

A Possible Dust Origin for an Unusual Feature in Io's Sodium Neutral Clouds

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15	ABSTRACT					
16	We report the results of model simulations performed to explain the nature of a sodium emission					
17	feature in Io Neutral Clouds. The feature was detected via high-resolution spectroscopic observations					
18	from the 3.6-meter Italian telescope TNG. The emission feature is blueshifted compared to the main					
19	emission (the banana-shaped Neutral Cloud of Io) by a few tens of km s ⁻¹ , and it is most prominent					
20	when Io is a few tens of degrees before eclipse behind Jupiter's shadow. The feature's morphology					
21	changes with time, indicative of a geometrical effect. We constrained its direction, velocity, and column					
22	density with a model of sodium atom trajectories under the influence of Io's and Jupiter's gravity and					
23	solar radiation pressure. The model that best explains this emission feature has the atoms injected into					
24	the exosphere from the leading/sub-Jovian hemisphere of Io (45-68° West longitude), with velocities					
25	from 50 to 90 km s ⁻¹ relative to Io. These trajectories are consistent with those of negatively charged					
26	dust grains (radius ~ 10 nm) accelerated by the co-rotational electric field of Jupiter's magnetosphere.					
27	We propose that sputtering of sodium atoms from Na-bearing molecules (NaCl and Na_2SO_4) in these					
28	nanodust grains is the process responsible for our emission feature. Both modeling and observational					
29	constraints provide an order-of-magnitude estimate of the sodium production rate of $\sim 10^{26}$ s ⁻¹ . Our					
30	work provides another method to monitor the amount of material that Io is supplying to its Neutral					
31	Clouds and plasma torus.					

A possible dust origin for an unusual feature in Io's sodium neutral clouds

Keywords: (not needed now) 32

1. INTRODUCTION 33

Io's Neutral Clouds are one of the brightest visible 34 manifestations of the intense volcanic and magneto-35 spheric activity in the Jovian system. All the material 36 that fills the Io Plasma Torus and Io's Neutral Clouds 37 ultimately comes from the intense volcanic activity of 38

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³⁹ Io. Since the discovery of sodium at Io (Brown 1974), and its Neutral Cloud (Trafton et al. 1974), this mi-40 nor but bright species has been used to monitor the re-41 ⁴² sponse of Io's Neutral Cloud to the changes of its drivers 43 (Io volcanic activity and Jupiter magnetosphere). The resonant scattering efficiency (the so-called g-value) of 44 ⁴⁵ sodium is orders of magnitude greater than the domi-⁴⁶ nant species in Io's Neutral Clouds (S and O and their molecular compounds). Moreover, the wavelength of the 47 sodium doublet (the D2 line at D1 line around 5900 Å) 48 ⁴⁹ is such that it can be easily detected from the ground.

Over the past decades, observations and models have 50 identified structures in the Neutral Clouds, each related 51 to a particular source process and interaction with the 52 Jovian magnetosphere. The most prominent of these 53 structures, and the first to be discovered, is the corona, 54 sometimes referred to as the "banana cloud" (the "Re-55 gion B" in Brown et al. 1975), composed of slowly 56 escaping sodium atoms (a few km s⁻¹ relative to Io). 57 Its peculiar morphology, with the leading part more ex-58 tended (about 60° along the orbit) than the trailing part 59 $(30^{\circ} \text{ along the orbit})$, is controlled by celestial mechan-60 ics and by ionization from the plasma torus, which is 61 warmer outwards from Io's orbit compared to inwards 62 (Nash et al. 1986). Another feature of the sodium Neu-63 tral Clouds is the "jet" (or directional feature; Goldberg 64 et al. 1984), much more variable than the banana cloud, 65 and composed of much more energetic atoms. The "jet" 66 extends from Io in the anti-Jupiter direction, oriented 67 approximately perpendicularly to the local Jovian mag-68 netic field (Wilson & Schneider 1994). It is probably 69 caused by prompt pickup ion neutralization very close 70 to Io, its narrowness indicating an unperturbed Jovian 71 magnetic field at Io (Wilson & Schneider 1999). The 72 outer acceleration results from the corotational electric 73 field applied to positively charged ions. Finally, a more 74 diffuse feature is the "stream" (Schneider et al. 1991) of 75 fast moving neutral sodium atoms resulting from disso-76 ciative recombination of fast molecular sodium-bearing 77 ions (most likely NaCl⁺) corotating with Jupiter at \sim 78 70 km s⁻¹. These atoms can be found all around Io's 79 orbit. Over many orbits around Jupiter, this stream 80 creates the vast, faint neutral sodium cloud detected 81 hundreds of Jupiter radii from Jupiter (Mendillo et al. 82 1990). All these features contribute to the roughly 1 ton 83 of plasma that is injected in the Io Plasma Torus every 84 second (Schneider & Bagenal 2007). Their morphol-85 ogy depends on several factors, including Io's position 86 (both orbital longitude and magnetic latitude) Jupiter's 87 magnetic field, and Io's volcanic activity (see review by 88 Bagenal & Dols 2020). For example, it has long been 89 debated whether the sodium Neutral Clouds decrease 90 in extent during eclipses behind Jupiter, due to con-91 densation of Io's atmosphere and/or to a suppression of 92 solar photons available for photodissociation of sodium-93 bearing molecular compounds. It was to test these pos-94 sibilities that we performed ground-based observations 95 of Io before and after eclipses, in 2007. We discovered 96 that solar flux is an important factor in supplying the 97 sodium atoms to the Neutral Clouds, and that suppres-98 sion of photo-dissociation of sodium-bearing molecules ٩q (most likely NaCl) during eclipse drives a decrease in ex-100 ospheric Na atoms soon after egress (Grava et al. 2014). 101



Figure 1. Two-dimensional spectra of Io with the continuum subtracted, stacked over a scheme of the observational geometry. The spectra progress in time from right to left, and wavelength run from bottom to top. The width of the spectra, corresponding to the length of the slit, is 27 arcsec. $R_J = Jupiter radius \sim 70,000$ km. In the spectra, Jupiter direction is to the left of Io's subtracted continuum.

