that both indicators converge on similar grain 454 size values is a significant result, showing that the nonice material is not influencing too much 455 the water ice reflectance at these wavelengths. On the contrary, the presence of millimeter-456 sized grains, while compatible with the spectral indicators, appears to be inconsistent with 457 the properties of the synthetic spectra shown in Fig. 5 which are characterized by an intense 458 saturation of the 2  $\mu$ m band and by low levels of continuum. Similar properties are not seen 459 in the average spectra of Europa. 460

### <sup>461</sup> 8. Water ice amorphization

The environmental conditions necessary to maintain water ice in both crystalline and amorphous states exist on the surface of Europa: the amorphous phase is produced from radiolysis of crystalline ice by high energy electrons and ions from Jupiter's magnetosphere (*Carlson et al.*, 2009) and from condensation of sublimated and sputtered molecules (*Baragiola*, 2003). As reported in *Nordheim et al.* (2018), the areas of the surface more altered by radiation are those located within the two equatorial "lenses" centered on the apex of the leading and trailing hemi-

spheres and extending in latitude up to about  $\pm 40^{\circ}$ . According to these simulations, along the 468 jovian meridian the two radiation lenses have the lower extension in latitude, about  $\pm 15^{\circ}$  from 469 equator. This is the region mainly observed by JIRAM, especially during orbits JM0091 and 470 JM0111. We would expect, therefore, a prevalence of the amorphous phase in the equatorial 471 regions rather than on the polar areas where the crystalline form would be more abundant. In 472 the infrared range sensed by JIRAM, the two water ice forms can be recognized by measuring 473 the position of the 2  $\mu$ m band center and the relative intensity of the 3.1  $\mu$ m Fresnel peak. 474 As laboratory measurements by Leto et al. (2005) and Mastrapa et al. (2008) have shown, the 475 center of the 2.0  $\mu$ m absorption band is strongly influenced by the amorphous and crystalline 476 phases. While for crystalline ice the center of the  $\lambda_{BC}(2 \ \mu m)$  is temperature-dependent, shift-477 ing from 2.02  $\mu$ m at T=20 K to 2.05  $\mu$ m at T=155K (Grundy and Schmitt, 1998), for the 478 amorphous phase  $\lambda_{BC}(2 \ \mu m) = 2.00 \ \mu m$  independent of temperature. Within the limit of the 479 JIRAM spectral range, we compute the  $\lambda_{BC}(2 \ \mu m)$  by fitting JIRAM data in the 2.0-2.2  $\mu m$ 480 range with a 3<sup>rd</sup>-degree fit. The resulting distribution of the  $\lambda_{BC}(2 \ \mu m)$  indicator is shown 481 in Fig. 9-top panel. The distribution of the measurements has a median value of 2.05  $\mu$ m on 482 JM0002 data and 2.04  $\mu$ m on JM0081, JM0091 and JM0111 orbits datasets. For pure water ice 483 composition this corresponds to a prevalence of the crystalline form in the northern/antijovian 484 hemisphere (JM002) and a larger presence of amorphous form in the northern/jovian (JM0081) 485 and in the southern/jovian hemisphere regions (JM0091 and JM0111 orbits) in agreement with 486 the analysis of telescopic spectral data performed by *Liqier et al.* (2016). These results partially 487 match with the presence of amorphous water ice across the equatorial region as predicted by 488 magnetospheric models: the majority of observations with the shortest  $\lambda_{BC}(2 \ \mu m)$  occur in 489 orbit JM0111, where JIRAM has observed the south-equator region along the jovian merid-490 ian. As discussed in section 2, at 2  $\mu$ m photons can penetrate the ice down to about 10 cm 491 and for this reason the  $\lambda_{BC}(2 \ \mu m)$  is sensitive to the ice form within this depth. In order to 492 better evaluate the amorphization of the surface it is possible to use the ratio  $I/F(3.100 \ \mu m)$ 493

