Parametric estimation of neutral hydrogen density under charge exchange and quantification of its effect on plasmasphere-ionosphere coupling

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Abstract

The resonant charge exchange coupling between H+, H, O+ and O is a major driver of H+ and O+ transport between the plasmasphere and topside ionosphere. In this work, we present a new technique to derive model-independent neutral atomic hydrogen density, [H], based on parametric solution of the proton continuity equation including charge-exchange-driven transport. Estimation of [H] using the proton continuity equation incorporates atomic oxygen density [O] derived from the inversion of 135.6 nm OI emission measured by TIMED/GUVI and coincident ionospheric parameter measurements from the Arecibo incoherent scatter radar. Furthermore, by solving both the H+ and O+ continuity equations simultaneously, this work also quantifies the field-aligned vertical transport of protons between the plasmasphere and ionosphere and its effect on maintenance of the nightside and dayside ionospheric composition. Case studies during geomagnetically quiet intervals show that the transport of protons from the plasmasphere during nighttime is sufficient for the maintenance of the observed ionospheric O+ composition through reverse charge-exchange with O. Resulting O+ can diffuse upward or downward away from the source, which leads to observed counter-streaming of H+ and O+. Higher O+ densities on the dayside result in the charge-exchange production of H+, which acts as a source of protons to the plasmasphere. In summary, this work provides an unprecedented, model-independent quantification of diurnal conservation of plasmaspheric protons and its effect on ionospheric variability during quiet-times.

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INTRODUCTION

The objectives of this work are:

To present a novel technique for estimation of [H] in the topside ionosphere using charge-exchange driven transport of H^+ and O^+ between plasmasphere-ionosphere

To quantify the proton flux transport between plasmasphere and ionosphere and investigate its effect on maintenance of ionosphere.

What is the major advantage of this work?

Presents concept study of model-independent method of [H] estimation

Motivates several important questions in MIT coupling which can be addressed using upcoming space missions.

PARAMETER SPECIFICATION

Ionospheric state parameters:

Electron density $[N_e]$, ion densities $[H^+]$ and, $[O^+]$, ion temperature T_i, electron temperature T_e from topside measurements by the Arecibo ISR from.

Thermospheric density and temperature:

Co-located neutral densities [H], [O], $[O_2]$, $[N_2]$ and temperatures T_n from NRL-MSISE00

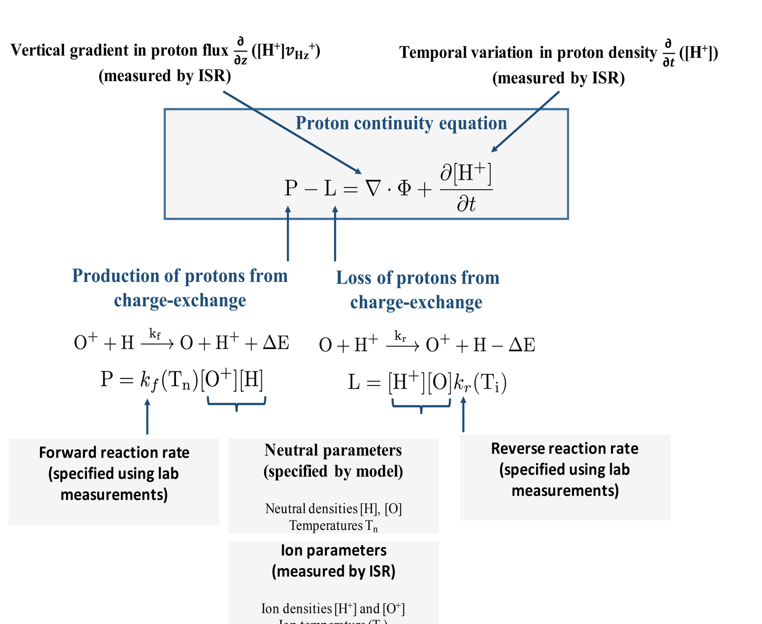
Neutral oxygen densities [O] from TIMED/GUVI inversions of Lyman-α radiance.