During those observing runs, we also discovered an 102 additional spectroscopic feature: an emission of sodium 103 (visible at both D-lines) blueshifted (i.e., directed to-104 wards the observer and thus towards Jupiter) by tens 105 of km s⁻¹ relative to Io, hence moving much faster than 106 the escape speed at Io (see Figure 1). We first reported 108 this feature in Schneider et al. (2008) and performed 109 additional observations at the same telescope in 2009. 110 This paper describes the analysis of this feature using 111 simulations of sodium atoms in Io's Neutral Clouds and 112 suggests possible explanations. 113

2. OBSERVATIONS AND DATA REDUCTION

Spectra were collected by the now-decommissioned 115 high-resolution échelle spectrograph SARG mounted 116 at the 3.6-meter Italian telescope TNG (Telescopio 117 Nazionale Galileo) during several nights spanning 2 118 vears, and different geometric configurations of Io. Spec-119 tra taken in 2007 were analyzed by Grava et al. (2014)120 and included in this work for completeness, while spectra 121 taken in 2009 are analyzed here for the first time. The 122 spectrograph's slit was 26.7-arcsec long and 0.4-arcsec 123 wide, had a spectral resolution of $\lambda/\Delta\lambda \sim 115,000$, and 124 was placed almost always parallel to Jupiter's rotational 125 equator and centered on Io (or on other Galilean satel-126 lites, when used for calibration). The exposure time was almost always 600 s. The 2007 spectra were ob-128

tained with an interference filter which blocked all pho-129 tons but those with wavelengths close to the sodium 130 doublet. This procedure allowed to use the full extent 131 of the long slit without order overlapping. The 2009 132 spectra were obtained without such interference filter, 133 to collect light from the entire bandpass of SARG (3700-134 10,000 Å) and to study therefore other species. As such, 135 only the central ~ 50 pixels were used, and the remain-136 ing ~ 30 pixels at the edges were excluded due to order 137 contamination. The effective length of the slit in this 138 case was 17.7 arcsec. 139

Data reduction of the spectra was described in depth 140 in Grava et al. (2014) and is summarized here. Stan-141 dard data reduction steps such as subtraction of bias, 142 flatfielding, and wavelength calibration (using a Th-Ar 143 lamp) were performed using IRAF routines. Specific 144 data reduction steps pertinent to our dataset were per-145 formed later and included: 1) removal of an interference 146 pattern caused by the sodium filter (for 2007 observa-147 tions only); 2) removal of a "pedestal" (residual back-148 ground); 3) removal of a "ghost" of Jupiter's spectrum 149 on top of Io spectra; 4) removal of telluric absorption, 150 performed using rapidly rotating O- and B-type stars 151 devoid of absorption lines observed at several airmasses 152 that bracketed ours; 5) subtraction of the "continuum", 153 i.e. the solar light reflected off Io's disk using spectra of 154 other Galilean satellites (Europa, Ganymede, and, more 155 rarely, Callisto) properly shifted to account for the dif-156 ferent Doppler speeds; 6) conversion of sodium bright-157 ness from counts s⁻¹ to Rayleighs (1 R = $10^6/4\pi$ photons 158 $cm^{-2} s^{-1} sr^{-1}$; Hunten et al. (1956)) using Jupiter spec-159 tra and the well-measured intrinsic brightness of Jupiter 160 at the sodium wavelength (5.5 MR Å⁻¹; Brown & Schnei-161 der 1981). During most of the nights the seeing was 162 good, never exceeding 1.6 arcsec as FWHM (calculated 163 as a deconvolution of a Gaussian fit to Io's continuum 164 165 and the theoretical diameter of Io's disk, 1.2 arcsec). Details of observations are summarized in Table 1. 160

168 3. THE BLUESHIFTED EMISSION FEATURE

Figure 2 shows a typical spectrum of Io. On the left 169 is the average of Io's brightness over detector columns 171 31-33, corresponding to a distance of 1.7-2.9 R_{Io} east-172 wards on the sky plane (towards Jupiter, in this case) 173 of Io's center (1 $R_{Io} \sim 1820$ km) and, in dashed line, 174 the g-values. The g-value (or g-factor) is the number of 175 solar photons resonantly scattered each second by each 176 sodium atom. In optically thin exospheres, like Io's neu-177 tral clouds, the brightness I (in Rayleighs) is directly 178 related to the line-of-sight column density N (in atoms 179 cm^{-2}) by the g-value g (Brown & Yung 1976): 180

$$I = g \cdot N \tag{1}$$

The g-value (expressed in photons atoms⁻¹ s⁻¹) is related 181 to the solar spectrum, and depends, among other things, 182 183 on the heliocentric radial velocity Δv of sodium atoms, owing to the deep Fraunhofer absorption in the solar 184 spectrum Hunten et al. (1988). We used g-values for 185 sodium from Killen et al. (2009). Δv is measured in 186 our spectra by the Doppler shift $\Delta \lambda$ of Io relative to the 187 reference wavelengths λ of the sodium D-lines (5889.95) 188 and 5895.92 Å for the D2 and D1 line, respectively): 189

