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Direct evidence of whistler-mode waves in Mercury's magnetosphere: BepiColombo Mio flybys

4

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25 **Abstract (< 150 words)**

26 Whistler-mode chorus waves are natural electromagnetic emissions known to play a key 27 role in electron acceleration and loss mechanisms via wave-particle interactions in planetary 28 magnetospheres. No evidence of the presence of chorus waves in Mercury's magnetosphere has been 29 reported, because of its small size largely occupied by the planet. Here we present the direct probing 30 of chorus waves in the localized dawn sector during the first and second Mercury flybys by the 31 BepiColombo/Mio spacecraft. Mio's search coil magnetometers detected chorus events with tens of 32 pico-Tesla intensities in the dawn sector, while no clear chorus activity was observed in the night 33 sector. Simulation results suggest that this regional difference could be due to the impact of 34 background magnetic field inhomogeneities on the nonlinear wave generation process. This 35 observational evidence is crucial for understanding the energetic electron dynamics of the localized 36 dawn sector of Mercury's magnetosphere and the diversity of planetary magnetospheres.

37

38 Introduction

39 The planets in our solar system are very diverse¹, with some of them being magnetized (and thus possessing a magnetosphere) while others are not, and some bearing an atmosphere while 40 others do not. This significantly impacts their interactions with the solar wind, a permanent 41 super-Alfvénic and super-sonic plasma flow emitted by the Sun². Understanding the differences 42 between the Solar System planets is extremely important for identifying potentially habitable 43 44 exoplanets where life can exist. The Earth's magnetosphere acts as an impenetrable barrier for 45 relativistic electrons, protecting lifeforms from direct exposure to such high-energy particles³. 46 Although Mercury and Earth are magnetized planets, they exhibit certain differences. Mercury does not hold a rich atmosphere⁴, as Earth does, and has weak (approximately 1% of the Earth's) internal 47 magnetic fields that form only a small magnetosphere, as discovered by the Mariner 10 flyby 48 49 observation in 1974⁵. Electron observations by Mariner 10 showed Earth-like interactions with the solar wind that develop a bow shock and a magnetosheath surrounding Mercury's magnetosphere 50 similar to the morphology of Earth's, but with different spatial and temporal scales⁶. The 51 52MESSENGER observations during its flybys in the 2000s and in orbit in the 2010s quantified behaviors (e.g., an axially aligned dipole offset to the north by 0.2R_M, where R_M is the radius of 53 Mercury) of internal magnetic fields^{7, 8, 9} and a small magnetosphere. The MESSENGER's Fast 54 Imaging Plasma Sensor (FIPS) detected ions with energies of 0.1-13 keV, and identified 55 quasi-trapped ring current ions in the planet's magnetosphere¹⁰, but the instrument did not measure 56 electrons. The MESSENGER electron measurements from ~10 keV to several 100 keV were made 57 either directly (e.g., solid state detectors) and/or indirectly using effects such as X-ray fluorescence 58 59 stimulated in anti-coincidence shields or within the structure of other instruments¹¹. The 60 MESSENGER electron observations revealed energetic electrons at all longitudes with energies

ranging from a few up to hundreds of keV, but those electrons have an asymmetric dawn to dusk 61 distribution^{11, 12}. The presence of supra-thermal electrons in 1 to 10 keV, inferred from X-ray data 62 and keV-electron precipitation events, were concentrated at the dawn sector of Mercury^{13, 14}. 63 MESSENGER also observed "loading and unloading" of the tail magnetic field strength similar to 64 65 what is observed during substorms on Earth, but with shorter temporal (only a few minutes) scales¹⁵. The MESSENGER data further showed that ~25% of the dipolarization events in the near-tail were 66 closely correlated with energetic electron injections¹⁶. Furthermore, those energetic particle 67 68 injections and dipolarization events are most frequent over the dawn side of the magnetosphere (see a review article¹⁵ and references therein). The planetary loss cone is large and it is not favorable to 69 70 keep stable particle trapping, because Mercury itself occupies a large portion of the small 71magnetosphere. However, Mariner 10's and MESSENGER's observations suggest that Mercury's 72 magnetosphere evolves with various dynamical kinetic processes.