Analysis Interval:

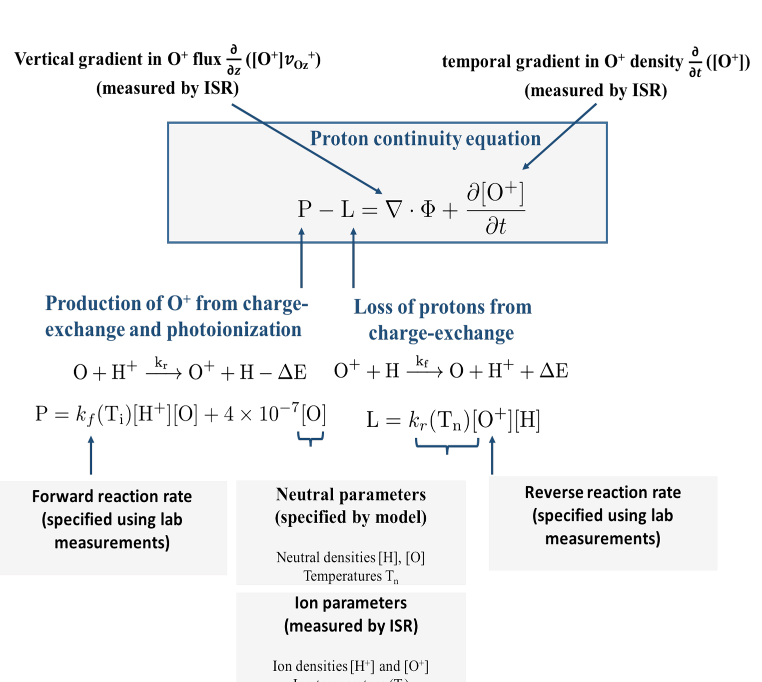
29 – 31 March, 2003 (Average Dst = -50 nT, F10.7 = 155 sfu)

