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Reiner Gamma albedo features reproduced by modeling solar wind standoff

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All lunar swirls are known to be co-located with crustal magnetic anomalies (LMAs). Not all LMAs can be associated with albedo markings, making swirls, and their possible connection with the former, an intriguing puzzle yet to be solved. By coupling fully kinetic simulations with a Surface Vector Mapping model, we show that solar wind standoff, an ion–electron kinetic interaction mechanism that locally prevents weathering by solar wind ions, reproduces the shape of the Reiner Gamma albedo pattern. Our method reveals why not every magnetic anomaly forms a distinct albedo marking. A qualitative match between optical remote observations and in situ particle measurements of the back-scattered ions is simultaneously achieved, demonstrating the importance of a kinetic approach to describe the solar wind interaction with LMAs. The anti-correlation between the predicted amount of surface weathering and the surface reflectance is strongest when evaluating the proton energy flux.

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Discovered by early astronomers during the Renaissance, the Reiner Gamma formation is a prominent lunar surface feature. Observations have shown that the tadpole-shaped albedo marking, or swirl, is co-located with one of the strongest crustal magnetic anomalies on the Moon¹. All known swirls are co-located with magnetic anomalies, but the opposite does not hold^{2,3}. The evolutionary scenario of the lunar albedo markings has been under debate since the Apollo era⁴. Three possible formation mechanisms are currently discussed in the literature: (1) recent cometary and micrometeoroid impacts might have left behind remnant magnetisation and fine-grained, unweathered material that locally brightens the surface^{5–7}; (2) solar wind standoff due to the presence of lunar magnetic anomalies (LMAs), locally preventing weathering by solar wind ions and the subsequent formation of nanophase iron (np-Fe⁰) that darkens the regolith^{2,8–13}; and (3) magnetic sorting of electrostatically levitated high-albedo, fine-grained, feldspar-enriched dust^{13,14}.

Reiner Gamma's magnetic topology produces a mini-magnetosphere^{15,16} that locally shields the lunar surface from impinging solar wind plasma^{17–20}. Its tadpole-shaped albedo pattern consists of two dark lanes surrounded by the inner and outer bright lobes. The geometry of the magnetisation is believed to have a crucial role in reproducing the combination of dark lanes (believed to be areas where the crustal magnetic field has primarily vertical orientation with respect to the surface) and bright lobes (areas believed to have a more horizontal field orientation) of the Reiner Gamma swirl pattern^{21,22}. If the surface weathering pattern generated by the solar wind interaction with

the magnetic topology matches the observed albedo markings, it supports the formation of lunar swirls by solar wind standoff.

The validity of the solar wind standoff model, however, cannot be determined through evaluating the magnetic topology and magnitude of the crustal field alone, as magnetic shielding on small scales is an ion–electron kinetic mechanism¹⁷. A fluid (magnetohydrodynamic) or hybrid (using a kinetic description for the ions but describing the electrons as a mass-less fluid) approach requires surface magnetic fields and/or spatial scales of at least an order of magnitude greater than what is at present day inferred from in-orbit observations to shield the underlying surface, form Reiner Gamma's three bright lobes, and focus the solar wind plasma into its dark lanes^{8,22}. Here we use the fully kinetic code, iPIC3D²³, which self-consistently resolves both the ion and electron dynamics. We implement the three-dimensional (3-D) geometry and topology of the lunar crustal magnetic field using an open source Surface Vector Mapping (SVM) model based on Kaguya and Lunar Prospector magnetic field measurements²⁴. Our simulation addresses only solar wind standoff, as the other suggested mechanisms fall outside the current capabilities of self-consistent plasma simulation tools.

In this work, we show that solar wind standoff explains the correlation between the lunar surface albedo patterns and LMAs. The magnitude, the direction, and shape of the charge-separation electric field are the key ingredients that regulate the proton energy flux to the surface. The weathering profile generated by the latter quantity matches best the surface reflectance pattern observed by the Lunar Reconnaissance Orbiter-Wide Angle Camera (LRO-

Fig. 1 Comparison of the relative brightness of Reiner Gamma with the simulated surface flux patterns after the simulation has reached steady state. **a** LRO-WAC empirically normalised reflectance image for the Reiner Gamma region^{60,61}. **b** Normalised proton charge density profile below 1.35 km above the lunar surface from simulation. **c** Normalised proton number flux profile below 1.35 km above the lunar surface from simulation. **d** Normalised proton energy flux profile below 1.35 km above the lunar surface from simulation. All panels share the same spatial scale and linear colour scale

