Plasma-neutral gas interactions in various space environments

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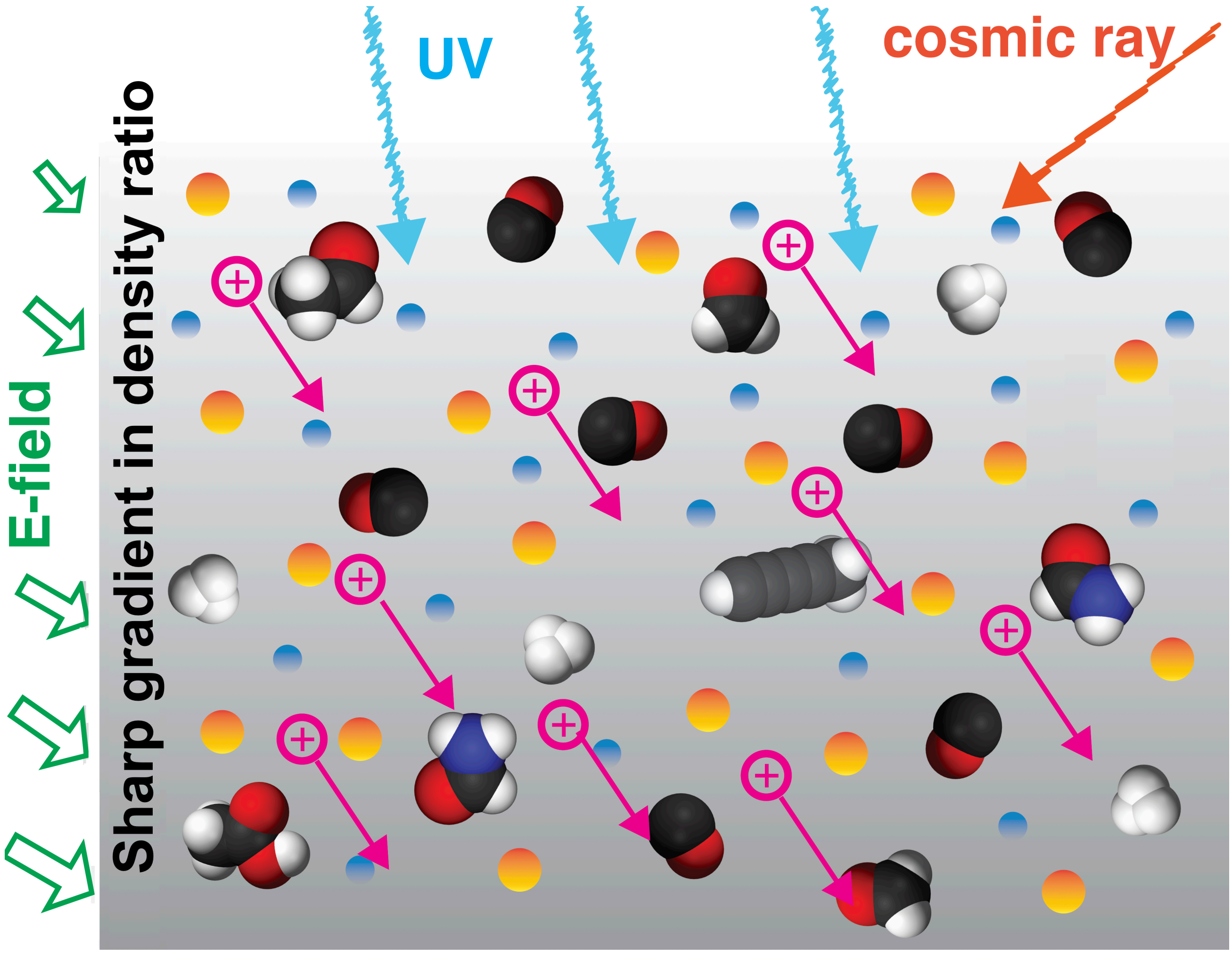

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Theme
Assessment of plasma-neutral gas interactions in space beyond simplified approximations

Advance our knowledge of plasma-neutral gas interactions to deepen our understanding of the partially ionized environments that are ubiquitous in the upper atmospheres of planets and moons, and elsewhere in space, by addressing the fundamental question:

(A) How and by how much do plasma-neutral gas interactions influence the re-distribution of externally provided energy to the composing species?
(B) How and by how much did plasma-neutral gas interactions contribute toward growth of heavy complex molecules and biomolecules?

Summary

Most matter in stars and interstellar space is composed of free ions and electrons, whereas the majority of planets, satellites, small bodies, and their envelopes are composed of neutral species. Given our very limited understanding of ***plasma-neutral gas interactions***, the small amount of neutral species in space above the exobase and the effects of electric charges on neutrals have been underestimated in considering plasma dynamics and the formation of planets, exoplanets, satellites, small bodies, and their atmospheres.

However, recent space observations in the upper thermosphere and exosphere where plasma-neutral gas collisions become important compared to neutral-neutral interactions suggest that this lack of knowledge of the plasma-neutral gas interactions is a serious drawback when trying to describe neutral behavior in a tenuous plasma such as the upper thermosphere and exosphere. This raises the first question **(A)**.

Furthermore, the finding of organic matter, including amino acids and other building blocks of life in comets and in interstellar space, indicates that they are formed in low-temperature environments where neutral-neutral interactions are negligible compared to neutral-ion interactions. This is the chemical aspect of the energy re-distribution problem. Since the amount and types of the required energy is different from physical energy re-distribution, the chemical aspect raises its own question **(B)**.

Answering these questions is an absolute prerequisite for addressing the long-standing question of atmospheric escape and origin of biomolecules, their role in the evolution of planets, moons, or comets under the influence of energy sources in the form of electromagnetic and corpuscular radiation.

Study of the ion-neutral and electron-neutral interactions requires accurate measurements of plasma and neutral species in relevant partially ionized media, including composition of the neutral and ion species, velocity distribution of ions and electrons, as well as ambient energy that is characterized by electric and magnetic fields, radiation, and temperature. Since such complicated environments, particularly under the influence of various electromagnetic fields and with complicated composition, temperature, and radiation fluxes, cannot easily be reproduced in a laboratory, the only way to understand the plasma-neutral gas interactions in space is through in-situ observations in various environments in space, suitable for space missions. Particularly, observations in low-density environments with substantial neutral particle content are needed, for examples, in the upper ionosphere near the exobase of a planet or natural satellite, in comets, or in interstellar space.

Ideally, measurements should be performed in partially ionized plasmas under diverse thermal conditions, for example, from extremely low to moderately high temperatures. Doing so in a long-period comet is one obvious candidate because it covers wide density and temperature ranges. The diversity of the target environments can also be achieved through several different missions performed by other space agencies. In this respect, we can start with a mission at a nearby planet (Earth or Venus) as small or medium class mission, while we could also aim to contribute relevant instrumentation to possible large-class solar system missions (e.g., interstellar probe, an ice giant mission, or a long-period comet mission). In this white paper, one possible mission scenario for the Earth's upper atmosphere is described, which can be copied to case of Venus, while the space physics community is simultaneously submitting white papers devoted to the other relevant environments.

1. Low-energy plasma-neutral gas interaction in space

One of the fundamental questions regarding the universe is how the different types of matter interact and shape stellar systems, planetary environments, and specific environments that allow life forms to emerge. The small-scale limit of such an interaction is between quarks and photons, and belongs to high-energy physics. The large-scale limit includes dark matter and dark energy, and belongs to cosmology.

For the habitable part of the universe such as planetary and exoplanetary systems, their evolution is driven by interactions between visible (traditional) matter through radiation, collisions, and collective forces such as electric and magnetic forces, in addition to gravity. For example, the lifetime of a comet is strongly affected by the solar radiation, the solar wind plasma interaction, and the tidal forces near perihelion. Chemical interactions start dominating to form complicated molecules including biomolecules from a mixture of low-energy (< 1 keV) ions and neutral (both in the gas phase and the condensed phase) that are exposed to strong external energy (such as cosmic rays), particularly at low temperature such as in the interstellar medium (e.g., Ruaud et al., 2015) and the upper atmosphere of planets and satellites. For example, the thermosphere and mesosphere of the Earth contain complicated molecules and even aerosols such as ion-water cluster molecules (Brasseur and Solomon, 1986; Verronen et al., 2016) and noctilucent clouds (e.g., Gadsden and Schröder, 1989; Bardeen et al., 2010). Considering the fact that the habitable part of the universe is composed of low-temperature ions and neutral species (T< 0.04 eV) and that the heavy molecules before being trapped by ice or dust in interstellar space are exposed to extremely low-temperature space plasma, understanding the actual plasma-neutral gas interaction at low energy through in-situ observations is very important.