$$\Delta v = c \cdot \frac{\Delta \lambda}{\lambda} \tag{2}$$

where c is the speed of light. The resulting Δv is referred 190 to Io's reference frame, which is in itself moving relative 191 to the Sun. An atom at rest at Io moving away from the 192 Sun (like at Western elongations) will "see" a redshifted 193 solar spectrum. Therefore, to properly convert bright-194 ness into column densities it is necessary to blueshift the 195 g-values, i.e. shifting them towards negative velocities. 196 This is shown in Figure 2, panel a, which shows that 197 the "dip" in the emission line (in Rayleighs) at -5 km 198 s⁻¹ is caused by the "dip" of the Fraunhofer line of the 199 g-value at -2.5 km s⁻¹. The resulting division gives the 200 column density without such "dip" (panel b), but with 201 a "bump" on the blue side of the peak (negative veloci-202 203 ties). This is the new emission feature. It is reminiscent of the "skirt" detected first by Trafton (1975) and then 204 by Cremonese et al. (1992) and interpreted by Trafton & 205 Macy (1977, 1978) to be due to sodium atoms streaming 206 away from Io at moderate speeds (18 km s⁻¹ at most) 207 in the leading direction. However, it is different from 208 that because the "bump" lies on the opposite side. Our 209 "bump" is more prominent on the short wavelength side 210 when Io is west of Jupiter. Moreover, as we shall see 211 briefly, the feature changes Doppler shift through the 212 night. Note that in our observations the West direction 213 corresponds to the orbital trailing side of Io. In terms 214 of plasma flow, the trailing side corresponds to the is 215 upstream side, and East is the leading (or downstream) 216 side. 217

We performed the conversion from brightness to col-218 umn density for all of our 2D spectra. An example of 219 the resulting 2D spectra, together with the geometry of 220 the observation, is shown in Figure 3 (the others can be 221 found in the supplemental material). In this figure, Io 223 is about to enter Jupiter's shadow and the main emis-224 sion feature (the "banana cloud"), being approximately 225 at rest relative to Io (white horizontal dashed lines), 226 dominates the spectra. The faint, straight emission line 227 traversing the whole slit length is Earth's sodium layer 228 at 90 km altitude resonantly scattering solar photons 229 shortly before dawn. The streak of diffuse emission very 230 close to Io on the Eastern side (negative R_{Io}) extending 231

Table 1. List of observations. $t = exposure time. ssl = subsolar longitude, counted Westward (or counterclockwise) on Io. It is also equivalent to Io's orbital longitude, with 0° corresponding to superior conjunction (Io opposite to Earth behind Jupiter) and 90° corresponding to Eastern elongation. <math>\lambda_{III}$ and Mlat are Io's system III longitude and magnetic latitude, respectively. p.a. = position angle, or the slit's angle relative to Jupiter's rotation axis, counted counterclockwise starting from Jupiter's north pole.

filename	obs. mid-time (UT)	t (s)	ssl ($^{\circ}$)	λ_{III} (°)	Mlat ($^{\circ}$)	p.a. (°)
JDEI0102	2007-04-25T02:01:33	600	316	29	-10	66
JDEI0106	2007-04-25T03:07:52	600	326	59	-8	66
JDEI0109	2007-04-25T03:39:07	600	330	74	-6	66
JDEI0112	2007-04-25T04:14:26	600	335	90	-4	66
JDEI0114	2007-04-25T04:50:26	600	340	107	-1	66
JDEI0115	2007-04-25T05:02:42	600	342	112	0	66
JDEI0119	2007-04-25T05:41:37	600	347	130	3	90
JDEI0120	2007-04-25T05:53:17	600	349	136	4	90
JDEI0121	2007-04-25T06:04:55	600	351	141	5	90
JDEI0122	2007-04-25T06:12:44	120	352	146	5	90
JDWF0002	2007-05-11T00:16:32	600	316	213	9	85
JDWF0004	2007-05-11T00:39:57	600	319	223	9	90
JDWF0008	2007-05-11T01:22:55	600	326	243	7	90
JDWF0010	2007-05-11T01:37:36	600	328	250	6	90
JDWF0015	2007-05-11T02:30:28	600	335	274	3	90
JDWF0017	2007-05-11T02:46:03	600	337	282	2	90
JDWF0022	2007-05-11T03:37:23	600	345	305	-2	90
JDWF0024	2007-05-11T03:52:34	600	347	312	-3	90
JDWF0025	2007-05-11T04:04:15	600	348	318	-4	90
JDWF0026	2007-05-11T04:18:16	600	350	324	-5	90
JFQI0034	2007-06-20T23:37:43	600	11	183	9	90
JFQI0035	2007-06-20T23:49:40	600	12	188	9	90
JFQI0037	2007-06-21T00:05:42	600	14	196	10	90
JFQI0043	2007-06-21T01:05:08	600	23	224	9	90
JFQI0045	2007-06-21T01:19:53	600	25	230	8	90
JFQI0049	2007-06-21T01:59:44	600	31	249	7	90
JFQI0051	2007-06-21T02:14:04	600	33	256	6	90
JFQI0056	2007-06-21T03:12:27	600	41	282	2	90
JFQI0058	2007-06-21T03:28:22	600	43	290	0	90
JGGV0044	2007-07-06T21:53:49	600	10	7	-9	90
$\rm JGGV0045$	2007-07-06T22:05:48	600	12	13	-9	90
JGGV0049	2007-07-06T22:36:19	600	16	27	-10	90
$\rm JGGV0052$	2007-07-06T23:06:43	600	21	41	-9	90
$\rm JGGV0058$	2007-07-07T00:02:07	600	29	67	-7	90
$\rm JGGV0062$	2007-07-07T00:36:20	600	33	83	-5	90
$\rm JGGV0067$	2007-07-07T01:20:25	600	40	103	-1	90
KPBB0028	2009-09-07T21:55:26	180	234	86	-4	-270
KPBB0034	2009-09-07T23:38:40	600	249	132	3	-270
KPCB0056	2009-09-08T23:43:16	600	93	81	-5	-270
KPCB0059	2009-09-09T00:24:09	600	99	100	-2	-180
KPFB0035	2009-09-09T20:22:05	600	268	296	-1	-270
KPFB0038	2009-09-09T20:59:06	600	273	313	-3	-180
KPFB0041	2009-09-09T21:33:50	600	278	329	-6	-270
KPFB0047	2009-09-09T22:27:46	600	286	353	-8	-270
KPIB0078	2009-09-12T23:43:39	600	187	230	9	-180
KPIB0081	2009-09-13T00:25:12	600	193	249	7	-270
KPJB0031	2009-09-13T21:33:57	600	12	116	1	-270
KPJB0033	2009-09-13T21:51:41	600	14	124	2	-270
KPJB0050	2009-09-14T01:30:31	600	45	226	9	-270



Figure 2. Left: spectrum of one Io observation (solid line) and the g-value used (dashed line) around the D2 emission line. Right: their ratio, which is the column density.



