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The origin of observed magnetic variability for a sol on Mars from InSight

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.8	Key	Points:
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• InSight magnetometer data for sols 14 - 389 show daily magnetic field variations.

- The field strength consistently peaks in early-mid morning, with typical amplitudes 20 - 40 nT but can reach almost 80 nT.
- Wind-driven ionospheric currents predict some of the observed signal, including the increased amplitude during a regional dust storm.

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24 Abstract

Day-night variations in the magnetic field at Mars have been previously observed at satel-25 lite altitudes. The InSight Fluxgate Magnetometer (IFG) has provided the first evidence 26 for daily magnetic field variations at the martian surface. IFG data show diurnal vari-27 ations with typical peak amplitudes of of 20–40 nT in the early to mid morning; the am-28 plitude of the magnetic field varies over the first 389 sols of the mission and peaks be-29 tween sols 50 and 100. Temperature variations, solar array currents and lander activ-30 ities all generate magnetic fields. Particularly, the first two of these produce signals with 31 clear diurnal variations. We first assess the IFG data calibration and conclude that tem-32 perature and solar array currents have only minimal effects on the variability we observe 33 in the final calibrated magnetic field data. We use satellite magnetic field data and a Mars 34 Global Circulation Model to make predictions for the temporal evolution of wind-driven 35 fields in the ionosphere. Such fields vary due to seasonal changes in the ionization pro-36 file and the winds, and in the altitude range of the dynamo region, i.e. the region in which 37 electric currents can be produced. We find that the amplitude and seasonal variability 38 of the surface magnetic fields are generally consistent with those predicted from wind-39 driven currents. Moreover, a regional dust storm in the vicinity of the InSight landing 40 site, that started around sol 45, might be responsible for the higher magnetic field am-41 plitudes observed in the IFG data in the early part of the mission. 42

43 Plain Language Summary

The InSight lander carries a magnetometer, that has for the first time measured 44 magnetic fields on the surface of Mars. The observed magnetic field strength varies from 45 day to night and peaks in the early-to-mid morning. We report how the diurnal varia-46 tions have evolved over the first 389 sols (martian days) of the InSight mission, and show 47 that there are substantial sol-to-sol changes as well as more gradual changes over longer 48 timescales. We investigate whether these are caused by the diurnal variations in tem-49 perature of the magnetometer instrument and the electronics box, day-night-variations 50 in the currents drawn from the lander's solar arrays, and lander activities such as move-51 ment of the arm and satellite communications. We conclude that these sources are gen-52 erally well accounted for in the processed magnetometer data. We then investigate whether 53 the daily variations in the field could be caused by charged particles in the upper atmo-54 sphere (ionosphere) that move with the wind and generate electric currents. We model 55 this process using a climate model for Mars and find that the predicted magnetic fields 56 are consistent with the observed evolving diurnal pattern. This indicates that at least 57 some of the magnetic field variability on ground is indeed generated in the ionosphere. 58

⁵⁹ 1 Introduction

InSight, the Interior Exploration using Seismic Investigations, Geodesy and Heat 60 Transport mission, landed on Mars in November 2018 with the primary goal of study-61 ing the deep interior of Mars (Banerdt et al., 2020). The main science payload includes 62 a seismometer, a heat flow probe and a radio antenna. Several auxiliary instruments were 63 included to monitor environmental conditions that could be detected by the seismome-64 ter. One of those, the InSight Fluxgate Magnetometer (IFG) is providing the first mag-65 netic field measurements from the surface of Mars and has been operating almost con-66 tinuously since sol 14 (Johnson et al., 2020). 67

Magnetic field data recorded by the IFG have revealed a static crustal magnetic field with an amplitude of 2013±53 nT, much stronger than the surface field strength predicted from models based on satellite observations (Smrekar et al., 2018; Johnson et al., 2020; Banerdt et al., 2020). Furthermore, IFG data show time-varying fields (Johnson et al., 2020) including variations at the daily period, i.e., the period of one martian sol, and its harmonics, magnetic 'pulsations' with frequencies of ~100 seconds to ~10 min⁷⁴ utes that occur on some sols at specific local times (Chi et al., 2019), and transient sig-⁷⁵ nals, many of which are of lander and not martian origin.

Here we examine the daily variations in the martian surface magnetic field. These 76 can result from electric currents in the ionosphere that are driven by atmospheric winds 77 between ~ 130 km and ~ 180 km altitude, in the so-called dynamo region. In this region, 78 ions are collisionally coupled to neutral winds, while electrons gyrate about field lines. 79 The differential motion of ions and electrons builds up ionospheric currents. The heights 80 at which electrons or ions are no longer coupled to neutral winds are given by $h_{\rm e} = \nu_{\rm en} m_{\rm e}/|q_{\rm e}|B$ 81 and $h_i = \nu_{in} m_i / |q_i| B$ respectively, where m_i, m_e are the ion and electron masses, B is 82 the ambient magnetic field strength and ν_{in}, ν_{en} are the ion-neutral and electron-neutral 83 collision frequencies. At a given altitude above the surface on Mars, both $\nu_{\rm in}, \nu_{\rm en}$, as well 84 as B, are lower than on the Earth, because of the thinner atmosphere and the absence 85 of a global magnetic field (Opgenoorth et al., 2010). However, the difference in the mag-86 netic fields between the two planets is much larger than the differences in collision fre-87 quency, and thus the dynamo region on Mars is at higher altitudes than on Earth (Opgenoorth 88 et al., 2010). As a consequence, the dynamo region on Mars overlaps a region of higher 89 plasma density, whereas on Earth it lies in a region of higher neutral densities, well be-90 low the peak ionization altitudes. 91

