



Energetic Fe Ions In And Near The Magnetospheres Of Earth, Jupiter, And Saturn



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S.P. Christon (1), D.C. Hamilton (2), J.M.C. Plane (3), D.G. Mitchell (4), W. Spjeldvik (5), V.L. Frankland (6), and S.R. Nylund (4)

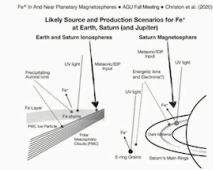
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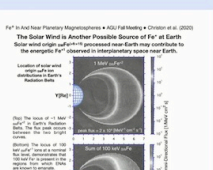
Abstract

We examine long-term energetic heavy ion measurements from three planets' magnetospheres, focusing on Fe ions (specifically, but not exclusively, Fe⁺) in and near Earth's magnetosphere. We compare Fe data to that of other energetic ion species with masses greater than C (carbon) and consider the relationship(s) of energetic Fe ion measurements at the three planets to internal (ionospheres, exospheres, moons, rings, and trapped radiation) and external (solar wind and interplanetary dust) source candidates. Fe⁺ has been observed at Earth and Saturn, but not yet at Jupiter, as our observations there were brief. Measurements are from two

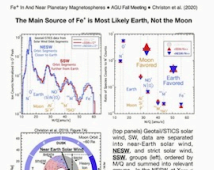
Possible Sources - Most Likely



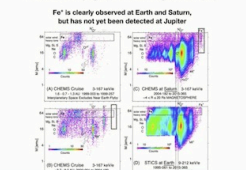
Possible Sources - Next Most Likely



Unlikely Source Candidates



Selected Observational Aspects



Summary and References

Summary
Fe⁺ is clearly observed at Earth and Saturn, but has not yet been detected at Jupiter. Although clearly observed inside Saturn's magnetosphere, Fe⁺ was not detected outside it. Although rare, Fe⁺ is observed in all near-Earth (~9-35 R_E) plasma regimes. Fe⁺ occurrence times show little relation to lunar orbital location/timing and/or to meteor shower occurrences. Fe⁺ production likely results from UV irradiation, auroral precipitating particles, and

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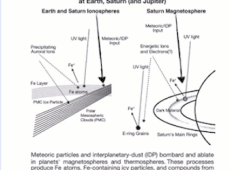
Abstract

We examine long-term energetic heavy ion measurements from three planetary magnetospheres, focusing on Fe ions (specifically, but not exclusively, Fe⁺) in and near Earth's magnetosphere. We compare Fe data to that of other energetic ion species with masses greater than C (carbon) and consider the relationship(s) of energetic Fe ion measurements at the three planets to internal (ionospheres, exospheres, moons, rings, and trapped radiation) and external (solar wind and interplanetary dust) source candidates. Fe⁺ has been observed at Earth and Saturn, but not yet at Jupiter, as our observations there were brief. Measurements are from two functionally identical charge-energy-mass ion spectrometers: one on Geotail (~87-212 keV), orbiting Earth at ~30 Re, and the other on Cassini (~85-167 keV), in interplanetary space, during Jupiter flyby, and at ~4-20 Rs on its constantly varying orbits around Saturn. These ion spectrometers efficiently separate energetic light and heavy ions by mass, as well as lower charge state ions from higher charge state ions by mass-per-charge. Energetic low-charge-state ions often derive from magnetospheric sources, while

Possible Sources - Most Likely

Fe⁺ In And Near Planetary Magnetospheres • AGU Fall Meeting • Christon et al. (2020)

Likely Source and Production Scenarios for Fe⁺ at Earth, Saturn (and Jupiter)

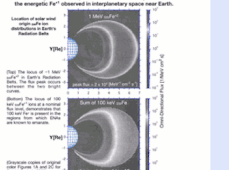


Meteoric particles and interplanetary dust (IDP) bombard and sputter in planetary magnetospheres and thermospheres. These processes produce Fe atoms, Fe-containing particles, and compounds from which singly ionized Fe⁺ (Fe⁺) can result either immediately by precipitating neutral particles or indirectly by solar UV. That Fe⁺ often originates as neutral gas in these environments (Plane, 2012; Frankland et al., 2015; Christon et al., 2017, 2018) and elsewhere traverses the resulting Fe⁺ can then participate in the outward transport processes from the upper magnetosphere into the magnetosphere. The same overall processes involving precipitating energetic particles, impact and reactions, ionization/ionization help occur at all planetary thermospheres, rings, and ring atmospheres. To our knowledge, though, no test of observation has yet provided detailed measurements and identification of the specific acceleration mechanisms involved in these processes for Fe⁺ in any magnetosphere.

Possible Sources - Next Most Likely

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The Solar Wind is Another Possible Source of Fe⁺ at Earth

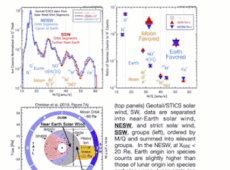


Solar wind Fe⁺ ions, ionized in Earth's radiation belts were calculated using a distributed Fe⁺ ion spectrum (Spjeldvik et al., 2000; Spjeldvik, 2000) during these distributions inside ~10¹¹ m² of length. These atoms, which are produced locally at ~10¹¹ m² from charge exchange (Bland et al., 2002) energies comparable to those of Fe⁺ measured inside Earth's magnetosphere (Christon et al., 2017). This may be test from the magnetosphere continually, in all magnetospheres, during distributed magnetospheric storms.

Unlikely Source Candidates

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The Main Source of Fe⁺ is Most Likely Earth, Not the Moon

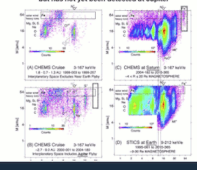


Our parallel Geotail/STICS solar wind data are reported only near-Earth solar wind, NEEMO, and other solar wind, SWF, spectra that, limited by M2D and summed into several groups, in the M2D of 10-20 Re, Earth origin ion spectra counts are slightly higher than those of solar origin ion spectra and solar wind, solar origin ion spectra counts are slightly

Selected Observational Aspects

Fe⁺ In And Near Planetary Magnetospheres • AGU Fall Meeting • Christon et al. (2020)

Fe⁺ is clearly observed at Earth and Saturn, but has not yet been detected at Jupiter



Summary and References

Summary

Fe⁺ is clearly observed at Earth and Saturn, but has not yet been detected at Jupiter

Although clearly observed inside Saturn's magnetosphere, Fe⁺ was not detected outside it

Although rare, Fe⁺ is observed in all near-Earth (~8-35 Re) plasma regimes

Fe⁺ occurrence times show little relation to lunar orbital location/tilting and/or to meteor shower occurrence

Fe⁺ production likely results from UV irradiation, auroral precipitating particles, and meteoric/IDP bombardment of and sputtering in the thermospheres at Earth, Saturn, and Jupiter - as well as in other outer planet's thermospheres, rings, and ring atmospheres

High-charge-state (+6 to +15) solar wind origin ions, SWFAs, processed in Earth's radiation belts may result in Fe ENAs