METHODOLOGY

H^+ CONTINUITY



O^+ CONTINUITY

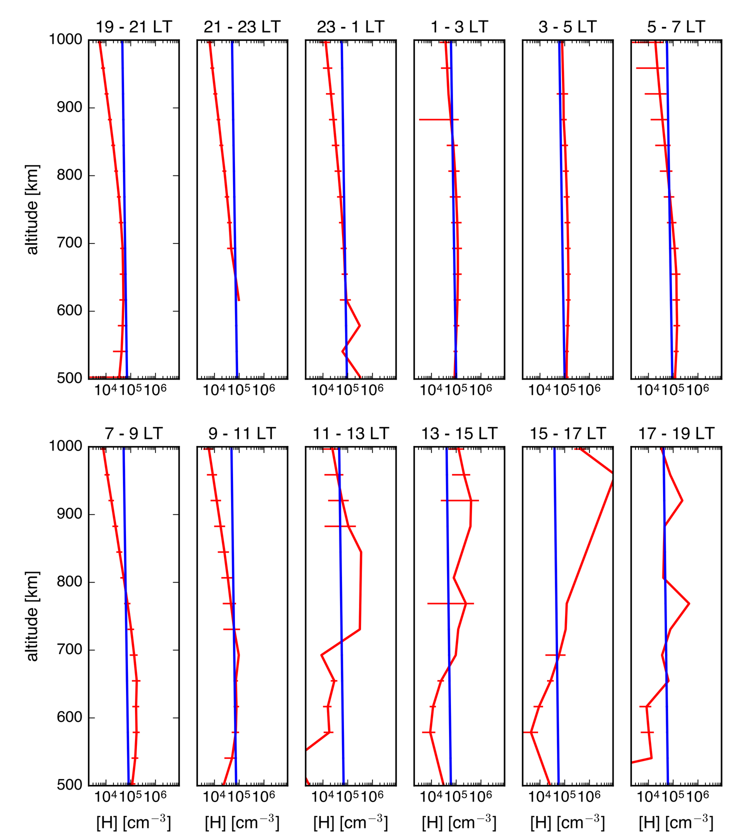


RESULTS AND DISCUSSION

NEUTRAL HYDROGEN DENSITY ESTIMATION

[H] ESTIMATION using $[O]_{MSIS}$

$$[\mathrm{H}]_{\mathrm{CB}} = \frac{k_r(\mathrm{T_i})}{k_f(\mathrm{T_n})}\frac{[\mathrm{H}^+]}{[\mathrm{O}^+]}[\mathrm{O}]_{\mathrm{MSIS}} + \frac{\nabla\cdot\Phi + \frac{\partial[\mathrm{H}^+]}{\partial t}}{k_f(\mathrm{T_n})[\mathrm{O}^+]}$$



Night side:
$[H]_{CB}$ under charge-exchange equilibrium is larger than $[H]_{MSIS}$ from 21 LT – 9 LT with peak difference at ~23 LT

Day side:
$[H]_{CB}$ under charge-exchange equilibrium is smaller than $[H]_{MSIS}$ from 9 LT – 21 LT with peak difference at ~13 LT

IMPLICATONS

MSIS significantly overestimates [H] during the day from 9-21 LT and slightly underestimates [H] during the night from 21-9 LT.

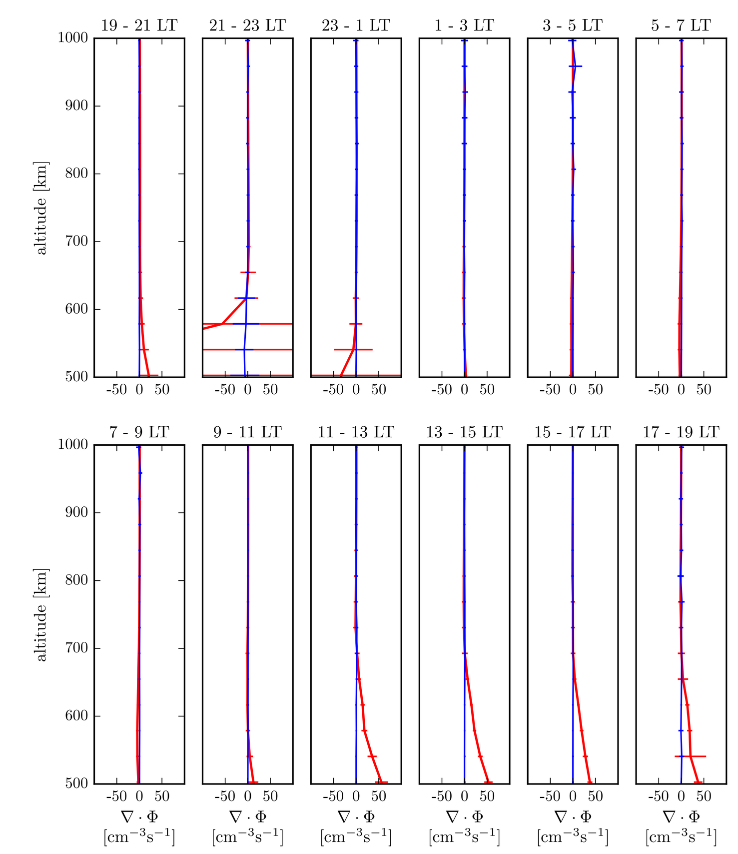
MSIS significantly underestimates [O] during the day from 9-21 LT and slightly overestimates [O] during the night from 21-9 LT. Recent paper Joshi et al [2018] has reported that MSIS slightly overestimates [O] at night side during solar maximum.

Ionosphere should act as proton source during the day and sink for the protons from the plasmasphere during night.

Existence of another significant proton source besides charge exchange of H and O^+. Enhanced storm-time charge-exchange of N^+ with H ($N^+ + H \rightarrow H^+ + N$) could be a possibility. Motivates need for independent measurements of N^+ in future missions.