Figure 3. Composite image to put our 2D spectra in the observational perspective. The two right panels show our 2D Io spectra converted into column densities, in logarithmic color scale (D2 and D1, respectively). The region enclosed within the cyan dashed rectangles (7-22 km s⁻¹ and 3-7 Io radii) is used to compute the average source rate discussed in Section 5 and listed in Table 2. The gray arrows indicate the direction to Jupiter (towards left, in this case). The left panels show a simplified view of the geometry of the observations, from the celestial north pole (top) and from Earth (bottom), similar to Cremonese et al. (1992). Black solid circle on top (and gray on bottom) represents Io's orbit, in Jupiter's equatorial plane. Orange dashed circles on both top and bottom left panels represent Jupiter's magnetic equator at Io's distance, and include the tilt of 9.8° towards System III magnetic longitude $\lambda_{III} = 200^{\circ}$ and the offset of 0.12 R_J towards $\lambda_{III} = 149^{\circ}$. Cyan circle in bottom left panel represents the centrifugal equator, where the cold plasma ions reside. The arrow in the lower left panel indicates the rotation axis of Jupiter, and is black or gray if it points towards or away from the observer, respectively. Dashed lines in lower left panel indicate portions of the circles away from the observer. The blue circle and the small black line crossing it represent Io's disk and the spectrograph's slit, respectively. All objects in the two left panels are drawn to scale, except Io, for which the size has been magnified by 10. Corresponding images for the other observations can be found in the supplemental material.

²³² to \sim 75 km s⁻¹ is the stream of fast sodium atoms that ²³³ feed the giant sodium nebula (e.g. Flynn et al. 1992). ²³⁴ The feature modeled in this paper is the extended emis-²³⁵ sion blueshifted by few of tens of km s⁻¹ with respect to ²³⁶ Io, meaning these sodium atoms are moving towards the ²³⁷ observer. The feature is seen here in the eastern half of ²³⁸ the slit (left, in the figure), i.e. towards Jupiter.

4. MODELING THE EMISSION FEATURE

We applied our Monte Carlo model of sodium atom trajectories (Burger et al. 2014) to reproduce our observations as closely as possible, by including the location and direction of ejection and the velocity distribution of ejected atoms. These parameters are constrained by our observations. The goal is to reproduce the emission feature and its temporal variability.

Figure 4 illustrates the change in time of the new fea-247 ture's morphology at different orbital (or subsolar) lon-248 gitudes . This sequence shows that the blue-shifted fea-259 ture, more prominent towards the end of the observing 251 run, early in the night is red-shifted by a similarly high 252 speed (> 10 km s⁻¹). The transition from red to blue 253 shifts suggests that Na is ejected in a direction that is 254 roughly perpendicular to the Io-observer line when the 255 subsolar longitude is $\sim 330^{\circ}$ (between the 4th and the 256 5^{th} spectrum in Figure 4). This red-to-blue shift can 257 then be explained by the changing observing geometry 258 as Io orbits Jupiter. This peculiar behavior inspired 259 our modeling approach. We first modeled the trajecto-260 ries of the neutral sodium atoms (Section 4.1) and then 261 found a plausible physical mechanism that can bring 262 these sodium atoms at the location and with the speed 263 we observe them (Section 4.1). 264

4.1. Neutral sodium atoms trajectories

To simulate the observations we used the Monte Carlo 266 model that is described in Burger et al. (2014). In this 267 model, atoms are tracked under the forces of gravity and 268 solar radiation pressure. The equations of motion are 269 solved with a 5th order, adaptive step-size Runge-Kutta 270 algorithm. Atoms are ejected at randomly selected times 271 between the start and end of the model run so that the 272 simulation contains a mixture of freshly released and 273 older atoms. Loss processes include photoionization, 274 electron-impact ionization, and charge exchange, though 275 the atoms in the simulations shown below are mostly lost 276 by leaving the small field of view. The observation ge-277 ometry was recreated using the SPICE toolkit (Acton 278 1996). 279

We ran the model many times with different initial conditions in order to determine the direction and speed of Na that would reproduce the red-to-blue shift in Figure 4. Sodium atoms are ejected radially in intervals ²⁸⁴ 11.25° wide. The origin of the ejected atoms is labeled ²⁸⁵ in Io's West longitude, where 0° corresponds to the sub-²⁸⁶ Jupiter meridian and 90° points along Io's orbital mo-²⁸⁷ tion (the "leading" direction). Speeds values from 4 to ²⁸⁸ 130 km s⁻¹ were used, each with a narrow distribution ²⁸⁹ (each bin being 10 m s⁻¹ wide).

Each of the two free parameters we used to reproduce our observations affects only one aspect of the emission feature. The ejection speed distribution affects the Doppler shift (wavelength dimension), while the ejection location affects the morphology of the emission feature (spatial direction). This is illustrated in Figure 5, where we show the effects of changing these parameters, compared to the nominal, best model.