It is widely accepted that whistler-mode chorus waves^{17, 18}, which are natural 73 74 electromagnetic wave emissions in the very low frequency range (VLF) (several hundreds to tens of 75 kHz), play an important role in electron acceleration and loss around magnetized planets via wave-particle interactions^{19, 20, 21, 22}. In particular, chorus waves interact with energetic electrons via 76 cyclotron resonance, which can lead to a localized enhancement of relativistic electrons that form the 77 Earth's and other planetary (Jupiter and Saturn) radiation belts^{19, 20, 21, 22, 23, 24}. Chorus waves are 78 79 commonly observed in the Earth's and other planetary (Jupiter, Saturn, and Uranus) 80 magnetospheres²⁵, but have not been identified in Mercury's magnetosphere. The Mariner 10 and MESSENGER spacecraft were not equipped with wave instruments that could probe into the VLF 81 82 range of chorus waves. The BepiColombo/Mio (another name for the Mercury Magnetospheric Orbiter (MMO)) spacecraft that was launched on 20th October 2018^{26, 27} fills this gap by carrying a 83 full set of plasma and wave instruments^{28, 29}, which will allow us to probe the dynamics of the 84 85 Hermean environment over a broad range of timescales. In particular, the search coil magnetometers on board Mio³⁰ were carefully designed for probing high-frequency magnetic fluctuations at 0.1 86 Hz-640 kHz, which include whistler-mode chorus waves, despite the harsh temperature environment 87 that varies from $+200^{\circ}$ C at Mercury's orbit to -55° C during the cruise. To take advantage of the 88 89 planned Mercury flybys during the cruise phase, the Mio search coil magnetometers were operated 90 to tentatively detect VLF magnetic fields before the instruments are operated with their full 91 capabilities after the final insertion at Mercury and boom deployment. Below, we show that this 92 attempt proved to be conclusive since the Mercury flyby observations gave evidence of chorus 93 waves based on the wave spectrum measured onboard, although finer structures of typical 94 rising-tone elements in the time domain could not be acquired due to the telemetry limitations.

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97 **Results**

98 Wave observations by Mio during Mercury flybys

Mio is in a cruise phase and will reach its final orbit around Mercury in December 2025, when all instruments will be deployed and full observations of plasma waves and plasma particles in the magnetosphere will be possible. Nevertheless, there are several other opportunities for measuring plasma waves, such as during planetary flybys. We present wave magnetic field data for the 1st and 2nd Mercury flybys in the VLF range measured by the Mio search coil magnetometers of the plasma wave instruments (PWI)²⁹ (see Wave magnetic field measurements in Methods section).

105 Figure 1 shows the Mio orbits and the wave spectra for the 1st (1st October 2021) and 2nd 106 (23rd June 2022) Mercury flyby events, in which the spacecraft crossed the nightside 107 magnetospheric tail toward the dayside region. The orbit is drawn in the Mercury solar 108 magnetospheric (MSM) coordinate system, where +X is oriented sunward, +Y is directed toward 109 dusk perpendicular to the Mercury–Sun line, +Z is oriented parallel to the north magnetic pole, and the origin is the magnetic dipole of Mercury located northward with an offset of 0.2 R_M from the 110 111 planet center. The closest approaches are at altitude of approximately 200 km at 23:34 UT and 09:44 112 UT in the 1st and 2nd flybys, respectively. The raw wave spectra include some electromagnetic interference from the spacecraft body (see Figure S1 in Supplementary Information (SI)) because the 113 114 5-m MAST boom on which the search coil sensors are mounted is not deployed during the cruise 115 phase. However, whistler-mode waves below the electron cyclotron frequency (estimated from an 116 empirical model⁹) were clearly observed in the frequency range 0.6-2 kHz during the 1st flyby event 117 (23:37 to 23:39 UT). Other wave activity below 1 kHz was observed from 23:20 to 23:22 UT when 118 Mio crossed the magnetic equator (and during 23:29 to 23:31 UT), but it is difficult to determine 119 whether they are natural wave emissions or electromagnetic interference from the spacecraft because 120 of their low signal-to-noise ratio (SNR). Similarly, whistler-mode waves were observed in the 121 frequency range 0.6-1.8 kHz during the 2nd flyby event (09:45 to 09:51 UT). Note that other 122 broadband plasma waves were also observed above 10 kHz, when Mio crossed the dayside magnetopause at 23:42 UT (1st flyby) and 09:50 UT (2nd flyby) and the boundary between the 123 124 closed and open field lines of the magnetospheric tail in the nightside at 23:19 UT (1st flyby). The 125 frequency of these broadband waves (that extend from ~10 to over 20 kHz, not shown) is higher than 126 the electron cyclotron frequency and possibly lower than the plasma frequency, and may play an 127 important role in locally heating the particles at these boundary layers.

