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Small Jovian lightning flashes indicating shallow electrical storms

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23 **Jovian lightning flashes were characterized by a number of missions that visited Jupiter**
24 **over the past several decades. Imagery from the Voyager 1 and Galileo spacecraft led to a**
25 **flash rate estimate of $\sim 4 \times 10^{-3}$ flashes/ km^2/yr on Jupiter.^{1,2} The spatial extent of Voyager**
26 **flashes was estimated to be ~ 30 km at half-width half-maximum intensity (HWHM), but**
27 **the camera was unlikely to have detected the dim outer edges of the flashes given weak**
28 **response to the brightest spectral line of Jovian lightning emission, the 656.3 nm H-alpha**
29 **line of atomic hydrogen (known from lab experiments).^{1,3-6} The spatial resolution of Galileo**
30 **and New Horizons cameras allowed investigators to confirm twenty-two flashes with**
31 **HWHM > 42 km and estimate one between 37-45 km.^{1,7,8,9} These flashes, with optical**
32 **energies only comparable to terrestrial “superbolts” (2×10^8 - 1.6×10^{10} Joules), have**
33 **historically been interpreted as tracers of moist convection originating near the 5 bar level**
34 **of Jupiter’s atmosphere (assuming photon scattering from points beneath the clouds).¹⁻**
35 **^{3,7,8,10-12} All previous optical observations of Jovian lightning have been limited by camera**
36 **sensitivity, proximity to Jupiter, and long exposures (~ 680 ms to 85 s) hence some**
37 **measurements were likely superimposed flashes reported as one.^{1,2,7,9,10,13} Here we report**
38 **optical observations of lightning flashes by Juno’s Stellar Reference Unit¹⁴ with energies of**
39 **$\sim 10^5$ - 10^8 Joules, flash durations as short as 5.4 ms, and inter-flash separations of tens of**
40 **milliseconds. The observations exposed Jovian flashes with typical terrestrial energies. The**
41 **flash rate is $\sim 6.1 \times 10^{-2}$ flashes/ km^2/yr , more than an order of magnitude greater than**
42 **hitherto seen. Several flashes are of such small spatial extent they must originate above the**
43 **2 bar level, where there is no liquid water.^{15,16}**

44 Juno’s Stellar Reference Unit (SRU) captured images of Jovian lightning on the dark side of
45 Jupiter from a unique perspective of as close as 53,000 km above the 1 bar level (30 km/pixel
46 resolution). The SRU is a broadband (450 -1100 nm) imager designed to detect dim stars in
47 support of spacecraft attitude determination. The camera’s point spread function (PSF) spreads
48 the optical signal of a point source over $\sim 5 \times 5$ pixels, allowing unambiguous identification of
49 small optical sources (see Extended Data Fig. 1). Fourteen lightning flashes (see Extended Data
50 Table 1) were observed between $\sim 46^\circ\text{N}$ and 75°N , and one at 51°S , (planetocentric) during a 9-
51 image lightning survey between perijoves 11 (7 February 2018) and 17 (21 December 2018) that
52 covered 1×10^{10} km^2 of the planet. The storms observed in motion compensated images (such as
53 Figure 1 panel a) were confirmed to appear in cyclonic “belt” regions, consistent with prior

54 optical observations of Jovian lightning by Galileo¹. Juno's Microwave Radiometer¹⁷ (MWR)
55 provided supporting microwave observations, detecting lightning¹⁸ within ~0.4 seconds to 3
56 minutes of each SRU detection in the Northern hemisphere while its 600-MHz beam covered the
57 SRU flash location (see Extended Data Fig. 2 and Supplementary Data 1).

58 The novel combination of close observation distance, camera sensitivity, and the spin of the Juno
59 spacecraft (two revolutions per minute) enabled lightning detection at higher resolution than
60 previously possible. Two 1 s SRU exposures were collected without motion compensation
61 (hereafter "NoTDI") allowing the camera's field of regard to be panned across Jupiter at a rate of
62 1 pixel every 2.7 ms. A dim "string of pearls" trail of multiple spots along the scan direction was
63 observed in one of these images (Figure 1 panel b), assumed to be flashes from the same storm
64 location. Inter-flash separations of only tens of milliseconds, and flash durations as short as 5.4
65 ms, were deduced. The global flash rate estimate based on the NoTDI imagery is 6.1×10^{-2}
66 flashes $\text{km}^{-2} \text{ year}^{-1}$, 15 times higher than previous estimates derived from optical observations.^{1,2}

67 The Juno observations have unveiled Jovian lightning flashes with optical energies similar to
68 typical terrestrial flashes ($1 \times 10^5 - 2 \times 10^7 \text{ J}$).¹⁹ Figure 2 illustrates that the optical energies of
69 the SRU flashes extend far below the $2 \times 10^8 - 1.6 \times 10^{10} \text{ J}$ range that was detectable in prior
70 broadband surveys.^{1,2,7} Although optical energy is just part of the total energy generated by
71 lightning (for example, 5-18 kHz radio emissions from terrestrial lightning range from 10 to 10^8
72 J, where strokes above 10^6 J are considered "superbolts"²⁰), optical detection of lightning in this
73 new regime, and the higher flash rate suggested for it, provides important constraints for
74 understanding energy dissipation rates in Jupiter's atmosphere and reduces the reliance on
75 terrestrial-based assumptions where data are lacking.^{2,11}