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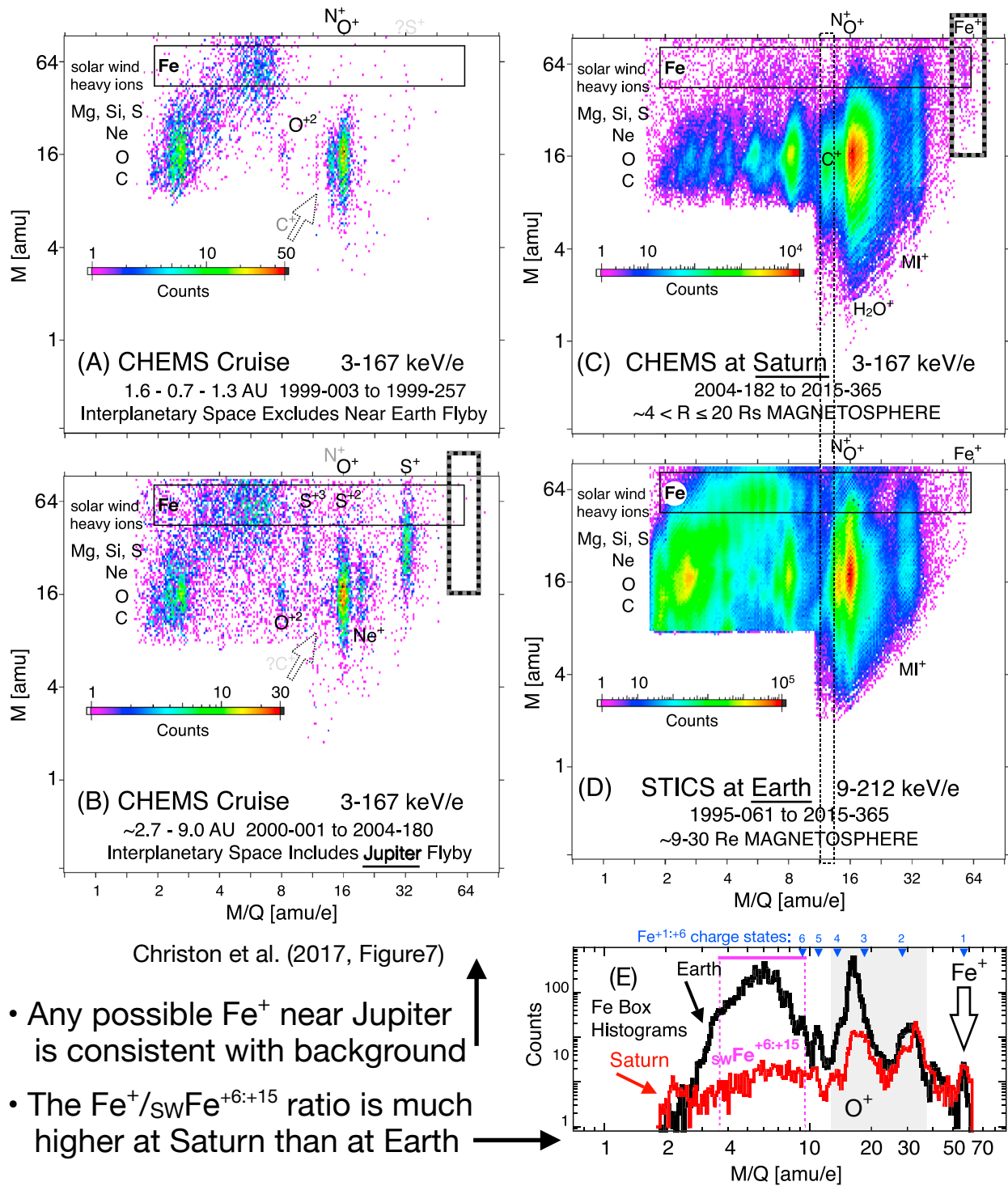
Energetic Fe Ions In And Near The Magnetospheres Of Earth, Jupiter, And Saturn

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We examine long-term energetic heavy ion measurements from three planets' magnetospheres, focusing on Fe ions (specifically, but not exclusively, Fe⁺) in and near Earth's magnetosphere. We compare Fe data to that of other energetic ion species with masses greater than C (carbon) and consider the relationship(s) of energetic Fe ion measurements at the three planets to internal (ionospheres, exospheres, moons, rings, and trapped radiation) and external (solar wind and interplanetary dust) source candidates. Fe⁺ has been observed at Earth and Saturn, but not yet at Jupiter, as our observations there were brief. Measurements are from two functionally identical charge-energy-mass ion spectrometers: one on Geotail (~87-212 keV/e), orbiting Earth at ~9-30 Re; and the other on Cassini (~83-167 keV/e), in interplanetary space, during Jupiter flyby, and at ~4-20 Rs on its constantly varying orbits around Saturn. These ion spectrometers efficiently separate energetic light and heavy ions by mass, as well as lower charge state ions from higher charge state ions by mass-per-charge. Energetic low-charge-state ions often derive from magnetospheric sources, while energetic high-charge-state ions most often derive from the solar wind. Data from Geotail locations in the near Earth solar wind indicate that Earth, not the Moon, is the likely Fe⁺ source. Heavy ion measurements from AMPTE/CCE, closer to Earth, are used for C and Fe radiation-belt-modeling content, consideration, and estimation.

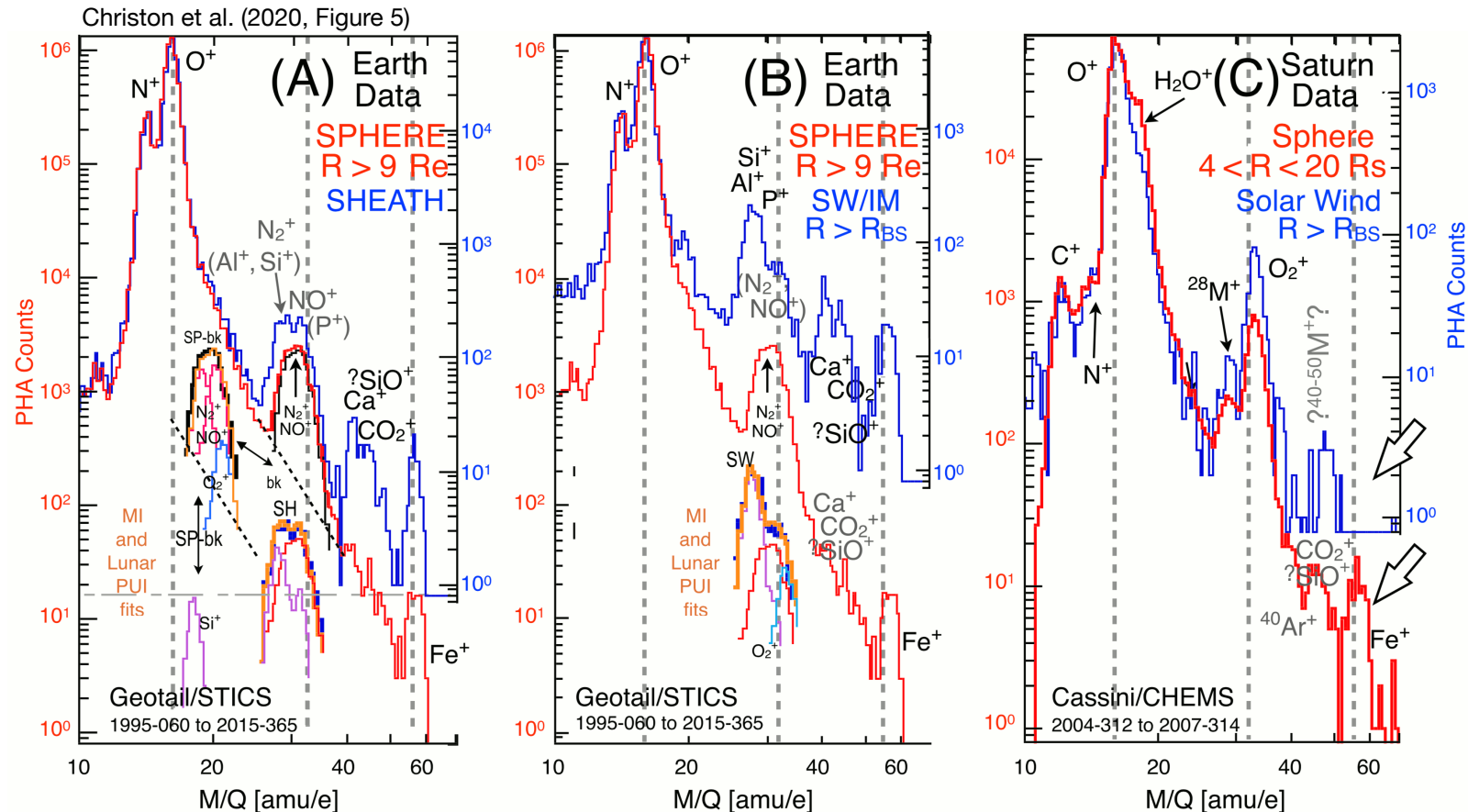
Fe⁺ is clearly observed at Earth and Saturn, but has not yet been detected at Jupiter