Several previous studies have attempted to predict the magnitude and variability 92 of ionospheric currents and the resulting magnetic field, using satellite observations, as 93 well as ionospheric, magnetohydrodynamic (MHD) and Mars Global Climate Models (MGCM). 94 Withers et al. (2005) analytically calculated the expected altitude range of the dynamo 95 region, as well as the electrical conductivities and current densities in that region and 96 the resulting magnetic fields. They assumed a background magnetic field strength of 100 97 nT (appropriate to regions of moderate-strength crustal fields), a constant electron num-98 ber density, $n_{\rm e}$, across the dynamo region and a horizontal wind speed of 100 ms⁻¹. The 99 resulting current densities, j, were $\sim 1 \ \mu \text{Am}^{-2}$ producing a magnetic field of $\sim 40 \text{ nT}$ at 100 ionospheric altitudes. Further, it was shown that the presence of strong crustal magnetic 101 fields influences the electrical conductivity structure. Specifically, weak crustal magne-102 tization was shown to enhance conductivity especially at altitudes around 130 km (Opgenoorth 103 et al., 2010). Other studies using different approaches and assumptions also predicted 104 the magnitude of neutral-wind-driven ionospheric currents to be $\sim 1 \ \mu \text{Am}^{-2}$ (Fillingim 105 et al., 2010, 2012; Riousset et al., 2014; Lillis et al., 2019), approximately two orders of 106 magnitude greater than currents generated in nondynamic conditions, e.g., driven by plasma 107 pressure gradients (Fillingim et al., 2010; Withers et al., 2005; Riousset et al., 2014; Lil-108 lis et al., 2019). Mittelholz et al. (2017) assessed the average diurnal signal of the exter-109 nal (non-crustal) magnetic field as observed by the Mars Global Surveyor (MGS) satel-110 lite at around 400 km altitude, i.e., well above the ionospheric peak. They found that 111 the observed magnitude of ~ 10 nT at MGS altitudes and the zonal structure of the av-112 eraged field could be explained by wind-driven currents in the ionosphere. This is con-113 sistent with the work of Fillingim et al. (2012) who predicted ionospheric contributions 114 of ~ 10 nT at the surface and ~ 50 nT at 150 km. A recent study by Lillis et al. (2019) 115 specifically focused on the predicted surface field at the InSight landing site using atmo-116 spheric conditions from a MGCM and the ambient magnetic field from a MHD model 117 assuming a constant interplanetary magnetic field (IMF) for the duration of the MHD 118 simulation. Predicted field strengths at the surface were 10 - 100 nT, depending on sea-119 son and therefore on $n_{\rm e}$ and wind direction. A further complication is that in some re-120 gions crustal fields are sufficiently strong that they modify the ambient field direction 121 in the ionosphere, thereby influencing the currents and resulting fields that are generated (Riousset et al., 2014). 123

From this, we conclude that daily magnetic field variations at the surface from ionospheric currents (with $j \approx 1-10 \ \mu \text{Am}^{-2}$) are expected with amplitudes of a few nT up to ~100 nT. The magnitude likely varies with time because conditions in the ionosphere

change; $n_{\rm e}$ and the winds will vary with season and local time (Withers et al., 2015; Zou 127 et al., 2011), and the IMF varies with a 26-day cycle corresponding to Carrington ro-128 tations, i.e., the solar synodic rotation period at Mars, as well as on shorter periods (Marquette 129 et al., 2018). A priori, we thus expect daily variations in the magnetic field that may also 130 have aperiodic, seasonal and 26-day (and harmonics thereof) modulations. Such mod-131 ulations were observed in MGS magnetic field measurements (Langlais et al., 2017; Mit-132 telholz et al., 2017). IFG data at the inSight landing site provide the first surface con-133 straints on the daily variations in the magnetic field, and these can be compared with 134 model predictions to provide new constraints on ionospheric processes. 135

Analyses of the diurnal magnetic field variations recorded by the IFG require con-136 sideration of variations that are not of natural origin. Specifically, these include diur-137 nal temperature variations that affect the gain of the magnetometer, solar array currents 138 that are present during the daytime, as well as day-night variations in the occurrence 139 rate of lander operations, such as movement of the robotic arm or communication (Thorne 140 et al., 2020; Johnson et al., 2020; Banerdt et al., 2020). In fluxgate magnetometers such 141 as the IFG, ambient T changes affect the windings of the sensor coils and/or the feed-142 back coils and hence the resulting measured magnetic field. The ambient temperature 143 at the sensor head is measured directly. In addition to the winding geometry changes, 144 there can be changes in the magnetic permeability of the sensor mu metal core with large 145 temperature variations (Miles et al., 2017). 146

In this paper, we first show the evolution of diurnal magnetic field variations over 147 376 sols on Mars, spanning the time period from the beginning of the InSight mission 148 up to December 31, 2019 (Section 2). We then assess the temperature and solar array 149 calibrations used in processing IFG data, to determine the extent to which diurnal sig-150 nals in the calibrated IFG data might still contain contributions that are not of martian 151 magnetic origin (Section 3 and Supplementary Information). We use an MGCM (Forget 152 et al., 1999; González-Galindo et al., 2013) to predict neutral density profiles, electron 153 density profiles and neutral winds as a function of altitude, local time and season above 154 the InSight landing site. We also investigate how these quantities can vary during dust 155 season. We take magnetic field data from MAVEN and MGS, as well as models for the 156 crustal magnetic field, to characterize the altitude-dependence of the magnetic field, and 157 combine this information with the outputs of the MGCM to assess how the lower alti-158 tude of the dynamo region varies seasonally and during times of dust. We then compute 159 the electric current densities in the resulting dynamo region. Such currents produce mag-160 netic fields; we estimate the resulting magnetic field at ionospheric altitudes and scale 161 to predict the corresponding surface field strength. Finally, we compare such wind driven 162 magnetic fields with InSight IFG predictions to date (Section 4). 163