If the organic matter is formed in the low-temperature plasma, a similar process that involves plasma-neutral gas interactions might take place during the formation of the Solar System, which should have had its effect on comets in, e.g., the Oort Cloud. By looking back to 4.6 billion years ago, the formation of the solar system might have undergone a period when the plasma-neutral gas interactions played a critical role, which is not only relevant for the formation of heavier materials but also for re-distributing (partitioning) the energy or even degrading the material. On the other hand, plasma-neutral gas interactions in the thermosphere and ionosphere have substantially influenced the planetary evolution through the atmospheric escape (Yamauchi and Slapak, 2018; Lundin et al., 1990, 2009).

However, our knowledge of the actual plasma-neutral gas interactions in tenuous space plasmas with some neutral particle content – either gaseous or in the form of icy grains – is still incomplete. The chemical pathways to forming heavy (organic) molecules are only partially understood. This is partly because low-energy ion-neutral and electron-neutral interactions in low-temperature plasma vary across different environments, depending on the external DC and AC electric and magnetic fields, as described in §1.3 below. Although the cross section of a single interaction between a simple ion and a neutral particle in the gaseous phase without complicated force or energy is known from both theory and laboratory experiments (e.g., Fok et al., 1991), a substantial change in the plasma conditions (composition and velocity distribution of the ions and neutrals) or in the ambient energy (electric and magnetic fields, radiation, and temperature) can cause a significant change in the ion-neutral particle and electron-neutral particle interactions, particularly in a tenuous plasma. Also, the electron impact ionization properties (e.g., Mazelle et al., 2018) are not well understood at distant environments and for different neutral species, although they provide a dominant source of ionization, especially when far from the Sun, as photo-ionization is subdominant because of a too low solar UV flux.

With such a variety of environments and ambient energy distributions, it is not easy to pinpoint the exact conditions for relevant laboratory experiments without in-situ measurements in space. This made the plasma-neutral gas interactions in actual space environments less well understood when compared to the present knowledge on the dynamics and interactions in fully ionized space plasma. Particularly, our knowledge on the interaction between low-energy ions and neutral species is far from complete.

Here we did not include the cases when either neutral part or ion plasma part is in the solid form, because such interaction problem opens up another world of fundamental questions. For instance, electrostatic charging of icy grains under the influence of cosmic ray or UV radiation may grow or dismantle the grains (e.g., Ivlev et al., 2015; Millar, 2015), thus controlling the grain size distribution and also the total grain surface area available for chemical reactions. The charged grain and dusty plasma behavior is another region where plasma-neutral interaction is significant, such as Saturn's rings (e.g., Christon et al., 2015), composing another dedicated field.

1.1. Present-day knowledge

The low-energy plasma-neutral gas interaction in partially and weakly ionized plasmas has long been studied as one of the central themes of ionospheric physics and aeronomy. Plasma-neutral gas interactions include both the direct collisional interaction and the indirect interaction through the electric, magnetic, and radiation fields. Unlike ion-ion, ion-electron, and electron-electron interactions, the role of the indirect interaction between ions and neutral species is generally ignored in standard formulations to describe the dynamics of a gas state, such as the Boltzmann equation (and Vlasov equation when the collisional term is ignored). In these equations, all the external forces are separated from collisional effects (e.g., Schunk and Nagy, 2009). Unless the actual force at each location is not significantly different from locally averaged forces, such as radiation with wavelengths less than the inter-particle distance (which can be treated in a chemical manner like UV-induced reactions), such equations provide a good description of the plasma dynamics.

However, solving the Boltzmann equation for the velocity distributions requires vast computational resources in numerical modeling, and therefore, fluid equations derived from integrals of the Boltzmann equation are normally used to solve the large-scale dynamics. The most complex model currently used for the dynamics and chemistry in the partially ionized plasma of the ionosphere-thermosphere system (with collective plasma-neutral gas interactions) is the set of 13-moment multi-fluid equations (mass, 3 elements of velocity, temperature, 5 elements of stress tensor, and 3 elements of heat flow) with Boltzmann collision integrals under the assumption that each species has a smooth distribution (Maxwellian, bi-Maxwellian, tri-Maxwellian, and toroidal, including anisotropic case) so that a truncated expansion can be applied to the collision terms (Bougher et al, 2008; Schunk and Nagy, 2009). This assumption works well for a small net energy loss (using a sort of linear approximation) such as Coulomb collisions, elastic plasma-neutral gas collisions, collisions between different neutral species, and a resonant charge exchange interaction between an ion and its corresponding neutral particle, which is pseudo-elastic.

Models are further simplified in various manners. For the Earth's upper atmosphere there is TGCM (Thermosphere General Circulation Model); GITM (Global Ionosphere Thermosphere Model); WACCM (Whole Atmosphere Community Climate Model); TIE-GCM (Thermosphere Ionosphere Electrodynamics General Circulation Model); TIME-GCM (Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model); CTIM (Coupled Thermosphere Ionosphere Model); CTIP (Coupled Thermosphere Ionosphere Plasmasphere Model); and CMAT (Coupled Middle Atmosphere Thermosphere Model) (Bougher et al, 2008 and references therein). All these models are designed under the assumptions of (a) a Maxwellian-type distribution, (b) no minor components except WACCM that is specialized for climate change, and (c) well-defined boundary conditions, a specified energy input, and other conditions.

On the other hand, collisions play a fundamental role in the dynamics and energetics of ionospheres. They are responsible for the production of ionization, the diffusion of plasma from high to low density regions, the conduction of heat from hot to cold regions, the exchange of energy between different species, and other processes. The collisional processes can be either elastic or inelastic. Some interactions lead to chemical reactions.

It is not easy to learn from the interaction when the neutral particles are in the form of grains, which deserves its own study field. The plasma-grain interactions, often taking place at the grain surfaces, are an important ingredient. Interstellar medium embody this situation, where equilibrium is assumed between the ambient interstellar gas and dust grain condensation nuclei. However, modeling the composition depends on freezing temperature, ambient UV flux, cosmic ray radiation field, charging, and surface area during the growth of the grain. The UV flux may also lead to grain charging and dusty plasma effects. Regarding proto-planetary disks when such interaction is under the influence of young star, significant progress has been made, partly in view of the growing body of observational data (e.g. with ALMA), but also in view of the study of comets and asteroids as relics of solar system formation that have undergone limited alteration. Even minor species can play a major dynamic role, as they may behave as catalysts, changing the surface albedo or the sublimation temperature of ices. Thus, plasma-grain interaction or ion-neutral problem constitutes its own fundamental questions that are unsolved, and hence we have to tackle the ion-neutral gas interaction in the gas form (including heavy molecules) as a separate problem.

1.2. Limitations

The exact nature of the collision process depends both on the relative kinetic energy of the colliding particles and on the type of particles. In general, for low energies, elastic collisions dominate, but as the relative kinetic energy increases, inelastic collisions become progressively more important. The excess energy during inelastic collision is normally transferred, as the relative kinetic energy increases, to rotational, vibrational, electronic excitation, and ionization. However, the different collision processes may affect the continuity, momentum, and energy equations in different ways.

This makes the plasma dynamics and chemistry complicated **when the externally provided variable energy density exceeds the pre-existing energy density under quasi-static state** because collisions take place under the influence of short-range external fields and just adding an AC electric field alters the collision configuration. In such cases, it is difficult to evaluate the external force terms in the multi-fluid equations and the collective effects on the collisional term. Even the derived distribution can already violate the Maxwellian assumption. Since the relative energy between the variable external energy and pre-existing energy must play an important role, **unexpected plasma behavior can be seen in low-energy density plasma, with low density and low temperature** (which agrees with the mixed state between neutral species and ions).