Christon et al. (2017, Figure7)

- Any possible Fe⁺ near Jupiter is consistent with background
- The Fe⁺/swFe^{+6:+15} ratio is much higher at Saturn than at Earth

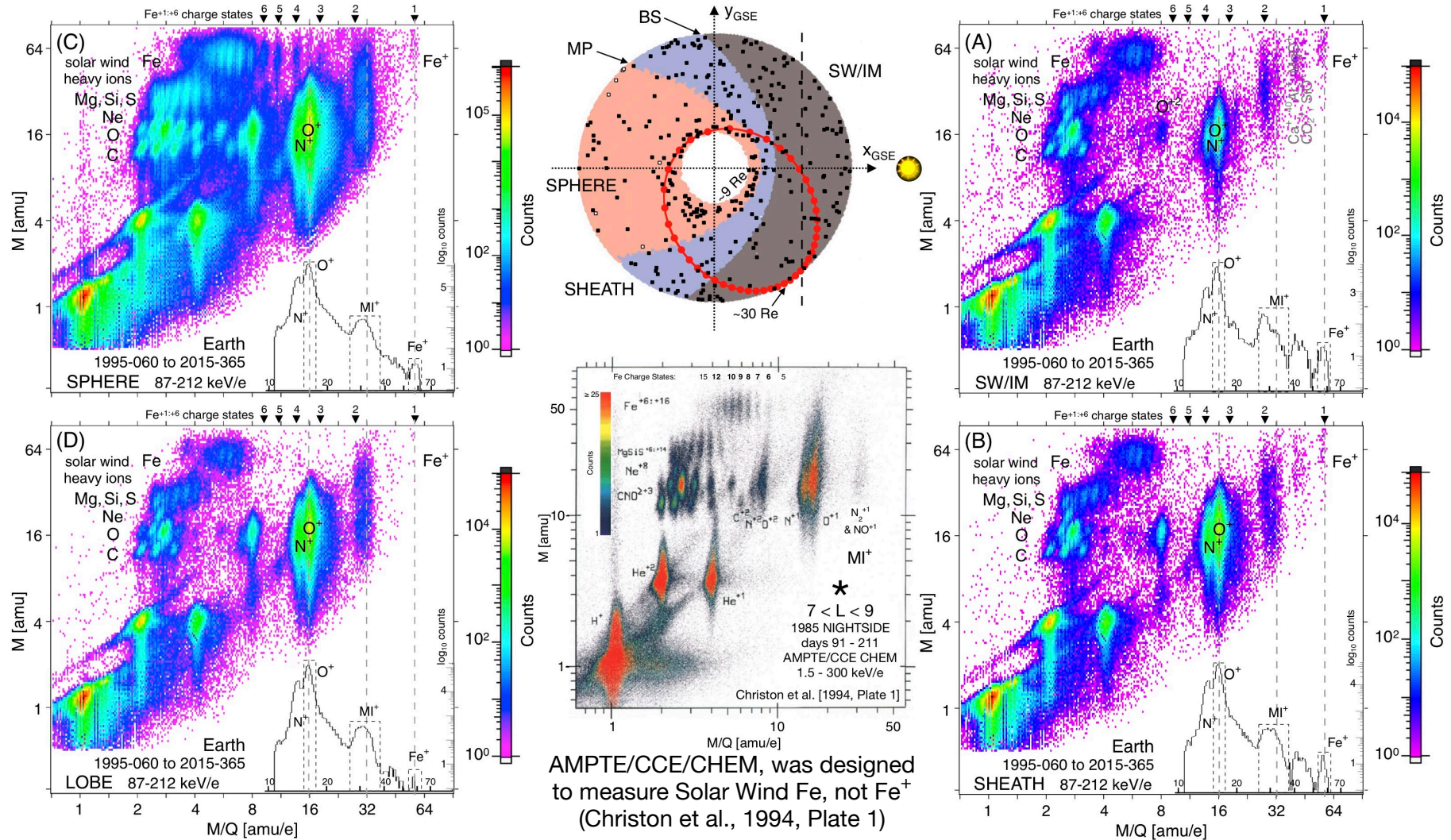
Although clearly observed inside Saturn's magnetosphere, Fe⁺ was not detected outside it

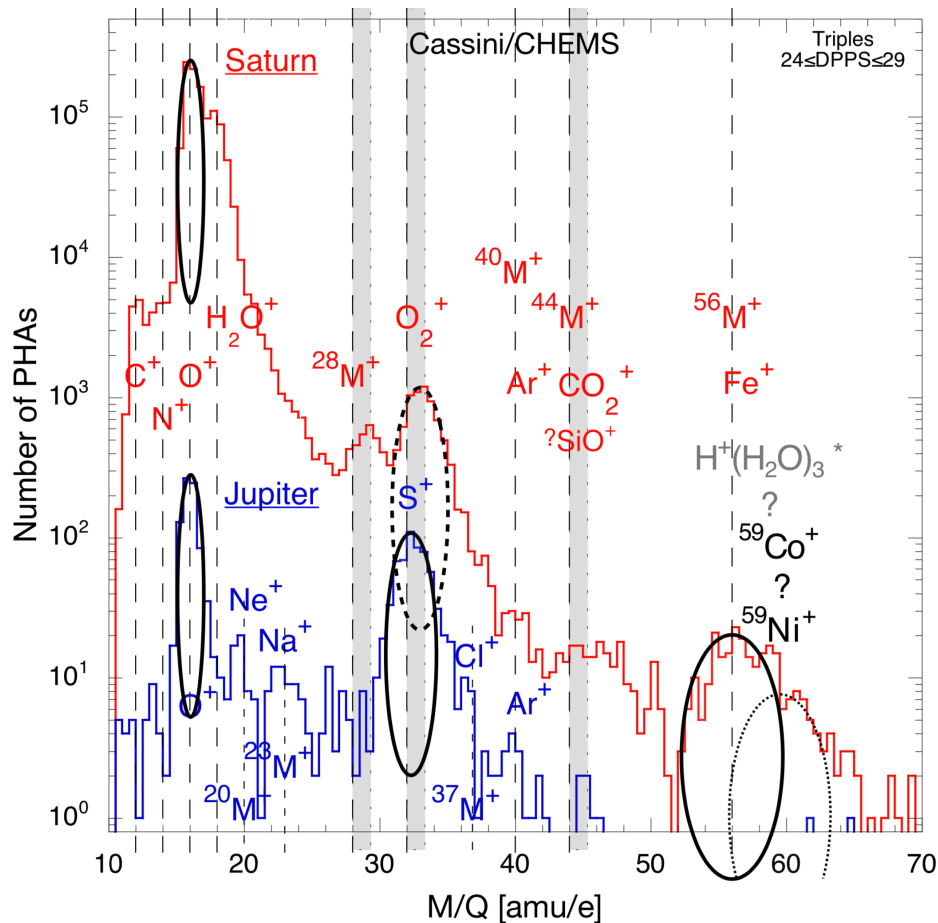


- At Earth (~21 years) and Saturn (~3 years), continuous, successively-sampled plasma regime intervals of Solar Wind (Sheath) and Sphere are compared
- No Fe⁺ was measured outside Saturn's magnetosphere during these intervals (right panel)
- A lack of Fe⁺ escape from Saturn's magnetosphere might result from internal dynamics or its size. In contrast, other unique internal heavy-ion species escape (i.e., $^{28}\text{M}^+$, O_2^+ , $?^{40-50}\text{M}^+$)

Although rare, Fe⁺ is observed in all near-Earth (~9-35 R_E) plasma regimes

Christon et al. (2017, Figures 1 and 2)



Q: Is Fe⁺ The Only Ion Observed At M/Q > 50 amu/e?