¹⁶⁴ 2 The Evolution of the Magnetic Field over Time

2.1 Data

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We select IFG data from the beginning of continuous IFG operations on sol 14 un-166 til sol 389 (Figure 1a), all publicly available as V4 data on the Planetary Data System 167 (PDS) (Joy et al., 2019). We use 0.2 Hz data whenever this is the continuous data rate 168 (sols 14-182 and sols 261-269). For time spans where 2 Hz data are continuously avail-169 able (sols 182-261 and since sol 284), we use 2 Hz data downsampled on the ground to 170 0.2 Hz (labeled as gpt2 on the PDS). The coordinate system is the Lander Level frame 171 (Joy et al., 2019), a local reference frame akin to that used in geomagnetism, in which 172 $\hat{\mathbf{x}}$ is north, $\hat{\mathbf{y}}$ is east and $\hat{\mathbf{z}}$ is down. Gaps occurred during Payload Auxiliary Electron-173 ics (PAE) anomalies and also between sols 270 and 283, when InSight experienced an 174 anomaly that could not be diagnosed and fixed until after communication with the space-175 craft resumed following the end of solar conjunction. 176



Figure 1. (a) Magnetic field strength, B, for sols 14–389. (b) The median daily signal over sols 14–389 as a function of local true solar time (LTST) for each component, in 10000 local time bins. B_x is red, B_y is green, B_z is blue, |B| is black, with the mirror image of B (i.e., -B) also shown so that time intervals in which any one component dominates the signal can be easily identified. (c)-(i) Median signal over 26-sol intervals, shown for alternating 26-sol time periods to cover the discussed time frame. The shaded grey, blue and green regions highlight local times from 05.00 hr - 10.00 hr, 10.00 hr - 15.00 hr, and 15.00 hr - 20.00 hr.

2.2 Magnetic Field Observations: Diurnal Variations

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IFG data exhibit clear temporal variations (Figure 1a). Detailed inspection of the 178 time series suggests that these are diurnal in nature, and this was confirmed by spectral 179 peaks at the daily period and its harmonics (Johnson et al., 2020). The longer time se-180 ries now available shows an overall decrease in amplitude over the almost 400 sols of data 181 (Fig. 1a). We examine the diurnal variation and its evolution as follows. First, we com-182 pute the median signal as a function of local true solar time (LTST) using all data be-183 tween sol 14 and 389. We detrend the data by removing the linear trend to remove the 184 background crustal field and any long time-scale variation, bin the data into 10000 LTST 185 bins corresponding to ~ 9 seconds per bin and take the median in each local time bin (Fig-186 ure 1b). The resulting signal is small at night, with the largest amplitude signals occur-187 ring in the morning between 05.00 hr and 10.00 hr LTST. Individual sols sometimes ex-188 hibit high-frequency variations (not shown); however these are often correlated with spe-189 cific lander operations (see extended data Figure 5 of Johnson et al. (2020)) and are not 190 the focus of this study. We prefer the median over the mean so that such outliers do not 191 bias the diurnal signature. 192

Motivated by these observations we examine the evolution of the median diurnal 193 signal on 26-sol timescales. For each 26-sol time frame, we remove sols that contain data 194 gaps longer than 10 minutes. For time frames that contain more than 50% of the sols 195 (i.e., 13 days), we detrend the data by subtracting the linear trend of the time frame, 196 bin and compute the median as a function of LTST as for the complete time series. We 197 choose 26-sol as our time interval (i.e., the approximate time frame of a Carrington ro-198 tation) to ensure sufficient statistics for obtaining a reliable estimate of the 'typical' di-199 urnal signal over a fairly short time period. At the same time a 26-sol window is short 200 enough so that we can capture seasonal variations and the effects related to the Carring-201 ton rotation should be averaged out. The 26-sol median signals show some consistent structure (Figures 1b-i). The largest amplitude fields always occur in the early-to-mid 203 morning. Earlier sols in general show a pronounced early morning peak up to almost 40 204 nT, that for later sols does not exceed 20 nT. An increase in magnitude is also seen in 205 the 10.00-15.00 hr interval, but its structure changes through the mission. The very pro-206 nounced peak just past 10.00 hr (e.g., Figure 1c, d) that is seen earlier in the mission, 207 vanishes at later sols, but a peak just before 15.00 hr develops with maximum amplitude 208 around sol 200. Evening and nighttime data exhibit mostly low amplitude signals. 209



Figure 2. The (a) mean and (b) peak amplitude of the magnetic field (circles) per sol (i.e., no running window) to highlight the day-to-day variability for all LTST (purple), and LTST time intervals 05.00 hr - 10.00 hr (black).

