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BepiColombo Mio Observations of Low-Energy Ions During the First Mercury Flyby: Initial Results

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Key Points:

- We present initial reports on low energy ion observations during BepiColombo's first Mercury flyby
- Mio observed large fluctuations of ion flux with time scales down to a few seconds around the magnetopause and within the magnetosphere
- Ion energy spectra obtained in the midnight magnetotail suggest the presence of an unexpectedly dense cold component

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Abstract

We present initial results of low-energy ion observations from BepiColombo's first Mercury flyby. Unprecedentedly high time resolution measurements of low energy ions at Mercury by BepiColombo Mio reveal rapid (a few seconds) and large (1–2 orders of magnitude) fluctuations of ion flux around the magnetopause and within the magnetosphere. Around the magnetic equator in the pre-midnight magnetotail, Mio observed plasma sheet ions consistent with previous observations. In the midnight magnetotail near the closest approach, Mio observed the co-existence of high-energy ($\sim\text{keV}/q$) and low-energy ($<\sim 300\text{ eV}/q$) ion components. The low-energy component is inferred to be cold with a temperature well below 100 eV and have a major contribution to the total density as opposed to previously reported cold tenuous ions. Future observations by Mio will provide insights into the sources, transport, and acceleration of the newly identified ion components.

Plain Language Summary

BepiColombo, launched on 20 October 2018, is now en route to Mercury. Along its 7-year journey to the Mercury orbit insertion, BepiColombo conducted, and will conduct, nine planetary flybys in total. This paper presents brand-new observations of ions (positively charged particles) in Mercury's magnetosphere by BepiColombo Mio during its first encounter with Mercury. Thanks to high-time resolution measurements by Mio, it is revealed that ions around Mercury change dramatically and rapidly just over a few seconds. Mio also observed an unexpectedly dense ion population with low energies, for which we do not have a definitive explanation yet. Future flyby and in-orbit observations by BepiColombo will provide key information for unraveling the dynamics and sources of ions in Mercury's magnetosphere.

1 Introduction

Driven by the intense solar wind in the inner heliosphere, Mercury's magnetosphere is known to be small and dynamic. Mercury's weak dipole magnetic field of $190\text{ nT}\cdot R_M^3$ (Anderson et al., 2012), where R_M is Mercury's radius, and high solar wind dynamic pressures at Mercury's orbit ($\sim 5\text{--}10$ times higher at $0.31\text{--}0.47\text{ AU}$ than those at 1 AU) result in small spatial dimensions of the magnetosphere with an average subsolar stand-off distance of $1.45 R_M$ (Winslow et al., 2013). Consequently, time scales of magnetospheric dynamics driven by the solar wind are considerably short at Mercury (e.g., Siscoe et al., 1975). Our understanding of Mercury's magnetosphere has been greatly advanced thanks to the two previous missions to Mercury, Mariner 10 and MESSENGER, but there remain many open questions as to the plasma sources, energy and mass transport, and particle acceleration processes in Mercury's magnetosphere, and their coupling to the exosphere, surface, and interior of the planet (J. Slavin, 2004; Raines et al., 2015; W. Sun, Dewey, et al., 2022).

BepiColombo conducted its first Mercury flyby on 1 October 2021. Near the closest approach, BepiColombo traversed low-altitude regions in the southern hemisphere, which were poorly sampled, or even never visited, by Mariner 10 and MESSENGER. During the flyby, the two spacecraft of BepiColombo, Mio and Mercury Planetary Orbiter, were in a stacked configuration (Murakami et al., 2020), and the Mercury Plasma Particle Experiment (MPPE) onboard Mio successfully measured low-energy ions and electrons in the vicinity of Mercury. This paper reports on initial results from low-energy ion observations by Mio during the first Mercury flyby. A broader overview of simultaneous observations of low-energy ions and electrons in Mercury's magnetosphere by Mio will be reported elsewhere.