PHA M/Q histograms (with eyeball-fit ellipses) compare ion data at:

Saturn : red, $R < 20 R_s$2004-181 (SOI) to 2013-365;
and

Jupiter : blue, bow shock-to-sheath.....2000-363 to 2001-091.

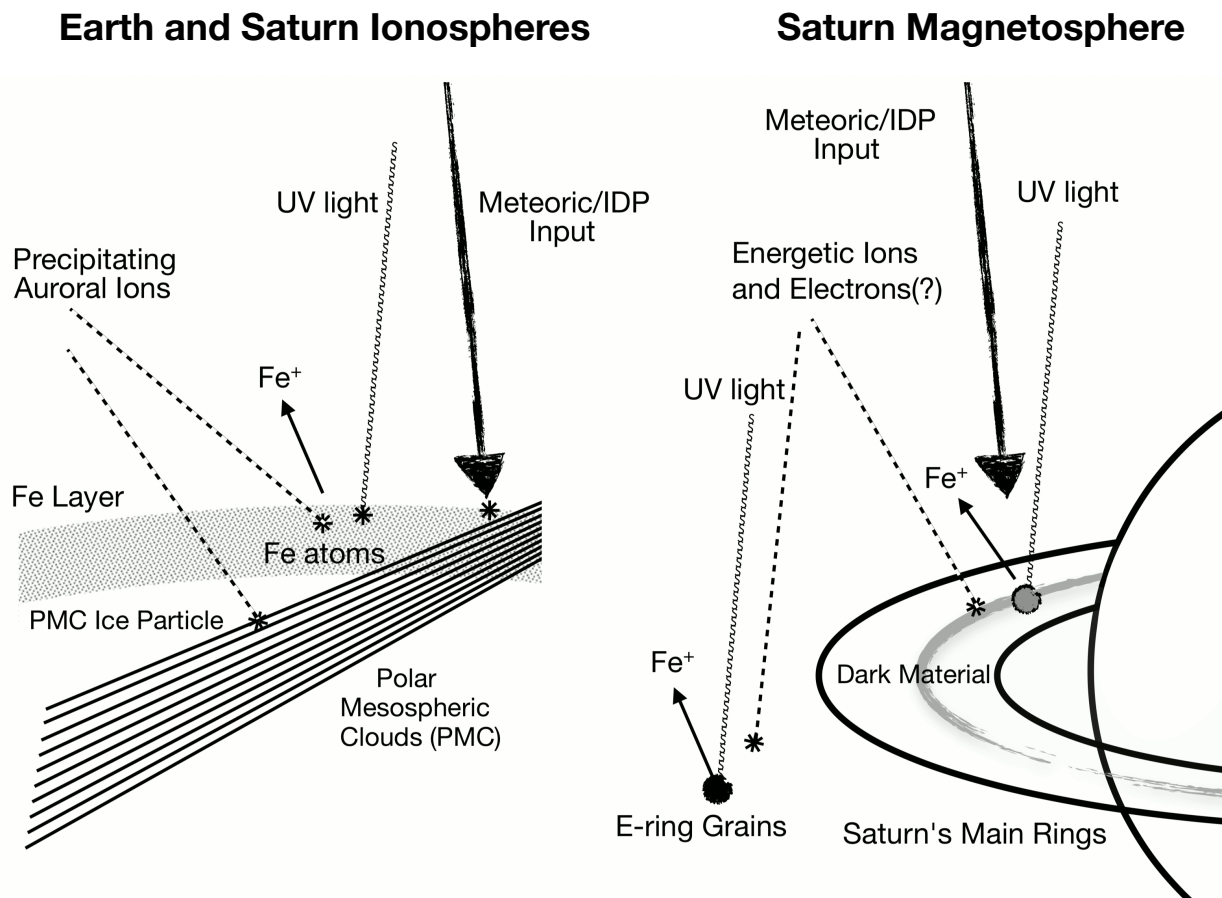
For the molecular ions $^{28}\text{M}^+$, O_2^+ , and CO_2^+ (?or SiO^+), nearly equal-mass atoms, gray bars extend from the ion's true M/Q to its peak's M/Q centroid location which is found at higher M/Q - as the molecular ion's energy losses are higher than those of its independent atomic ions, resulting in a lower time-of-flight.

$^{59}\text{Co}^+$ and $^{59}\text{Ni}^+$, likely IDP products, may be present at M/Q ~ 60 amu/e

*or possibly $\text{H}^+(\text{H}_2\text{O})_3$, as suggested by Cassini/CDA (Postberg et al., 2018)

A: Probably Not At Saturn!

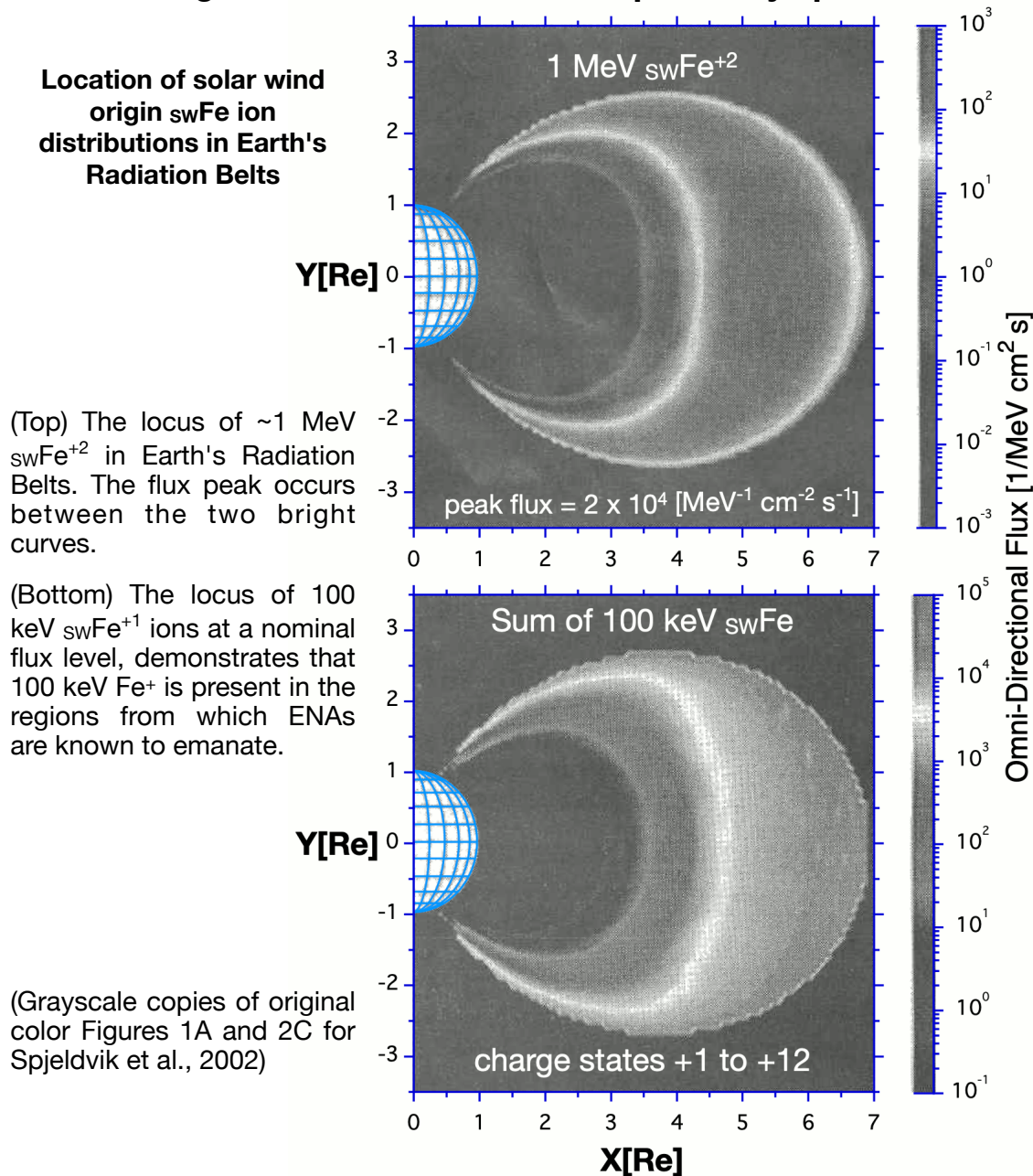
Likely Source and Production Scenarios for Fe⁺ at Earth, Saturn (and Jupiter)