/ I/F(2.847  $\mu$ m) as a further proxy. At 3.1  $\mu$ m the water ice acts like a reflector and the 494 photons are probing a very shallow (submicron) layer of the surface. The ratio measures the 495 intensity of the 3.1  $\mu$ m Fresnel's peak with respect to the maximum absorption at 2.847  $\mu$ m. 496 As laboratory studies have demonstrated, the intensity of the Fresnel's peak is much higher on 497 crystalline water ice than on amorphous ice (Mastrapa et al., 2009). A qualitative analysis of 498 the JIRAM data distribution, shown in Fig. 9-bottom panel, evidences that the ratio increases 499 from a median value of 3.8 in JM0002 orbit data to 4.5 in JM0081, to 5.6 in JM0091, to 7.1 in 500 JM0111. The maximum amorphization on the surface, as indicated by the lower ratio values, 501 is therefore observed on the northern hemisphere. 502

# 503 9. Temperature

The last spectral indicator we have measured is the wavelength of the I/F peak around 504 3.6  $\mu$ m,  $\lambda$ (3.6  $\mu$ m), which in pure water ice depends on the temperature of the sample. This 505 technique has been used to retrieve diurnal temperatures of Saturn's ice satellites (Filacchione 506 et al., 2016a) and rings (Filacchione et al., 2014). When water ice cools down the minimum 507 of the imaginary index k at about 3.6  $\mu$ m shifts towards shorter wavelengths (Mastrapa et al., 508 2009). Laboratory measurements on small water ice grains observed under standard illumi-509 nation conditions (phase  $30^{\circ}$ ) by Clark et al. (2012) have shown that the 3.6  $\mu$ m reflectance 510 peak shifts in wavelength from 3.675  $\mu$ m for a sample temperature of T=172 K to 3.58  $\mu$ m at 511 T=88 K. This corresponds to a spectral shift of about 90 nm (10 JIRAM spectral bands) in the 512 3.6  $\mu$ m continuum peak feature. At intermediate temperatures, T=123 K and T=131 K, the 513 peak's wavelength is placed at 3.62  $\mu$ m and 3.65  $\mu$ m, respectively. We compute the  $\lambda(3.6 \ \mu m)$ 514 as the wavelength of the maximum I/F fitted by means of a  $2^{nd}$ -degree fit in the 3.3-4.0  $\mu$ m 515 spectral range. The bands corresponding to the position of the instrumental order sorting filter 516 at about 3.8  $\mu$ m have been filtered out. Despite the low signal to noise ratio in this spectral 517 range, which causes a large dispersion in the fitted data, JIRAM data are dispersed around a 518

median value of 3.573  $\mu$ m which corresponds to diurnal temperature of 88 K. This is the average 519 temperature retrieved from observations taken along terminator ( $\approx 90^{\circ}$  phase angle, see Table 520 1). Averaging the observations during the four single orbits (Fig. 4), this method gives peak 521 positions of 3.620  $\mu m$  or  $\approx 124$  K on JM0002 (northern/antijovian hemisphere), 3.586  $\mu m$  or 522  $\approx 89$  K on JM0081 (northern/jovian hemisphere), 3.643  $\mu$ m or  $\approx 132$  K on JM0091 and 3.537 523  $\mu m$  or <<88 K on JM0111 (both on southern/jovian hemisphere). This variability is probably 524 the result of the different spatial resolution of JIRAM observations along the four orbits (see 525 Fig. 1). Noteworthy, the range of temperature retrieved by JIRAM (<<88 K to 132 K) is in 526 good agreement with previous results by Spencer et al. (1999). Finally, since this method is 527 valid for reflectance data it can be used only to retrieve diurnal temperatures. 528

# 529 10. Conclusions

Spectral indicators applied to JIRAM data have permitted inference of information about 530 composition, regolith grain size, water ice form and temperature across broad swaths of Europa's 531 surface. The surface composition appears dominated by water ice contaminated by the presence 532 of non-ice endmembers, like hydrated salts and acid-rich compounds, necessary to equalize the 533 ratio of the I/F within the 2  $\mu$ m band to the 2.5  $\mu$ m continuum. Purer water ice is observed 534 by JIRAM on the northern hemisphere than on the southern along the jovian meridian. Water 535 ice appears in both crystalline and amorphous forms: a prevalence of the first is obtained from 536 the 2  $\mu$ m band center wavelength on the northern hemisphere while the latter prevails when 537 analyzing the properties of the 3.1  $\mu$ m Fresnel peak. This result further evidences the different 538 skin depth at which radiation is efficient in water ice amorphization. The surface regolith grain 539 size distribution encompasses tens to hundred of microns sizes with a possible tail towards 540 larger grains suggesting possible water ice grain mobilization, aggregation and sintering. These 541 processes cannot be excluded since the diurnal maximum temperature, derived from the 3.6 542  $\mu m$  continuum properties, is 132 K and it is high enough to activate them. 543