128





Figure 1. Wave magnetic field spectra of whistler-mode waves in Mercury flybys. (a) BepiColombo 130 131 Mio orbits. The white solid-dotted line is the Mio trajectory during the 1st flyby (23:10–23:50 UT) 132 and the white dotted line is that for the 2nd flyby (09:10-10:00 UT). The blue, yellow, and sky-blue 133 curves are projections onto the corresponding planes. The dots indicate the Mio location every 5 134 minutes. The green shaded zone highlights the regions where the whistler-mode waves were 135 observed. (b and c) Wave spectra from 0.5 to 20 kHz measured by the search coil magnetometer 136 during the 1st and 2nd flybys. The white solid lines indicate the electron gyrofrequency estimated 137 from an empirical closed field lines model⁹. Note that panels b and c have different time ranges. The 138 color map image of Mercury in panel (a) is published at 139 https://photojournal.jpl.nasa.gov/catalog/PIA17386. Image credit of Mercury: NASA/Johns Hopkins 140 University Applied Physics Laboratory/Carnegie Institution of Washington.

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143 For both Mercury flyby events, clear whistler-mode wave activity appeared in the dawn 144 side after the closest approach, even for electron cyclotron frequencies of only a few kHz in the 145 nightside. In the 2nd flyby, which showed more activity, the whistler-mode waves were detected up 146 to near the dayside magnetopause. A video showing the spacecraft orbit and the location of the 147 magnetopause and bow shock boundaries is given in the SI (supplementary movies 1 and 2). Because Earth's magnetic moment points southward, the Earth's chorus emission waves also show 148 stronger wave activity in the dawn side^{31, 32} due to electron injections from the magnetotail that drift 149 150 eastward. Mercury's magnetic fields with highly compressed (dayside) and stretched (nightside) 151 structures should impact the wave growth rate (see Figure 2 and the discussion below). Although chorus wave spectra in the Earth's magnetosphere typically show a power gap at half the electron 152 gyrofrequency^{33, 34, 35}, the observed whistler-mode waves at Mercury do not show such a gap. The 153 154 reason might be related to the characteristics of wave normal angles at the Mio's off-equatorial 155 region. A power gap can be caused by damping of obliquely propagating waves away from the source region³⁴. Unfortunately, information on wave normal angles and polarization is not available 156

because of telemetry limitation, but this gap should be filled by future flybys that will cover higherlatitude regions.

159 The propagation distance from the source to the spacecraft location may be different 160 between the night and dawn sides. Figure 1a shows that both flyby paths in the nightside were 161 located near the lower magnetic latitudes. This implies that the propagation effects from the source 162 cannot explain the presence of localized whistler-mode waves, and that other physical conditions 163 that impact the wave generation and growth processes are at work. We focus on the difference in the 164 background magnetic field between the night and dawn sectors. Because of the single-point 165 observations, it is difficult to specify regions that grow while propagating from the source region. As a simple assumption, we considered the curvature around a region with B_{min} , which maximizes the 166 linear growth rate³⁶. Figure 2 shows the distance between Mio and Mercury, the wave magnetic field 167 168 intensity, and the curvature of the background magnetic field line for both flyby events. The 169 curvature of the background magnetic field line is calculated from the relation

170
$$a = \frac{1}{s^2} \left(\frac{B(s)}{B_{min}} - 1 \right),$$
 (1)