Fig. 2 Close-up of the Reiner Gamma albedo pattern and simulated energy flux to the surface after the simulation has reached steady state. **a** LRO-WAC empirically normalised reflectance image for the Reiner Gamma region^{60,61}. **b** Normalised proton energy flux profile below 1.35 km above the lunar surface from simulation. Both panels are extracted from Fig. 1 and share the same colour scale; **a**, **b** do not share the same spatial scale, **a** is zoomed 2.5 times compared to **b**

Table 1 Overview of the brightness and flux ratios surrounding the Reiner Gamma albedo pattern						
	WAC	<i>n</i>	<i>nv</i>	<i>nv</i> ²	<i>nv</i> ³	<i>nv</i> ⁴
BG/OB	0.18	1.53	0.94	0.48	0.46	0.12
BG/IB	0.27	0.18	0.08	0.04	0.22	0.01
BG/DL	0.50	2.61	1.56	0.99	0.65	0.37
DL/OB	0.36	0.59	0.60	0.48	0.7	0.33
DL/IB	0.54	0.07	0.05	0.04	0.34	0.02
IB/OB	0.66	8.5	11.5	11.6	2.09	11.2
χ^2		74.3	28.0	36.8	2.56	676

Each number is computed as the average over the relevant area(s) as indicated in Fig. 6. The two dark lanes and the two outer bright lobes are both evaluated as one region for this exercise. Note that slightly shifting the chosen regions (Fig. 6) may lead to slightly different ratios. The reported ratios are therefore only indicative for the observed trends. The simulated proton energy flux to the surface correlates best with the observed relative brightness. The bold values in the leftmost columns show the numbers (from simulation) which are the closest match with the observed numbers (WAC - from observations).
BG background, OB outer bright lobes, IB inner bright lobe, DL dark lanes

WAC). The reflected proton fluxes predicted by our fully kinetic simulations are in excellent agreement with in-orbit flux measurements from the Sub-keV Atom Reflecting Analyzer–Solar Wind Monitor (SARA-SWIM) ion sensor onboard the Chandrayaan-1 mission, reassuring that a kinetic approach to describe the solar wind interaction with LMAs is vital.

Results

Surface flux patterns. We focus on the plasma interaction under quiet solar wind conditions and for a solar wind velocity perpendicular to the modelled absorbing lunar surface at the centre of the computational domain (see Methods section for details). It is a scenario that allows us to extend our results for Reiner Gamma (Fig. 1a) to any LMA or sub-ion-inertial-scale magnetic structure embedded in plasma.

At steady state, the simulated proton charge–density pattern of Reiner Gamma at the surface (Fig. 1b) emerges, to first order, as the superposition of two horizontal dipoles/mini-magnetosphere structures¹⁷, and does not show any structural differences

compared to the input magnetic field model. Hence, the early two-dipole models²⁵ are a good first-order approximation for the Reiner Gamma magnetic field region. Locally the surface is shielded from up to 80% of the incoming solar wind plasma, while simultaneously protons are focused into the ‘cusp’ regions. The two regions of strongest magnetic field are co-located with the brightest albedo markings. As the solar wind interaction with magnetic dipoles has been well studied^{17–22,25–42}, it allows us better insight to confidently disentangle the plasma interaction with Reiner Gamma’s magnetic topology. The high proton density profile surrounding the density cavities (Fig. 1b), where supposedly the outer bright lobes are located, narrows significantly when evaluating the proton number flux to the surface (*nv*, Fig. 1c), and even disappears entirely on the outside of the profile and in between the two quasi-dipolar structures when evaluating the proton energy flux (*nv*³, Fig. 1d). This leaves behind two fine lanes inside the tadpole’s head that qualitatively appear to match the dark lanes of the Reiner Gamma albedo pattern. Most of the protons that break through the density halo have little energy flux when reaching the lunar surface (Fig. 1d) as also the magnetic pressure increases significantly towards the surface^{17,18}. The remaining areas of low proton energy flux surrounding the dark lanes are the outer bright lobes and the signatures of the tail. The SVM model overestimates the spatial scales (~2.5 times) when extrapolating the in-orbit measurements to the lunar surface, nevertheless it resolves all major components of the Reiner Gamma swirl (Fig. 2). Note that this spatial inconsistency does not bring us to a different characteristic magnetosphere scale⁴³. Note as well that in reality the surface magnetic field strength in the relatively small Reiner Gamma region may exceed the typically assumed magnetic field magnitudes of several hundred nanoTeslas by the SVM model. We argue that the latter is responsible for the fact that the finer-scale features of the Reiner Gamma swirl are not well resolved.