Furthermore, we evaluate the evolution of the daily mean and peak signal on a sol-210 by-sol basis (Figure 2) and for 26-sol windows (Figure 3). We also follow this procedure 211 using subsets of data limited in local time. Sol-to-sol variability (Figure 2) can be quite 212 large, with peak amplitudes that range from 20 nT up to almost 80 nT (Figure 2b), oc-213 curring almost always in the early morning. The mean daily signal is just below $\sim 10 \text{ nT}$ 214 over the entire sol and $\sim 15-25$ nT for the 05.00 to 10.00 hr period. Longer time-scale vari-215 ations are also seen, and are more clearly evident in the mean and peak amplitudes com-216 puted from 26-sol windows (Figure 3). For the 26-sol windows, we only calculate the mean 217 or peak daily value if at least 13 sols are available after removal of sols with data gaps 218 longer than 10 minutes. The steep decrease in the mean or peak amplitude after sol 100 219 is mostly caused by the decrease in amplitude of the signal between 5.00 hr and 10.00 220 hr (Figure 1). The evolution of the peak amplitude in the 10.00 - 15.00 hr interval shows 221 a similar pattern but with a smoother change around sol 100. In addition an increased 222 amplitude just before sol 200 is seen. The change in mean amplitude for all local times 223 is only a few nT, in the early morning the mean ranges from ~ 10 nT up to about 25 nT. 224

We investigated whether there was a characteristic correlation time scale for the 225 daily magnetic field variations by cross-correlating each complete sol with all other sols. 226 A characteristic time scale would be evidenced by e.g. several successive days of high cor-227 relation coefficients, followed by a drop in correlation. We found that the correlation co-228 efficient for the magnetic field strength was nearly always above 0.8 and did not show 229 times of higher correlation compared to others, i.e., no characteristic time scale was found. 230 This likely indicates that there is the same general diurnal variation in magnetic field 231 strength, even if there is no evidence that it repeats in a detailed fashion for multiple 232 days at a time. 233

We note that a time variable contribution is expected from the magnetization induced in the crust from inducing ionospheric magnetic fields. Although these two are coupled, calculations assuming an inducing field of maximum amplitude 100 nT and susceptibility values reported in Rochette et al. (2005) indicate that induced magnetization
is a very minor contribution to the total magnetization (i.e., < 1 %) at the InSight landing site (Johnson et al., 2020). Hence, we can disregard such induced contributions to
the measured time-varying magnetic field in this study.



Figure 3. The (a) mean and (b) peak amplitude of the magnetic field (circles) using a 26-sol running window of the binned days for all LTST (purple), and LTST time intervals 05.00 hr - 10.00 hr (black), 10.00 hr - 15.00 hr blue), and 15.00 hr - 20.00 hr (green). The mean and peak amplitude is plotted at the midpoint of the 26-sol window. Because the peak amplitude occurs between 05.00 hr and 10.00 hr the black and red symbols in (b) overly each other.

²⁴¹ **3** Artificial Drivers of Variations

As mentioned earlier the magnetometer was included in the InSight instrument payload for the purpose of characterizing magnetic signals of any origin (i.e., artificial or natural). Consequently spacecraft magnetic cleanliness was not required, and pre-launch characterization of magnetic sources was limited to two tests to evaluate the static magnetic moment of the lander itself, thermal calibration of the IFG from ~-60°C to room temperature, and a restricted set of tests regarding time-varying fields arising from specific spacecraft/commanding operations (Banfield et al., 2018; Joy et al., 2019).

For a full description of the calibration procedure and all raw calibration data we 249 refer to the SIS and Calibration Documentation available on the PDS (Joy et al., 2019). 250 In brief, the procedure involves steps (1)-(3) as follows: (1) Pre-launch calibrations of 251 the IFG dependence on sensor and electronics temperature are used to convert raw IFG 252 data from digital units into nT. (2) The pre-flight-determined spacecraft static field con-253 tribution is subtracted ([549, -434, 26.5] nT in the spacecraft frame). (3) Residual con-254 tributions from temperature and solar array currents are estimated via a linear least square 255 fit to the magnetic field at the end of step (2). Although temperature calibrations were 256 performed pre-launch, they did not encompass the full range of nighttime temperatures 257

expected at the InSight landing site and thus residual, uncorrected temperature-related signals were anticipated in the IFG data. The fit is expressed as $dB_{fit} = c_0 + c_1 ST + c_2 ET + c_3 SAC + c_4 SACT$, where c_0, c_1, c_2, c_3, c_4 are the constants determined by the fit which is done in the IFG frame. The typical variations of the sensor temperature (ST), electronics temperature (ET), fixed solar array currents (SAC) and 'total' solar array currents (SACT) with local time are shown in Figure 4(a-d) and are described further in the supplementary information. The fits are performed individually for each magnetic field component and subtracted from the step 2 data.

The ST, ET, SAC and SACT data are provided at different sampling rates, and furthermore the SAC and SACT data are not continuous in time, so each of these data streams are interpolated or modeled at the IFG data rate. Relevant issues are thus how well the models for ST, ET, SAC, SACT describe the actual calibration data, and what their influence is on the final magnetic field data product.

In the supplementary information, we discuss the four data channels used in the calibration, the uncertainties associated with them, and the resulting corrections to the data. We also summarize the effects of transient lander signals. As a result of these various corrections, our conclusion is that while we cannot rule out some remaining contributions of thermal effects, solar array currents and lander activities to the signals shown in Figures 1-3, we believe any remaining contributions to be small and not responsible for the temporal evolution we see in the daily variation.