76 We identified lightning flashes with estimated widths as small as ~33 km and as large as 250 km.
77 It is customary to use the half-width at half-maximum (HWHM) of a lightning flash (the radial
78 distance over which the flash radiance drops to half the peak value) to infer the lightning's depth
79 within the atmosphere.^{1,3,7,8} The deeper the origin of the flash photons, the more they will expand
80 radially outward as they scatter through the atmosphere before being released to space, and the
81 larger the observed HWHM. The HWHM was estimated for six flashes where the de-convolved
82 brightness distribution had sufficient symmetry and simplicity to make a reasonable estimate (see
83 Extended Data Fig. 3). These are estimated maxima as we could not confirm sub-pixel values;

84 many are the half-width value and the actual HWHM is suspected to be smaller. We estimated
85 SRU flash depths based on a radiative transfer model where $\text{depth} = 1.5 \times \text{HWHM}$ and the top
86 scattering layer is at the 0.14 bar level¹ (40 km above the 1 bar level¹⁵). At this “top” scattering
87 level ammonia ice crystals would likely be the predominant scattering particles although water
88 ice particles might also be carried up to this level by strong updrafts.^{12,21} The pressure-
89 temperature-depth data from the Galileo probe¹⁵ provided the pressure levels corresponding to
90 the computed depths below the top scattering layer.

91 Four of the SRU flashes originate between ~1.4 and 1.9 bars (inset Figure 3), hereafter “shallow
92 lightning,” which is a surprising result given that conventional models of lightning generation by
93 charge separation require both liquid and solid condensate.¹⁰ Although intense storms are
94 expected to loft water-ice crystals to such heights,²¹ no liquid water can exist at these altitudes as
95 temperatures above the 2 bar level are below -66°C ,¹⁵ which is well below a plausible minimum
96 temperature for supercooled water (-40°C)¹⁶. If a non-inductive charge separation mechanism
97 involving mixed-phase clouds is responsible for the shallow lightning, then another source of
98 liquid is required. The possible role of ammonia is shown conceptually in Figure 3. Should water
99 ice particles from below be lifted by very strong updrafts to altitudes between 1.1 and 1.5 bars,
100 equilibrium thermodynamics predicts that they can adsorb ambient ammonia vapor and create a
101 mixed ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) liquid.^{22,23,24} The collision of this falling liquid with upward
102 moving water-ice particles, or falling ice crystals with lower terminal velocities, would constitute
103 a mixed phase liquid- and solid-bearing cloud in which charge transfer, charge separation, and
104 cloud electrification might occur (see Methods). This would be unlike any process which occurs
105 on Earth, but it is enabled by the large presence of ammonia at Jupiter which acts as a strong
106 H_2O antifreeze at the extremely low temperatures in the 1.1-1.5 bar region.

107 Alternatively, Juno’s SRU may have observed lightning generated without any liquid. On Earth,
108 lightning flashes have been observed to originate in cloud anvils (“cumulonimbus incus”) at
109 altitudes above ~10 km (below -45°C) and significant charging was inferred to have occurred
110 locally within the anvil.²⁵ Recent airborne measurements have confirmed that charge separation
111 can occur in the extremely dynamic environment inside anvils, without any detected supercooled
112 liquid water, due to the collision and transfer of charge between ice particles of broadly differing
113 size.^{26,27} Anvils have been predicted to form above the 2 bar level at Jupiter²⁸, and modeling has

114 shown that updrafts in Jovian thunderclouds can loft water ice particles of different sizes up to
115 the 1 bar level.²¹ It is therefore plausible that shallow Jovian lightning is the result of non-
116 inductive charge separation from ice-ice collisions in high reaching cumulonimbus clouds or
117 within anvils (see Methods).

118 Finally, it is possible that local cloud clearings could allow flashes originating in the water cloud
119 to appear small due to reduced scattering by a lower cloud top. We argue that the small flash
120 located above the elevated cloud in the moonlit SRU image (lower flash in Figure 1 panel a) is
121 evidence against a lower cloud top explanation. This flash is also consistent with prior
122 observations that linked lighting flashes to local elevated cloud structures in dayside or moonlit
123 imagery.^{1,12}

124 The remaining SRU flashes originate in the liquid water cloud layer (deeper than the 3 bar level),
125 suggesting that the more familiar liquid water and water-ice electrification mechanism is also
126 occurring at greater depths. The more poleward latitudes of the shallow lightning are noted (see
127 inset Figure 3), however the existing sample set is too small as of yet to infer any latitudinal
128 meteorological significance.

129 Although some SRU detections are consistent with the conventional theory of lightning
130 originating in regions of mixed-phase water condensation, the presence of shallow lightning
131 implied by the Juno observations requires that we consider the possibility of multiple
132 mechanisms for generating lightning in different pressure-temperature environments. By
133 extension, multiple shallow lightning events would suggest that strong localized updrafts are
134 frequent events in Jupiter's atmosphere. Because ammonia is only visible in the microwave when
135 in vapor form, an ammonia-water liquid created by adsorption of ammonia vapor onto water ice
136 particles may partially explain the decades long mystery of observed ammonia depletion in
137 Jupiter's atmosphere.²⁹⁻³¹ Continued observations by Juno's SRU are anticipated to increase our
138 knowledge of the occurrence rate of shallow lightning with latitude, providing an important
139 component of a broader effort to understand Jupiter's atmospheric convection and composition
140 using Juno instrumentation.