Importance of the charge-separation electric field. When comparing the brightness ratios between the various components of the Reiner Gamma albedo pattern with the inverse of the

Fig. 3 Overview of the simulated electromagnetic fields in the Reiner Gamma region after the simulation has reached steady state. **a** The surface magnetic field magnitude. **b** Difference of the horizontal and vertical magnetic field components at 10 km above the surface. **c** Normal (charge-separation) electric field at 10 km altitude. The profile cuts across the surface through the halo (below its density pile-up) for the larger mini-magnetosphere, but intersects the electrosheath around the tadpole's head and for the smaller quasi-dipolar structure to the North. Overlaid in black on all panels are selected contours of the proton energy flux to the surface

Fig. 4 3-D structure of the simulation. This figure is meant to illustrate the 3-D topology. **a** Side view of the reflected proton flux profile. The cut plane is indicated in the inset (top-down view). Although the number flux is a surface quantity, we assume this value constant per cell by construction. **b** Overview of the 3-D electromagnetic field structure surrounding the Reiner Gamma region. The density of field lines here is not an indication of field strength, but rather an ensemble to provide insight into the magnetic topology at steady state. Indicated as well are the regions where the charge-separation electric field is greatest¹⁸ (bright green shading: $E_x > 40 \text{ mV m}^{-1}$) and where magnetic null points might be found⁶² (red shading: $|B| < 10^{-4} \text{ nT}$). The bright green volume above the tadpole's head has a maximum thickness of 8.2 km. The normal charge-separation electric field, generated by the interaction of the solar wind with the magnetic structure, indicates the electrosheath location¹⁸

simulated flux moments to the surface, defined here as a proxy for the relative brightness of the surface²², the proton energy flux (Fig. 1d) correlates best with the observed relative brightness (Table 1; see Methods section for details). This means that even if a substantial number of protons hit the lunar surface, solar wind standoff might still initiate differential darkening as long as enough kinetic energy is lost due to the charge-separation electrostatic field before reaching the surface. The proton charge density (Fig. 1b) and proton number flux (Fig. 1c) do not follow the observed trend, as the outer bright lobes are not or barely present. Only the higher flux moment shows the presence of the outer bright lobes. Compared to the LRO-WAC reflectance ratio, the brightness of the inner bright lobe is overestimated by all simulated profiles, up to four times for the proton energy flux, and more than 12 times for the other moments. In contrast to the inner bright lobe, the magnetic field situated above the outer

bright lobes has a horizontal component that is not directly connected to a second cusp (a vertical magnetic field topology) across the density halo¹⁷ (Fig. 3a, b). The charge-separation electric field above this area (Fig. 3c) does not become strong enough to prevent enough protons from reaching the surface. They are merely slowed down. In the electrosheath directly above the largest density halo, where the surface magnetic field magnitude is greatest (Fig. 3a), the charge-separation electric field reaches $E_x = 141 \text{ mV m}^{-1}$, a number comparable to earlier estimates above mini-magnetospheres¹⁸. The speed and direction of the solar wind flow to the lunar surface significantly alter the weathering pattern^{18,40}.

Reflected proton fluxes. The 3-D simulated reflected proton flux distribution is highly non-uniform, both spatially and

Fig. 5 The simulated reflected proton number flux compared to Chandrayaan-1 observations at 20 km altitude. **a** The simulated reflected proton number flux at the full spatial resolution, normalised to the solar wind number flux. **b** The simulated reflected proton number flux scaled to the chosen Chandrayaan-1 spatial resolution (60×60 km), normalised to the solar wind number flux. Note that almost all fine-structure present in panel **a** has disappeared. **c** Proton number flux as observed by the SARA-SWIM ion sensor onboard Chandrayaan-1, traced back to 20 km altitude, normalised to the solar wind number flux. Bins with no data are coloured in white. The contours of the Reiner Gamma surface magnetic field pattern from the SVM model are indicated as well