We find that the best combination of parameters to re-298 produce our observations is a broad speed distribution, 299 with ejection velocities relative to Io of 50-90 km s⁻¹, 300 and a relatively narrow range of ejection location: 45-301 68° of Io West longitude, meaning an ejection from the 302 subjovian/leading hemisphere. Models with the nomi-303 nal direction but lower speed (40 km s^{-1}) or higher speed 304 (130 km s^{-1}) fail to match the magnitude of the Doppler 305 shift, though they maintain the red-to-blue transition 306 at a subsolar point of $\sim 330^{\circ}$ (left-right panels in Fig-307 ure 5). The mismatches in direction include one angular 308 bin toward the leading direction and one bin toward the 309 subjovian direction, and these both fail to reproduce the 310 ³¹¹ red-to-blue transition and the magnitude of the Doppler shift (top-down panels in Figure 5). 312

313 Figure 6 shows the best simulations compared to some of the observations. The rest of the data-model comparison can be found in the movie in the Supplemental 315 Material. The nominal model shown here (in both Fig-316 ure 5 and 6) includes speeds of 57 km s⁻¹ and 90 km s⁻¹, 317 though lower speeds could be included without signifi-318 cantly changing the result. Figure 6 illustrates how our 319 320 model can reproduce the shift in velocity relative to Io (from red, or positive, to blue, or negative) within the 321 same amount of time (about 4 hours). 322

Figure 7 shows a top-down view of the nominal model 323 of sodium trajectories near the beginning and end of the 324 observing sequence. In this image, directions toward the 325 observer (Earth, \oplus) and Jupiter (4) are indicated. The 326 red-to-blue shift is seen here as a change in ejection di-327 rection as seen from Earth. Also, it can be noted that the ejection direction is roughly halfway, in terms of 329 degrees, between the leading direction and Jupiter di-330 331 rection.

4.2. Dust grains trajectories

332

Having found the characteristics of the sodium feature (speed distribution and direction), we need to identify

IO'S DUST JET



Figure 4. Observations taken in May 2007, calibrated in column density per unit velocity at different orbital (or subsolar) longitudes. Doppler velocities less than 10 km s⁻¹, which include the "banana cloud", have been blacked out to highlight the feature, which transitions from red-shifted to blue-shifted in this 4-hour time span. Io's orbital position is given as subsolar longitude and is indicated at the top of each plot. Io's continuum has been carefully removed with the procedure discussed in the text.



Figure 5. The simulation from the best model is shown at the center. The other four sub-panels show models with the right ejection direction but too low (left panel) or too fast (right panel) ejection speed, or models with the right ejection speed but wrong directions (top and bottom panels). Velocities within 10 km s⁻¹, marked by horizontal dashed lines, have been masked to leave out the main emission feature. The vertical dashed line represents the region of Io's continuum.



Figure 6. Comparison between four spectra in May 2007 (top panel) and their best fit model simulations (bottom panel). Note how the simulations are able to reproduce the shift in Doppler velocity, from positive relative velocities (moving away from the observer) to negative ones (moving towards the observer).



Figure 7. Top-down view of the model shown in Figure 6. The left panel shows the beginning of the observation sequence, when the Na is directed away from the observer to produce a red Doppler shift. The right panel shows the end of the sequence, when the Na is blue shifted. The white arrow points toward Jupiter, Earth is straight down.

a process that may bring sodium atoms at the location 335 and speed observed. The direction of the blueshifted 336 sodium feature (towards Jupiter) is consistent with neg-337 atively charged particles that move following Jupiter 338 magnetosphere's co-rotational electric field (e.g. Horányi 339 et al. 1997). There are two possible candidates: sodium-340 bearing negative ions that are promptly neutralized 341 and negatively charged Na-rich dust grains from which 342 sodium atoms are liberated. In this section we discuss 343 the latter, as many of the grains' properties agree with 344 our directional feature; at the end of Section 5.1 we 345 briefly discuss the negative ions hypothesis. 346

³⁴⁷ Dust in the Jovian environment has been detected by ³⁴⁸ multiple spacecraft: Ulysses (Grün et al. 1993), Galileo

(Grün et al. 1996), and Cassini (Postberg et al. 2006). 349 All these observations are consistent with electrically 350 charged dust grain of radius $\sim 10 \text{ nm}$ (Zook et al. 1996). 351 The periodicity of the dust impact signal in Galileo data 352 was one of the early indicators that Io, and not the gos-353 samer rings, was the source of such dust grains (Graps 354 et al. 2000). Subsequently, the Cosmic Dust Analyser 355 (CDA) onboard Cassini was able to distinguish the com-356 position of these grains. NaCl was the dominant species 357 identified by CDA, followed by other components like 358 Na_2SO_4 and K_2SO_4 (Postberg et al. 2006). This is in 359 contrast with the main composition of Io's atmosphere 360 and neutral clouds, where NaCl, Na⁺, and Cl⁺ are just 361 trace species (NaCl fraction in composition is less than 362 1%, while the Na⁺ and Cl⁺ concentration in the torus 363 is between 2 and 6%; Lellouch et al. 2003; Küppers & 364 Schneider 2000) The inverse trend in composition for 365 dust may be related to the process that ultimately ejects 366 these particles in the first place, i.e. volcanic eruptions. 367 Because of their high condensation temperature, NaCl 368 and KCl are abundant condensates 20 min after out-369 gassing from the vent, while sulphuric components, due 370 to their lower condensation temperature, are still far 371 from condensation (Zhang et al. 2004). 372

We performed simulations of the trajectory of neg-373 atively charged nanodust grains of various sizes. We 374 assume that the dust particles 10nm in radii start with 375 a circular Keplerian motion at Io's orbit and an initial 376 charge of 20 electric charge, corresponding to a surface 377 potential of -3 V. The charging and dynamical evolu-378 tion of nanometer-sized grains is modeled as described in Horányi et al. (1997). For individual dust grains, two 380 equations are integrated simultaneously: the equation 381 382 of motion and the grain charging equation. The equation of motion considers the gravity of Jupiter and the 383 Lorentz forces acting on the grain from the co-rotating 384 385 magnetosphere. The grain charging equation depends on plasma properties at the grain's location and determines the grain charge-to-mass ratio, essential to cal-387 culate the Lorentz forces. Grains can be charged neg-388 atively or positively, depending on the plasma environ-389 ment, and the charging begins almost instantaneously. 390