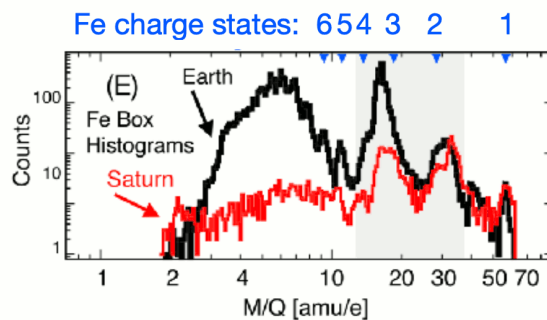
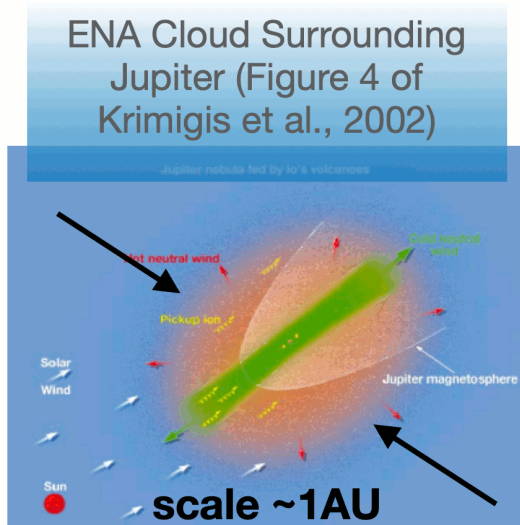
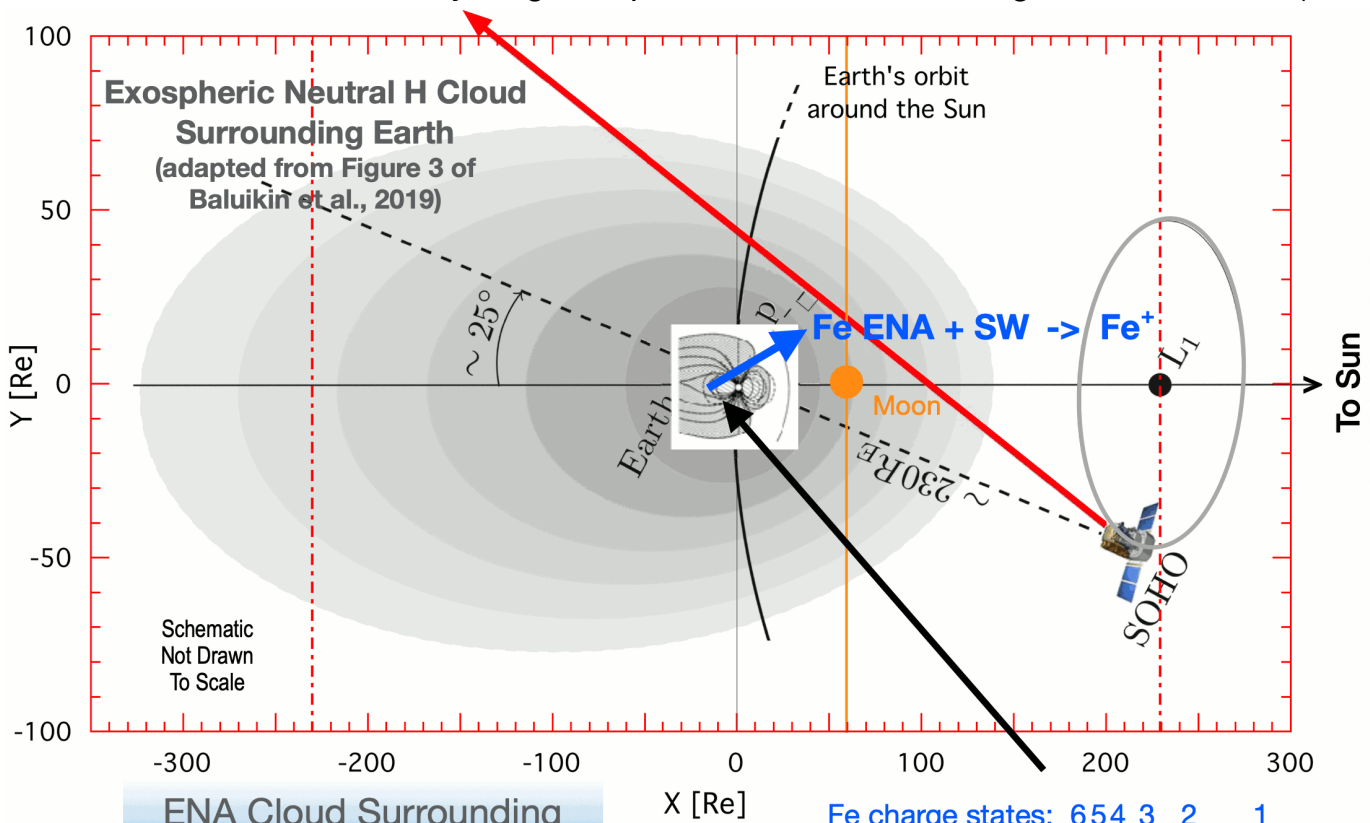
Meteoric particles and interplanetary-dust (IDP) bombard and ablate in planets' magnetospheres and thermospheres. These processes produce Fe atoms, Fe-containing icy particles, and compounds from which singly-ionized Fe, Fe⁺¹ (\equiv Fe⁺), can result when impacted by precipitating auroral particles or irradiated by solar UV. That Fe⁺¹ often becomes an integral part of their ionospheres (Plane, 2012; Frankland & Plane, 2015; Christon et al., 2015; 2017, and references therein). The resulting Fe⁺¹ can then participate in the outward transport processes from the upper ionosphere into the magnetosphere. The same overall processes involving precipitating energetic particle impact and meteoric bombardment/ablation likely occur in all planets' thermospheres, rings, and ring atmospheres. To our knowledge though, no set of observations has yet provided detailed measurement and identification of the specific acceleration mechanisms involved in these processes for Fe⁺¹ in any magnetosphere.