Our analyses are performed through spectral indicators calibrated on water ice composition 544 and do not take into account the presence of nonice materials. To better constrain the nature 545 of these contaminants and disentangle their influence on water ice grain properties is necessary 546 to measure the spectral reflectance at wavelengths shorter than 2  $\mu$ m, a range precluded to 547 JIRAM, where diagnostic spectral features of nonice materials are located. Before the end of 548 the Juno mission other possibilities to observe the surface of Europa will occur. The JIRAM 549 team will exploit them to continue to acquire infrared spectra and images of the surface nec-550 essary to enlarge the dataset and improve the spatial coverage and resolution. These infrared 551 observations will be the last acquired by a spacecraft before the future ESA's Juice and NASA's 552 EuropaClipper missions currently scheduled after year 2030. 553

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Figure 3: Europa's observation JM0002\_160802\_213108 on the northern/antijovian hemisphere. Top panel: the plot shows the median I/F spectrum measured by the JIRAM-SPE channel on the dayside fraction of the disk (black curve). The shadowed region shows the instrumental noise. Wavelengths used to derive spectral indicators are labeled and discussed in the text. An observation of Galileo/NIMS acquired on the Europa's north polar region is shown for comparison (red curve). Both JIRAM and NIMS spectra are normalized at 2.227  $\mu$ m. The inset panels contain polar projections of concurrent images acquired by the IMG channel in L (3.455  $\mu$ m, left panel) and M (4.780  $\mu$ m, right panel) bands (*Tosi et al.*, 2018). Centre panel: the 19 individual JIRAM spectra used to compute the average in top panel are compared to NIMS. Bottom panel: JIRAM noise-equivalent spectral radiance (NESR) used to compute the instrumental noise.



Figure 4: Europa's median I/F spectra collected during orbits JM0002, JM0081, JM0091, JM0111 compared with NIMS.



Figure 5: Left: synthetic spectra of water ice grains with sizes between 10  $\mu$ m to 1 cm. Right: laboratory reflectance spectra of frozen eutectic chlorine salts MgCl<sub>2</sub>, NaCl, KCl at T=-30°C (from *Hanley et al.* (2014)).



Figure 6: Distribution of the I/F(2.541  $\mu$ m) / I/F(2.020  $\mu$ m) ratio on the dataset. A ratio similar to 1 is an indicator of the presence of non ice material, like hydrated salts, while larger values correspond to more pure water ice composition. Blue, yellow, green and magenta data points correspond to ratio values measured during orbits JM0002, JM0081, JM0091, JM0111, respectively.



Figure 7: Top panel: distribution of the I/F( $3.630 \ \mu m$ ) / I/F( $2.227 \ \mu m$ ) ratio in the dataset. Bottom panel: distribution of the BD( $2 \ \mu m$ ). Reference grain size values **4** bm Table 2 are shown. Blue, yellow, green and magenta data points correspond to ratio values taken during orbits JM0002, JM0081, JM0091, JM0111, respectively.



Figure 8: Left panel: trend of the BD(2  $\mu$ m) and I/F(3.630  $\mu$ m) / I/F(2.227  $\mu$ m) as a function of water ice grain size. Right panel: distribution of JIRAM observations.



Figure 9: Top panel: distribution of the  $\lambda_{BC}(2 \ \mu m)$  in the dataset. Reference wavelengths for amorphous and crystalline phases are shown. Bottom panel: distribution of the ratio I/F(3.1  $\mu m$ ) / I/F(2.847  $\mu m$ ). High ratio values are indicative of crystalline ice, low ratio values for amorphous ice. Blue, yellow, green and magenta data points correspond to values measured during orbits JM0002, JM0081, JM0091, JM0111, respectively.