Contrary, when the external field is not that strong, its collective effects on the collision process cannot be ignored. Therefore, such collective forces are also formulated with, e.g., quasi-linear approximation for ion dynamics. However, quantitative verification of the Boltzmann collision integrals in the real space environment is not easy even if the distribution function is known. What makes space environments special, however, are the unique combinations of phenomena and their interplay. Studying plasma-neutral gas interactions becomes more challenge when a part of the neutral particles is condensed to form cloud or heavy molecules, but not as big as grains or dust.

1.3. Observation-model discrepancy

For high-density collisional regions, such as the lower thermosphere, existing models provide a good estimate of the bulk ion properties from bulk neutral properties when compared with ionospheric and thermospheric observations. However, when the partially ionized plasma is become tenuous with very low collision rate both for neutral species and ions, such as altitudes above 300 km for the Earth's case, observations start to depart from what we expect from combinations of empirical models and theoretical models and laboratory experiments because the assumptions of Maxwellian distributions are no longer valid, particularly near the exobase.

1.3.1. Earth: neutral behavior in the upper thermosphere and exosphere

TIMED observation of N_2 and O in the Earth's upper thermospheric density and temperature profile found significant discrepancy from the empirical MSIS model (Meier et al., 2015). Even the scale height for density is not yet clear: for the hydrogen, the UV observations of the exosphere beyond 3 R_E indicates a scale height of about 20000 km for one order of magnitude decrease (Zoennchen et al., 2015), whereas it is only 3000 km for the thermospheric model based on outdated in-situ measurements (Johnson, 1969; Pfaff, 2012), as shown in **Figure 1**.

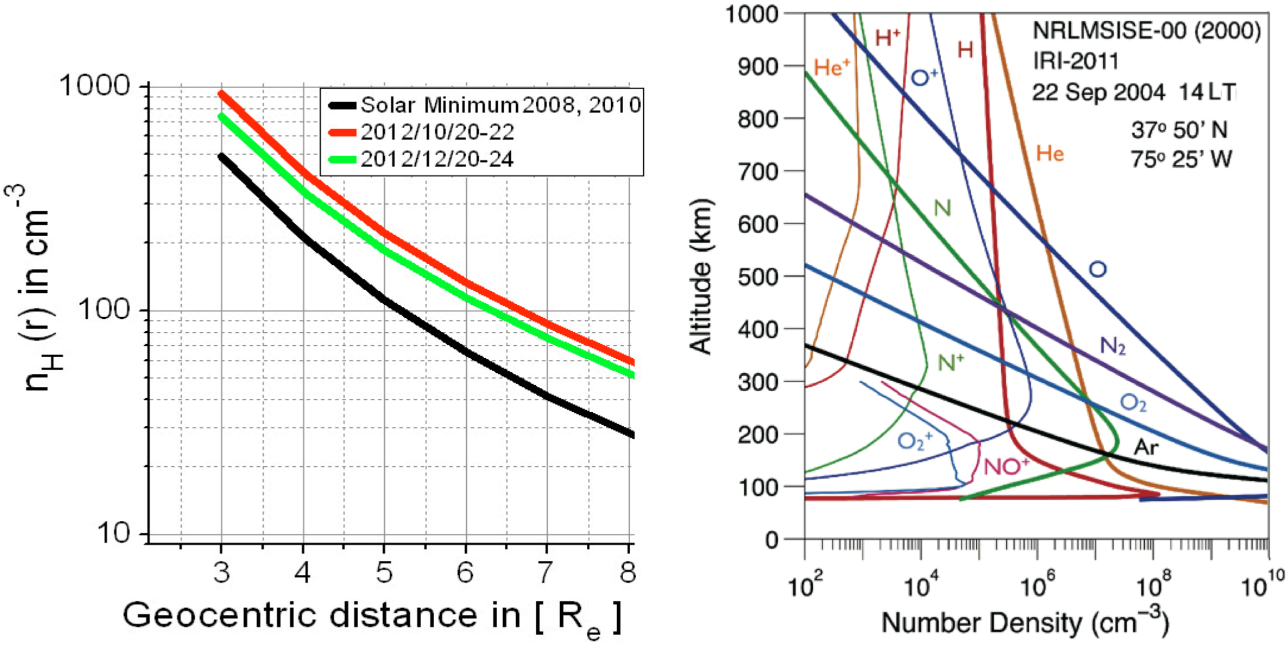


Figure 1: Left: Average exospheric hydrogen density profile that is model-fitted from Lyman-alpha line-of-sight observations by the two TWINS spacecraft (Zoennchen et al., 2015). Right: Example altitude profile by the International MSIS model (Johnson, 1969; Pfaff, 2012). The smoothness of the profile (nearly exponential above 200 km for neutral species) comes from lack of observations.

For the range between 500 km and 3 R_E, where the exospheric profiles are basically obtained from the hydrostatic assumption, there is no reliable information. This comes partly from insufficient observational knowledge on the energy re-distribution in that region, and partly from the lack of sufficient in-situ observations of neutral species and ions in the upper thermosphere and above (e.g., Lühr et al., 2004). Modern spacecraft that carry accelerometers for total density measurements do not cover that altitude range, and we still rely on measurements from the 1960's–1970's (except DE-2, 1981) that are already nearly 50 years old.

The discrepancy or unexpected dynamics becomes more significant when a massive energy input is provided from space, e.g., near the cusp and during geomagnetic storms. **Figure 2** illustrates the cusp case. CHAMP observed narrow channels with a density increase of neutral particles near the cusp, where strong field-aligned currents, both DC and AC, are continuously providing electromagnetic energy to the ionosphere in a narrow region (Lühr et al., 2004). Such a density enhancement is conventionally considered to be the result of upward neutral wind sustained by the Joule heating at 120–130 km altitude, but simulations of neutral wind in a narrow channel (Shinagawa and Oyama, 2006) do not reproduce simple upward flow but require downward flow at the sides. The strong structuring of density and temperature has also been found by TIMED, which showed the structure within 5° in latitude during geomagnetic storms, while models predict essentially constant density (less than a factor of 2 change, Meier et al., 2015).

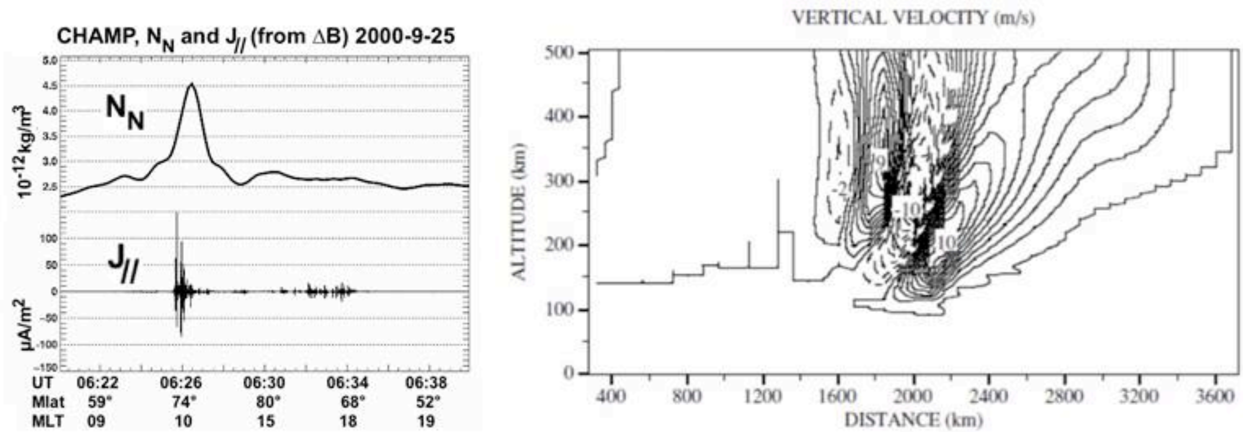


Figure 2: (a) CHAMP observation of density (using accelerometer) and fine-scale field-aligned current derived from magnetic field at above 400 km altitude (Lühr et al., 2004). (b) Simulation of neutral wind in narrow channel (Shinagawa and Oyama, 2006).