Total proton flux divergence

$$\nabla\cdot\Phi = k_f(\mathrm{T_n})[\mathrm{O}^+][\mathrm{H}] - k_r(\mathrm{T_i})[\mathrm{H}^+][\mathrm{O}] - \frac{\partial[\mathrm{H}^+]}{\partial t}$$



Night side:
Negative proton flux divergence (proton sink) is needed from 21 LT – 9 LT with peak difference at ~23 LT

Day side:
Positive proton flux divergence (proton source) is needed from 9 LT – 21 LT with peak difference at ~13 LT

Vertical proton flux divergence accounts for the transport at higher altitudes (>750 km) but is insufficient at lower altitudes (<750 km)

IMPLICATIONS

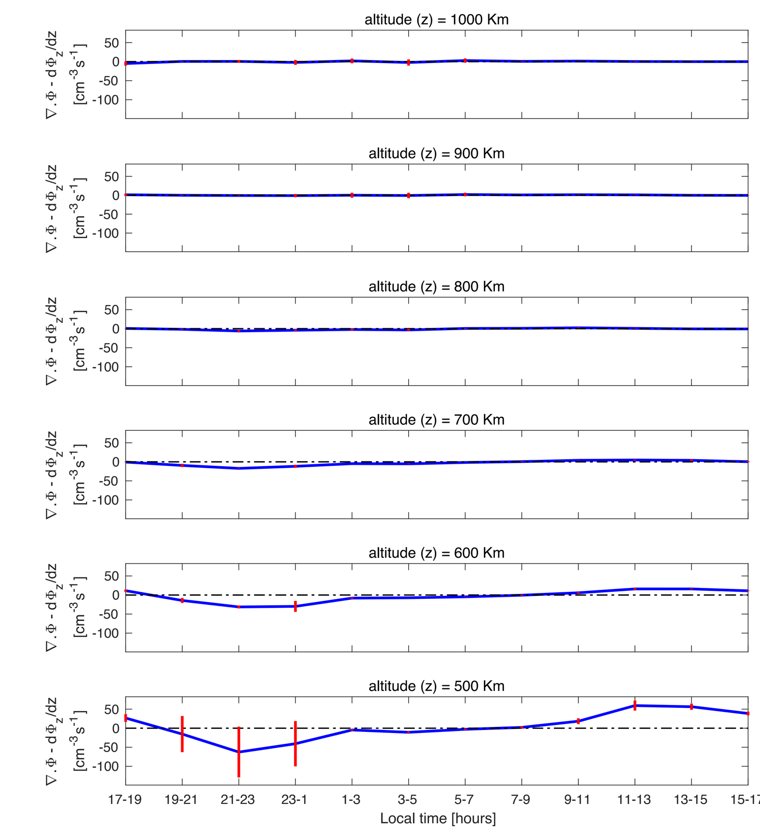
ISR underestimates the vertical proton velocity, especially from ~500-750 km.

New techniques should be developed for ISR for precise derivation of species-specific plasma velocities. Optimization of regularization parameter in the traditional ISR inverse technique for velocity estimation is a potential direction.

There exists a significant source of horizontal proton transport during the day and sink of horizontal proton transport during the night.

Horizontal proton flux divergence

$$\frac{\partial\left(v_{O_u^+}[\mathrm{O}^+]\right)}{\partial u} + \frac{\partial\left(v_{O_v^+}[\mathrm{O}^+]\right)}{\partial v} = \nabla\cdot\Phi - \frac{\partial\left(v_{O_z^+}[\mathrm{O}^+]\right)}{\partial z}$$



Night side:
Negative horizontal proton flux divergence (proton sink) is needed from 21 LT – 9 LT with peak magnitude at ~23 LT

Day side:
Positive horizontal proton flux divergence (proton source) is needed from 9 LT – 21 LT with peak magnitude at ~13 LT

The magnitude of horizontal proton flux divergence decreases from ~ -20 $cm^{-3}s^{-1}$ at 500 km to negligible amount at higher altitudes of 800 km.