²⁷⁸ 4 Wind-driven Ionospheric Currents

Wind-driven magnetic fields depend on atmospheric conditions, i.e., electron num-279 ber density and winds, as well as the geometry and amplitude of the background mag-280 netic field. All these quantities are dynamic and continuous observations at a given al-281 titude and geographic location are not available. MAVEN (Jakosky et al., 2015) provides 282 measurements of the magnetic field in the ionosphere that are intermittent in time and 283 space because of its precessing, elliptical orbit. These data, can however be used to build 284 a statistical picture of the magnetic field at ionospheric altitudes. Winds and electron 285 number density are variable, but have seasonal variations that can be modeled using a 286 MGCM. Furthermore, the altitude range of the dynamo region itself is dynamic and varies 287 with factors such as neutral density, electron temperature and the background magnetic 288 field. 289

In the following, we discuss the magnetic field (Section 4.1) and atmospheric properties (Section 4.2) in the dynamo region. We estimate the seasonal variations in the altitudes of the lower boundary of the dynamo region (Section 4.3). We compute the peak daily current-densities in the dynamo region, the resulting surface magnetic field strength and compare the magnitude and temporal variations in this strength with the InSight IFG data (Section 4.4).

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4.1 Magnetic Field at Ionospheric Altitudes

The background magnetic field depends on both the static crustal field and the lo-297 cally draped IMF. The contribution from the crustal field can be estimated using crustal 298 field models built with MAVEN and Mars Global Surveyor (MGS) data. These data sets 200 provide good coverage of ionospheric orbital altitudes down to about ~ 135 km (Mittelholz 300 et al., 2018; Langlais et al., 2019) and the field models at lower altitudes are downward 301 continued. They predict crustal magnetic field amplitudes around 40–70 nT within the 302 dynamo region (Figure 5), somewhat larger than the predictions of 20–30 nT, from ear-303 lier models based only on MGS data (e.g., Morschhauser et al. (2014)). 304



Figure 4. (a-d) Five representative sols of (a) sensor temperature, ST, (b) electronics temperature, ET, (c) fixed solar array current data, SAC, and (d) total solar array current data, SACT showing the models used for calibration (black solid line) and the data on which the models are based (blue circles). For ET we also show the actual ET (red stars), but the model was built using a proxy (blue circles) due to limited ET availability until sol 347. (e) The amplitude of the dB fit resulting from step (3) (see supplementary info for more explanation).



Figure 5. Three different models of the crustal magnetic field predicted at the InSight Landing Site. Mo14 (blue) includes only MGS data (Morschhauser et al., 2014)), the others also include MAVEN data and L19 is a global model (Langlais et al., 2019) and Mi19 is a local model (updated with data up to December 2019 from (Mittelholz et al., 2018)). The grey zone represents the dynamo region.

MAVEN data from November 2014–February 2020 can be used to investigate the 305 residual magnetic field after subtraction of the crustal field (Figure 6). Above weak and 306 strong crustal field regions (Figure 6a and c respectively) external fields show statisti-307 cally different characteristics during the day. Regions of strong crustal fields show large 308 external fields down to the lowest MAVEN altitudes, whereas weak crustal field regions 309 show lower peak residual fields, up to ~ 50 nT, at ~ 300 km altitude. The crustal field 310 above the InSight landing site is substantial, but less than that over e.g. regions of the 311 southern hemisphere (Figure 6 caption), and Figure 6 shows that the day-side residual 312 magnetic fields above InSight (6b) are intermediate between those above weak (6a) and 313 strong (6c) crustal field regions. All regions clearly show a dependence on LTST with 314 little to no external field contributions on the night-side. 315

The magnetic field residuals in Figure 6 represent the net effect of any external fields, 316 including the draped IMF and any interaction with the crustal field, as well as the iono-317 spheric fields that we are attempting to estimate here. Unmodeled crustal fields are also 318 included, but should be fairly small for shown altitudes because these data directly dic-319 tate the model and are not result of downward continuation (Langlais et al., 2019). Fur-320 thermore, crustal fields should be invariant with respect to local time; any residual sig-321 nal should be seen at night and such signals are notably absent in Figure 6. We cannot 322 separate contributions to the residual field above from ionospheric currents and the draped 323 IMF. Furthermore, depending on the orientation and magnitude of the draped IMF rel-324 ative to the crustal field at a given altitude, the external fields can either enhance or re-325 duce the crustal field. As a result, in what follows we simply use the crustal field strength 326 as background magnetic field strength at dynamo altitudes, but we discuss how this as-327 sumption might affect the results in Sections 4.3 and 4.4. 328



Figure 6. Binned residual amplitudes (data minus the model prediction of L19) above (a) weak crustal magnetization, (b) the InSight landing site, and (c) strong crustal magnetization includes $235^{\circ}E-285^{\circ}E$ in the Northern hemisphere (b) the InSight region includes a squared area 10° in each direction from the Landing Site Coordinates $4.5^{\circ}N$ and $135.6^{\circ}E$, (c) strong magnetization includes $135^{\circ}E-240^{\circ}E$ and below -5° in the Southern hemisphere. The mean and standard deviation crustal field (subtracted and thus not shown in figure) of all data between 140 and 150 km altitude for the different regions are: (a) $4 \text{ nT} \pm 2 \text{ nT}$, (b) $29 \text{ nT} \pm 23 \text{ nT}$, and (c) $230 \text{ nT} \pm 168 \text{ nT}$.