2 Data and Model

We analyze low-energy ion data obtained by the Mercury Ion Analyzer (MIA), one of the seven sensors of the MPPE consortium onboard Mio (Saito et al., 2021). An energy-time (Et) spectrogram with a nominal time resolution of 4 s (which is the planned spin period) is generated from the MIA “Et” data product. This data product contains ion energy spectra for four directions according to spin phase such that energy spectra will be obtained separately for ions traveling approximately sunward, anti-sunward, dawnward, and duskward in the nominal in-orbit operation (see Figure 31 and Table 12 of Saito et al. (2021)). In a given spin, a full spin period is divided into 8 groups of spin sectors, spin sector groups 0–7. MIA generates the Et product for 4 directions consisting of spin sector groups 0 and 7 (direction 1), 1 and 2 (direction 2), 3 and 4 (direction 3), and 5 and 6 (direction 4). During the cruise phase, we can exploit this functionality to effectively enhance the time resolution from 4 s down to 1 s because the spacecraft does not spin and the field of view does not change rapidly during the cruise and flyby observations. By ordering the three sequential data points, namely directions 2 through 4, according to the data acquisition times and discarding the direction 1, which accumulates non-sequential data points from the first 1/8 and last 1/8 of the spin period, we obtain “quasi-1 s” resolution data recorded at a cadence of 1 s, 1 s, 2 s, 1 s, 1 s, 2 s, and so on. Due to the ongoing calibration of the lowest energies of the MIA energy sweep, we restrict our analysis to the MIA data above 80 eV/q in this paper. We note that mass-resolved ion data from the Mass Spectrum Analyzer (MSA) are unavailable near the first closest approach to Mercury. As Mio is behind the thermal shield during the cruise phase, most of the field of view (FOV) of MIA is blocked (Murakami et al., 2020), and we need to consider its unblocked, effective FOV when interpreting the data.

To aid the interpretation of the particle data, we utilize an empirical magnetospheric magnetic field model (KT17) developed by Korth et al. (2017). The KT17 model is parameterized by the heliocentric distance of Mercury and the disturbance index (DI) of Mercury’s magnetosphere (Anderson et al., 2013). For the former, we use the instantaneous heliocentric distance at the time of the observation. For the latter, we chose DI of 100, which represents the most compressed state of the magnetosphere that can be expressed by the model, based on locations of outbound magnetopause crossings identified from the ion observations as described in the following section. We conducted tests with different choices of DI, which did not qualitatively change the results presented in this paper.

Unless otherwise noted, we use the aberrated Mercury Solar Magnetospheric (MSM) coordinate system, which takes into account the northward offset of Mercury’s dipole and the solar wind aberration according to the instantaneous orbital velocity of Mercury and a typical solar wind speed of 400 km/s in the same manner as Korth et al. (2015).

3 Observations

Figure 1 shows the observation geometry of Mio’s first Mercury flyby on 1 October 2021. As seen in Figures 1a, 1c, and 1d, the spacecraft entered the duskside magnetotail from the flank magnetosheath around 23:10 UTC, crossed the magnetic equator ($Z_{MSM} = 0$) in the pre-midnight magnetotail at 23:17:37 UTC, traveled from midnight to dawn in the southern MSM hemisphere around 23:30–23:40 UTC near the closest approach, and exited from the post-dawn magnetosphere into the dayside magnetosheath around 23:41 UTC. Magnetic field line mapping with the KT17 model suggests that the spacecraft was located on closed field lines connected to the magnetic equator at radial distances of $\sim 1.7\text{--}4.9R_M$ (Figure 1a) and to the surface foot points near the open-closed boundary (Figure 1b).

Figure 2 presents the overall time series of MIA data along with predictions from the KT17 model. The white areas in Figure 2a represent data gaps. The colored labels on top of Figure 2a indicate plasma regions inferred from the ion data and the observation geometry. For selected time intervals (indicated by the horizontal bars with labels of “3a”–“3h” in Figures 2a and 2b), we present detailed characteristics of the ion data in Figure 3. In the following, we investigate ion signatures in each region.

Mio was presumably located in the magnetosheath before 23:07:45 UTC. During this time interval, MIA observed a relatively low flux of ions at a few 100 eV/q (Figure 2a). This signature can be interpreted as a small portion of magnetosheath ions detected by MIA’s limited FOV, which was directed mostly duskward (Figure 1a).