171 where s is an infinitesimal distance along a background magnetic field line from the minimum background magnetic field B_{min} plane with a simple assumption of a parabolic curve³⁷. We use 172 $s = 0.2 R_M$ for the wave growth due to magnetic inhomogeneity. The background magnetic field 173 174 lines are plotted in Supplementary Figure S2 for reference. We found that whistler-mode waves can 175 be generated in a region with a lower curvature (below 1.5×10^{-12} m⁻²) on the dayside compared 176 with the wave activity measured at the same distance from Mercury in the nightside. The magnetic 177inhomogeneity is an important parameter that controls the threshold amplitude of the nonlinear wave growth rate for the chorus emission waves^{38, 39}. Previous electron observation¹² and simulation^{40, 41} 178 179 studies indicate that moderate energy (keV) electrons can be quasi-trapped at distances ranging from 180 1.1 to 1.5 R_M. The fact that Mio observed an enhancement of whistler-mode wave activity of several tens of pT for distances of 1.1 to 1.5 R_M is consistent with the region containing quasi-trapped 181 moderate energy (1–10 keV) electrons^{40, 41}, as these^{6, 11, 16, 40, 41} can act as seed electrons that feed the 182 183 instability leading to the observed whistler-mode waves. The observed whistler-mode waves should 184 become chorus emission waves at Mercury via a nonlinear wave growth process related to the magnetic inhomogeneity⁴². Assuming an electron density of 10 to 20 cm⁻³ in the plasma sheet^{6,43}, 185 the resonant electron energy for whistler-mode waves⁴⁴ at $0.2f_{ce}$ becomes 60 to 10 keV in both 186 events. The resonant electrons can then precipitate to Mercury's surface, which in turn can cause the 187 X-ray aurora observed at Mercury^{13, 14}. Our observations of dawn whistler-mode waves support the 188 MESSENGER observations of localized high-energy electrons concentrated at the dawn side¹² near 189 190 the equatorial region. The observed dawn whistler-mode waves reported here should also explain (at least partly) the precipitation of keV-energy electrons in the dawn sector^{13, 14}. 191



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Figure 2. Observed whistler-mode wave intensity related to the distance from Mercury and the background magnetic curvature. (a1 and a2) Distance from Mercury. (b1 and b2) Chorus wave intensity (gray) and smoothed data (black) using a running average. The green areas indicate the observed regions of clear dawn chorus. (c1 and c2) Curvature of the background magnetic field line at the location showing the minimum strength deduced from an empirical model⁹.

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201 Simulation results

To numerically estimate the effects of background magnetic field curvature on the generation of chorus emission waves at Mercury, we conducted a one-dimensional full particle-in-cell (PIC) simulation⁴⁵ along an ambient background magnetic field line modeled in a Mercury environment (see PIC simulations in Methods). Based on our previous PIC simulation studies, which successfully reconstructed chorus emission waves in the Earth's magnetosphere³⁶ and revealed the importance of nonlinear resonant currents in the generation of chorus emission waves⁴².

208 We note that the present simulation parameters (see PIC simulations in Methods) are different from the typical values taken for the chorus generation region of the Earth's inner magnetosphere, in 209 particular, we use a 10 times higher density of cold electrons⁴³, a one-tenth slower velocity of 210 energetic electrons (based on the scaling law⁴³ and Mariner 10 observations⁶), a 3 times wider loss 211 212 cone angle at the magnetic equator, and a much larger (10 thousand times) stretching of the 213background magnetic field line (based on the empirical model⁹). The assumed density ratio of energetic to cold electrons is smaller than that for the Earth's outer magnetosphere $(L\sim 10.5)^{34}$. 214 215 Therefore, our simulations offer new conditions to study the chorus wave generation, different from 216those at Earth.

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Figure 3. PIC simulations in Mercury's environment. RUN1 is for a less stretched field line condition estimated from the model for flyby observations. RUN2 is for a more stretched field line condition (4 times RUN1). In the lower panels, the black solid curves indicate the optimum amplitudes for $\tau = 0.15, 0.25, 0.5$, and 1.0 from the above curves (see Nonlinear wave growth in Methods section for the definition of τ), the dotted black curves are the threshold amplitude for triggered wave emissions at the source region, and the orange dots are simulated wave amplitudes.