The Solar Wind is Another Possible Source of Fe⁺ at Earth

Solar wind origin $\text{swFe}^{(+6:+15)}$ processed near-Earth may contribute to the energetic Fe⁺ observed in interplanetary space near Earth.



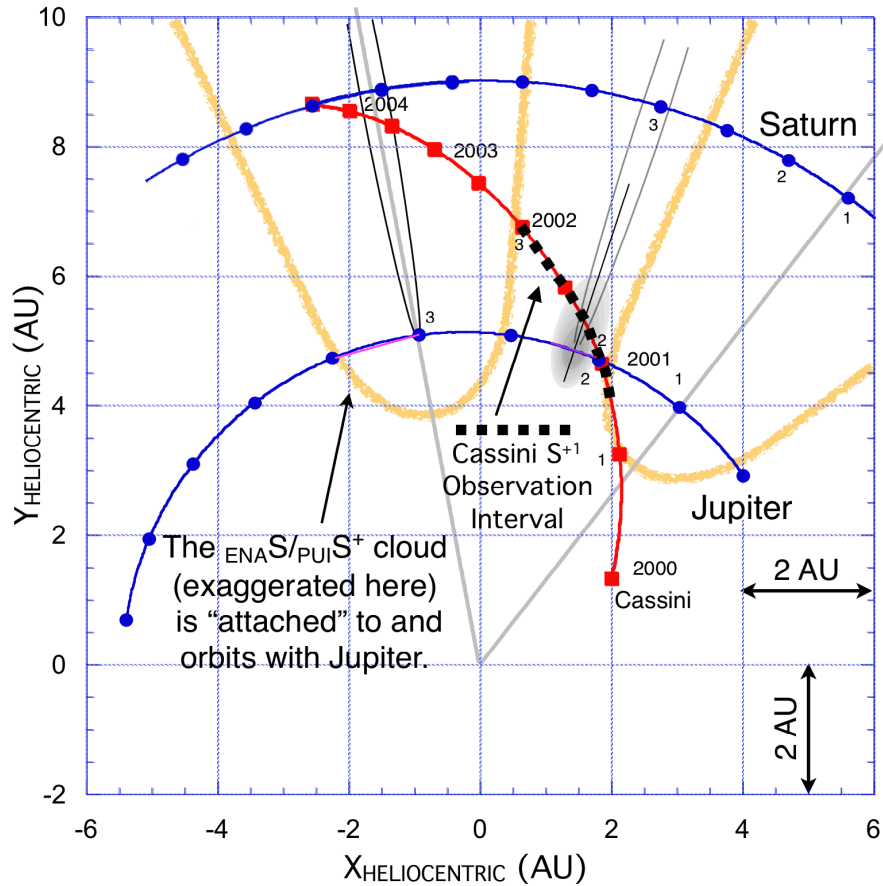
Solar Wind origin Fe, swFe , ion fluxes in Earth's radiation belts were calculated using a data-based swFe^{+12} input spectrum (Spjeldvik et al., 2002; Spjeldvik, 1996). (bottom) These distributions include $\text{swFe}^{+1:+5}$. ~ 100 keV Energetic Neutral Atoms, ENAs, are produced locally at $< 7 R_E$ from charge exchange (Brandt et al., 2002) - energies comparable to those of Fe⁺ observed outside Earth's magnetosphere (Christon et al., 2017). ENAs may be lost from the magnetosphere continually, or, at minimum, during disturbed magnetospheric intervals.



Neutral atom clouds surround Earth, Jupiter, and Saturn. Jupiter's energetic neutral atom (ENA) cloud of H, O, (and probably S,) is estimated

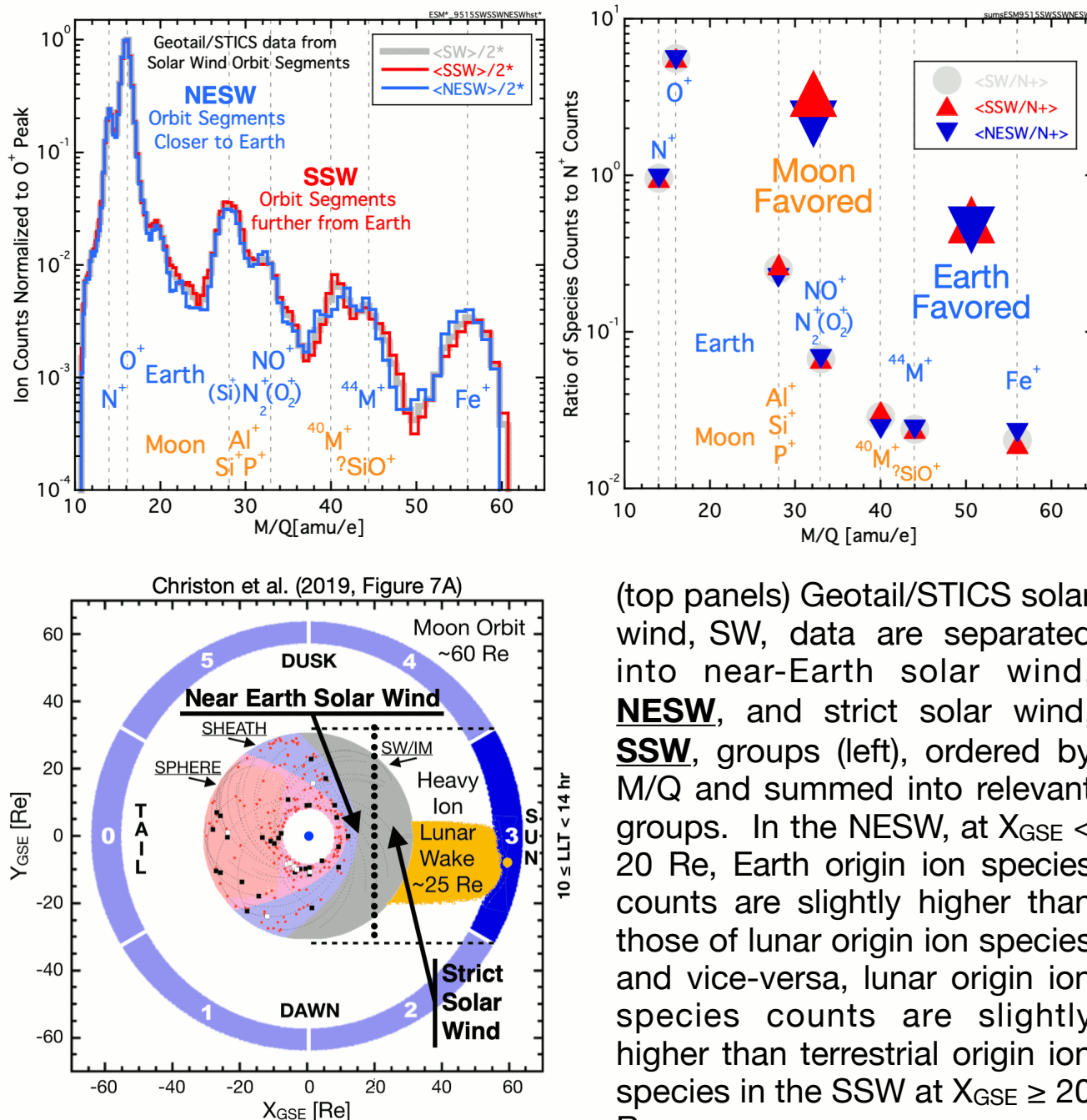
to be $\sim 1\text{AU}$ (Krimigis et al., 2002). The recently discovered exospheric H cloud that surrounds Earth and extends to $\sim 100\text{ Re}$ sunward of Earth, encompasses the Moon's orbit (Baluikin et al., 2019). If Earth has an ENA Fe component (sourced by solar wind Fe ions transported into the Radiation Belt), the resulting pickup Fe^+ ion flux in the solar wind might account for some of the Fe^+ observed by Geotail between Earth and the moon. No Fe^+ was observed near the Moon using a nearly identical ion spectrometer on Wind (Mall et al., 1998; Kirsch et al., 1998), so it might be that any of Earth's Fe ENAs are quickly ionized and picked up by the solar wind, never reaching the Moon.