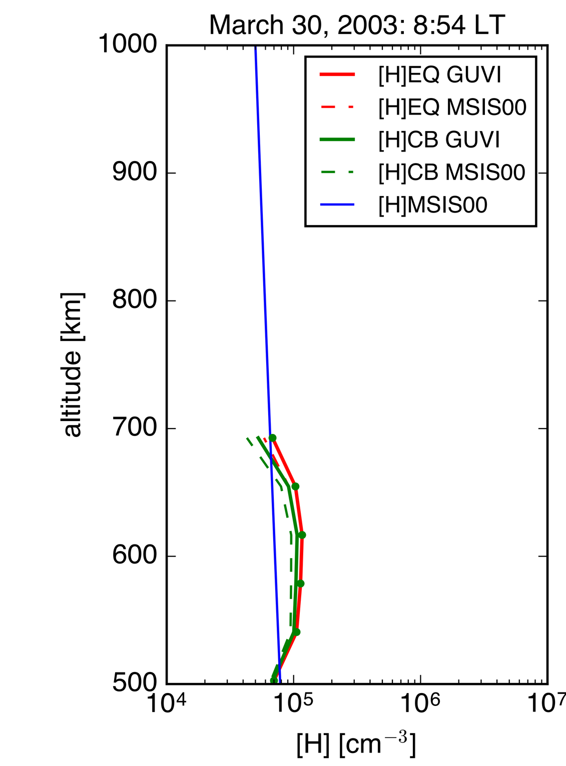
IMPLICATIONS

Existence of a large storm-time source and sink of horizontal proton transport over Arecibo from ~500-750 km.

To investigate this possibility, 3-dimensional topside ion measurements are needed from rotating-beam experiments at Arecibo or from in-situ mass spectrometer measurements.

[H] estimation using $[O]_{GUVI}$

$$[\mathrm{H}]_{\mathrm{CB}} = \frac{k_r(\mathrm{T_i})}{k_f(\mathrm{T_n})}\frac{[\mathrm{H}^+]}{[\mathrm{O}^+]}[\mathrm{O}]_{\mathrm{GUVI}} + \frac{\nabla\cdot\Phi + \frac{\partial[\mathrm{H}^+]}{\partial t}}{k_f(\mathrm{T_n})[\mathrm{O}^+]}$$



Coincidence interval:
TIMED/GUVI limb scan measurements were coincident over Arecibo for a single time instant of 8:54 LT on March 30, 2003.

$[H]_{CB}$ under charge-exchange equilibrium is larger than $[H]_{MSIS}$ similar to 7 LT – 9 LT interval in Figure 1.

IMPLICATIONS

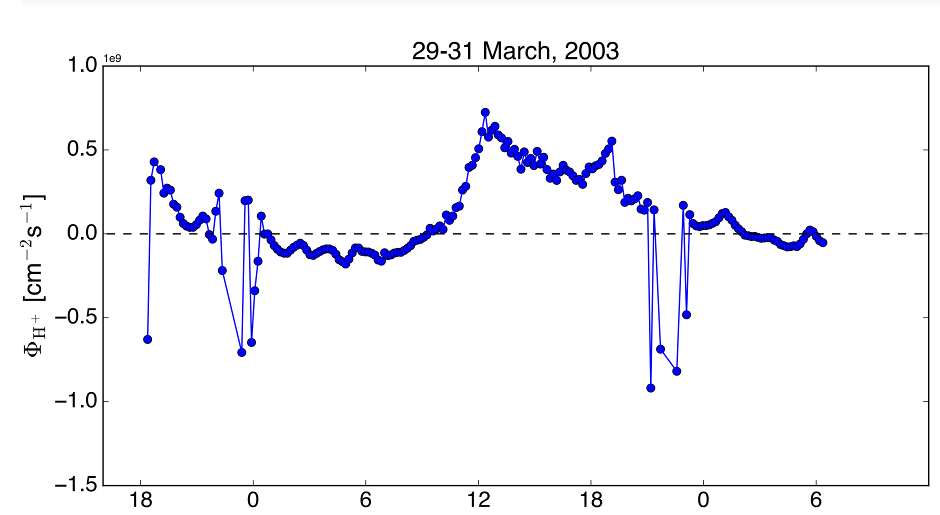
MSIS potentially underestimates [H] and/or overestimates [O] around 8:54 LT.