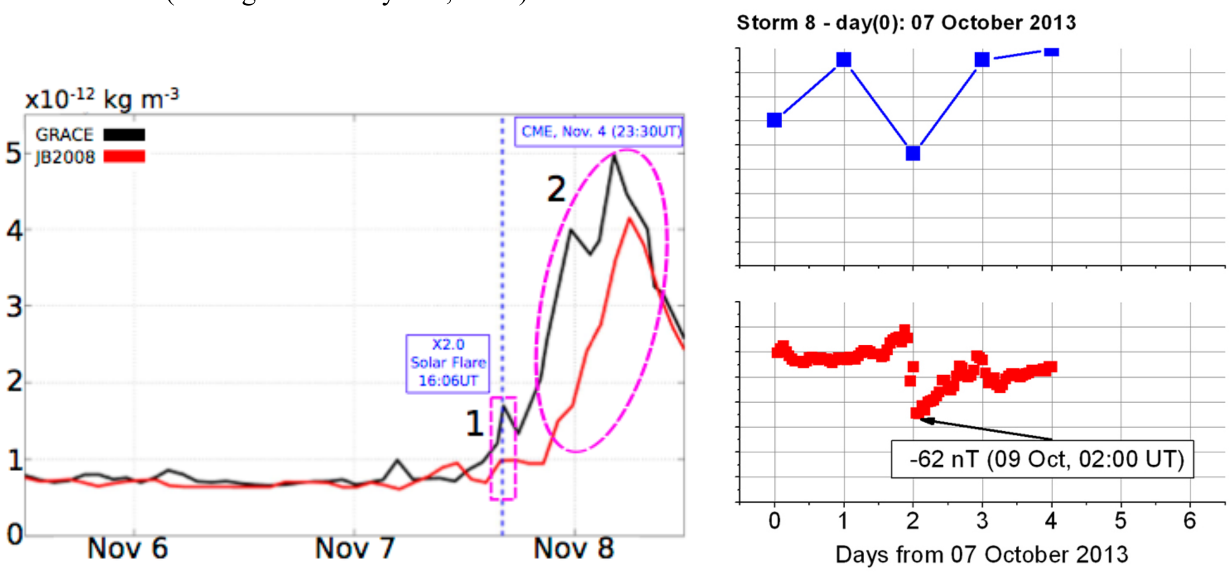


Figure 3: (left) Neutral densities from GRACE measurements (black) and the empirical thermosphere JB08 model (red) using average daily indices in November 2004 (Krauss et al., 2014). The sudden increase due to the X2.0 solar flare is marked as 1, whereas the impact of an ICME a few hours later is marked as 2. (right) TWIN Ly-alpha observations of relative variation in the column density of exospheric H that is represented by total solar Ly-alpha flux (%) when a large geomagnetic storm took place (Zoennchen et al., 2017).

During geomagnetic storms, when the energy flow from the magnetosphere to the thermosphere is enhanced, neutral properties deviate over an area that is wider than the local cusp where the energy input is locally high. The TIMED satellite (Shematovich et al., 1999; Hubert et al., 2001; Meier et al., 2015; Lakhina and Tsurutani, 2017) showed large variability of neutral temperature and density of O and N_2, responding to both the solar EUV flux and the magnetospheric activity, which are significantly different from the model predictions (Picone et al., 2002, Gordiets et al., 1982, Tian et al., 2008). For example, during geomagnetic storm periods, the temperature nearly doubled and the N_2 density increased by one order of magnitude within 10 days. **Figure 3** shows TWIN and GRACE observations of neutral density during major geomagnetic storms. The enhancement of the neutral density in response to major geomagnetic storms is much more than predicted by the empirical model during similar but stable conditions. This also indicates that the enhanced energy inflow caused an unexpected response of the neutral atmosphere (Sutton et al., 2005).

In summary: our knowledge is not sufficient to even understand the basic behavior of the terrestrial upper ionosphere and upper thermosphere. This equally applies to ion-neutral phenomena in the mesosphere, such as polar mesospheric summer and winter echoes that seem to be partially influenced by solar activity (Latteck and Strelnikov, 2015). ESA's proposed Earth Explorer 10 mission Daedalus (Sarris et al., 2019) will contribute to improving our understanding of the plasma-neutral gas interactions in the lower thermosphere and ionosphere in view of its special orbit (with perigee between 120 and 150 km altitude) and its instrument suite that consists of ion, neutral, and electromagnetic field instruments.

1.3.2. Venus and Titan: super-rotation and fast ion flow

The cause of the super-rotation of Venus' atmosphere (Schubert and Whitehead, 1969) is a long-standing mystery. Such large-scale atmospheric convection, much faster than the surface rotation, was also found on Titan (Bird et al., 2005), suggesting that this might be a common feature of atmospheric dynamics on planets or moons with sufficient atmosphere and slow solid rotation. There are two fundamentally different ideas regarding the driver: (i) the momentum of the extremely slow surface motion keeps transferring a massive total momentum to the upper atmosphere so that it flows 100 times faster than the ground; and (ii) plasma transfers a sufficient amount of momentum to the neutral atmosphere although the plasma density is much smaller than the neutral density. The transferred energy does not have to be very much (like terrestrial global circulation) because intrinsic modes of planetary convection might exist, such that a very small momentum transfer from either below the ground or above may maintain the mode. The Japanese Akatsuki Venus mission is dedicated to this problem by examining details of the atmospheric convection to evaluate the energy transfer from smaller-scale to larger-scale convection. However, the observations have not yet solved this problem.

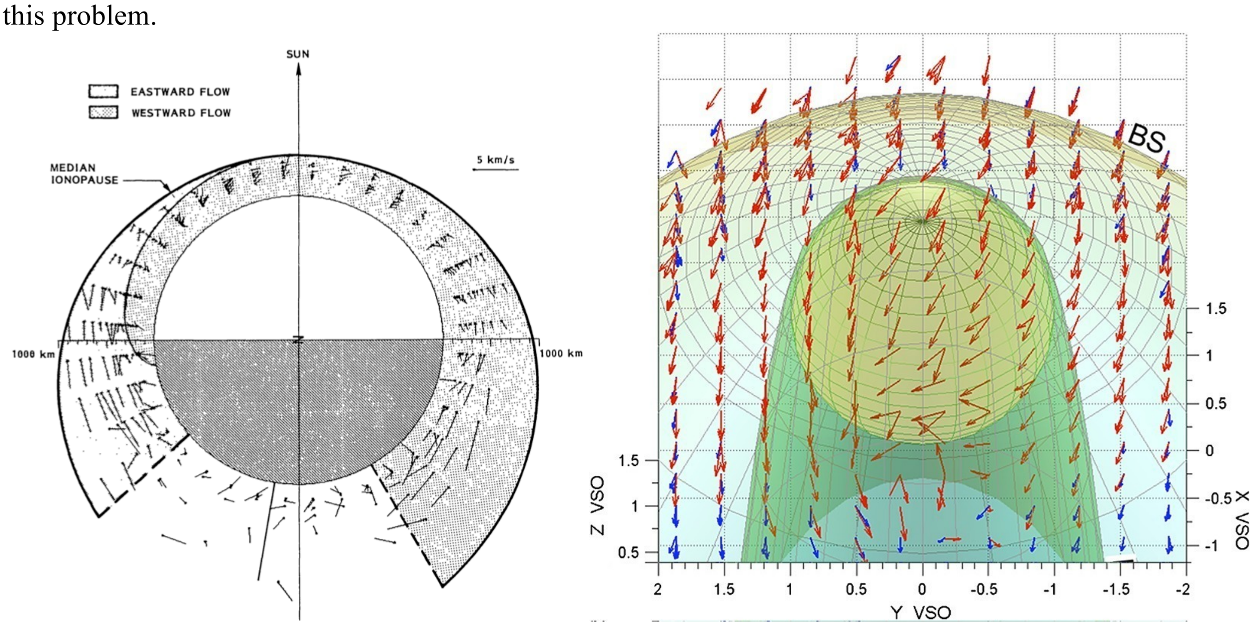


Figure 4: Ion convection directions observed by (left) Pioneer Venus Orbit (Miller and Whitten, 1991) and (left) Venus Express (Lundin et al., 2013).