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Figure 3 shows simulated dynamic spectra of magnetic field fluctuations of the forward wave packet with two different magnetic inhomogeneities at the magnetic equator: RUN1 has a small magnetic inhomogeneity whose value was determined from the observation conditions using an empirical

magnetic field model⁹; RUN2 has the same setup as RUN1 but with a magnetic inhomogeneity 230 231 4-times larger to reflect the conditions in the night sector, thus allowing us to study the impact of the 232 day/night magnetic field asymmetry on the wave generation. In RUN1 we clearly see the rising-tone 233 fine structure of the discrete chorus element similar to Earth's chorus emission waves, but we see no 234 specific wave excitation in RUN2. The spatial development of wave growth in both RUN1 and 235RUN2 are shown in Supplementary Figures S3 and S4. In the absence of accurate measurements of 236 the cold and energetic electrons densities, it is not possible to compare the wave amplitude observed 237 by Mio with the theoretical amplitude. However, we can compare the chorus amplitudes for the simulation with the theoretical prediction of nonlinear wave growth theory⁴² (see Methods). In 238 nonlinear theory, coherent and strong (a few percent of the amplitude of the background magnetic 239 240 field) chorus emission waves with rising-tone structures can nonlinearly grow from an incoherent seed and weak whistler-mode waves by the effects of a nonlinear resonant current⁴². The triggered 241 condition for the nonlinear wave growth process⁴² is given by 242

243
$$\frac{\Omega_{\rm w}}{\Omega_{\rm eo}} > \frac{\Omega_{\rm th}}{\Omega_{\rm eo}},$$

244 where Ω_w is the wave amplitude, Ω_{th} is the threshold wave amplitude given for the absolute 245 instability, and Ω_{e0} is the electron cyclotron frequency at the magnetic equator (source region). In the nonlinear process, the wave amplitude can take the optimum wave amplitude Ω_{op} for an 246 247 optimum wave growth condition⁴². The simulated chorus wave amplitudes in RUN1 are consistent 248 with the theoretical optimum amplitudes when the threshold amplitude is lower than the optimum 249 amplitudes. On the other hand, the threshold amplitude in RUN2 is larger than the optimum 250 amplitudes in the whole frequency band. The simulated waves in RUN2 show only thermal and 251particle noise coming from the limited number of energetic particles in the simulation system, which 252 are not fed by energy transfer from the electrons, and thus did not grow. Therefore, the fine 253 structures of the discrete chorus element observed in the simulation suggest that nonlinear 254wave-particle energy exchanges can occur under the specific Mercury magnetospheric conditions.

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256 **Discussion**

Despite operating with a non-deployed boom and limited telemetry in the cruise configuration toward Mercury, the Mio search coil magnetometers of the PWI found dawn chorus waves during the two flybys. This result suggests that chorus emission waves, which control the dynamics of energetic electrons through wave–particle interactions, are ubiquitous in all magnetized planets of our Solar System. The flyby observations strongly support the idea that the background magnetic inhomogeneity has a strong impact on the generation process of planetary chorus waves, which is complemented by the results of simulations in a Mercury environment.

The existence of dawn chorus waves in Mercury suggests the following three-step scenario,

265 illustrated in Figure 4. (1) The quasi-trapped electron ring current develops a temperature anisotropy, 266 in particular on the dayside, which is the seed for initial whistler-mode wave growth. Mercury's 267 magnetosphere has a larger loss cone angle of approximately 20 to 30 degrees than that of Earth of a few degrees⁹. The effects of drift electron motion in Mercury's complex background magnetic field 268 structures with such large loss cone angles are favorable for the development of temperature 269 270 anisotropy⁴¹. Large compressional background magnetic fields in the dayside take bifurcated background magnetic field minima at northward and southward latitudes above the magnetic equator. 271 272 Then, electrons with high equatorial pitch angles are forced to drift and get reflected at high latitudes without passing through the equatorial plane, the so-called Shabansky orbits⁴⁶. The MESSENGER's 273 plasma observations strongly support the effects of Shabansky orbits in Mercury¹⁶. These 274 non-energizing (drift shell splitting and Shabansky orbits⁴¹) processes based on the background 275276 magnetic field structures should play a role in developing the temperature anisotropy of seed 277 electrons. (2) Chorus waves strongly and rapidly scatter energetic electrons through wave-particle interactions^{47, 48}. The observed dawn chorus waves contribute to electron precipitation on the dawn 278 side, which can generate part of the X-ray aurora observed at Mercury^{13, 14}. However, the X-ray 279 280 aurora for Mercury is widely distributed from midnight to predusk sectors in contrast with the dawn chorus region identified during the 1st and 2nd flybys. A global map of chorus waves in Mercury is 281 282 important for understanding loss mechanisms of energetic electrons. In particular, the asymmetric 283 loss cone width in the northern and southern hemispheres may influence the northward and 284 southward chorus wave generation. (3) Chorus waves can also rapidly accelerate seed electrons from hundreds of keV to MeV^{20, 21, 22, 23, 24} in the limited L-shell. Unlike Earth, Jupiter, and Saturn, 285 Mercury has no permanent electron radiation belt^{6,40}. If a short-duration quasi-trapped radiation belt 286 could be generated at Mercury, chorus waves would play an important role in generating tentative 287 288 enhancement of higher energy electron populations.