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Fig. 1 | Images from Juno SRU Jovian lightning survey. Scale bars show pixel signal levels in
analog-to-digital units. Background signal has been subtracted. **a.** SRU image 12 from perijove
11, collected using image motion compensation. Yellow arrows point to flashes of Jovian
lightning on Jupiter's dark side. The dim "tail" below the top flash is an artifact of the motion
compensation. Insets are magnified views of these small signatures which are spread out by the
camera's point spread function. Cloud top illumination is due to moonlight from Jupiter's moon,
Io. **b.** Scanned SRU image 12 from perijove 14 ("NoTDI" image #2), collected without motion
compensation. A dim "string of pearls" trail of multiple flashes from the same storm location is
seen in the along-scan direction, as well as an adjacent "neighbor" flash observed 258-13,800 km
away depending on when the flashes occurred during the scan. "String of pearls" flashes are
numbered 1-4 with inter-flash time separations shown in the magnified view of the region (Flash
3 may be three separate events, with time separations so indicated). Latitudes grids shown in the
background correspond to the start of the image scan.

223 **Fig. 2 | Optical energies of lightning flashes observed by the Juno SRU and past broadband**
224 **visible imagers.** The flash energy data from each instrument are plotted as a cumulative
225 frequency distribution in order of increasing optical energy. Galileo's Storm 10 observations are
226 plotted separately from Storms 7 & 8 due to the difficulty encountered by Galileo investigators
227 in distinguishing flashes from Storm 7 from those of Storm 8.¹ SRU flash energies are shown for
228 computations which treat each flash as a patch of light on a Lambertian surface (green stars) and
229 as a point source (blue stars). The SRU cumulative frequency distributions have been shifted up
230 by a factor of ten to highlight the lower optical energies detectable by the SRU. Optical energies
231 of terrestrial flashes and "superbolts"¹⁹ are indicated by grey bars.

232

233 **Fig. 3 | Conceptual illustration of lightning generation above and below Jupiter's 3 bar**
234 **level.** Energetic updrafts (black arrows) loft water ice particles to altitudes between 1.1 and 1.5
235 bars where adsorption of ammonia gas onto ice particles melts the ice, creating falling liquid
236 ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) particles (green drops). Charge separation occurs as the $\text{NH}_3\text{-H}_2\text{O}$
237 particles collide with upward moving water-ice, followed by lightning. At pressures greater than
238 ~3 bars, temperatures are above the limit for supercooled water (white line, ~233K) and
239 lightning is generated in pure water clouds. Radial half-width at half-maximum intensity
240 distances, estimated maximum depths of origin (pressure levels), and latitudes of observed SRU
241 lightning flashes are shown (inset).

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250 **Methods**

251 **Instrument properties.** The SRU is a visible imager with a 16.4 degree square field of view, a
 252 29.924 mm focal length, and spatial resolution of 0.57 mrad per pixel. The camera utilizes a
 253 frame transfer silicon CCD with a 17 micron pixel pitch and a 512 x 512 pixel imaging region.¹⁴
 254 No filters are used in the optical system.

255 **Camera sensitivity.** We used the radiometric calibration method that was used for the Galileo
 256 solid-state imaging camera³² to calculate SRU camera pixel response in units of output analog-to-
 257 digital data number (DN) pixel⁻¹ s⁻¹ in response to a spectrally neutral scene radiance (having
 258 equal energy at each wavelength, and the units W cm⁻² sr⁻¹ nm⁻¹).

$$259 \quad \text{camera pixel response} = \frac{A_o a_{ij}}{f^2 C} \int \frac{QT(\lambda) I \lambda}{hc} d\lambda$$

260 A_o is the 4.155 cm² collecting area of the optics, a_{ij} is the area of a CCD pixel (2.89×10^{-6} cm²),
 261 f is the camera focal length, C is the SRU camera gain of 15.47 signal electrons/DN, QT is the
 262 total throughput of the SRU optical system (the CCD quantum efficiency \times the optics
 263 transmission, shown as a function of wavelength in Extended Data Fig. 1), I is the scene radiance
 264 (assumed to be constant), h is the Planck constant, c is the speed of light, and λ is wavelength.
 265 The integration was performed over the SRU bandpass (450 to 1100 nm), and solved using a
 266 1000 DN pixel⁻¹ s⁻¹ response assumption. The SRU camera sensitivity is 3.346×10^{13} DN/W
 267 cm⁻² sr⁻¹ nm⁻¹ (per pixel, per second), and the energy incident on the collecting area of the optics
 268 is 2.6×10^{-17} J per DN. We repeated the calibration using simulated Jovian lightning spectra at 1
 269 bar and 5 bars⁶ which yielded lower camera responses of 2.683×10^{13} and 2.297×10^{13} DN/W
 270 cm⁻² sr⁻¹ nm⁻¹ (per pixel, per second), respectively. The greater dominance of the 656.28 nm H α
 271 line in the 1 bar spectrum is responsible for the differences. The two simulated spectra address
 272 pressure levels near the general regions of our inferred flash origins, but they are not exceedingly
 273 different from the neutral spectrum result. We used the neutral spectrum result for the flash
 274 energy calculations reported herein in order to be consistent with the approach used by the
 275 Galileo investigators¹ and to allow direct comparison to the Galileo data.