While Akatsuki targeted only the first scenario (instrumentation to examine the second scenario was not included due to mass limitations), both Venus Express (Lundin et al., 2013) and Pioneer Venus Orbiter (Miller and Whitten, 1991) showed strong ion convection in the super-rotation direction, with velocity 10 times faster with Venus Express, as shown in **Figure 4**. The observation suggests a much more effective momentum transfer than predicted by any model of plasma-neutral gas interaction, and even raises the possibility that ion motion maintains the super-rotation.

In addition to super-rotation, Titan has several other mysteries that are relevant to the plasma-neutral gas interaction. One is the cause of the massive cold ion outflow from Titan ionosphere, which is believed to be too cold to produce such outflow. Cassini found unexpectedly high-density cold ions in Titan's upper ionosphere and high escape rates with ~100 km/s velocity, as shown in **Figure 5** (Wahlund et al., 2005). If the ion velocity is maintained by the magnetospheric convection of Saturn or by other plasma processes, scenario (ii) to maintain the super-rotation may apply here. However, the opposite scenario in which momentum is transferred from neutral atmosphere super-rotation (which is much slower than the observed ion flow) to the ion flow is also a possibility. In both scenarios, the observations suggest a momentum transfer that is higher than predicted in any model of plasma-neutral gas interaction.

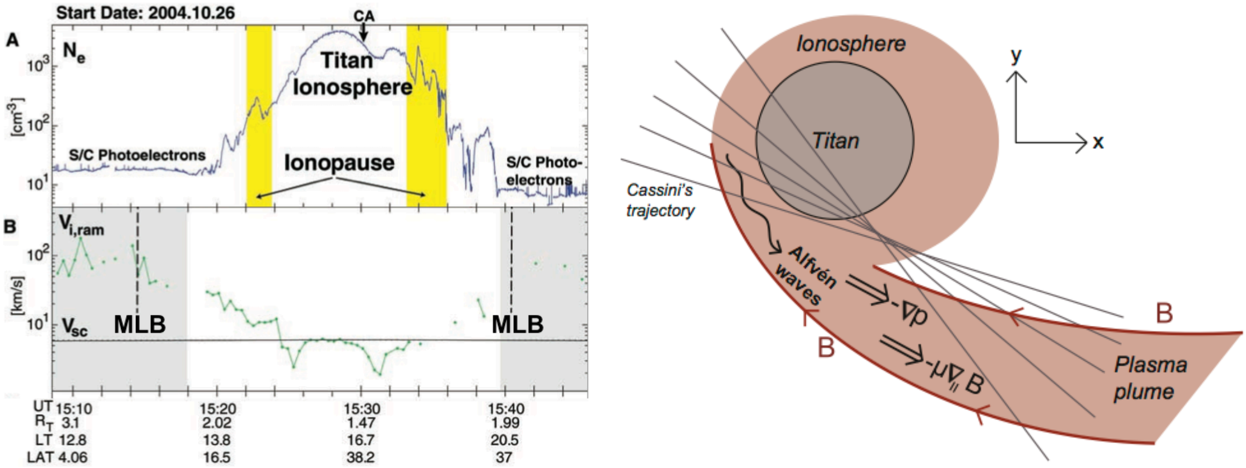


Figure 5: (a) Cassini observations of density and velocity of cold (thermal) ions above the Titan ionosphere (Wahlund et al., 2005). (b) Summary of cold ion escape observed by Cassini (Edberg et al., 2011)

1.3.3. Cold environments such as interstellar space: formation of organic matter

Another important issue relevant to the plasma-neutral gas interaction at Titan is the formation of heavy molecules, including organic matter (e.g., Vinatier et al., 2007). The process is more chemistry-led in a collisional atmosphere rather than being controlled by collective effects of external forces. In the terrestrial middle atmosphere, cold environments are known to enhance certain types of chemical reactions such as the ozone depletion (Denton et al., 2018) and the formation of noctilucent clouds and heavier particles causing specific radar echoes near the mesopause (Nishiyama et al., 2018). Similarly, the enhanced plasma-neutral gas chemistry in Titan's upper atmosphere is expected to behave as a rather purely chemical system (Keller et al., 1992). However, this chemistry is initiated by external energy provided by the solar UV, high-energy photons, electrons, and ions, through ionization of the major neutral species like nitrogen and methane.

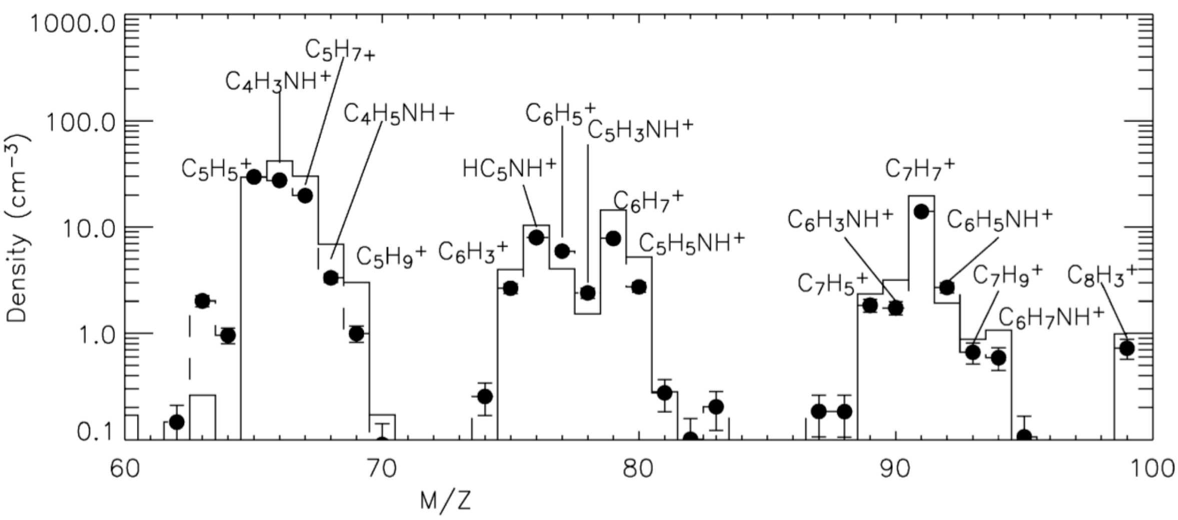


Figure 6: Cassini observation of ionospheric heavy ions (Vuitton et a., 2007).

The Cassini mission confirmed that Titan has the most compositionally complex ionosphere in the Solar System, with roughly 50 molecular ions at or above the detection threshold, most of which are composed only of C, H, and N, as shown in **Figure 6** (Vuitton et al., 2007). Unlike terrestrial atmospheric chemistry, where heavy molecules imply water compounds (ref), the observed composition naturally should lead to the formation of amino acids (Hörst et al., 2012) although Cassini's instruments was not capable of identifying them. It appears that much of the interesting chemistry, even to high mass, occurs in the upper atmosphere rather than at lower altitudes, which indicates energetic particles from above may be one of the key elements in addition to the UV irradiation.

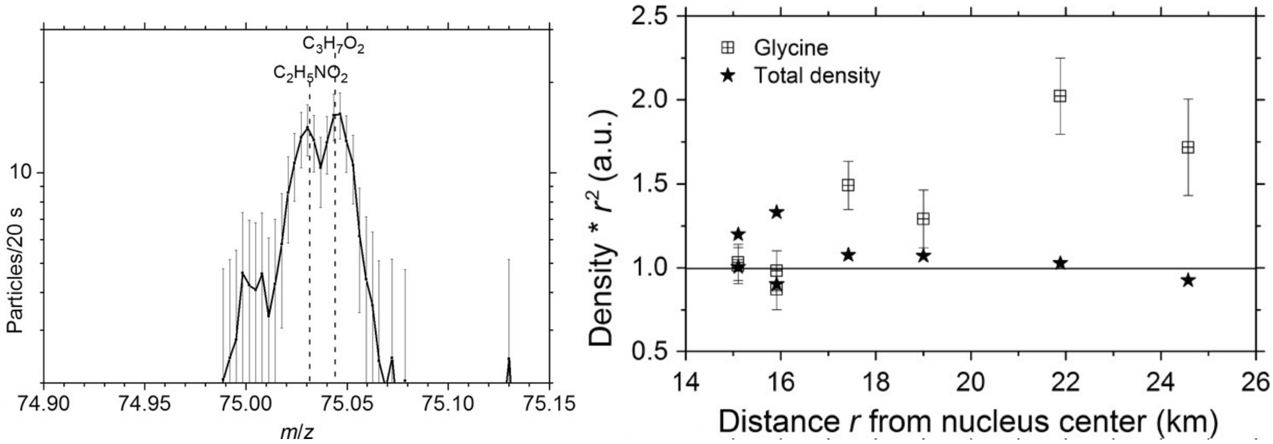


Figure 7: Rosetta observations of volatile Glycine ($C_2H_5NO_2$) and other amino acids (Altwegg et al., 2016).