4.2 Atmosphere at Ionospheric Altitudes

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MGCMs allow us to build an understanding of the variability of atmospheric con-330 ditions that influence the current density, j, in the dynamo region. We use the Mars cli-331 mate database V5.3 (Millour et al., 2017), to produce a set of simulations of the Mar-332 tian atmosphere using the Laboratoire de Météorologie Dynamique MGCM (Forget et 333 al., 1999). This MGCM computes the seasonal evolution of the large-scale meteorolog-334 ical variables and transported species, from the surface to the exosphere at an altitude 335 of 250 km (González-Galindo et al., 2013; Chaufray et al., 2015). It is coupled with an 336 ionospheric module that predicts electron density in the upper atmosphere of Mars (González-337 Galindo et al., 2013). 338

We first generated a time series of the horizontal winds $(v_{\rm H})$ and electron number 339 density (n_e) above the location of Insight (4.502 °N, 135.623 °E) as a function of LTST 340 every 30° of solar longitude at an altitude of 130 km, close to the altitude of peak ion-341 ization in the atmosphere (Figure 7 a,b). These show that $n_{\rm e}$ is roughly symmetrical about 342 noon, and varies by 25% over a martian year. In contrast, wind speeds peak in the morn-343 ing and the amplitude of the peak speed varies by more than a factor of 3 over the year. 344 We approximate the current density at this altitude (assuming that it is within the dy-345 namo region) as $j = n_{\rm e}q(v_{\rm i} - v_{\rm e})$ where $n_{\rm e}$ is electron number density (and ion num-346 ber density assuming charge neutrality is preserved), q is the elementary charge and v_i 347 and $v_{\rm e}$ are the speed of ions and electrons respectively. Furthermore, we assume the dif-348 ferential velocity is driven by ions. In reality, electrons drift perpendicular to the neu-349 tral wind while they are also pushed in the wind direction by collision with neutrals. At 350 the base of the dynamo region, the net result is that they drift at a 45° angle to the neu-351 352 tral wind, with a speed of half the neutral wind speed both parallel and perpendicular to the neutral wind. Higher in the dynamo region, the electrons drift at a higher angle 353 to the neutral wind, but as the electron collision frequency decreases, the electron ve-354 locity decreases approximately as the ratio of the collision frequency to the gyrofrequency. 355 Thus our assumption that the electrons are stationary overpredicts the magnitude of the 356 current by less than 30% at the base of the dynamo region. Higher in the dynamo re-357 gion, this assumption becomes increasingly more valid. Therefore, in the following we 358 assume that electrons are stationary which gives an upper limit on the estimated cur-359 rent and the associated magnetic field. 360

Ions however are transported by winds, so we use the horizontal wind speed from 361 the MGCM for v_i . The vertical wind contribution is minimal, about one order of mag-362 nitude weaker (González-Galindo et al., 2009), and can thus be ignored. The LTST at 363 which j peaks lies between ~ 09.00 and ~ 11.00 hr (Figure 7c). This peak occurs at 9 am 364 for solar longitudes between 330° - 360° and 0° - 120° . Note that adding dust in the atmo-365 sphere (in the MGCM runs) delays the local time of the current peak for solar longitudes 366 330° -360° by up to 2 hours (not shown here). InSight data show a recurrent dominant peak (Figure 1 b-i) just before 10 am and a second peak after 10 am for earlier sols (Fig-368 ure 1 c-d), which could be driven by dust in the atmosphere. We can however make an 369 important prediction that is confirmed by InSight data: the current density at a given 370 altitude, and hence the resulting magnetic field, peaks in the mid morning. 371

However, the total ionospheric current depends on the vertically integrated current 372 density in the dynamo region, and requires (a) altitude profiles of $n_{\rm e}$ and $v_{\rm H}$ as a func-373 tion of $L_{\rm S}$ (b) consideration of changes in these profiles depending on dust conditions 374 in the atmosphere, and (c) estimation of the altitude range spanned by the dynamo re-375 gion for each of the scenarios in (a) and (b). We thus obtained profiles of $n_{\rm e}$ and $v_{\rm H}$ for 376 altitudes between 0 and 220 km as a function of $L_{\rm S}$, as well as the neutral density pro-377 file for CO_2 which is needed for estimating the lowermost altitude of the dynamo region. 378 We used average solar conditions, both with and without a dust storm scenario during 379 dust storm season, $L_{\rm S} = 180^{\circ} - 360^{\circ}$ (Figure 8a). Because we are interested in the evo-380

lution of the peak current and the resulting magnetic fields we proceed with the anal-

vsis at LTST 10.00 hr, motivated by the results above (Figure 7c). 382



Figure 7. (a) Electron number density, n_e , and (b) horizontal wind speed, $v_{\rm H}$, at 130 km altitude with local time for different solar longitudes (Ls) and (c) the resulting current i.

We first calculate current densities assuming that they can be produced at any al-383 titude (i.e., we simply compute $j = n_{\rm e}qv_{\rm i}$). We assess the actual altitude range of the 384 dynamo region below. The current densities vary with season and the peak amplitudes 385 fluctuate by more than a factor of two, reaching between 2.8 and 7.2 μ Am⁻² (Figure 8a). 386 The dust scenario also affects the current density amplitude, which reaches a maximum 387 current density of 8.2 μ Am⁻² for $L_{\rm S} = 180^{\circ}$. The main effect of the dust is an increase 388 in the altitude of the peak compared to the no-dust scenario. 389