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Figure 4. Three possible interpretations deduced from the dawn chorus in Mercury. The map of Mercury is published at https://photojournal.jpl.nasa.gov/catalog/PIA17230. Image credit of Mercury: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

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296 Further investigations of chorus wave activities are required to better understand the 297 electron dynamics in Mercury. This observational evidence of chorus waves obtained by Mio during 298 its Mercury flybys calls for designing and planning more ambitious scientific observations, even 299 with limited telemetry data, such as probing waveform data during future flybys and the science 300 phase after the final orbit insertion in 2025. The MAST boom on which the search coil sensors are 301 mounted will be fully deployed (up to 5-m length) from the spacecraft body. This deployment will 302 minimize potential electromagnetic interference from the spacecraft, allowing the search coil magnetometers to obtain data with the highest SNR to fully probe the plasma wave environments in 303 304 Mercury's magnetosphere (including refractive indices, wave-normal angles, polarizations, and fine 305 structures). To date, we still do not know whether the Earth and Mercury have similar spatiotemporal 306 properties of their electron-driven chorus. This question will be investigated by a comparison using 307 new observations of alternating current magnetic fields probed by the search coil magnetometers onboard the Arase satellite at Earth⁴⁹ and the Mio spacecraft at Mercury³⁰. The present study paves 308 309 the way for these challenging future investigations that will reveal how magnetized planet 310 environments are shaped by the solar wind in our Solar System, with potential extrapolation to 311 exoplanets and their interactions with stellar winds.

312

313 Wave magnetic field measurements

The wave magnetic field signals measured by the search coil magnetometers³⁰ are 314 processed by plasma wave instruments (PWI)²⁹ and the VLF wave spectrum is covered by the 315316 onboard frequency analyzer (OFA) of the PWI. In the 1st Mercury flyby, we took a higher temporal 317 resolution of 1 s using relatively few frequency bins of only 90 points from 32 Hz to 1.8 kHz in a 318 linear increase of a 32-Hz bandwidth and from 1.8 kHz to 20 kHz in a logarithmically increasing 319 bandwidth. In the 2nd Mercury flyby, we used a lower temporal resolution of 4 s and a higher 320 frequency resolution with 360 points for 32 Hz to 10 kHz in a linear increase and 10 kHz to 20 kHz 321 in a logarithmic increase. In both flybys, only wave spectra were measured (no waveforms) because 322 of the limited telemetry data in the cruise phase during which the spacecraft is not spinning.

323 Unfortunately, the wave magnetic field below 1 kHz was contaminated by electromagnetic 324 interference, though this will be reduced after the separation of Mio from the cruise module after 325 Mercury orbital insertion. Figures 1, 2, and S1 are plotted using the square root of the intensity by 326 the beta-axial sensor of the low frequency search coil (LF-SC) and the gamma-axial sensor of the 327 dual-band search coil (DBSC) mounted on the top plate. The raw wave magnetic field spectra that 328 include some noise are shown in Figure S1 in SI. The denoised wave spectra are shown in Figure 1 329 to provide further details on the whistler-mode waves. The line spectra showing the 1st to 10th 330 maximum power were suppressed during the denoising process. The noise-equivalent magnetic 331 induction (NEMI) for the LF-SC is approximately 40 fT/Hz^{1/2} and the NEMI for DBSC is 60 fT/Hz^{1/2} at a frequency of 1 kHz³⁰, which are sufficiently low for probing the observed 332 whistler-mode waves showing pT-intensity levels. In Figure 2, the wave magnetic field intensity is 333 calculated by integrating the raw spectrum in the frequency range from $0.2f_{ce}$ to $0.75f_{ce}$ for the 334 1st flyby and from $0.2f_{ce}$ to $0.45f_{ce}$ for the 2nd flyby for a typical frequency range of chorus 335 336 emission waves, where f_{ce} is the local cyclotron frequency calculated from an empirical model⁹. 337 We considered a narrower integration bandwidth during the 2nd flyby because the wave data is 338 subject to stronger interference. If the value of $0.2 f_{ce}$ is lower than 500 Hz, the wave magnetic field 339 intensities were not calculated to avoid noise contamination. The characteristics of the magnetic field 340 curvature in Figure 2 did not change when using a different value of $s = 0.4 R_M$.

