Session Title: What is the composition of the exosphere and how does it influence the topside ionosphere and plasmasphere?

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Report: The impact of exospheric O and H on geospace

Oxygen and hydrogen densities in the thermosphere and exosphere can affect the polar wind composition [Schunk], the strength of the magnetospheric ring current [Illie, Glocer] and the rate of plasmasphere refilling following a storm [Krall]. The O density varies daily by up to 20% [Krall] while the H density appears to be increasing as a result of climate change [Nossal]. This latter fact reminds us that current empirical H models have uncertainties and assumptions that should perhaps be re-examined [Burns]. While H is difficult to measure [Mierkiewicz, Viereck, Qin, Noto], ground-based measurements from the Wisconsin H-alpha Mapper (WHAM) [Mierkiewicz, Nossal] and limb scans from the GUVI (Global Ultraviolet Imager) instrument on the TIMED satellite are promising [Qin].

Uncertainties in the composition of the exosphere and thermosphere

Measurement limitations, model limitations, our limited understanding of atmospheric chemistry, and climate change each introduce uncertainty into our understanding of the exosphere. Uncertainties in H are particularly large and were a main focus of the session.

Numerous atmospheric measurements have gone into the development of the commonly-used MSIS empirical atmosphere model (MSIS is named for the mass spectrometer and incoherent scatter data from which it was first developed). The composition measurements from which MSIS was first developed included all thermospheric altitudes [Hedin, 1983]. Knitting all of these measurements together and extending them into the exosphere, however, requires assumptions that may not be valid [Burns]. The latest version of MSIS is NRLMSISE-00 [Picone et al., 2002].

We know little about the transport of neutrals in the topside ionosphere or exosphere [Noto]. Plots of MSIS H at 300 km show strong gradients versus latitude and longitude [Burns]. So much so that winds are likely to disrupt any form of dynamic equilibrium (thermosphere) or diffusive equilibrium (exosphere) that is assumed [Burns]. Unfortunately, we do not know the neutral wind field anywhere above the F2 peak [Noto]. The H profile versus altitude is further influenced by the partial pressures of other constituents in such a way that its density in the upper thermosphere is a factor of 3-5 lower at solar maximum relative to solar minimum [Burns].

Water chemistry at lower altitudes (< 100 km) that is the source of thermosphere H is not fully understood; chemistry in the topside ionosphere is also uncertain [Mierkiewicz]. These affect Earth as well as other planets. Clues to this problem can be obtained using comparative aeronomy [Mierkiewicz].

Solar or cosmic Lyman-α scatter from exospheric H can be measured using TWINS (Two Wide-Angle

Imaging Neutral-Atom Spectrometers) or GUVI limb scans [Qin, Viereck]. Inverting these limb scans involves a radiative transfer model along with either additional assumptions or the application of forward modeling. Results show a population of non thermal H atoms in the thermosphere, where the models assume thermal equilibrium [Qin]. Lyman-α scattered from the outer exosphere can be measured using GOES (Geostationary Operational Environmental Satellite [Viereck]. GOES data show that the solar cycle variation in H density, which is very strong in the thermosphere, is absent at 8 Re [Viereck].

Our changing climate introduces further uncertainty as well as likely secular growth in the H density. Using a global mean model, Nossal et al. [2016] showed that the density of thermosphere H increases with an increase in greenhouse gases. With a doubling of CO2 relative to a pre climate-change baseline, hydrogen can increase by as much as 50%. This effect varies with the solar cycle in a way that differs from the known strong variation of H with the solar cycle, complicating established patterns [Nossal]. Methane also has an effect, increasing water vapor at mid-latitudes [Nossal]. Analysis of 35 years of ground-based hydrogen Balmer-α measurements shows long-term upper thermospheric H increases from solar maximum to solar maximum [Nossal]. However, these increases are larger than can be accounted for by increases in greenhouse gases [Nossal].

Model limitations are a further source of uncertainty

Like any empirical model, MSIS has inherent limitations. Over the course of a solar cycle, MSIS O densities vary relative to CHAMP (Challenging Minisatellite Payload) and GRACE (Gravity Recovery and Climate Experiment) measurements [Weimer] and densities obtained via satellite drag data [Emmert et al., 2014]. Typical monthly-average discrepancies between measurements and NRLMSISE-00 are of order 10%. The ill-understood annual and semi-annual density oscillations, as represented in NRLMSISE-00, often fall out of phase with corresponding measurements [Weimer]. Corrections to the O content in the NRLMSISE-00 were derived to match the measured density values. The oxygen corrections that were found, showing the variability in the annual and semi-annual oscillations, were found to have a high correlation with the CO_2 emissions that were measured with the SABER instrument on TIMED [Weimer et al., 2016].