quantitatively (Fig. 4a). This non-uniformity is directly correlated with the 3-D structure of the charge-separation electric field (Fig. 4b) and channels the reflected protons along certain directions only³⁹. Comparing the simulated reflected proton number flux fraction (Fig. 5a, b) with the measurements of the SARA-SWIM ion sensor onboard the Chandrayaan-1 spacecraft^{44,45} (Fig. 5c), we find a maximum of $(7 \pm 3)\%$ just north of the largest magnetic field component, corresponding well with the equivalent number from our simulation $((7.4 \pm 2.3)\%)$. Whereas Chandrayaan-1 observes a narrow pattern of reflected flux associated with Reiner Gamma, the simulation shows reflected protons over a much wider area. Note the slight difference in location of the maxima between the simulated and observed pattern. This is most likely due to the limited precision of the SVM model. Our simulation shows that even with a relatively small reflection fraction, it is possible to have a magnetised region that is almost completely shielded from the impinging solar wind plasma due to the horizontal magnetic field component (Fig. 1b).

Discussion

Our simulation presents the ‘toughest’ case, as a solar wind velocity perpendicular to the surface needs to re/deflect ions over the greatest angles to prevent them from impinging the lunar surface at the locations of the bright lobes. It is also the case which shows most clearly that the bright lobes correlate with regions where the magnetic field is mostly parallel to the surface, and that the dark lanes are co-located with the vertically oriented magnetic cusps²¹. In the case of Reiner Gamma, the latter does not receive more energy flux than the unmagnetised terrain surrounding the LMA (Figs. 1d and 3b). In addition, weaker magnetic field features away from the tadpole do not significantly distort the solar wind ion flow to the surface. This is evidence that only LMAs with a certain magnetic topology and with a sufficiently large magnetic field magnitude affect the flow of incoming solar wind ions enough to result in significant differential weathering. For example, the weaker magnetic features around Reiner Gamma (Fig. 4) do not influence the solar wind flow to the

surface, they show little structure and are more than an order of magnitude weaker than the main tadpole. As many LMAs have magnetic topologies that are far less structured as compared to Reiner Gamma, typically this means that the topology does not show any clear dipolar components, it suggests a straightforward explanation as to why not all LMAs are co-located with an observable swirl pattern. Our method outlines the underlying (plasma-)physical process: the formation/absence of a sufficiently large charge-separation electric field generated by the magnetic topology above the crust. Finding the best correlation with the simulated proton energy flux suggests a surface darkening mechanism that scales with energy flux, rather than particle or momentum flux^{46,47}. This may provide a new observational constraint as different observed states of np-Fe^0 can be associated with different space weathering processes⁴⁸.

For the first time, we show qualitative agreement between optical remote observations and in situ measurements of the back-scattered protons simultaneously coupled together by a fully kinetic simulation. With a spatial resolution matching the Chandrayaan-1 results⁴⁹, however, most of the fine-structure that could reveal the details of the underlying magnetic topology at spacecraft altitudes is lost (compare Fig. 5a and b). Fully kinetic simulation studies are the way forward until measurements of the lunar near-surface plasma environment on a kilometre-scale resolution become available, including fluxes, electric and magnetic fields, and dust movement on the lunar surface.

A finer insight of the kinetic interaction with sub-gyroradius-scale magnetic structures on the Moon will also benefit the analysis of related laboratory experiments⁴² and the study of magnetic anomalies on other (airless) bodies in our solar system⁵⁰. To understand the formation of the Moon, characterising the origin of the crustal magnetic anomalies has a key role⁵¹. Their possible consequences for lunar swirl formation are essential for the interpretation of our Moon’s geological history and evolution. They may help constrain the near-surface magnetic field, in this way providing new information to assist in planning the target areas for future lunar exploration opportunities^{51,52}.

Fig. 6 Comparison of the relative brightness of Reiner Gamma with the simulated surface flux patterns after the simulation has reached steady state. In contrast to Fig. 1, the colour scale is unsaturated. In addition, we indicate the areas used to calculate the brightness/flux ratios from Table 1. The background (BG) areas are coloured green, the outer bright (OB) lobes red, the dark lanes (DL) pink, and the inner bright (IB) lobe in black. **a** Lunar Reconnaissance Orbiter Wide Angle Camera (LRO-WAC) empirically normalised reflectance image for the Reiner Gamma region^{60,61}. **b** Normalised proton charge density profile below 1.35 km above the lunar surface from simulation. **c** Normalised proton number flux profile below 1.35 km above the lunar surface from simulation. **d** Normalised proton energy flux profile below 1.35 km above the lunar surface from simulation. All panels share the same spatial and colour scale

Methods

iPIC3D. In this work, we support the formation of the large-scale characteristics of the Reiner Gamma lunar swirl through solar wind standoff by simulating the solar wind plasma interaction with a reconstructed three-component lunar magnetic field topology, based on all available Kaguya and Lunar Prospector magnetic field measurements²⁴. Complementary to earlier work⁴⁰, we use a 3-D fully kinetic, electromagnetic particle-in-cell code (iPIC3D²³) that self-consistently resolves both the ion and electron dynamics. Our code implements the implicit moment method^{53–55}.