The S ENA - S⁺ PUI Component at Jupiter

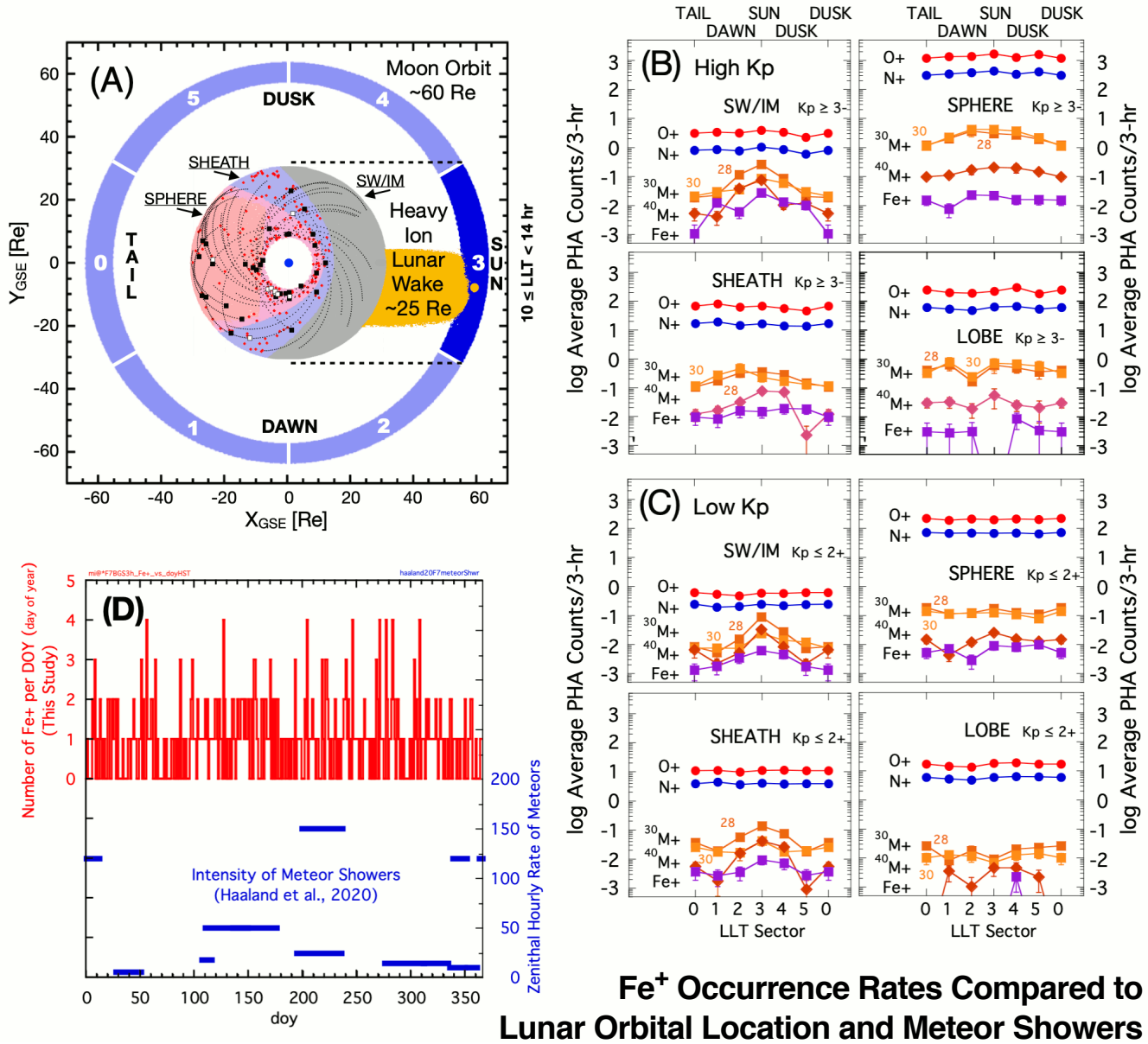


A sketch of Cassini's trajectory and Jupiter and Saturn orbits in heliocentric solar ecliptic coordinates. Shown at the start of each year, blue circles identify planets and red squares show Cassini spacecraft locations from 2000 to 2004. Cassini colocates with Saturn after mid-2004. Three common times are numbered along the trace and at the planets for reference. Jupiter's H, O, and S ENA/PUI cloud (e.g., Krimigis et al., 2002) is drawn both (1) exaggerated, as golden hyperbolae (radius of curvature ~ 1.4 AU), and (2) minimal, using a scaled image of Earth's neutral H cloud, width ~ 0.75 AU. Jovian origin S⁺, detected along the heavy, black-dashed trace (Christon et al., 2020), are likely pickup ions, $_{\text{PUI}}\text{S}^+$, expected from Jupiter's energetic neutral atoms, $_{\text{ENA}}\text{S}$ (Gruntman, 1997; Luhmann, 2003). As some of the S⁺ can travel along the IMF to the point of observation from the cloud, the cloud's nominal size is probably somewhere between these estimates.

The Main Source of Fe⁺ is Most Likely Earth, Not the Moon



(top panels) Geotail/STICS solar wind, SW, data are separated into near-Earth solar wind, **NESW**, and strict solar wind, **SSW**, groups (left), ordered by M/Q and summed into relevant groups. In the NESW, at $X_{GSE} < 20$ Re, Earth origin ion species counts are slightly higher than those of lunar origin ion species and vice-versa, lunar origin ion species counts are slightly higher than terrestrial origin ion species in the SSW at $X_{GSE} \geq 20$ Re.



(A, B, C) Panels from Figure 7 of Christon et al. (2020) show heavy ion occurrence rates collected in six equal Lunar Local Time (LLT) sectors in the ~80-200 keV/e range. When measured in the solar wind/interplanetary medium, SW/IM, the heavier ions shown are expected to exhibit higher SW convection-peaking centered in LLT = 3. Lunar ions (³⁰M⁺ and ⁴⁰M⁺) exhibit pronounced peaks centered on LLT = 3. Fe⁺ exhibits a broad LLT = 3 centered enhancement in the SW/IM during high and low Kp intervals, not necessarily consistent with a lunar source. **(D)**. The Fe⁺ DOY-occurrence rate shows little relation to that of meteor showers listed by Haaland et al. (2020). Neither comparison supports an argument that Fe⁺ occurrence depends on these factors.

Energetic Fe Ions In And Near The Magnetospheres Of Earth, Jupiter, And Saturn

- Fe⁺ is clearly observed at Earth and Saturn, but has not yet been detected at Jupiter
- Although clearly observed inside Saturn's magnetosphere, Fe⁺ was not detected outside it
- Although rare, Fe⁺ is observed in all near-Earth (~9-35 R_E) plasma regimes
- Fe⁺ occurrence times show little relation to lunar orbital location timing and/or to meteor shower occurrence
- Fe⁺ production likely results from UV irradiation, auroral precipitating particles and meteoric/IDP bombardment of and ablation in the thermospheres at Earth, Saturn, and Jupiter - as well as in other outer planet's thermospheres, rings, and ring atmospheres
- High-charge-state (+6:+15) solar wind origin iron, _{sw}Fe, processed in Earth's radiation belts may result in Fe ENAs which are then ionized and picked-up by the solar wind, becoming or contributing to the energetic Fe⁺ observed in interplanetary space near Earth. Such a Fe/Fe⁺ ENA/PUI cloud would be smaller than the H/H⁺ ENA/PUI cloud
- Fe⁺ is likely not the only ion observed at M/Q > 50 amu/e at Saturn
- At Earth, our data show that the main source of Fe⁺ is most likely Earth, not the Moon
- Data: • Cassini/MIMI/CHEMS data are at <http://pds.nasa.gov>.
 • Geotail/EPIC/STICS data are at http://spdf.gsfc.nasa.gov/pub/data/geotail/epic/stics_pha_ascii_gzip and the JHU/APL Space Department.