390

4.3 Estimating the lower boundary of the dynamo region

Wind-driven magnetic fields can be estimated using the vertically-integrated cur-391 rent density within the dynamo region. The upper boundary of the dynamo region is at 392 \sim 180 km altitude, in a region where any current density would be very small (see Fig-393 ure 8a). However, the lower boundary lies around 130 km, in a region where the current 394 density as calculated above can be large (Figure 8a). Thus the position of this lower bound-395 ary is important and can greatly increase or decrease the vertically-integrated current 396 density if it moves down or up respectively. The lower boundary is defined by the alti-397 tude at which the electron gyrofrequency, $\omega_{\rm e}$, and the electron-neutral collision frequency, 398 $\nu_{\rm e,n}$, are equal. The background magnetic field modulates $\omega_{\rm e}$, and the neutral density 399 n and electron temperature $T_{\rm e}$ modulate $\nu_{\rm e.n}$. We use the L19 crustal field model (Langlais 400 et al., 2019) to calculate ω_e under the assumption that the crustal field is the most im-401 portant contribution to the ambient magnetic field at 130 km. Doubling the crustal field 402 estimate, which is probably an overestimate of possible external field contributions and 403 unmodeled crustal fields at this altitude (see Figure 6), leads to a change of about 2 km 404



Figure 8. (a) Wind driven current densities for different seasons, initially assuming currents are possible at any altitude. For solar longitude (Ls) 180-360 dashed lines represent a dust storm scenario. (b) Electron gyration frequency, ω_e (blue), and electron-neutral collision frequency, $\nu_{e,n}$, for different Ls (black) and with a dust scenario (red). The lower dynamo boundary is where $\nu_{e,n} = \omega_e$ and is shown in (c) as a function of season for the dust-free and dust scenarios.

in the lower boundary and we conclude that sensitivity to the magnetic field is small enough to justify neglecting additional external fields. We further estimate $\nu_{e,n}$ under the assumption that CO₂ is the dominant neutral constituent below 200 km (Chen et al., 1978; Schunk & Nagy, 2009). For T_e we use a functional fit derived from daytime MAVEN Langmuir probe data (Ergun et al., 2015). The resulting lower bound of the dynamo region (Figure 8b) fluctuates with season, from 115 km to 126 km altitude and a mean of 121 km, and dust consistently raises the altitude of the boundary up to 141 km.

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4.4 Magnetic fields due to ionospheric currents

The current density integrated between the lower and upper dynamo boundaries, notated as $\sum j(z)$ in the following, allows us to estimate the magnetic field strength from the wind-driven current system (Figure 9a) at ionospheric altitudes (Withers et al., 2005), B_{dynamo} . This requires an assumption about the geometry of the current and we calculate two end-members for (i) an infinite current sheet and (ii) a line current. For both of these end-members we can also approximate the resulting field strength at the surface $B_{surface}$.

For an infinitesimal current sheet, we assume steady-state currents of large extent in horizontal direction with a finite thickness. This case reflects a continuous line of line currents in the ionosphere each determined by the "right-hand-rule" and thus, the field does not change with distance from the sheet, but only changes sign depending on the location above or below the current sheet. The field at the edge of the dynamo region and at the surface are given by $B_{surface} = B_{dynamo} = \mu_0 * \sum j(z) * 1/2$.

For a line current, we assume that the width and thickness of the current region are equal resulting in the expression for the field at the edge of the dynamo region, $B_{dynamo} = \mu_0 * \sum j(z) * 1/\pi$. The magnetic field estimate can be scaled to the surface, using the scaling with distance from a line current at the mid-altitude of the dynamo region, as $B_{surface}/B_{dynamo} = L/(2H\pi)$, where L is the extent and H the altitude of the midpoint of the dynamo region. These two parameters vary with season, but are about 55 km for L and 150 km for H.

We calculate the values for B_{dynamo} and $B_{surface}$ for the InSight mission so far and 433 projected until the end of the primary mission, i.e., to the end of a martian year. For 434 the current sheet, the predicted magnetic field amplitude at ionospheric altitudes and 435 at the surface are equal and thus the surface prediction gives an upper bound estimate 436 of $B_{surface}$. This results in a mean and standard deviation of $B_{dunamo} = B_{surface} = 83$ 437 \pm 15 nT, and 105 \pm 22 nT in a dust scenario. The line current approximation results 438 in a mean and standard deviation magnetic field amplitude of $B_{dynamo} = 53 \pm 10 \text{ nT}$ 439 and 67 \pm 16 nT in a dust scenario and $B_{surface}$ = 9.5 \pm 1.8 nT and 12.1 \pm 2.5 nT in 440 a dust scenario. Dust leads to an increase in magnetic field amplitude because although 441 the altitude of the lower dynamo boundary increases, it is also results in an increase in 442 the altitude of the peak current density. The net result is that the peak current density 443 moves into in the dynamo region. In contrast, for the non-dust scenarios the peak cur-444 rent densities do not always lay in the dynamo region. 445

These estimates are consistent with previous estimates from MHD simulations (Lillis 446 et al., 2019), and the predicted fields at ionospheric altitudes from satellite data (Fig-447 ure 6). However, two aspects are important in comparison with Figure 6: (1) The lack 448 of data at dynamo altitudes with peak current densities does not allow for a direct com-449 parison of predicted and observed magnetic field amplitudes. (2) The region shown to 450 represent the external field environment around InSight includes data within 10° of the 451 landing site (Figure 6b) to increase the number of MAVEN data and even then, there 452 are fewer than 100 points per altitude bin at altitudes below 160 km. The crustal field 453 in this region is quite heterogeneous with field strengths at 130 km altitude varying by 454 a factor of two (see extended data figure in Johnson et al. (2020) for surface field). This 455 would affect currents produced in the dynamo region and predictions in this study are 456 limited to the crustal field right above the InSight landing site. 457