The simulation input parameters used in this work represent an electron–proton solar wind plasma at 1 AU. The upstream solar wind density equals $n = 3 \text{ cm}^{-3}$ and has temperatures $T_e = 13 \text{ eV}$, $T_i = 3.5 \text{ eV}$. The solar wind streams at 350 km s^{-1} perpendicular to the lunar surface. The interplanetary magnetic field measures 3 nT and is directed at a 45° angle towards the lunar surface. To keep the computational resources within budget, we use a reduced proton–electron mass-ratio of 256, a common practice in fully kinetic simulation methods. At steady state, as long as the separation of scales is guaranteed (which is typically the case for a mass-ratio greater than ~ 100), a reduced mass-ratio can be regarded as one more normalisation parameter⁵⁶. All input parameters are normalised accordingly, scaling to the proton charge-to-mass ratio. The simulation has a spatial resolution of 1.35 km in all three Cartesian directions, uses a time step $t = 1.75 \times 10^{-5} \text{ s}$ and hence resolves the electron inertial and gyro-scales. Our numerical scheme does not require us to resolve the Debye length.

The SVM model. To minimise distortions and induced magnetic field effects as much as possible in the magnetic field model, quiet solar wind and night-side magnetic field observations from the Lunar Prospector and Kaguya spacecraft were selected between 10 and 45 km altitude above the lunar surface to compute the lunar crustal field geometry and topology²⁴. The mean altitudes of the observations included in the model for the Reiner Gamma region ranged between 20 and 32 km (see Fig. 1 in Tsunakawa et al.²⁴). The 3-D spherical harmonic model is constructed

using the SVM method⁵⁷. The model is corrected for the solar wind pressure and the interplanetary magnetic field. Although extrapolating the magnetic field model from the observed altitudes to the lunar surface is mathematically sound at least if one assumes no contributions from sources external to the surface (highly unlikely), it remains an inverse boundary value problem. It is therefore almost certain that the surface magnetic field is poorly estimated near the surface, both in magnitude as well as in size and shape, because any short wavelength noise in the orbital magnetic field data will be amplified exponentially when approaching closer and closer to the surface⁵⁸. Magnetic field maps are most sensitive when the characteristic wavelength of the magnetisation is equal or comparable to the orbital altitude. Shorter wavelength variations are lost exponentially with altitude. For example, the kilometre-scale variations in the surface magnetic field discovered by Apollo 14 and 16⁵⁹ would not have been detected measuring from orbit. In reality, hence, the surface magnetic field strength in the relatively small Reiner Gamma region may exceed the typically assumed magnetic field magnitudes of several hundred nanoTeslas by our models. We argue that the latter, rather than the validity of the solar wind standoff, is responsible for the fact that the finer-scale features of the Reiner Gamma swirl are not well resolved. Independent of our efforts, the full richness of the crustal magnetic field topology will remain a mystery until in situ measurements become available that significantly extend the measurements by Apollo 14 and 16⁵⁹.

We calculate the magnetic field $\mathbf{B} = -\nabla V$ as the gradient of the magnetic potential V (r is the distance from the centre of the dipole, θ and ϕ are the spherical angular coordinates, m is the mode number, and N is the number of modes included)^{24,57}:

$$V = R_M \sum_{n=1}^N \left(\frac{R_M}{r} \right)^{n+1} \sum_{m=0}^n \left(g_n^m \cos(m\phi) + h_n^m \sin(m\phi) \right) P_n^m(\cos\theta), \quad (1)$$

which is given by

$$B_r = R_M \sum_{n=1}^N \left(\frac{(-n-1)R_M^{n+1}}{r^{n+2}} \right)^{n+1} \sum_{m=0}^n (g_n^m \cos(m\phi) + h_n^m \sin(m\phi)) P_n^m(\cos\theta), \quad (2)$$

$$B_\phi = \frac{1}{r \sin\theta} R_M \sum_{n=1}^N \left(\frac{(-n-1)R_M^{n+1}}{r^{n+2}} \right)^{n+1} \sum_{m=0}^n (-g_n^m m \sin(m\phi) + h_n^m m \cos(m\phi)) P_n^m(\cos\theta), \quad (3)$$