The formation of organic matter, including amino acids, in cold tenuous environments may also occurs in the formation region of comets (such as the Kuiper belt and the Oort cloud) and in interstellar space where the environment is very cold (Geiss, 1987). **Figure 7** shows Rosetta observations of an amino acid (Altwegg et al., 2016). Because of the intimate relationship between the condensed and gas phases in molecular clouds and their exposure to strong UV from young OB stars in star-forming regions, and also due to their long-duration immersion in the cosmic ray background, the formation pathways leading to organic matter can be multiple and complex, beyond what we can model so far. Such cold environments favor the situation in which an external one-time energy deposit exceeds the background energy density in a non-thermal processes (e.g., cosmic ray energy deposition inside an icy dust grain triggering the formation of chemical radicals), but interaction mechanisms in such environments are not easy to examine in a laboratory experiment (Johnson and Quickenden, 1997).

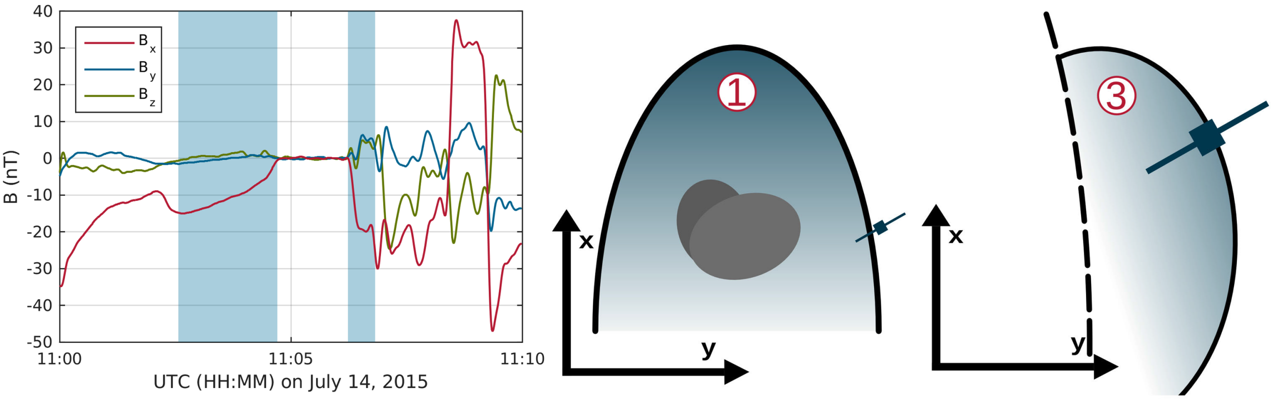


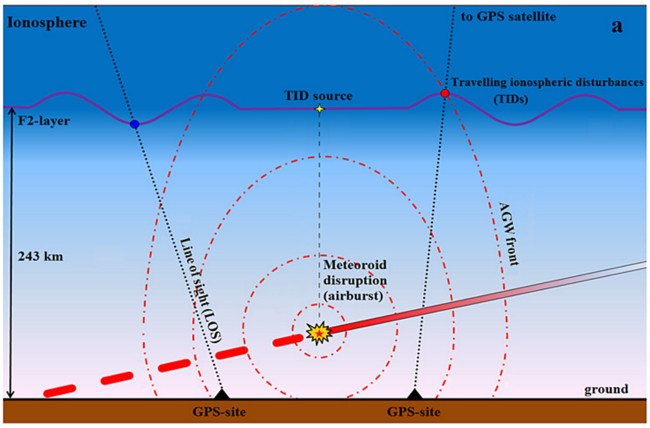
Figure 8: (left) Rosetta observations of magnetic cavity; (middle) The observed location and the boundary normal direction (bar direction); (right) Illustration of the temporal boundary of the cavity (solid line) that is rippled from the average boundary (dashed line) (Goetz et al., 2016). x points sunward, z points northward in the orbital plane.

1.3.4. Comet: unexpected structures in plasma-neutral gas mixed plasma

Comets are fascinating laboratories for studying plasma-neutral gas interactions, both for the formation of heavy molecules and for the solar wind interaction with the outgassing of neutral species. Rosetta was able to explore the diamagnetic cavity, a completely field free region, at comet 67P/Churyumov-Gerasimenko (Goetz et al., 2016). **Figure 8** shows an example of these measurements. The boundary normal direction is variable which implies that the structure is not spherical in shape. Henri et al., (2017) found that the boundary location can be organized by the electron-neutral collision rate, but the formation mechanism has not been found yet. At high activity comets like 1P/Halley the ion-neutral collisions are an important mechanism of energy transfer in the inner coma. There, the ions are efficiently cooled and remain coupled to the neutral species. Then the influence of collisions with neutral species is deemed important in forming these diamagnetic cavities at comets. Indeed, the neutral particle density and their composition determines the amount of ionization and thus the mass-loading of the solar wind plasma, which then affects the size of the diamagnetic cavity. The role of charged dust in the coma remains largely unexplored.

1.3.5. Meteor: air burst

Meteors are known to produce a shock front leading to an enhanced ionization of the ambient atmosphere (because of intense heating at the shock) and of ablated meteor material (through high-speed collisions with air) (Silber et al., 2018). The Chelyabinsk meteor burst in 2013 produced more energy than the traditional models predicted. A large part of its kinetic energy was unexpectedly consumed in the atmosphere rather than at ground impact, causing various effects in the geomagnetic field, lithosphere and atmosphere. Most of the energy was emitted as a result of disruption (airburst) at around 27-30 km altitudes, affecting the ionospheric electron density in a wide area, as illustrated in **Figure 9** (Perevalova et al., 2015). This indicates that energy conversion from the meteor motion to the atmosphere through the plasma around the meteoroid was more effective plasma-neutral gas interaction than our present-day knowledge suggests.



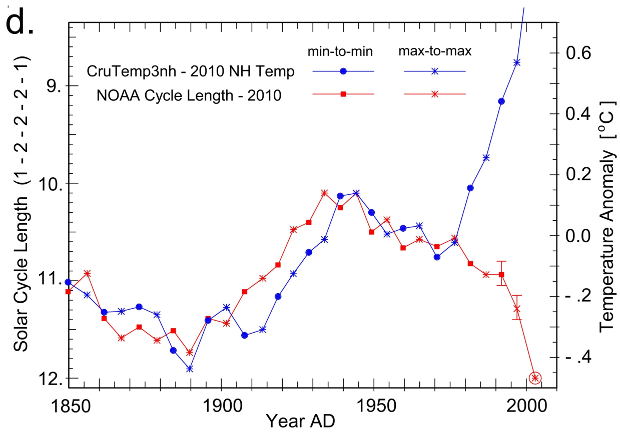


Figure 9: Illustration of how the Chelyabinsk meteoroid airburst affected the ionosphere (Perevalova et al., 2015).

Figure 10 Northern hemisphere average temperature (red line) and length of sunspot cycle (blue line). Before the human effect took over during 1980's, they are strongly correlated (Stauning, 2011).