We compare the variability observed in the InSight magnetic field data (Figure 9) 458 with our estimates for wind-driven ionospheric fields. Such fields for the 26-day median 459 sols are 20 - 40 nT peaking during the dust storm and lying between our two end-member 460 scenarios for the wind-driven estimates. An increase in the daily peak amplitude is seen 461 in InSight data at the time of the regional dust storm, with peak values 10-20 nT larger 462 than at subsequent times. The wind-driven currents predict a steady increase in the peak 463 field from InSight Sol 180 to Sol 300 that is not seen in the IFG data. Regional or global 464 dust storms in the upcoming dust season will be of particular interest because larger am-465 plitude fields are predicted during those times. Sol-to-sol variability in the peak fields 466 observed by InSight (Figure 2b) likely reflects local changes in ionospheric currents that 467 are not captured in our simple, slowly-time-varying model. 468



Figure 9. Wind driven magnetic field response, |B| at the surface assuming that the dynamo region is a line current (solid line) or a current sheet (dashed line). The black line shows an average scenario, the red line shows a dust storm scenario during dust season. The brown area highlights the time at which a dust storm actually occurred during the InSight mission. The curve from Figure 3b shows the maximum amplitude of the observed magnetic field in a 26-sol running mean (purple) for easier comparison with wind-driven predictions.

Finally, we also note that the vertically-integrated currents depend strongly on the 469 location of the lower dynamo boundary, and this in turn is affected by the background 470 magnetic field. For example, a weaker background field such as the region shown in Fig-471 ure 6a would lead to an increased altitude of the lower boundary and thus a smaller am-472 plitude vertically-integrated current in the dynamo region and weaker resulting fields. 473 Similarly a stronger background field, which in the regions of strong crustal fields can 474 be several hundred nT at ionospheric altitudes and sometimes over 1000 nT, could de-475 crease the altitude of the lower boundary resulting in a larger amplitude vertically-integrated 476 current in the dynamo region and stronger resulting fields. Taking 0.1 and 10 times the 477 crustal field magnitude from the InSight landing site result in lower dynamo boundary 478 altitudes from 129 - 141 km and from 100 - 112 km respectively. This could contribute, 479 at least in part, to explaining the differences in the residual fields observed by MAVEN 480 on the dayside at ionospheric altitudes over weak and strong field regions (Fig 6a and 481 c) compared with those observed over the InSight region. Thus, we would expect to qual-482 itatively observe a similar pattern at a different landing site, but different amplitudes 483 of such signals. This might be of interest in future mission planning in which external 484 magnetic fields are of interest. This includes future electrical conductivity studies in which 485 external fields are used as inducing source fields. 486

487 5 Conclusions

Magnetic field data recorded by the IFG over the first 389 sols of the InSight mis-488 sion reveal daily variations in the magnetic field with typical peak amplitudes of 20–40 nT. The peak amplitude fields usually occur in the early- to mid-morning. Larger am-490 plitude fields were observed during the first ~ 100 sols. Sol-to-sol variability in peak am-491 plitudes can be large, and the peak field at the surface to date, unassociated with lan-492 der activities is ~ 80 nT. Assessment of the calibration procedure for IFG data, indicate 493 that temperature and solar array current variations have minimal influence on the final 494 calibrated data product. The largest uncertainty in any such remaining contributions 495 is the effect of solar array currents. This results from the lack of information on the ge-496 ometry of the solar array currents at any given time and the resulting magnetic fields 497 that would be expected at the IFG. We also note that solar array current data at a 1 498 Hz frequency whenever the lander is on has recently (since sol 426, February 7, 2020) 499

become available, which will be of benefit to future calibration efforts. Lander activities 500 have clear signals, that cannot be completely removed, but these are intermittent and 501 occur on time scales that are short compared to the daily variations of interest here. Wind-502 driven ionospheric currents produce magnetic fields; these depend on atmospheric prop-503 erties such as horizontal wind speed and electron density that we model with a Mars Global 504 Circulation Model. We compare this "average" state with that during a dust storm sce-505 nario, and compare the resulting magnetic field predictions with data observed during 506 the first 389 InSight sols. This simple model predicts the observed magnetic field am-507 plitude to within an order of magnitude. Furthermore, the predicted increase in mag-508 netic field amplitude of up to a factor of two during a dust storm scenario can be iden-509 tified in the data. We conclude that wind-driven currents are a major contributor to the 510 diurnal signal seen at the surface. These results indicate that ionospheric currents on Mars 511 provide a daily time-varying source field that could be used to probe the electrical con-512 ductivity structure of the martian mantle. 513

Data analyzed in this study comprise just over half a year (0.58 Mars years) on Mars. 514 Continued operation of InSight on Mars would allow future studies to investigate sea-515 sonal variability in greater detail, and in particular elucidate the effects of regional ver-516 sus global dust storms. It will also allow investigations of modulation of the diurnal sig-517 nal at periods such as the 26-day cycle associated with the IMF. Although the time frame 518 we discuss covers 15 such cycles, multiple PAEs early in the mission and a communica-519 tion issue during solar conjunction interrupt the existing time series, making such anal-520 yses difficult. However, even visual inspection of the data collected so far indicate that 521 any 26-day signal (or harmonics thereof), if present, are smaller in amplitude than the 522 typical sol-to-sol variability in the diurnal magnetic field signal. Finally, the time-varying 523 magnetic fields reported here provide steps toward characterizing the surface electromag-524 netic environment on Mars, specifically during the minimum between solar cycles 24 and 525 25. Changes in the surface magnetic field during the ascending phase of solar cycle 25, 526 in particular the effects of space weather, will be of particular interest and greatly fa-527 cilitated by joint surface (InSight) and satellite (MAVEN) observations. 528

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