276 **Lightning flash identification.** Raw pixel data for the nine SRU lightning survey images are
 277 provided in Supplementary Data 2. To supplement visual inspection an automated search was

278 performed on the images to locate candidate lightning signatures. The approach was similar to
279 the method used by Juno's Radiation Monitoring Investigation to identify bright radiation
280 signatures in SRU images.¹⁴ Each pixel was assessed to determine whether its signal was a local
281 maximum in the 5×5 pixel region around it. If so, its signal was further assessed to determine
282 whether it was brighter than all eight of the immediately adjacent pixels by a threshold amount
283 ("Th").¹⁴ A threshold of 30 DN above the local background was generally used. When dimmer
284 flashes were suspected (the faint "string of pearls" flashes in NoTDI image #2) the threshold was
285 dropped to 15 DN. Thresholds were at least five times the noise of the local background level,
286 depending on the level of signal from moonlit clouds or scattered sunlight. To accommodate
287 larger lightning flashes which did not meet the criterion for all eight immediate neighbors, a $7 \times$
288 7 pixel region around the pixel was assessed. The criterion for this assessment was that the pixel
289 be $>Th$ above at least 18 pixels in the region, or $>Th$ above all sixteen of its second-nearest
290 neighbors, to be identified as a candidate.¹⁴ In practice, all of the lightning signatures that were
291 found by the automated search were also easily identified using visual inspection. Visual
292 inspection was the final deciding factor in confirming lightning signatures. Following
293 thresholding, an 11×11 pixel window was placed around the brightest pixel of each identified
294 signature and the median value of each border was calculated. The process was repeated for the
295 inner 9×9 , and 7×7 , pixel windows about the brightest pixel. The minimum of the 12 median
296 values was taken as the sum of the local background level plus the electronic offset level (~545
297 DN for SRU-1, the SRU unit used for the survey) and was subtracted from the raw values of all
298 pixels in the region local to the candidate storm (hereafter referred to as "background
299 subtraction"). The sum of all background-subtracted pixel values from the flash signature is the
300 "DNsum" used to estimate flash optical energy. Background-subtracted signature morphology
301 was visually inspected to exclude ionizing radiation signatures from the lightning flash candidate
302 list. Extended Data Fig. 4 illustrates the morphology differences between signals from optical
303 sources and ionizing particles. Lightning could be differentiated from penetrating radiation
304 signatures as the later have asymmetric morphologies which fall off abruptly to background
305 levels and do not follow the energy distribution of the camera PSF (the appearance of penetrating
306 particle signatures is not influenced by the optics).

307 Background subtraction for flash 13_12_0 was based on visual inspection of the image and the
308 raw pixel array values, due to the complexity of auroral emission local to the flash. An additional

309 step was taken prior to thresholding and background subtraction for NoTDI Image #2. Hot pixels
 310 are pixels with atypically high signal rates due to defects acquired during fabrication or radiation
 311 exposure. The expected hot pixel signal levels following a 1 s exposure were subtracted from the
 312 known hot pixel locations to aid clean assessment of the relatively dim “string of pearls”
 313 signatures. The mapping of the hot pixel signal rates (per second) is provided in Supplementary
 314 Data 3.

315 **Mapping flash locations on Jupiter.** To determine the locations of the lightning flashes on
 316 Jupiter, we first computed the centroid of each identified lightning flash (x_{cent} , y_{cent}) in pixel
 317 units, with array pixels numbered 1 to 512 (Extended Data Table 2). The coordinate system
 318 origin was placed at the center of pixel (1,1). The flash centroid was then converted to the 0 to
 319 511 pixel coordinate system of the SRU (instrument) frame, which has a boresight coordinate
 320 (255.5, 255.5) and a reversed y-axis numbering scheme (see Extended Data Fig. 5). We then
 321 used the following approach¹⁴ to convert the centroid components into a unit vector, correct for
 322 the camera’s optical distortion, and transform the unit vector into the spacecraft frame in J2000
 323 at the start of the image exposure time (time “t”). The intercept of this vector on Jupiter is the
 324 flash location.

325 The centroid measurements define a vector in the SRU frame. The tangents (\tan_{xref} , \tan_{yref}) of this
 326 vector, projected onto the focal plane, are computed by

$$327 \quad \tan_{xref} = \frac{x_{cent} - 255.5}{f_{lref}}, \quad \tan_{yref} = \frac{y_{cent} - 255.5}{f_{lref}}$$

328 where $f_{lref} = 1760.21137$ pixels (the focal length of the camera expressed in pixel units).

329 The position (\tan_{xref} , \tan_{yref}) is radially corrected for optical distortion using following formulae:

$$330 \quad R = (\tan_{xref}^2 + \tan_{yref}^2)^{1/2} \text{ and } f(R) = a_0 + a_1 R + a_2 R^2 + a_3 R^4$$

331 where $a_0 = 0.999432579$, $a_1 = -0.0295412410$, $a_2 = 0.2733020107$, and $a_3 = -1.9368112951$. $f(R)$
 332 is the radial correction factor, and (t_x, t_y) is the optical distortion corrected position of the
 333 measurement in the image plane computed by $(t_x, t_y) = f(R)(\tan_{xref}, \tan_{yref})$.