1.3.6. Past climate change: solar influences

The role of the Sun's plasma and magnetic activity in the paleoclimate (4 billion years ago) and past climate change over the past millennia and longer (but prior to major anthropogenic impact on climate) is the subject of a long-standing debate for nearly 30 years after the introduction of non-linear methods to correlate the solar activity (length of the solar cycle, length of solar minimum, or strength of solar dipole magnetic field, instead of simple sunspot number) with the terrestrial climate (not only the average temperature but also the regional pressure such as north Atlantic oscillation or cloud coverage) (Friis-Christensen and Lassen, 1991; Svensmark et al., 2009; Stauning 2011; Barnard et al., 2011; Airapetian et al., 2017). **Figure 10** shows the correlation study by Stauning (2011). The reason that the solar impacts have been ignored in climate models is because there exists as yet no understanding of a possible physical link between the solar wind and tropospheric temperature or meteorological phenomena (Airapetian et al., 2019).

In the upper thermosphere the ion and neutral density are comparable. If the plasma-neutral gas interactions strongly intensify when the external energy source grows, as has been suggested from observational discrepancies (cf. §1.3.1 above), the neutral atmosphere could be affected too because of the vertical coupling of the energy in the atmosphere through, e.g., gravity waves. Thus, the influence of the Sun or of and other external sources (e.g., galactic cosmic rays) on atmospheric chemistry and escape that shapes the past climate variability cannot be evaluated unless we understand the interaction between the plasma and the neutral atmosphere.

1.4. Science questions related to the plasma-neutral gas interactions

As illustrated above, there are many unexplained observations that are most likely related to the plasma-neutral gas interactions. The above examples are mainly focused on ion-neutral interactions, but our understanding of electron-neutral interaction also needs to be updated.

The behavior of comet atmospheres and magnetospheres, including diamagnetic cavities (§1.3.4), indicates that the plasma-neutral gas interactions can play an important role in their dynamics. The terrestrial examples (§1.3.1, §1.3.5, and §1.3.6) illustrate how the importance of the plasma-neutral gas interactions on the energy re-distribution between energized ions and neutral species and the ambient environment has often been overlooked, i.e., how external energy feeds into the energization of ions, of neutral species, or of the background populations (acceleration and thermalization). Either ions or neutral species could depend more sensitively on the external drivers than what the present models predict. This problem is formulated as the first fundamental question:

(A) How and by how much do plasma-neutral gas interactions influence the re-distribution of externally provided energy to the composing species?

This modification of the plasma-neutral gas interaction and subsequent energy re-distribution is expected to be large when the external energy (characterized by energy flux density) is large compared to the background energy (characterized by pressure), which is more readily the case in the upper ionosphere near the exobase. Although the most affected region has a limited extent, the consequences of the enhanced energy re-distribution through the plasma-neutral gas could be far-reaching. They are classified into the following 4 major topics.

(A1) Impact of atmospheric particle energization on long-term large-scale evolution: A more extreme energy re-distribution, such as focusing the energy into specific form, causes more atmospheric heating for both ions and neutral species directly in the upper thermosphere in addition to the Joule heating in the lower thermosphere. This is important for understanding the origin of certain types of ion escape that need neutral species to rise up to altitudes from which adiabatic acceleration and ion acceleration through ambipolar and/or auroral electric fields become effective, for assessing the present-day atmospheric escape rate and its effects on magnetospheric circulation and dynamics, and for understanding atmospheric escape over geological time (Airapetian et al., 2019). This is related to the question whether a magnetic field protects an atmosphere against escape, or not (Nilsson, 2011, Gunell et al., 2018). The problem can even be generalized to the solar system size, e.g., in the interaction region between the heliosphere and the interstellar medium.

(A2) Structures and variability of the upper thermosphere and exosphere: Since the external energy that is provided from space to the upper thermosphere is localized in the dayside cusp or very variable in the auroral oval, the energy re-distribution in the upper thermosphere through the ion-neutral interaction there should be enhanced locally and globally (§1.3.1), causing a structure and variability in the exobase and exosphere. The exobase altitude and temperature as well as local expansion of the exosphere determines a large part of neutral escape for Mars and the ancient Earth, the local anomaly and temporal change of them significantly changes neutral escape and related neutral dynamics from the lower part of the atmosphere. Through the vertical coupling through gravity waves and other mechanisms, such variability may even influence the lower thermosphere and the mesosphere as well as the local plasma-neutral gas interactions, particularly during magnetic storms and other severe magnetospheric activities. An improved understanding of the thermosphere will have immediate benefits for technological applications such as satellite drag in low Earth orbit, space debris management, and spacecraft reentry. The anomaly of the exobase altitude is a natural nature of comet that has localized outgassing region, and the same argument applies to the naturals satellites with plumes. The non-uniform neutral density is even expected at the heliospheric boundary.

(A3) The turbulent energy cascade and the Kolmogorov scale in partially ionized plasma: Different interactions imply different scale sizes (in both space and time) in the energy transfer. In the small-scale limit of the turbulent energy cascade, an enhanced energy re-distribution through the plasma-neutral gas interaction will change the scale size of the energy cascade, influencing even the Kolmogorov scale. This cascade will become even more complex in the layered region where the ionization rate and the collision frequency rapidly change, like comet and the ionosphere. Since the turbulence energy is small, such a modification through the plasma-neutral interaction is expected to be substantial.

(A4) Roles of ions in the transfer of angular momentum and energy to neutrals: The possibility that the dawn-dusk asymmetric plasma motion helps to maintain the super-rotation of the Venus atmosphere (§1.3.2) indicates possibility of more effective momentum and energy transfer from the Sun or proto-planetary disk to the proto-planets, with higher roles of the plasma and the electromagnetic fields in the formation of the solar system. A higher energy transfer from the proto-planetary disk to the proto-planets may even heat the proto-planets more during their formation when the Sun was colder than present. For example, strong solar flares are recently proposed as possible extra heat source to the ancient cold Earth. Since the effect is expected to be large scale but slow, it is also relevant to the plasma effects on the upper atmosphere on the time scale of climate variability. A more effective energy re-distribution also means a larger plasma energy input to the neutral atmosphere, which particularly affects the mesospheric climate, with a possible long-term influence on the stratosphere and even the tropopause.

The observations of organic matter in Titan, comets, and the interstellar medium (§1.3.3) indicate that the plasma-neutral gas interactions in low-density and low-temperature environments might contribute to chemistry and changes in composition, including the formation of heavy molecules and organic matter such as biomolecules and amino acids. Also, sputtering chemistry by ion-atmosphere interaction is another candidate in forming heavy particles as an analogy of the surface sputtering chemistry. These indications lead to the second fundamental question:

(B) How and by how much did plasma-neutral gas interactions contribute toward growth of heavy complex molecules and biomolecules?

Here, the interaction includes both the chemical reactions and plasma physical interaction, but excluding surface interaction which has its own important science. Both types of reaction constitute major topics of scientific study.

(B1) Favorable conditions of plasma and external energy in enhancing the chemical reaction: Since the basic elements of organic matter (N_2, NH_3, NO, CH_4, CO_2, CO, H_2, H_2O, O_2) have very low condensation temperature, low-temperature conditions are considered favorable for developing organic molecules in space. However, the conditions in space where organic matter is most likely formed (interstellar medium, Oort cloud, and Titan's ionosphere) are impossible to reproduce in the laboratory without in-situ measurements that provide the exact parameters, although some of the pure chemical interactions or reaction efficiencies have been determined pretty well with laboratory experiments and quantum chemistry modeling.

(B2) Formation of plasma structure that may work as catalysts in tenuous environments: The terrestrial stratospheric chemistry is enhanced when the stratospheric thin clouds (i.e., layer of condensed molecules) are formed through rarefaction that is sustained by horizontal wind (Lowe and MacKenzie 2008). Thus, the neutral dynamics and resultant density structures (e.g., rarefied layers) may work as catalysts for the condensation and chemistry resulting from photolysis and electron-impact, and identifying such structure from many structures in the solar system (as mentioned in (A2)) and examining relation to the chemical reactions and to the roles of neutral species provide fundamental information in chemistry in space. Thus this is not limited to the Earth. For example, the organic matter in Titan is found in altitudes where vertical convection is weak, while we have no knowledge on structures in the formation regions of comet or interstellar space. Since energy density is very low and the plasma is collocated with substantial amounts of neutral species, making small external energy causing large modifications in the plasma-neutral gas interactions, such interaction may complicate the reactions significantly.