341

342 **PIC simulations**

We model the dawn chorus in Mercury by flyby events using fully kinetic PIC code, which self-consistently solves Maxwell's equations and equations of particle motion taking into account the nonlinear Lorentz force and the mirror force coming from the background magnetic inhomogeneity. The simulation focuses on the region near the magnetic equator, which gives the maximum linear wave growth³⁶. The physical spatial scale is $\pm 10.24 \ c/\Omega_{e0}$ centered on the magnetic equator. The cell size satisfies the Courant condition⁴². To evaluate the generation process for chorus emission 349 waves in the stretched Mercury background magnetic inhomogeneity and prevent nonphysical 350 diffusion by enhanced electrostatic thermal fluctuations, we neglect the parallel electric field with 351 respect to the background field line and the difference in the loss-cone width for both the northern 352 and southern hemispheres. The background magnetic field line is simply modeled as a parabolic 353 function as written in Equation 1 ($a = 2.4 \times 10^{-3} c^{-2} \Omega_{e0}^2$ for RUN1) and the loss-cone size at the magnetic equator is 15.5 degrees. Hot electrons in Mercury's plasma sheet were identified using 354 in-situ observations of Mariner 10⁶. Electron density in Mercury's magnetosphere were of the order 355 356 of 5 particles/cm3 on an average and the typical energies ranged from 0.1 to 1 keV based on the 357 Mariner 10 electron measurements. A part of these hot plasma sheet electrons with a temperature 358 anisotropy should become a source to excite initial whistler-mode waves. The Mariner 10 electron 359 measurements revealed the presence of cold and dense plasma sheet and also hot and tenuous plasm 360 sheet with a rapid change. The plasma mass density was found to vary from 1 to 650 amu/cm3 using field line resonance by MESSENGER magnetometer data⁵⁰. We simply use two populations of 361 362 electrons in the simulation: a cold population described by an isotropic Maxwellian distribution and 363 an energetic population obeying an anisotropic Maxwellian distribution with a loss cone. We set the initial perpendicular and parallel velocity components (with respect to the background magnetic 364 field) to $V_{\text{th}\perp} = 0.079c$ and $V_{\text{th}\parallel} = 0.053c$, where c is the speed of light. We further assume 365 366 background immobile ions to neutralize the total plasma electric charge. In the linear wave growth 367 phase, as the temperature anisotropy of energetic electrons is an important parameter, we assume a weak temperature anisotropy $A_T = \frac{T_{\perp}}{T_{\parallel}} - 1 = 1.2$, where T_{\perp} and T_{\parallel} are electron temperatures 368 369 perpendicular and parallel to the field line. Typical temperature and densities of both cold and

perpendicular and parallel to the field line. Typical temperature and densities of both cold and energetic electrons for Mercury are determined from a scaling law between the Earth's plasma sheet and the solar wind⁴³. The density ratio of energetic to cold electrons is 0.05 and the ratio of plasma and cyclotron frequencies is 12. We assumed a severe condition using a dense cold component because the wave growth rate depends on the density ratio of energetic to cold electrons³⁶ and can take a larger value in a case with a hot and tenuous plasm sheet where the density ratio can be relatively high.

376

377 Nonlinear wave growth

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The threshold and optimum wave amplitudes are written as⁴²

379
$$\frac{\Omega_{\rm th}}{\Omega_{\rm eo}} = \frac{100\pi^3 \gamma^4 \xi}{\widetilde{\omega} \widetilde{\omega}_{\rm ph}^4 (\chi \widetilde{U}_{\perp 0})^5} \left(\frac{\widetilde{a} s_2 \widetilde{U}_{t\parallel}}{Q}\right)^2 \exp\left(\frac{\gamma^2 \widetilde{V}_{\rm R}^2}{\widetilde{U}_{t\parallel}^2}\right)$$