We infer that Mio crossed a transition region from the magnetosheath into the magnetosphere during 23:07:45–23:14:06 UTC. During 23:07:45–23:09:41 UTC, MIA measured intermittent flux enhancements at broad energies up to several keV/q superimposed on the continuous presence of a few 100 eV ions (Figure 2a). Figure 3e shows a zoom-in of the intermittent flux enhancements. The durations of the individual flux enhancements range from several seconds to a few tens of seconds, with the spacing of similar durations. Subsequently, MIA observed sustained broad energy spectra up to several keV/q along with a relatively high flux of low-energy ions at $< \sim 300$ eV/q during 23:13:04–23:14:06 UTC (Figure 2a). Figure 3a shows a representative energy spectrum at this time along with a two-component (a cold Maxwellian and a hot kappa distribution (Vasyliunas, 1968)) fitting result. When fitting the data, we assume that ions are isotropic and are all protons. We note that if planetary heavy ions are present, their fractional density is underestimated by a factor of $\sqrt{m/q}$ under the proton-only assumption (McFadden et al., 2008). In Figure 3a, it is seen that the observed spectrum is well represented by a superposition of a relatively cold, dense component and a hot, tenuous component. The hot component with broad energies is likely to be magnetospheric ions. The intermittent appearance of the hot ions (Figure 3e) and the mixture of relatively cold and hot ions (Figure 3a) suggest a structured and gradual transition from the flank magnetosheath into the low-latitude magnetotail encountered by Mio rather than a single crossing of a sharp boundary.

Mio crossed the magnetic equator in the pre-midnight magnetotail (Figure 1) at 23:17:37 UTC (indicated by the vertical black line in Figure 2). Around this time, MIA observed broad energy spectra, presumably of plasma sheet ions (Figure 2a). Figure 3b shows an energy spectrum obtained just before the magnetic equator crossing. We observe a one-component distribution well represented by a kappa distribution.

Next, we investigate ion signatures observed at low altitudes below 1000 km near the closest approach. Around 23:30 UTC, we observe the co-existence of two well-separated components, one at ~ 1 –3 keV/q and the other at $< \sim 300$ eV/q (labeled “3c” in Figure 2a) on field lines connected to the midnight magnetotail (Figure 1). Figure 3c shows the energy spectrum of the two-component ions. We observe two humps in the energy spectrum, which clearly deviates from a single Maxwellian or kappa distribution. The colored lines show two-Maxwellian fits to the data (for this spectrum, the hot component has too few data points to be adequately fitted by a kappa distribution). The cold component is inferred to have a low temperature (well below 100 eV) and relatively high density compared to the hot component. After the hot component disappeared at 23:30:20 UTC, a similar two-component signature reemerged around 23:32 UTC, and subsequently, the hot and cold components merged into one component at broad energies of ~ 100 –3000 eV/q (labeled “3d” in Figure 2a). As shown in Figure 3d, the merged component is characterized by a single Maxwellian-like distribution with a large kappa value.

The MIA quasi-1 s data reveal that the \sim keV/q ion component comprises finer substructures. Figures 3f and 3g show zoom-ins of flux variations at representative energies (during the time intervals labeled “3f” and “3g” in Figure 2b). In the quasi-1 s data, we

171 observe large, rapid flux fluctuations with ~ 1 – 2 orders of magnitude variations within
 172 just a few seconds. This time scale of the rapid flux variations corresponds to several pro-
 173 ton gyroperiods and to a fraction of the gyroradius divided by the spacecraft velocity
 174 (see the horizontal bars in Figures 3f and 3g). Thus, if these substructures originate en-
 175 tirely from temporal variations, they represent proton-scale time variations. If the ob-
 176 served variations are purely spatial and result from crossings of static structures, they
 177 represent sub-proton-scale spatial structures (see Figure 2e for ion gyroradii in kilome-
 178 ters).

179 We also observe signatures suggestive of absorption of magnetospheric ions by the
 180 surface of Mercury. Between the two vertical dashed lines in Figures 2a and 2b, the ob-
 181 served ion flux is reduced by a factor of >10 compared to that at the adjacent times. The
 182 reduced ion flux coincides with the time interval during which the effective FOV of MIA
 183 is predicted to be within the loss cone according to the KT17 model (Figure 2c). The
 184 predicted size of the loss cone is relatively large because of the strong local magnetic fields
 185 at low altitudes (Figures 2d and 2e).