A top-down view of the trajectory of a negatively 391 charged dust grain of radius 10 nm, as well as a pos-392 itively charged one (same size), is shown in Figure 8. Figure 9 shows the direction, the relative speed and dis-394 tance with respect to Io of a negatively charged dust grain of radius 10 nm. The gray circle in that figure rep-396 resents the parameter space (both velocity and distance to Io) consistent with our observations. The dynamical 398 evolution of charged nanoparticles largely depends on 399 the grain charge polarity: the positively charged parti-400



Figure 8. Top-down view of the trajectories of a negatively charged and a positively charged 10-nm-radius dust grain. $R_J = Jupiter radius \sim 70,000 \text{ km}.$

cle is accelerated away from Jupiter in almost a straight 401 trajectory, while the negatively charged one exhibits a 402 cycloidal motion along Io's orbit similar to pick-up ions. 403 In general, negatively (positively) charged grains are ac-404 celerated towards (away from) Jupiter because of the 405 outward-pointing co-rotating electric field (e.g. Horanyi 406 et al. 1993). Within the first cycloid (within the first 407 ~ 15 minutes), when the grain is within ~ 10 Io radii, 408 both its direction and speed are comparable to the prop-409 erties of the sodium jet. Grains of larger size (e.g. 100 410 nm), with a much smaller charge-to-mass ratio, are less 411 accelerated by Lorentz forces compared to 10-nm-radius 412 dust grains. Therefore, their velocity relative to Io is 413 much smaller than the observed one. Similarly, much 414 smaller particles (size <10 nm) have a much smaller gy-415 roradius and tend to stay much closer to Io (a couple 416 of Io radii at most) than our sodium feature. We shall 417 return to this point in the next Section. 418

5. DISCUSSION

419

Nanodust particles get charged at high altitude at Io 420 by capture of ionospheric electrons or photoelectron pro-421 duction (Krüger et al. 2003a). Only the most energetic 422 plumes are expected to bring grains to high altitudes so 423 that they collect sufficient charge from ambient plasma 424 to overcome Io's gravity (Johnson et al. 1980). Flan-425 des (2004) showed that particles need to reach at least 426 ~ 400 km altitude to be able to escape, and the flight 427 time from vent to this height is 15-20 minutes. 428



Figure 9. Simulation of trajectory of a negatively charged 10-nm-radius dust grain (of 20 e⁻ initial charge) moving under the influence the co-rotational electric field of Jupiter's magnetosphere. The line threading through the colored squares is the direction (angle), while the colored squares represent the velocity. The gray circle indicates the parameter space of the modeled neutral sodium atoms: speed range of 50-90 km s⁻¹ (cyan to yellow colors) and direction of ~ 45°. The negatively charged particles have the right velocity at the right time to match our observations. The dashed line is the distance from Io and is also referred to the y axis (in Io radii) and that is also consistent with our data (Figure 4). Tick marks on the x axis are 5 minutes.

Once they get charged, these nanodust particles fol-429 low trajectories that are determined by the corotational 430 electric field of Jupiter's magnetosphere, in the radial 431 direction. The dependence of dust trajectories on the 432 highly variable magnetosphere in turn implies a certain 433 variability in the expected dust flux with Jovian local 434 time even if the dust ejection rate is constant. This 435 variability, combined with the narrow field of view of 436 our slit, might explain the variability seen in our dataset 437 within a couple of hours (Figure 4). Most previous Io 438 nanodust detection were carried out at distances further 439 away from Io's orbit. In this respect, our observations 440 probe a much closer region to Io than all previous dust 441 measurements. 442

The spatial information of the observed Na jets also provides constraints on the dynamics of its possible dusty source. The observed Na speeds correspond roughly to $\sim 50 \text{ km s}^{-1}$, but grains in the dust model (10 mm in radius with 20 e⁻ initial charge) need to be accelerated for some distance before reaching those speeds, at least 7 R_{Io} as seen from Earth.

A dust grain with lower initial charge gets charged 450 later, and thus farther away, and therefore its distance 451 from Io would not match our observations. Only grains 452 with proper charge-to-mass ratio can be sufficiently ac-453 celerated by the Lorentz forces and maintain a direction 454 comparable to the observed sodium jet. To first order, 455 regardless of the grain size, grains in the same plasma 456 environment will be charged to roughly the same elec-457

trostatic potential determined by the ambient plasma 458 conditions. For a given electrostatic potential, the grain 459 charge-to-mass ratio is inversely proportional to the 460 square of the grain size. Negatively charged grains much 461 larger than 10 nm have lower charge-to-mass ratio and 462 would not be accelerated to the observed speed in the 463 vicinity of Io. Negatively charged grains much smaller 464 than 10 nm, on the other hand, have much smaller gy-465 roradius and will produce both red- and blue- shifted 466 components in the vicinity of Io, which is also not con-467 sistent with the observation. The grain dynamics thus 468 suggests that the sodium jet can only be produced by 469 charged grains with radius ~ 10 nm. This is in good 470 agreement with previous grain size estimate of the Jo-471 vian stream particles based on space dust instruments 472 on board Galileo and Cassini spacecraft (Postberg et al. 473 2006; Hsu et al. 2012). 474

It is possible to perform a rough estimate of the source rate from the spectra and compare it to the source rate from the neutral model. The sodium source rate r is the product of the peak column abundance, the vertical extent d of the emission, and the velocity v_{\perp} perpendicular to the observer's line of sight (Schneider et al. 1991):