ISR underestimates the vertical proton velocities (and hence vertical proton flux) and needs an improved technique for derivation of proton velocity.

If both, $[H]_{MSIS}$ and ISR velocities are accurate, then negative horizontal proton flux divergence (proton sink) is needed similar to 7 LT – 9 LT interval in Figure 2. Zonal and meridional velocities from ionospheric models like SAMI3 could be used to investigate this effect.

PLASMASPHERE-IONOSPHERE COUPLING

Height integrated proton flux



Proton transport from plasmasphere

Average incoming H^+ flux from plasmasphere (325-850 km) during 21-9 LT: 0.88 x 10^8 $cm^{-2}s^{-1}$

Average outgoing H^+ flux from plasmasphere (325-850 km) during 9-21 LT: 3.44 x 10^8 $cm^{-2}s^{-1}$

Number of incoming protons from plasmasphere (325-850 km) during 21-9 LT: 8.82 x 10^{13} ± 27% cm^{-2}

Number of outgoing protons from ionosphere (325-850 km) during 9 LT – 21 LT: 9.96 x 10^{13} ± 15% cm^{-2}

Diurnal conservation of protonospheric protons is possible within error limits with equal number of incoming and outgoing protons.

Nightside ionosphere maintenance

Calculated nightside O^+ peak density calculated from the average downward proton flux during 21-9 LT using expression given by Rishbeth [1968] : 3.54 x 10^6 cm^{-3}

Observed nightside peak O^+ density during 21-9 LT: 2.21 x 10^6 cm^{-3}

Average downward proton flux is sufficient to support the maintenance of the ionospheric densities at night by production of O^+ through charge exchange (also observed as a positive nightside O^+ flux using O^+ continuity balance)

Presence of meridional neutral winds can also lift up the F layer post-sunset which can lower the loss coefficient and help in maintenance of the layer. HWM model winds can give some evaluation of that effect.

Limiting upward flux

Altitude of limiting flux calculation would be ~700 km based on O^+/H^+ transition height.

Limiting average H^+ flux outgoing from the ionosphere at 700 km during 9-21 LT using expression from Banks and Holzer [1969a]: ~7.34 x 10^8 $cm^{-2}s^{-1}$

Peak H^+ flux in the ionosphere at 700 km during 9-21 LT: 6.12 x 10^8 $cm^{-2}s^{-1}$ which is smaller than the limiting flux (within error bounds).

Daytime upward fluxes have substantial fraction of limiting flux which describes maintenance of the ionospheric composition on the dayside.

SUMMARY AND FUTURE WORK

Proposed technique for [H] estimation is very promising and motivates several important questions which can be addressed using upcoming space missions and ionospheric models.
Proposed technique has strong potential to address long-standing discrepancies between models and observations in quantification of plasmasphere-ionosphere transport through model-independent calculations.

1. SAMI3 measurements of species-specific 3-dimensional ion velocities on a global scale could allow for improved estimates of vertical and horizontal transport terms and large-scale implementation of [H] estimation.
2. In-situ mass spectrometer measurements of ion densities and velocities from constellation satellite missions like NASA Dellinger and Exocube would be highly useful for model-independent implementation and investigation of [H] estimation.
3. Derivation of neutral hydrogen density [H] from inversion of Lyman-alpha radiances from upcoming mission like NASA ICON and GOLD would allow for MSIS-independent implementation of [H[estimation.
4. Derivation of [H] and/or [O] using self-consistent solution of both, O+ and H+ continuity balance would allow for validation of new inversion algorithms for ICON/GOLD, MSIS models as well as impact all ionosphere-thermosphere studies.

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