380 and

$$381 \qquad \frac{\Omega_{\rm op}}{\Omega_{\rm eo}} = 0.8\pi^{-5/2} \frac{|\varrho|\widetilde{V}_{\rm p}\widetilde{V}_{\rm g}}{\tau\widetilde{\omega}} \frac{\widetilde{U}_{\perp 0}}{\widetilde{U}_{t\parallel}} \widetilde{\omega}_{\rm ph}^2 \left(1 - \frac{\widetilde{V}_{\rm R}}{\widetilde{V}_{\rm g}}\right)^2 \exp\left(-\frac{\gamma^2 \widetilde{V}_{\rm R}^2}{2\widetilde{U}_{t\parallel}^2}\right),$$

- where the symbol "~" indicates normalized parameters (i.e., $\tilde{V}_{\rm p} = V_{\rm P}/c$, $\tilde{V}_{\rm g} = V_{\rm g}/c$, $\tilde{V}_{\rm R} = V_{\rm R}/c$, $\tilde{\omega} = \omega/\Omega_{\rm e0}$, $\tilde{\omega}_{\rm ph} = \omega_{\rm ph}/\Omega_{\rm e0}$, $\tilde{U}_{\perp 0} = U_{\perp 0}/c$, $\tilde{U}_{t\parallel} = U_{t\parallel}/c$, $\tilde{a} = ac^2/\Omega_{\rm e0}^2$),
- a is the coefficient of background magnetic field inhomogeneity at the generation region (magneticequator),
- Q is the depth of an electron hole,
- 387 γ is the Lorentz factor,
- 388 τ is the ratio of the nonlinear trapping time to the nonlinear transition time,

389 $\xi^2 = \omega(\Omega_e - \omega)/\omega_{pe}^2$ is a dimensionless parameter,

- 390 $\chi^2 = (1 + \xi^2)^{-1}$ is a dimensionless parameter,
- 391 ω is the wave frequency,
- $392 \qquad \omega_{pe}$ is the plasma frequency for background cold electrons,
- $\omega_{\rm ph}$ is the plasma frequency for energetic electrons,
- 394 Ω_e is the electron cyclotron frequency,
- $V_{\rm P}$ is the phase velocity,
- $V_{\rm g}$ is the group velocity,
- $397 \quad V_{\rm R}$ is the resonance velocity,
- 398 $U_{\perp 0}$ is the average perpendicular momentum of energetic electrons, and
- 399 $U_{t\parallel}$ is the thermal momentum in the parallel direction. All parameters except for Q and τ are 400 determined from the initial conditions in the PIC simulations. In Figure 3, the value of Q is 401 assumed to be 0.5 since this is a typical value.
- 402
- 403
- 404

405 **Data availability**

The spacecraft orbit data is available from SPICE data for BepiColombo https://www.cosmos.esa.int/web/spice/spice-for-bepicolombo. The PWI data will be available from the Center for Heliospheric Science https://chs.isee.nagoya-u.ac.jp/en/, or from the corresponding author upon reasonable request.

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411 **Code availability**

- The PIC simulations are based on the literatures^{36, 42} and the PIC code (KEMPO1) is available at http://space.rish.kyoto-u.ac.jp/software/.
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579 Author contributions

580 M.O. developed the scientific content of the study, analyzed the search coil data, numerically computed the chorus waves modeled in Mercury's environment, wrote this manuscript, 581 582 produced the figures, and contributed to the development of the LF-SC of the PWI. S.Y. led the 583 development of the LF-SC of the PWI and contributed to the PWI data analysis. Y.Kasaba is the principal investigator of the PWI and led the PWI observations during the flybys. Y.Kasahara and 584585 S.M. contributed to the PWI data production and analysis. Y.O. and M.H. contributed to the PIC 586 simulations, the numerical analysis based on the nonlinear wave growth theory, and its interpretation. 587 S.K is a member of BepiColombo young scientist group and contributed to the PWI data analysis. 588 F.S., L.M., and G.C. contributed to the evaluation of the DBSC data, its interpretation, and editing of 589 the manuscript. S.N. led the electromagnetic compatibility assessments of the Mio spacecraft and 590 contributed to the improvement of the PWI data by removing spacecraft noise. G.M. is the project 591 scientist and contributed to the Mercury flyby operations. All the authors provided feedback on the 592 manuscript.

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594 **Competing interests**

595 The authors declare no competing interests.596