186 We next examine the outbound magnetopause crossing. Overall, the peak energy
 187 shifted from ~ 1 keV/q down to ~ 200 eV/q during 23:40:30–23:41:10 UTC (Figure 2a).
 188 The ~ 1 keV/q peak energy is consistent with the ion population observed well within
 189 the magnetosphere. The relatively low energy peak at ~ 200 eV/q and intense ion flux
 190 exceeding 10^8 eV/cm²/s/sr/eV observed after 23:41:00 UTC suggest that the spacecraft
 191 crossed the magnetopause into the magnetosheath. Note that the direction of MIA’s FOV
 192 is more favorable for detection of the bulk component of magnetosheath ion flows de-
 193 flected along the magnetopause in the outbound magnetosheath as opposed to the in-
 194 bound magnetosheath (Figure 1). Figure 3h presents the time variation of 210 eV/q ion
 195 flux around the inferred magnetopause crossing. The MIA data clearly resolve multiple
 196 crossings, exhibiting at least 3 crossings within a 40 s interval.

197 4 Discussion

198 We now discuss Mio’s observations of low-energy ions in comparison with relevant
 199 observations at Mercury by the two previous missions, Mariner 10 and MESSENGER,
 200 and provide implications for future observations by BepiColombo.

201 Around the magnetic equator in the pre-midnight magnetotail, MIA observed a broad
 202 energy spectrum characterized by a kappa distribution with a density of ~ 16 cm⁻³, tem-
 203 perature of ~ 470 eV, and kappa of ~ 4.8 (Figure 3b). These parameters are generally
 204 in accordance with previously reported results (Gershman et al., 2014; Zhao et al., 2020).
 205 Specifically, the density (temperature) is near the higher (lower) end of the MESSEN-
 206 GER observations in the pre-midnight plasma sheet reported by Gershman et al. (2014).
 207 They also reported that the high-density, low-temperature plasma sheet tends to be ob-
 208 served under slower (and generally denser) solar wind conditions. According to Figure
 209 1 of Gershman et al. (2014), the MIA observation of relatively cold (~ 470 eV ~ 5.5 MK),
 210 dense (~ 16 cm⁻³) plasma sheet may indirectly imply a slow ($< \sim 300$ km/s) and gener-
 211 ally dense condition of the upstream solar wind during the flyby.

212 MIA measured the two components of high-energy (~ 1 keV/q) and low-energy ($< \sim 300$
 213 eV/q) ions (Figure 3c) around midnight in the magnetotail. The cold component pro-
 214 vides a predominant contribution to the total density (Figure 3c) as opposed to the re-
 215 portedly small cold to total density ratios ($\sim 10\%$) based on case studies (W. J. Sun et
 216 al., 2017) and average proton energy spectra in various spatial regions sampled by MES-
 217 SENDER (Zhao et al., 2020). The two-component energy spectra observed by MIA are
 218 reminiscent of multiple ion beams observed in the terrestrial Plasma Sheet Boundary Layer
 219 (PSBL) (Eastman et al., 1984, 1985; Nakamura et al., 1992; Hirahara et al., 1994; Parks
 220 et al., 2001). In the terrestrial PSBL, the high-energy component often represents a high-

221 speed ion flow, while the low-energy component comprises cold ions of ionospheric ori-
 222 gin. In this regard, a notable difference between Mercury and Earth is the lack of a sig-
 223 nificant ionospheric source at Mercury. The sources of magnetospheric plasma at Mer-
 224 cury are thought to be mainly provided by the entry of the solar wind plasma (Sundberg
 225 et al., 2012; Korth et al., 2014; DiBraccio, Slavin, Raines, et al., 2015; Jasinski et al., 2017)
 226 with a minor number density contribution from planetary heavy ions on average (Gershman
 227 et al., 2014). Thus, the cold dense component could be either a low-energy portion of
 228 magnetosheath ions that are transported to the low-altitude midnight magnetotail or plan-
 229 etary heavy ions that are denser than previously thought. To elucidate the sources and
 230 transport processes of the two-component ions, 3D velocity distribution functions and
 231 ion composition should be investigated in detail, much as done for the terrestrial mag-
 232 netotail. It is also remarkable that the hot component ions exhibit large variability over
 233 several proton gyroperiods in time and within a fraction of the proton gyroradius in space,
 234 implying their fundamentally kinetic nature. There appear to be plenty of possible drivers
 235 of the rapid ion flux variations in Mercury’s magnetosphere, which contains a variety of
 236 rapid ($< \sim 10$ s) fluctuations such as flux transfer events (FTEs) (e.g., J. A. Slavin et al.,
 237 2012), magnetotail flux ropes (e.g., DiBraccio, Slavin, Imber, et al., 2015), cross-tail cur-
 238 rent sheet flapping (Poh et al., 2020; Zhang et al., 2020), and Pi2-like pulsations (W.-
 239 J. Sun et al., 2015). The properties of the relatively dense, cold ions and the highly vari-
 240 able, hot ions in Mercury’s magnetosphere should be systematically investigated with
 241 future observations.