334 The unit vector of the measurement in the SRU (instrument) frame is given by

$$335 \quad \mathbf{V}_{SRU} = \frac{(1, -t_x, -t_y)}{(1 + t_x^2 + t_y^2)}$$

336 and the calibrated transformation $\mathbf{T}_{SRU_to_SC}$, maps the SRU measurement vector \mathbf{V}_{SRU} to a Juno
 337 spacecraft frame pointing vector \mathbf{V}_{SC} by

$$338 \quad \mathbf{T}_{SRU_to_SC} \mathbf{V}_{SRU} = \mathbf{V}_{SC}$$

339 with

$$340 \quad \mathbf{T}_{SRU_to_SC} = \begin{bmatrix} 0.420419 & 0.90732884 & 0.001389 \\ -0.000795 & -0.000795 & 1.0 \\ 0.907330 & -0.42042011 & 0.000233 \end{bmatrix}$$

341 The time dependent transformation from the Juno Spacecraft frame to J2000 at ephemeris time t
 342 is $\mathbf{T}_{SC_to_J2000}(\mathbf{t})$, determined using the Juno SPICE kernels,³³ which compute the position and
 343 attitude of Juno. The SRU measurement in J2000, \mathbf{V}_{J2000} , is given by

$$344 \quad \mathbf{V}_{J2000} = \mathbf{T}_{SC_to_J2000} \mathbf{V}_{SC} = \mathbf{T}_{SC_to_J2000} \mathbf{T}_{SRU_to_SC} \mathbf{V}_{SRU}$$

345 The CCD x-axis (along-row direction) and y-axis (along-column direction) are designated “Y”
 346 and “Z”, respectively, in the Juno frame kernel³³, where “X” is the SRU boresight vector. We
 347 mapped the planetocentric latitude and System III West longitude of each flash and computed
 348 Juno’s range to the flash location making standard SPICE Toolkit³⁴ corrections for one-way light
 349 time and stellar aberration. Pixel resolutions shown in Extended Data Table 1 include correction
 350 for optical distortion at the flash location in the image plane and represent the average of the
 351 along-row and along-column pixel dimensions (which differed by no more than one percent). We
 352 do not have knowledge of when the flashes occurred during the NoTDI image scans, therefore
 353 the lack of motion compensation introduces uncertainty as to their location. To bound the range
 354 of possible storm locations for these flash centroids, the computations were repeated for the
 355 spacecraft geometry corresponding to the end of the exposure time.

356 **Flash deconvolution.** To estimate the true profiles of the SRU flashes (prior to having been
 357 convolved with the camera PSF), background-subtracted pixel windows containing the flash
 358 signatures were de-convolved using MATLAB’s Richardson-Lucy iterative restoration
 359 algorithm, *deconvlucy*³⁵. The energy distribution shown in Extended Data Fig. 1 was used as the
 360 input PSF. The “readout” parameter (variance of the camera read noise; read noise squared) was
 361 set to 9. SRU CCD read noise is ~ 3 DN (48 signal electrons, rms), and dark current is negligible
 362 at the -40°C flight temperature. Photoresponse non-uniformity is 0.02, 1-sigma. Background

363 subtraction produced small negative values (close to the camera noise) in some pixels
364 surrounding the flash area. These negative values were set to zero prior to deconvolution. Three
365 hundred to one thousand iterations were used, which converged all solutions. Extended Data Fig.
366 6 shows an example reconstruction.

367 “NoTDI” image #2 was approached differently due to the dimness of the flash signatures and the
368 relatively high proximal signal from moonlit clouds encountered during the scan (cloud signal
369 was smeared due to the lack of motion compensation). The pixel array input to the algorithm
370 contained all signal above the electronic offset level and the “readout” parameter was set to 13 to
371 account for the highest locally observed pixel noise in the window. The background level
372 determined during the thresholding stage was subtracted after de-convolution. Only “string of
373 pearls” Flash 1 had sufficient intensity to be de-convolved for the purpose of assessing its shape.
374 Uneven cloud signal close to the remaining dimmer flashes prevented a reliable de-convolution
375 of their shapes.

376 **Flash duration.** The minimum resolvable flash duration at Juno’s 2-revolutions per second spin
377 rate is 2.7 ms. When the SRU is operated without motion compensation (NoTDI mode) the scene
378 is smeared along the CCD column direction at a rate of one pixel every 2.7 ms.¹⁴ Therefore, a
379 flash with duration ≤ 2.7 ms would have an along-column dimension of only 1 pixel following
380 de-convolution. Each additional pixel of along-column smear adds 2.7 ms to the estimated
381 maximum duration. The number of rows of pixels between each flash indicates the inter-flash
382 time separation. Extended Data Fig. 7 illustrates maximum duration for the three NoTDI flashes
383 that could be de-convolved. The true profile of “string of pearls” Flash 1 had an along-column
384 size of two pixels (and an along-row size of 1 pixel). Because the two pixels have similar
385 intensities and encompass the entire flash, we suspect that the center of the flash resides near the
386 boundary of these two pixels and that the actual flash size is one pixel or smaller. The actual
387 duration may therefore be shorter than 5.4 ms. Another possibility, not resolvable by the SRU, is
388 that all NoTDI flashes have a duration < 2.7 ms and the flash measurements represent the true
389 dimensions without any image smear. Maximum dimension estimates for this assumption are
390 shown as the second entry for each NoTDI flash in Extended Data Table 1.

391 When the SRU is operated with motion compensation (TDI mode) the rows of the image are
392 shifted towards an opaque storage region at a rate of one row every 2.7 ms.¹⁴ The first row of

393 useable data (numbered 1 in Supplementary Data 2) experiences an effective exposure time of
394 only 8.1 ms (two “dummy” rows of unexposed pixels precede this row). The flash duration
395 resolution is computed by determining the boundary of the flash signature that is closest to the
396 storage region and multiplying 2.7 ms by a factor equal to its row coordinate, plus two. The
397 result is the total time this row of the image was exposed to the scene, the total time the storm
398 was detectable by the SRU. When this computed value exceeds the commanded exposure time
399 (for example, flashes from 1 s exposures with boundaries above row 368) the exposure time is
400 the resolvable flash duration. These are the “effective exposure times” shown in Extended Data
401 Table 1. As with the NoTDI flash signatures, the durations of the flashes collected in TDI mode
402 may have been much shorter than the effective exposure time.