$$r = d \cdot v_{\perp} \cdot \int_{v_1}^{v_2} n(v) dv \tag{3}$$

In the above formula, we used Io's diameter as verti-482 cal extent d of our feature; n is the column density per 483 unit velocity averaged between 3.0 and 7.0 R_{Io} and the 484 integral is performed between $v_1 = 7$ and $v_2 = 22$ km 485 s⁻¹ relative to Io, where the blueshifted feature is more 486 prominent. Finally, the velocity perpendicular to the 487 observer's line of sight is defined as $v_{\perp} = v_{los} \cdot tan(\theta)$, 488 where v_{los} is the line-of-sight velocity (the one our spec-489 troscopic observations are sensitive to) and θ is the angle 490 between our line of sight and the jet (we assume our di-491 rectional feature, or "jet", to be the axis of the cone of 492 sodium atoms - see Figure 7). This angle is necessarily 493 taken out of our modeling, since with spectroscopic ob-494 servations we can only measure the radial (line of sight) 495 velocity and have no information on the true orientation 496 of the sodium feature. For each spectrum, we average 497 the D2 and the D1 source rates and report these num-498 bers in Table 2. The median of the resulting sodium 499 source rates is 7.0×10^{25} Na s⁻¹ from the data, corre-500 sponding to 2.7 kg s⁻¹. The source rate from the neutral 501 model is somehow greater $(2.6 \times 10^{26} \text{ Na s}^{-1}, \text{ correspond}^{-1})$ 502 ing to 10.0 kg s^{-1}), but this was derived assuming a wide 503 "jet" (30° in the vertical direction). A narrower feature 504 would require proportionally less sodium. 505

5.1. Sputtering of Na from nanodust grains

Table 2. Sodium source rate for the emission feature discussed in this paper. The data source rate is the average of the source rates from the D2 and D1 emission lines). Model source rates for some of the April 2007 observations are not available because the emission feature was not well defined.

filename	data source rate (s^{-1})	model source rate (s^{-1})
JDEI0119	$7.0 imes 10^{25}$	$1.6 imes 10^{26}$
JDEI0120	1.1×10^{26}	2.6×10^{26}
JDWF0002	1.4×10^{25}	$5.8 imes 10^{25}$
JDWF0004	2.8×10^{25}	9.2×10^{25}
JDWF0008	4.6×10^{25}	1.4×10^{26}
JDWF0010	$7.0 imes 10^{25}$	$2.1 imes 10^{26}$
JDWF0015	2.3×10^{26}	$2.9 imes 10^{26}$
JDWF0017	1.7×10^{26}	$2.7 imes 10^{26}$
JDWF0022	9.8×10^{25}	2.8×10^{26}
JDWF0024	$7.7 imes 10^{25}$	$3.0 imes 10^{26}$
JDWF0025	6.9×10^{25}	2.2×10^{26}

For the dust hypothesis to work, we need a mechanism 507 that releases sodium atoms from these nanodust grains. 508 Possible processes include photon-stimulated desorption 509 (PSD), electron-stimulated desorption (ESD), or ion 510 511 sputtering. The first two have too low a source rate. From experiments of PSD of Na from surfaces that sim-512 ulate the lunar silicates (Yakshinskiy & Madey 1999), 513 scaling the solar flux to Jupiter's distance, and taking 514 into account our derived distribution of dust grains, the 515 source rate from PSD is 10^9 s⁻¹. The same authors also 516 showed that electron-stimulated desorption has an only 517 slightly higher cross section compared to PSD. The other 518 mechanism, ion sputtering, gives higher source rates, al-519 though there are several uncertainties that affect the 520 calculation of the rate. First, an absolute value for 521 sputtering yield of sodium atoms has only been mea-522 sured on Na₂S: Chrisey et al. (1988) report a sputtering 523 yield of 0.1 and 0.2 Na₂S ion⁻¹ from O^+ and S⁺ ions, 524 respectively. The molecules of interest in our case are 525 sodium chloride (NaCl) and sodium sulfate (Na_2SO_4), 526 given that these were the compositions of the Na-bearing 527 dust grains detected by Cassini CDA (Postberg et al. 528 2006). Sodium sputtering yield for NaCl has been estimated by Johnson (2000) to be ~ 1.0 Na ion⁻¹, assum-530 ing that NaCl has the same atomic ejection efficiency 531 as Na₂S. Sodium sputtering yield for Na₂SO₄ has only 532 been reported as a relative value: it is 100-1000 times 533 greater than the sputtering yield for NaS (Wiens et al. 534 1997). Assuming the absolute sputtering yield of NaS 535 to be the same as that of Na₂S, we can estimate the 536 Na sputtering yield from Na_2SO_4 to be 100-1000 times 537 greater than that of NaCl, or 100-1000 Na ion⁻¹. The

⁵³⁹ flux Φ of precipitating ions responsible for the sputtering ⁵⁴⁰ (mostly S⁺ and O⁺) can be calculated by multiplying ⁵⁴¹ the velocity of the ions (co-rotation, or 57 km s⁻¹) by ⁵⁴² the density of these heavy ions close to Io, or about 1500 ⁵⁴³ cm⁻³ (Dougherty et al. 2017). We obtain $\Phi = 8.6 \times 10^9$ ⁵⁴⁴ cm⁻² s⁻¹.

The second uncertainty is the dust available for sput-545 tering. Over the course of the 7-year mission and from 546 a distance between 13 and 400 R_J from Io, the Galileo 547 Dust Detector System (DDS) measured dust production 548 rates at Io between 10^{-3} and 10^2 kg s⁻¹ (with an average 549 value between 0.1 and 1.0 kg s⁻¹), possibly correlated 550 to volcanic eruptions at Io (Figure 2 of Krüger et al. 551 2003b). 552

With these numbers, we can estimate the number of 553 Na atoms sputtered by nanodust grains and compare it 554 to our observed sodium production rate. We start by 555 assuming a dust production rate of 1 kg s⁻¹, the up-556 per value of the average range reported by Krüger et al. 557 (2003b). Assuming a spherical shape and a density of 558 1.5 g cm^{-3} (Krüger et al. 2003b), this corresponds to 559 1.6×10^{20} grains s⁻¹ of radius 10 nm. We now multiply 560 this number by the time it takes for the dust grains to 561 reach the point where we do see sodium emission, or 0.05 562 hours (from Figure 9), to get $N_{grains} = 2.9 \times 10^{22}$. The 563 total area available for sputtering will be $N_{qrains} \cdot A \cdot c$, 564 where A is the area of a 10-nm-radius spherical nanodust 565 grain, and c the concentration of either NaCl (90%) 566 or Na_2SO4_4 (10%), from Cassini CDA measurements 567 (Postberg et al. 2006). These areas are 3.2×10^{11} cm⁻² 568 and 3.6×10^{10} cm⁻² for NaCl and Na₂SO₄, respectively. 569 Multiplying them by the corresponding sputtering yields 570 Y and the heavy ion flux, we get the sodium production 571 rate for sputtering s: 572

$$s = N_{qrains} \cdot A \cdot c \cdot \Phi \cdot Y \tag{4}$$

⁵⁷³ We obtain 2.8×10^{21} Na s⁻¹ from NaCl, and 3.1×10^{22} ⁵⁷⁴ Na s⁻¹ from Na₂SO₄ from 1 kg s⁻¹ of dust material.