242 Neither of the inbound and outbound magnetopause crossings was a simple, sin-
 243 gle crossing of a sharp boundary. The high-time-resolution ion measurements by MIA
 244 indicate complex and rapid variations of ions of magnetosheath and magnetospheric ori-
 245 gins. Rapid, multiple magnetopause crossings at Mercury have been identified and an-
 246 alyzed mainly by high-time resolution magnetic field measurements, and were interpreted
 247 as quick relative motion of the magnetopause (Ness et al., 1974; DiBraccio et al., 2013;
 248 J. A. Slavin et al., 2014) and as a spatially structured and temporally evolving bound-
 249 ary such as Kelvin-Helmholtz waves and FTEs at the magnetopause (J. A. Slavin et al.,
 250 2008, 2012; Sundberg et al., 2012; Liljeblad et al., 2014; Gershman et al., 2015; Aizawa
 251 et al., 2020). Combination of high-time-resolution ion and magnetic field measurements
 252 by BepiColombo will shed new light on the dynamics of the magnetospheric boundaries
 253 at Mercury.

254 During the time interval in which the MIA FOV is directed within the loss cone
 255 predicted by the KT17 model, the ion flux measured by MIA is >10 times lower than
 256 that at the adjacent times. This is in agreement with the ion loss cone observed by MES-
 257 SENDER within Mercury’s magnetosphere (Winslow et al., 2014; Zhao et al., 2020, 2022),
 258 though we cannot conclusively confirm the ion loss cone from the flyby MIA data due
 259 to the limited FOV. In-orbit observations by MIA will provide the full 4π coverage, and
 260 in combination with magnetic field measurements, comprehensive energy–pitch-angle dis-
 261 tributions of ions will be available. Such data will enable ion reflectometry to remotely
 262 probe the surface magnetic field strength (Winslow et al., 2014) and possibly electrostatic
 263 potentials (Harada et al., 2017), as well as investigate surface-emitted ions such as backscat-
 264 tered and sputtered ions (Saito et al., 2008; Yokota et al., 2009; Raines et al., 2014; W. Sun,
 265 Slavin, et al., 2022).

266 5 Conclusions

267 This paper presents initial reports on low-energy ion measurements by Mio dur-
 268 ing the first Mercury flyby. The high-time resolution data obtained by MIA highlight
 269 the dynamic nature of low-energy ions in Mercury’s magnetosphere. Both of the inbound
 270 and outbound magnetopause crossings show the complex behavior of magnetosheath and
 271 magnetospheric ions as opposed to a simple, sharp boundary singly crossed by the space-
 272 craft. Around the magnetic equator in the pre-midnight magnetotail, MIA observed plasma

273 sheet ions with broad energies. The inferred density (temperature) of the pre-midnight
 274 plasma sheet ions is near the higher (lower) end of the reported range of the MESSEN-
 275 GER results, possibly resulting from a generally slow and dense condition of the upstream
 276 solar wind. In the midnight magnetosphere, MIA observed the co-existence of high-energy
 277 (\sim keV/q) and low-energy ($< \sim 300$ eV/q) components. The low-energy component is
 278 inferred to be cold ($T < 100$ eV) and have a major contribution to the total density
 279 in contrast to the previous results suggesting only a minor density contribution by cold
 280 ions. The hot ion flux shows ~ 1 – 2 orders of magnitude variations just over a few sec-
 281 onds, suggesting the presence of proton-scale time variations and/or sub-proton-scale spa-
 282 tial structures. The sources, transport mechanisms, and acceleration processes of the two-
 283 component ions remain elusive. As demonstrated by the rich information derived from
 284 Mio’s particle measurements with the still limited capabilities during the first flyby, fu-
 285 ture flyby and in-orbit observations by BepiColombo will provide revolutionary data for
 286 understanding the structure and dynamics of Mercury’s magnetosphere.