403 **Estimates of flash size.** The maximum dimension of each flash was estimated based on visual
404 inspection of the deconvolution solution. We assessed the maximum number of pixels which
405 could be assumed fully illuminated by flash photons, given that SRU flashes are small and not
406 fully spatially resolved. The longest dimension of this patch in pixel units was multiplied by the
407 optical distortion-corrected resolution (in km). Because the SRU was not pointed normal to the
408 Jovian cloud surfaces where the flashes were observed, we then corrected for foreshortening due
409 to the emission angle. The flash width was multiplied by the secant of the appropriate emission
410 angle component as calculated in the SRU frame (along-row or along-column, depending on
411 flash orientation in the image plane). A second estimate was made for flashes observed in NoTDI
412 images. Here we assumed a smaller steady state flash was smeared along the scan direction
413 during the exposure (see Extended Data Fig. 7). Additionally, each NoTDI estimate was
414 performed for the mapping of the flash at both the start and end of the exposure, due to the
415 position uncertainty created by the scan and the resulting effect on pixel resolution. A similar
416 approach was used for the HWHM results discussed in the text.

417 We assessed potential transverse image smear due to Juno’s high linear velocity relative to
418 Jupiter (>40 km/s for northern hemisphere observations, and ~31 km/s for the southern
419 hemisphere observation) by computing the distance between the mapped flash locations at the
420 beginning and end of the effective exposure time. This transverse distance was mapped into the
421 image plane in along-row and along-column components and was typically found to be
422 negligible (much smaller than a pixel). The four flashes with the longest effective exposure times

423 (750 ms to 1 s) had computed components that ranged from 0.32 – 1.06 units of pixel smear.
 424 However, given the very short flash durations observed in NoTDI imagery, we did not
 425 incorporate these worst case smear factors into our flash size estimates.

426 **Flash optical energy.** The optical energy of each flash was estimated following the method used
 427 by the Galileo lightning investigators.¹

$$428 \quad \text{Flash Energy} = \frac{(DN \text{ Sum})(Pixel \text{ Area})2\pi(\text{bandwidth})}{(\text{camera sensitivity})(\text{vignetting})(\cos^4)}$$

429 DNsum is the background-subtracted signal from all pixels in the flash signature. The Pixel Area
 430 was computed by multiplying the along-row pixel size by the along-column pixel size at the
 431 centroid location (following corrections for optical distortion). The SRU bandwidth is 650 nm.
 432 Field-dependent energy corrections for vignetting and \cos^4 law losses³⁶ were made to the energy
 433 estimates. Vignetting correction factors were based on observations of relative signal losses in
 434 SRU images collected without motion compensation where stars appeared as along-column
 435 streaks and showed decreased signal levels towards the edges of the field of view.
 436 Supplementary Data 4 provides the star streak data. The along-row and along-column
 437 components of each flash centroid were matched to star streak data with similar coordinates in
 438 order to estimate the potential field-dependent signal reduction. For optical systems such as the
 439 SRU there is a slight fall off of illumination in the image plane in the direction heading away
 440 from the optical axis. We model this loss using the “cosine fourth law,” where the signal is
 441 adjusted by a factor of $\cos^4\theta$, and θ is the angular offset of the flash location from the boresight.
 442 Flash energies were divided by vignetting correction factors ranging from 0.75-1 and \cos^4 factors
 443 ranging from 0.94-0.99, shown in Extended Data Table 2.

444 Because SRU lightning flashes are small and not fully spatially resolved we performed a second
 445 energy estimate treating the flash as a point source which emits over 4π sr.

$$446 \quad \text{Energy (point source)} = \frac{(\text{Energy outside})4\pi}{(\Omega)(\text{vignetting})(\cos^4)}$$

447 where the vignetting and \cos^4 correction factors are as noted above. “Energy outside” is the
 448 energy of the flash that reached the SRU optics

$$449 \quad \text{Energy outside} = (\text{DNsum})(2.6 \times 10^{-17} \text{ J/DN})$$

450 and Ω is the solid angle subtended by the active collection area of the SRU optics as seen from
 451 the flash

$$452 \quad \Omega = \frac{A_o}{(Range \times 10^5)^2}$$

453 Range is the range of Juno to the flash in kilometers (calculated to the 1 bar level using an oblate
 454 spheroid Jupiter shape model).

455 For flashes acquired in NoTDI mode, the optical energy values reported herein are the average of
 456 the value computed at the start of the exposure and the value computed at the end of the
 457 exposure.