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• SM042-0010 • References •

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To support our reasons for referencing Brandt et al. (2002), we include the color copies of their inverted ion distributions derived from spacecraft ENA images, Figures 8-11, which appear on the article's webpage (whereas the downloadable pdf has only B/W low-resolution versions). Please see: <https://doi.org/10.1029/2002JA009307>

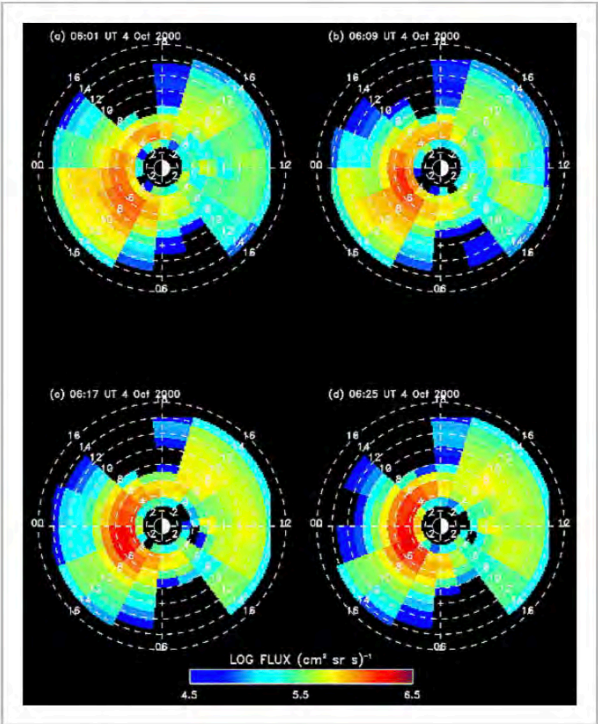


Figure 8

T(a-d) The inverted ion distributions in the 10–60 keV range (6 min integration) for the 06:11 UT substorm using the symmetric *Rairden et al. [1986]* model exosphere (see equations (8) and (9)).

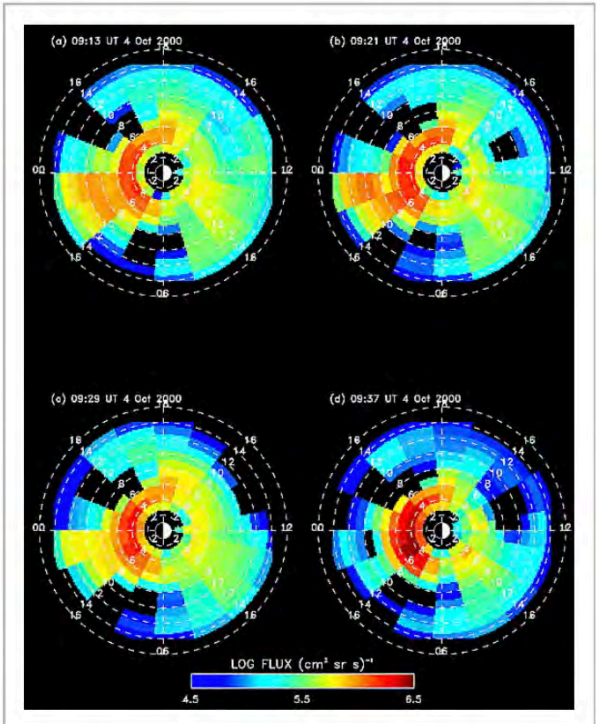


Figure 10

(a-d) The inverted ion distributions in the 10–60 keV range (6 min integration) for the 09:22 UT substorm using the *Rairden et al. [1986]* model exosphere (see equations (8) and (9)).

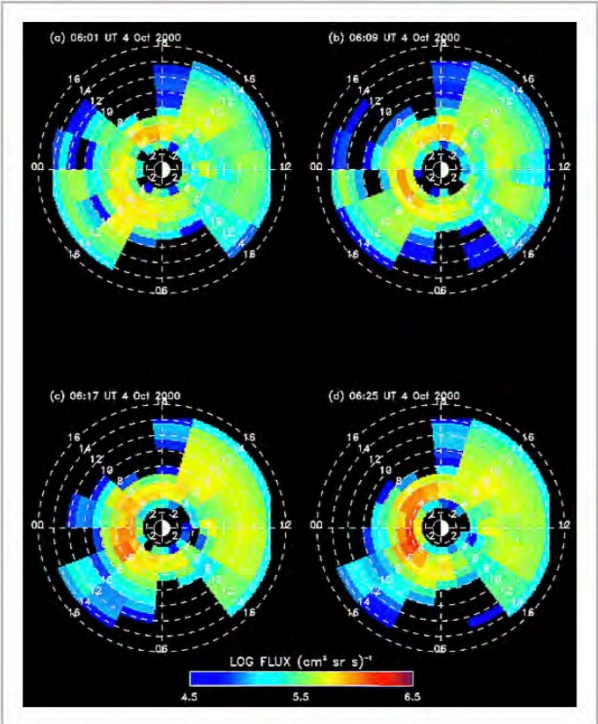


Figure 9

(a-d) The inverted ion distributions in the 10–60 keV range (6 min integration) for the 06:11 UT substorm using the asymmetric *Rairden et al. [1986]* model exosphere with $k = 0.3$ from equations (8) and (9).

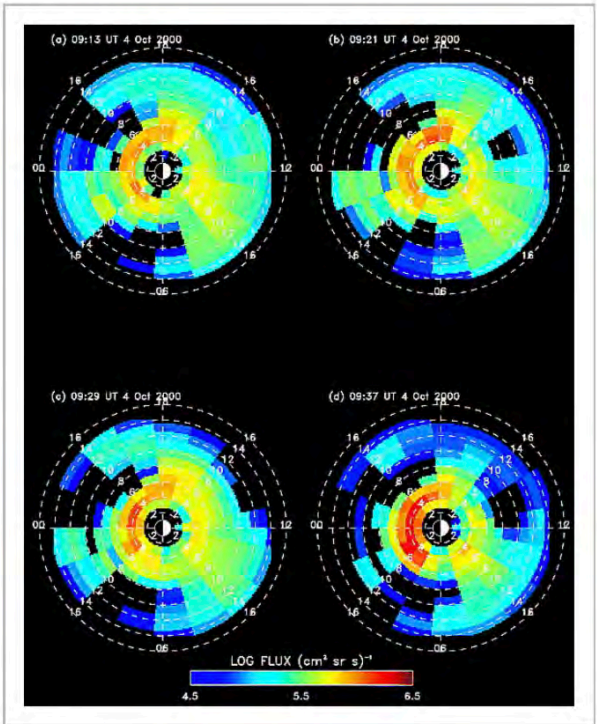


Figure 11

(a-d) The inverted ion distributions in the 10–60 keV range (6 min integration) for the 09:22 UT substorm using the asymmetric *Rairden et al. [1986]* model exosphere with $k = 0.3$ from equations (8) and (9).