287 6 Open Research

288 The MIA data used in this paper are archived and publicly available (Harada et
 289 al., 2022).

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Figure 1. BepiColombo trajectory (a) projected on the $X_{\text{MSM}}-Y_{\text{MSM}}$ plane, (b) mapped to the planet surface along magnetic field lines predicted from the KT17 model (Korth et al., 2017) as a function of the foot point MLT and the foot point geographic latitude, and projected on the (c) $X_{\text{MSM}}-Z_{\text{MSM}}$ and (d) $Y_{\text{MSM}}-Z_{\text{MSM}}$ planes. The curved line labeled “B-line magnetic equator mapping” in Figure 1a shows a magnetic field line mapping to the magnetic equator ($Z_{\text{MSM}} = 0$). We use the instantaneous heliocentric distance and a disturbance index (DI) of 100 as input parameters for the KT17 model. In Figures 1a, 1c, and 1d, the colored, thin curves show the KT17 model field lines traced from the spacecraft position, and the black fans indicate the effective field of view of MIA during the observation. The gray curve in Figure 1a shows the KT17 model magnetopause. The dashed line in Figure 1b shows the open-closed boundary at which the traced field line distance exceeds $10R_M$ (Korth et al., 2014). The gray curves in Figure 1c show the KT17 model field lines on the $X_{\text{MSM}}-Z_{\text{MSM}}$ plane.

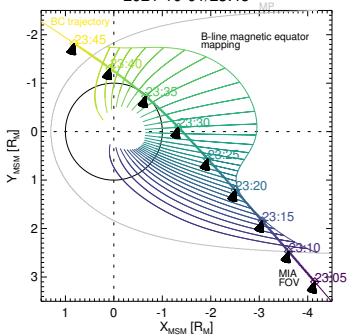
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Figure 2. BepiColombo Mio observations of low-energy ions during the first Mercury flyby. (a) Energy-time spectrogram of ions in units of differential energy flux ($\text{eV}/\text{cm}^2/\text{s}/\text{sr}/\text{eV}$) obtained by MIA with its nominal 4 s resolution, (b) quasi-1 s resolution data that are available only during the cruise phase, KT17 model predictions (Korth et al., 2017) of (c) pitch angle coverage of the effective field of view of MIA (black) and critical pitch angles of parallel and anti-parallel loss cones (magenta), (d) three components and magnitude of the magnetospheric magnetic field, and (e) gyroradii of 1 keV H^+ (blue) and Na^+ (red) ions as well as the spacecraft altitudes (black). The text label indicates the magnetic local time (MLT) and magnetic latitude (MLat) of the spacecraft position in the aberrated Mercury Solar Magnetospheric (MSM) coordinates as defined in Anderson et al. (2013). The horizontal bars in Figures 2a and 2b indicate the time intervals analyzed in detail in Figure 3.

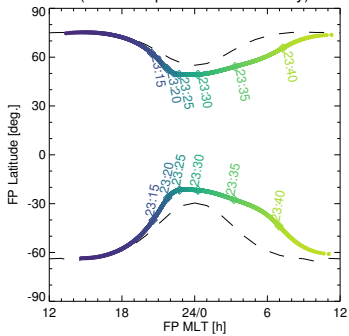
Figure 3. Detailed analyses of MIA data. Ion energy spectra obtained during (a) 23:13:26–23:13:42 UTC, (b) 23:16:20–23:16:36 UTC, (c) 23:30:00–23:30:16 UTC, and (d) 23:32:33–23:32:49 UTC. The colored lines show Maxwellian and kappa distribution fits to the data under the assumption of isotropy, proton-only composition, and a constant background (which is estimated from the average count rate at the two highest energy channels during 23:29–23:25 UTC). Two component distributions are assumed for Figures 3a (a cold Maxwellian and a hot kappa distribution) and 3c (two Maxwellian), while one component kappa distribution is used for Figures 3b and 3d. The best fit parameters are also shown (N is the density, T is the temperature, and kappa is the kappa parameter with subscripts c and h denoting the cold and hot components). MIA observations of rapid variations of ion fluxes (d) at 3130 eV/q during 23:29:50–23:30:20 UTC, (e) at 1795 eV/q during 23:31:50–23:32:20 UTC, and (f) at 210 eV/q during 23:40:30–23:41:10 UTC on 1 October 2021. The black lines show the quasi-1 s resolution data, while the blue lines show the nominal 4 s resolution data. The horizontal bars in Figures 3f and 3g denote the proton gyroperiod (T_{gp}) and the proton gyroradius divided by the spacecraft velocity (r_{gp}/V_{SC}) according to the magnetic field magnitude predicted from the KT17 model. In all panels, the error bars indicate uncertainties due to counting statistics.