458 **Global flash rate estimate.** A lower bound on the global flash rate can be computed by using
 459 both NoTDI image scans to determine the average flash rate per storm. The approach is similar
 460 to the method used for the Galileo global flash rate estimate,¹ but it utilizes two scanned
 461 observations. We make the conservative assumption that the “string of pearls” and “neighbor”
 462 flashes came from two separate storms and that both storms were visible for the full 1 s scan.
 463 Although there is a range of possible storm locations that would not have been visible for the
 464 entire 1 s exposure, this assumption will produce the minimum flash rate per storm. If we count 5
 465 flashes in NoTDI Image #2, conservatively treating “string of pearls” Flash 3 as a single event,
 466 the result is 2.5 flashes storm⁻¹ s⁻¹. A similar exposure time assumption for the two single-flash
 467 storms observed in NoTDI Image #1 (with maximum durations of 8.1 ms and 16.2 ms) yields a
 468 rate of 1 flash storm⁻¹ s⁻¹. The average rate is 1.75 flashes storm⁻¹ s⁻¹. Multiplying by 11 observed
 469 storms and dividing by the total surveyed area of 1×10^{10} km², the global flash rate is 6.1×10^{-2}
 470 flashes km⁻² yr⁻¹. This rate represents an average value and is not meant to imply that lightning is
 471 equally likely to occur at any location in Jupiter’s atmosphere. For comparison, the average
 472 annual global flash rate on Earth is ~ 3 flashes km⁻² yr⁻¹.³⁷

473 Some SRU images were not fully downlinked from the spacecraft due to imaging cadence
 474 constraints and some contained portions of dark sky. When this was the case, only the projected
 475 areas of pixels containing Jupiter were counted in the surveyed area. Pixels that were not
 476 downlinked are shown with zero values in Supplementary Data 2. The two dummy columns and

477 dummy rows are also represented with zero pixel values. The dummy rows are placed in the 511
478 and 512 row positions, which is an artifact of Juno's data de-commutation software.

479 **MWR lightning detection filtering criteria.** The MWR lightning detections recorded in
480 Supplementary Data 1 were selected based on the following criteria: the MWR antenna gain at
481 the projected location of the SRU flash detection was greater than -20dB relative to the peak
482 antenna gain, the time difference between the MWR detection and the start of the SRU exposure
483 was less than 185 s, and the MWR-detected lightning power was greater than three standard
484 deviations above the noise floor.

485 **Lightning generation above the 2 bar level.** We present two considerations for charge
486 separation in the 1-2 bar region of Jupiter's atmosphere.

487 In simulations of cloud formation at Jupiter²¹ small water ice crystals can be lofted to the 1 bar
488 region, but the sticking efficiency of ice particles is small relative to liquid. Hence, in a purely
489 icy regime, the efficiency of particle growth, charge separation, and lightning generation may be
490 less efficient, unless dynamical circumstances enhance the spread of particle sizes, such as in
491 anvils (discussed below). While liquid water is not expected at altitudes higher than the ~3 bar
492 level (as temperatures there fall below the ~-40 °C limit for supercooled liquid water), the
493 freezing point of water should not define the altitude limit of liquid droplets in Jovian clouds.
494 The equilibrium thermodynamics of the NH₃-H₂O mixture^{22,23} shows that for a volume mixing of
495 ammonia of 200 to 360 ppmv, as measured at Jupiter by Juno's microwave radiometer,^{29,30}
496 ammonia tends to be adsorbed into water ice crystals to form a liquid NH₃-H₂O mixture at
497 temperatures between -85 °C and -100 °C.²⁴ Hence these NH₃-H₂O droplets would be created
498 between ~1.1 and 1.5 bars, just above the 1.4 to 1.9 bar region where Juno's observations of
499 shallow lightning originate. As the droplets fall into the shallow lightning region they can collide
500 with water-ice particles that are still moving upward in the updraft, or even with water-ice
501 particles that are falling with a smaller terminal velocity than the droplets. Both the number of
502 particles and their terminal velocity differences would increase. The subsequent movement of the
503 particles away from each other would separate charge. Thus, this extension of the liquid field
504 provides a concomitant enlargement of the pressure-temperature regime over which charge
505 exchange, growth of particles, and hence lightning may occur.

506 Alternatively, lightning generation by charge exchange between solid icy particles is also
507 possible, because of additional effects in the microphysics of the collisions and potential large
508 scale dynamical effects. With regard to the former, additional effects that have been identified
509 include the enhancement of charge buildup by ionic impurities, and the formation of transient
510 liquid interfaces during ice-ice collisions.³⁸ With regard to the latter, lightning generation may be
511 enhanced in anvil clouds. Anvils are special environments in mature thunderstorms in which
512 strong horizontal winds and a transition from upwelling to downwelling flow are present; hence
513 a large range of particle sizes can be found there. A similar environment may be responsible for
514 Juno's observations of shallow lightning (we give credit to one of the referees for bringing this
515 option to our attention). Intense storms have been observed to reach above the 1 bar level and
516 have been attributed to deep rooted moist-convective water storms that can pierce Jupiter's
517 ammonium hydrosulfide and ammonia cloud decks.¹² Additionally, modeling has shown that
518 updrafts in Jovian convective clouds can transport condensates at velocities of several tens of
519 meters per second, allowing water ice particles of different sizes to develop and be lofted up to
520 these altitudes.^{21,39,40} Therefore ice-ice collisions in Jovian anvils²⁸ or high reaching moist-
521 convective water storms are plausible paths to lightning generation.