These numbers are between 3 and 4 orders of mag-575 nitude lower than our inferred rate of 7.0×10^{25} s⁻¹ 576 (from the observations). They can be reconciled with 577 our values if we assume some combination of the high-578 est estimate for dust production rate from Galileo (100 579 kg s^{-1}), the highest estimate for the sputtering yield of 580 Na from Na_2SO_4 (1000 Na ion⁻¹), and a surface area 581 for porous particles which is ~ 10 times higher than the 582 spherical area (this is the case for micron-sized lunar 583 regolith particles; Taylor & Meek 2004). Additionally, 584 the dust production rates from Galileo should be con-585 sidered a lower limit, as dust is likely to undergo other 586 destruction processes (not included in the calculations 587 of Krüger et al. 2003b) between Io and the distance at 588

which grains were detected by Galileo (between 13 and 589 $400 R_{\rm J}$ from Io). This is particularly true if some ejected 590 dust has a more volatile composition than NaCl. Finally, 591 it is not clear how the ion sputtering experiments, per-592 formed on flat surfaces, would change if the target is 593 composed of nm-sized porous surfaces. To further in-594 vestigate the discrepancy, a detailed calculation of the 595 release of Na from dust particles and full treatment of 596 dust destruction in Jupiter's highly complicated plasma 597 environment would be required, and these are outside 598 599 the scope of this paper.

We note that the new sodium feature was most promi-600 nent when Io was within 5° of the magnetic equator (Ta-601 ble 1). The bulk of the Io plasma torus is confined in the centrifugal equator, which is very close to the mag-603 netic one. The plasma environment of that region (high 604 plasma electron density and low electron temperature; 605 Meyer-Vernet et al. 1995) is consistent with the negative 606 grain charge polarity inferred from the trajectory simu-607 lation. In addition, the sputtering erosion responsible to 608 release sodium atoms from dust surfaces is also higher at 609 low magnetic latitudes because of the higher ion density. 610 Our results thus indicate an indirect pathway to deliver 611 sodium atoms, and likely other species, from Io to the 612 Neutral Clouds (and ultimately to the magnetosphere) 613 by sputtering from dust surfaces. 614

We conclude this section by evaluating and discarding 615 another possible candidate, mentioned in Section 4.2, 616 that is a population of negative ions formed inside Io's 617 618 plumes. In this case, the most likely process to create these ions is three-body electron attachment. The most 619 likely species to undergo this process is $NaSO_4$, a radical 620 species with a substantial electron affinity and the high-621 622 est rate coefficient among several Na-bearing species. The negative ions would then release the neutral sodium 623 atoms we observe following electron detachment. The 624 concentration of NaSO₄ inside Io's plumes is unknown, 625 but to match our observed source rate per unit volume, 626 a density similar to that of potassium would be required, 627 or 9 orders of magnitude greater than the the expected 628 concentration of Na₂SO₄ inside Io's plumes (Moses et al. 629 2002). For this reason, we favor the hypothesis of ion 630 ⁶³¹ sputtering from negatively charged dust nanograins as the most plausible source of our new sodium emission 632 feature. 633

6. CONCLUSIONS

We have performed Monte Carlo simulation of sodium atoms under the influence of Io's gravity and solar radiation pressure to explain an unusual Jupiter-oriented feature (Schneider et al. 2008) we detected in our highresolution spectra of Io's sodium Neutral Clouds from

the TNG telescope. This feature is directed towards 640 Jupiter and is rapidly variable in time. The best model 641 is the one that has the sodium atoms ejected in the 642 leading-sub/Jovian hemisphere of Io (45-68° West lon-643 gitude) with a broad velocity distribution (50-90 km 644 ⁻¹). We propose that the mechanism most likely re- \mathbf{S} 645 sponsible for creating sodium atoms with that orienta-646 tion and that speed is sputtering of Na from Na-bearing 647 molecules (NaCl or Na₂SO₄, both detected near Jupiter 648 by Cassini CDA) attached to negatively charged dust 649 grains (10 nm in radius) that move under the influence 650 of the co-rotational electric field of Jupiter's magneto-651 sphere. This is consistent with modeling of trajectories 652 of negatively charged nanodust grains, which present the 653 right velocity and orientation consistent with our ob-654 servations and our sodium model. The median sodium 655 source rate inferred from our observations is 7.0×10^{25} 656 Na s^{-1} , to be compared with the theoretical estimate 657 from ion sputtering of Na from NaCl or Na₂SO₄ be-658 tween 5.5×10^{21} Na s⁻¹ and 6.2×10^{26} Na s⁻¹, depending 659 on the choice of several uncertain parameters, such as 660 the sputtering yield, the dust production rate at Io, and 661 surface area available to sputtering. We point out the 662 need for detailed calculations of the release of Na from 663 dust particles and full treatment of dust destruction in 664 Jupiter's highly complicated plasma environment. 665

Our results uncover a new mechanism by which Io's sodium Neutral Clouds are replenished, and highlight the need for future observing campaigns to better constrain the escape rate of sodium atoms produced at Io by this mechanism, before the arrival of Europa Clipper spacecraft, whose dust counter will be able to study the dust population in the Jupiter environment at much closer range than any other spacecraft so far.

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