and

$$B_\theta = (\partial V / \partial \theta) / r, \quad (4)$$

where the derivative is computed via finite differencing:

$$\partial V / \partial \theta \sim (V(\theta + \Delta\theta) - V(\theta - \Delta\theta)) / 2\Delta\theta, \quad (5)$$

with $\Delta\theta = 10^{-5}$. $R_M = 1737.1$ km is the lunar radius assumed in the model. The spherical coefficients g_n^m and h_n^m are estimated up to $N \leq 450$. P_n^m is the Schmidt quasi-normalised associated Legendre function of degree n and order m . Finally, as our code uses a uniform rectangular mesh, the triple (B_r, B_θ, B_ϕ) is transformed to a Cartesian system. The unit vectors $(\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z)$ correspond locally to $(-\mathbf{e}_r, -\mathbf{e}_\theta, \mathbf{e}_\phi)$. $\mathbf{e}_x$ is directed normal and away from the lunar surface. Superimposed with the interplanetary magnetic field, this model is included in the simulation as an external magnetic field¹⁸. The surface is approximated as a perfect spherical absorber.

Brightness/flux ratios of the albedo pattern. As the spatial scales between our model and the observed albedo pattern are too different due to the inaccuracies of the SVM model, overlaying the observed and simulated quantities does not lead to a reliable estimate for their correlation, or better, for the ability of Reiner Gamma's magnetic topology to generate the characteristic features of its albedo pattern. Instead, we construct the brightness/flux ratios between the various major components of the Reiner Gamma albedo marking: the inner (IB) and outer (OB) bright lobes, the two dark lanes (DL), and the background (BG). The two dark lanes and the two outer bright lobes are both evaluated as one region for this exercise. The flux moment and WAC ratios were collected in the areas indicated in Fig. 6. For each area, the average brightness/flux was used to calculate the ratios reported in Table 1. To decide on the best correlation, a standard χ^2 -statistic is computed as well between the observed (the number of times the simulated flux moment ratios over/underestimate the WAC ratios) and expected (i.e., 1) values:

$$\chi^2 = \frac{(\text{observed} - \text{expected})^2}{\text{expected}}. \quad (6)$$

Although we do not assume an actual null-hypothesis to accept or reject, a relatively smaller χ^2 -value indicates a better correlation. Note as well that only the first 3 rows are included in the statistic. The lower three ratios are dependent and shown for completeness only.

Chandrayaan-1 data processing. The ion observations from the SARA-SWIM ion sensor⁴⁴ onboard the Chandrayaan-1 spacecraft are analytically backtraced down to an altitude of 20 km above the lunar surface (approximately 1 km above the density halo of the largest mini-magnetosphere) according to the solar wind magnetic and convection electric field as measured by the Solar Wind Experiment (SWE) and Magnetometer (MAG) instruments on the Wind spacecraft at the Earth-Sun L1 point, and time-shifted to account for the solar wind propagation time to the Moon. In our backtracing algorithm, we assume these fields uniform, hence, we do not account for perturbations by the crustal fields. This may cause small-scale tracing uncertainties. Given our spatial resolution these can be safely discarded. Note that Fig. 4 indicates relatively small perturbations of the solar wind magnetic field above ~20 km. These small perturbations are insignificant considering that the typical gyro-radii of the reflected protons in the solar wind are of the order of thousands of kilometres.

We select periods for which Reiner Gamma was at most at 60° solar zenith angle in correspondence with the simulation input parameters. The reflected flux is obtained by registering the inferred source location and differential number flux corresponding to each measurement. The differential fluxes are integrated over energy and multiplied by a solid angle of 1 sr to obtain an estimate of the total proton number flux. The latter value is chosen in accordance with the simulations that show a scattering cone width of roughly 60° × 60°. Based on the measurement variance, the maximum reflection rate is estimated to (7 ± 3)%.

Data availability. Access to the simulation data and code can be provided upon motivated request to J.D.

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Author contributions

J.D. and A.D. conceived the project. J.D. ran the production simulation and wrote the manuscript. A.D. provided the implementation of the SVM method and produced test simulations. T.A. helped with the implementation of the SVM method. C.L. provided the Chandrayaan-1 results. A.D., C.L., M.H. all contributed to the interpretation of the results and commented on the manuscript.

Additional information

Competing interests: The authors declare no competing interests.

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