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540 **Data availability.** The authors declare that the Juno SRU data supporting the findings of this
541 study are available within the paper and its supplementary information files. The Juno MWR
542 data that support the findings of this study are available from the Planetary Data System archive
543 (<https://pds.nasa.gov/index.shtml>) as ‘Juno Jupiter MWR reduced data records v1.0’ (dataset
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555 **Author Contributions** H.N.B. led the acquisition and interpretation of SRU lightning data,
556 wrote the manuscript with input from coauthors, and performed the SRU camera response
557 computations. S.Bo. and T.G. contributed to the interpretation of shallow lightning atmospheric
558 dynamics. M.B. contributed to the acquisition of SRU lightning data and performed the SRU
559 observation geometry computations. J.A. contributed to SRU camera response computations,
560 flash identification and mapping, and analysis of camera vignetting characteristics. A.G.
561 computed the SRU survey area. S.A. and P.S. contributed expertise in Jovian atmospheric
562 dynamics and composition. J.L. assisted with the ammonia-water thermodynamics, the lightning

563 generation discussion, and construction of Figure 3. Y.A. contributed to the lightning generation
564 discussion. A.I. contributed to the SRU data interpretation. S.Br. analyzed the MWR data to
565 extract and filter MWR lighting observations. S.L. is the lead of the MWR.

566 **Competing Interests** The authors declare no competing interests.

567 **Supplementary Information** is available for this paper.

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569 **Reprints and permissions information** is available at www.nature.com/reprints.

570

571 **Extended Data Table 1 | Record of lightning flashes observed by the Juno SRU**

572 Flash names are interpreted Perijove Number_Image Number_Flash ID Number. 14_12 is
573 NoTDI image #1 and 17_13 is NoTDI image #2 (see text and Methods). TDI denotes motion
574 compensation by time delay integration. Flashes observed without motion compensation in
575 NoTDI mode have entries which correspond to mappings at the start of the image exposure (first
576 entry) and at the end of the image exposure (second entry, with asterisk). The “Effective
577 Exposure” is the maximum time the flash location was observed by the SRU. Ranges are from
578 the Juno spacecraft to the flash location on Jupiter (at the 1 bar level). Longitudes are System III
579 West longitudes. HWHM is the half-width at half maximum intensity distance. Energies in the
580 second column from the right assume each flash is a patch of light on a Lambertian surface.
581 Energies in the rightmost column treat the flash as a point source.

582

583 **Extended Data Table 2 | Supplemental parameters used in flash mapping and energy**
584 **calculations**

585 Time tags correspond to the start of the SRU image exposure. Row and column coordinates of
586 calculated flash centroids, \cos^4 correction factors, and vignetting correction factors are shown.
587 Flash names are as in Extended Data Table 1.

588

589 **Extended Data Fig. 1 | Properties of the SRU optical system. a.** Energy distribution of the
590 camera's point spread function, shown for an image of a point source. The scale bar indicates the
591 percentage of the total signal. **b.** The combined throughput of the SRU optical system, QT (CCD
592 quantum efficiency "QE" \times optics transmission "T"), as a function of wavelength.

593

594 **Extended Data Fig. 2 | Overlap of MWR Antenna 1 beam and SRU field of view during**
595 **lightning detections.** Circular 17-degree MWR beam contours (green and red circles) for MWR
596 lightning detections acquired within 30 seconds of an example SRU lightning flash detection
597 (inside the yellow circle). Red MWR beam contours correspond to footprint locations during the
598 1 s SRU image exposure (start time 2018-144T04:57:50.263).

599

600 **Extended Data Fig. 3 | Estimated half-width at half-maximum values.** De-convolved
601 lightning flash signatures are shown for flashes where a HWHM could be estimated. Estimates
602 represent the maximum possible value. The white circle indicates the maximum pixel area which
603 can be assumed fully illuminated by flash photons given spatial resolution limitations. The
604 estimated HWHM was generally less than the size of one pixel width. The red line in Flash
605 15_13_1 (panel e) indicates the diagonal distance of the estimated HWHM.

606

607 **Extended Data Fig. 4 | Morphology of signatures from optical vs. ionizing radiation**
608 **sources.** SRU Image 12, Perijove 13. Insets show magnified views of example signatures from
609 an optical source (lightning, circled in yellow), and an ionizing radiation source (penetrating
610 particle, circled in blue). Dimmer pixels are blue and brighter pixels are yellow. Signatures from
611 optical sources have a more symmetric appearance which follows the camera point spread
612 function.

613

614 **Extended Data Fig. 5 | SRU pixel coordinate system conversion.** Illustration of the
615 transformation from a pixel array numbered 1 to 512, to the 0 to 511 pixel coordinate system of
616 the SRU instrument frame.

617

618 **Extended Data Fig. 6 | Reconstruction of flash true profile.** Example reconstruction for SRU
619 lightning flash 11_12_1. **a.** Observed flash signature. **b.** Deconvolution solution; estimated flash
620 shape on Jupiter. The white circle indicates the maximum pixel area which can be assumed fully
621 illuminated by flash photons given spatial resolution limitations. 1-2 pixels are estimated to be
622 fully illuminated in this example. **c.** Result following convolution of the estimated shape with the
623 camera point spread function. **d.** Residual signal (**a.** minus **c.**).

624

625 **Extended Data Fig. 7 | Maximum durations of flashes observed with NoTDI.** **a.** Deconvolved
626 SRU flash 14_12_15. The white circles indicate a possible flash area for a steady state source at
627 the start (lower) and end (upper) of the exposure. The spacecraft spin direction and the direction
628 in which the scene will smear are indicated with white arrows. The maximum possible duration
629 is 8.1 ms (~3 rows of smear along-column). **b.** same for SRU flash 14_12_17; maximum flash
630 duration 10.8 to 16.2 ms. **c.** same for SRU flash 17_13_4 (“string of pearls” Flash 1); maximum
631 duration 5.4 ms.