A significant source of uncertainty (or model error) is the limited validity of the diffusive equilibrium assumption that is generally used to extend thermosphere densities into the exosphere for each constituent. When this assumption does not hold, the effective temperature associated with the decrease in exosphere density with height is likely to differ from the measured temperature. Scatter plots of the effective neutral temperature, T_n, can be obtained from Lyman-α line widths measured above Arecibo. These suggest that T_n is not constant in the exosphere [Noto]. Lyman-β line widths from WHAM show that the effective temperature is lower than that computed using MSIS [Mierkiewicz] for the same conditions (i.e., the same values of the F10.7 index).

First-principles multi-fluid or diffuse models are generally not valid above 3000-4000 km, where physics is kinetic [Schunk]. For example, plasmasphere refilling flows are often supersonic [Schunk, Krall]. This also means that collisional thermal conductivities are not valid above 3000 km [Schunk]. These high-altitude model uncertainties can affect both exosphere models and the magnetosphere models that are used to compute the geospace implications of the exosphere H and O densities.

Impact on geospace: plasmasphere

Simulations using the Naval Research Laboratory SAMI3 ionosphere/plasmasphere code show that post storm plasmasphere refilling rates are sensitive to both O and H [Krall]. The refilling rate is limited by the supply of H^+ in the topside ionosphere. H^+, produced via charge exchange, is limited by O^+ and H. Preliminary simulations suggest that the sensitivity of the refilling rate to H is very simple. When the overall H density is increased by a factor of 2, refilling rates increase by nearly that same factor, independent of the level of solar activity [Krall].

At low solar activity, sensitivity to O is similarly straight-forward. The O^+ supply increases with increasing O in the thermosphere, leading to more H^+ and faster refilling. At high solar activity, O is more plentiful above the ionosphere F peak. O above the F peak acts as a diffusive barrier to O^+, with the result that an overall reduction of the O density in either the thermosphere or exosphere leads to increased exospheric O^+ and H^+. At very high solar activity, as represented by an F10.7 EUV index > 200, a 20% reduction in O and a 20% reduction in the exosphere O temperature (such that the O density falls off more quickly with height) can lead to a factor of 2 increase in refilling rates [Krall et al, 2016].

Impact on geospace: polar wind

Polar wind studies show that H^+ and O^+ outflows (and inflows) are significant and highly variable at high latitudes. Because charge exchange can produce corresponding neutral H flows, H in the polar wind is significant and highly variable [Schunk]. H^+ and O structures and flows are also present. If sizable O^+ densities become sizable O densities, through charge exchange, significant downward O flows can result, creating "holes" at high altitude [Schunk].

Impact on geospace: ring current

Loss of ring current ions via charge exchange would increase if more H were present in the inner magnetosphere. When more H is present, the ring current decays more quickly and, as a result, exosphere temperature increases. Because the O^+/H cross section is nearly constant with energy, H is an effective agent of ring current decay at all energies [Ilie].

The H population in the inner magnetosphere is often referred to as the geocorona. Its nature is highly uncertain. In ring current studies, ion lifetimes vary by an order of magnitude depending on the geocorona H model used [Ilie]. Synthetic ENA (energetic neutral atom) images are highly dependent on the geocoronal model used [Ilie].

The impact of H on the ring current can be demonstrated using the CIMI (Comprehensive Inner Magnetosphere-Ionosphere) model. When the density of background H in the model was doubled, the ring current contribution to the Dst index was halved [Glocer]. Increased H not only weakens the storm, it also delays its onset [Glocer].

Next steps

Measured magnetospheric cold mass densities at geosynchronous orbit, a region that is generally outside of the plasmapause, have clear dependencies on EUV flux, season, and solar wind parameters [Denton]. Improved outflow models might better explain these dependencies.

More importantly, improved measurements of H in the thermosphere and exosphere may be forthcoming. The planned Exocube cubesat will measure light-ion composition and transport in the exosphere. It will be the first atmospheric mass spectrometer to measure atomic mass 1. Exocube will measure 1083nm metastable He emission to obtain meridional winds [Noto]. The GOLD (Global-scale Observations of the Limb and Disk) satellite will measure the exobase temperature [Mierkiewicz].

Further missions might also be forthcoming. The proposed ESCAPE 1 (European SpaceCraft for the study of Atmospheric Particle Escape) mission would measure the flux of major atmospheric components N and O escaping from Earth. Such measurements would significantly improve our understanding of exospheric physics [Mierkiewicz].

References

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