Figure 1.

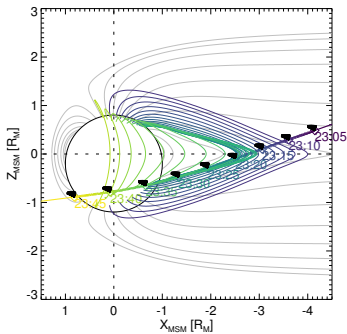
2021-10-01/23:05 ->
2021-10-01/23:45



(b) **B-line surface mapping**
(dashed: open-closed boundary)



(c)



(d)

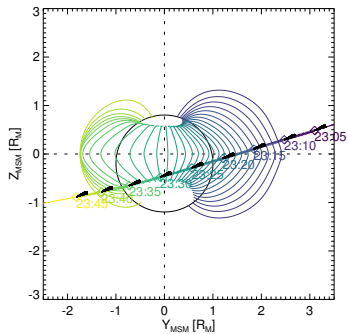


Figure 2.

BepiColombo Mio Mercury Flyby 1

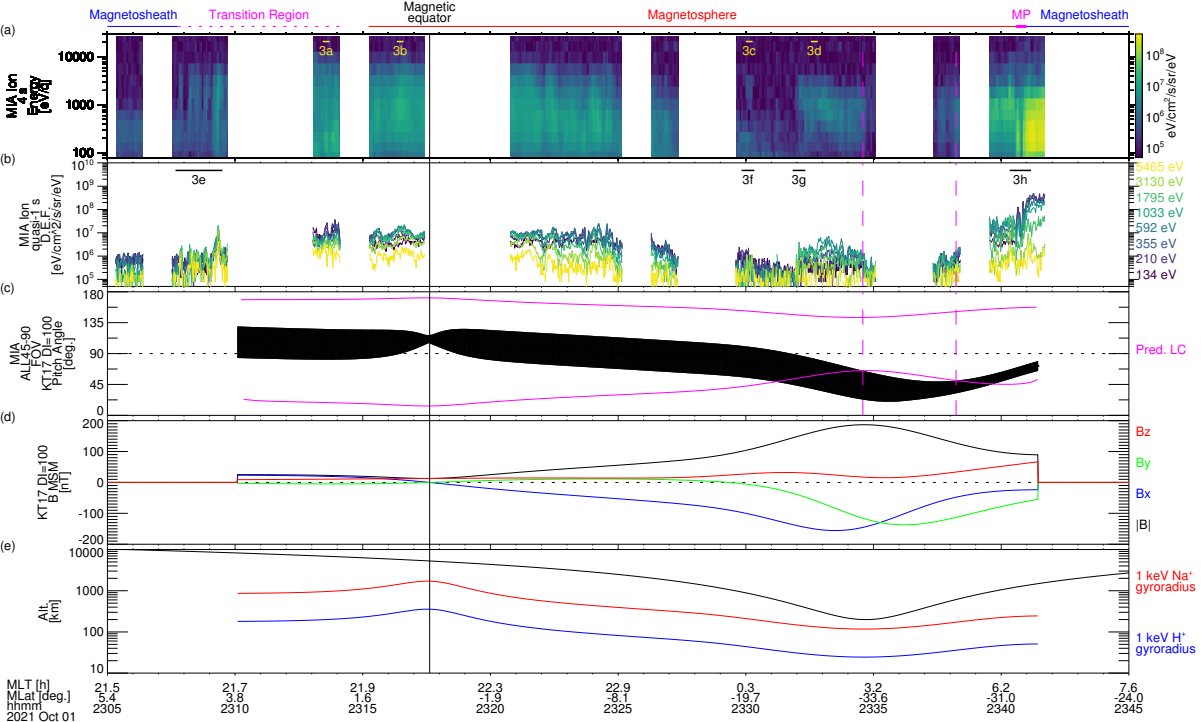


Figure 3.