2. Measurement strategy

As listed in examples of §1.3, our current knowledge regarding plasma-neutral gas interactions is not sufficient, particularly for cold and low-density environments. This comes partly from a lack of missions to such environments, but mainly from lack of appropriate instrumentation in past and present missions, including those to the Earth's upper atmosphere and Venus. To improve our knowledge on the plasma-neutral gas interaction at low energy (< 1 keV), the most fundamental observations are those of velocity and density distributions of ions and neutral species. In addition, at least some composition information is needed.

The most dramatic lack of observations is that of ions and neutral species at energies below 10 eV, which for ion energy spectrometers corresponds to the +1 eV limit on spacecraft potential, which can be controlled by existing methods. As a reference, a spacecraft velocity of 7.6 km/s (circular orbital velocity at the terrestrial exobase) corresponds to ram energy of only 0.3 eV for H, 1.2 eV for He, 5 eV for O, much lower than 10 eV, so that these species have gone largely undetected. Even for the Earth, past neutral particle measurements are limited to bulk (moment) information such as density, bulk velocity and temperature. Using Doppler shift in optical measurements to derive velocity and temperature requires high enough density in the target region such that emission or absorption is intense, but the region we consider is low-density. Also, the optical (emission and absorption) method cannot reveal the dynamics much below the exobase. The in-situ detections need a trade-off between mass resolution and energy resolution.

Recent developments in the in-situ instrumentation can solve some of what was impossible in past and on-going missions. A trade-off should also be considered when combining the remote sensing and in-situ observations, and between single- and multi-point measurements. This means that we must define mandatory measurements for each major topic (A1)-(B2).

2.1. Required measurements for ions and neutral species

For (A1): To examine the role of plasma-neutral gas interaction on the atmospheric escape, we must know the density profile and the velocity distributions at different altitudes for the most relevant species near the exobase and in the exosphere (H, He, N, N_2, NO, O, O_2, CO, CO_2 for the Earth's case) both for the thermal ion and neutral background components and for the non-thermal escaping components of ion and neutral particles. Here we note that the current empirical models of the exosphere and upper thermosphere, such as the MSIS model, are outdated (Meier et al., 2015) and not suitable for modeling the thermal escape. The TIMED results are even different from the estimates from ground-based observations of airglow (Bishop et al., 2004).

Even the baseline densities of the most abundant species (O and N_2) are 20-30% lower in the observation than the empirical model, while the temperature is in principle estimated from the density gradient (scale height). The model cannot be tuned for the best fitting because the discrepancy changes from year to year, and higher cross-section to produce low energy ENA (< 100 eV) than current estimate for different solar condition is suggested as one possibility (Meier et al., 2015). In this respect, covering H, He, N, N_2, and O, could already be sufficient for the Earth's case. Separation of N and O for the non-thermal component, which was difficult before but now becomes technically possible for < 100 eV, is needed to estimate the efficiency of nitrogen-related chemical and photochemical reactions, for which no good observational knowledge exists near the exobase and above. On the other hand, separation of the background velocity in the thermal energy range between different species does not require N-O separation.

For (A2): To reveal the structures of these regions, the spatial distribution of bulk quantities (density, bulk drift velocity, and ideally temperatures of thermal and non-thermal components) becomes more important than the velocity distribution. To obtain data from different altitudes simultaneously, we need to combine the optical "snapshot" from line-of-sight integrated measurements with in-situ "spot" observation. This is possible if the optical observation target region includes the spacecraft traverse like Reimei satellite (Asamura et al., 2009; Saito et al., 2011), although a combination of two spacecraft or a combination with ground-based optical and radar measurements would be a more standard method. To estimate the dynamics, isotope fractionation above the homopause can be used. Therefore, very high accuracy ion composition measurements are needed with mass resolution of $m/\Delta m > 1000$. This applies to both the Earth and extraterrestrial environments.

For (A3): To examine the small-scale limit, we need multi-point measurements of ions and neutral species with high-time resolution. Since this does not required fine composition information, small sub-satellites can provide the necessary information.

For (A4): To measure the momentum transfer from ions to neutral species through tangential stress, altitude profiles of velocity distribution for both ions and neutral species are needed. Since the composition information for such measurement can be minimum, the requirement for (A1) and (A2) is sufficient.

For (B1): To diagnose the conditions favorable for growing heavy molecules, bulk properties of ions and neutral species (density, bulk velocity, and temperature) need to be known. While temperature can be common for the cold backgrounds, and velocity can be measured only as an average over a long integration time, the separation of different species is needed in the density distribution measurements for H, N_2, NO, NH_3, O, H_2O, CH_4, CO, and CO_2. These requirements are covered by the measurements required for (A1) and (A2). In addition, detection of heavy molecules and organic molecules are needed. This means we need a mass spectrometer of high mass resolution ($m/\Delta m > 1000$) that has very high mass limit such as m>100 and a high sensitivity (supported by extensive ground based efforts for determination of fragmentation patterns, since untangling the contributions of the neutral species to the recorded fragment intensities is a major puzzle for heavy species). High mass resolution is also required to obtain the isotope ratio of simple molecules because this gives essential information on the location and process of molecular formation (Robert et al., 2000; Marty et al., 2011; Füri and Marty, 2015).

For (B2): The extra requirement from (B1) is measuring differential velocities between species, for at least two major species. Such instruments are more difficult to build than what is required for (A2) because the velocity is expected to be very slow. Therefore, they have not been used in space but are under development.

2.2. Required measurements of the background plasma

In addition to the background magnetic field that is mandatory in describing the plasma, electron temperature and the DC electric field are needed. Ideally, electromagnetic or electrostatic waves with slow group velocities also should be known, but most of them do not influence the plasma-neutral gas interactions unless the wave energy density is very high at a frequency that can cause any types of resonance with the ions. In this sense, the wave measurement can be low sensitivity at low frequencies below 100 Hz, although high frequency measurements can be useful, particularly for the Earth. The gravity field must be also considered but anyway has to be known beforehand to perform any mission.

2.3. Required measurements for external energy source

Obvious energy sources are non-thermal ions and energetic neutral species. Each target environment is driven by energy sources with its characteristic energies, such as the solar wind for comets and for the Earth, magnetospheric particles (keV-MeV) for the Earth and for moons, and cosmic rays including solar energetic particles for Earth, planets, and interstellar space. Another obvious energy source is the radiation that directly triggers photochemistry for short wavelengths (UV and soft X-ray) and absorption and scattering for long wavelengths (infrared and mm wave). The solar source and a large fraction of cosmic sources can be monitored by other spacecraft and space weather monitoring, while planetary and galactic source fluxes in the outer solar system might need local measurements. However, the energy flux is probably low, and therefore such measurements might be optional. Electromagnetic waves from local sources might be more important to measure, for which the energy flux is very high as mentioned in §2.2.

Table 1: Required and useful measurements

measurements	priority*1	Earth*2	in-situ method	remote method*3
Neutral/Ion density (major species)	1	n/a	mature	mature
Neutral/Ion mass spectrometer up to high mas:	2	1	mature	mature
Neutral temperature (average)	1	n/a	under development	(too heavy)
Ion temperature (average)	2	3	mature	(too heavy)
Neutral temperature (major species)	2	1	under development	(too heavy)
Electron temperature and density	2	1	mature	Earth only
Neutral bulk velocity (average)	2	n/a	need improvement	only limited case
Ion bulk velocity (average)	2	3	need improvement	Earth only
Neutral velocity distribution (major species)	1	1	under development	only limited case
Ion energy spectra (major species) < 10 eV	2	3	need improvement	-
Energetic neutral energy spectra >10 eV	2	1	need improvement	-
Ion energy spectra (major species) >10 eV	2	1	mature	-
Electron energy spectra	2	1	mature	-
Energetic particles (> 10 keV)	3	1	mature	-
Cosmic ray (> 100 MeV)	3	3	(too heavy)	Earth only
DC B-field	1	1	mature	Earth only
DC E-field	2	1	mature	Earth only
Electric current	3	3	mature	Earth only
EM waves < 10 kHz	3	3	mature	-

*1: 1: always mandatory, 2: mandatory depends on mission, 3: optional
*2: Priority for Terrestrial mission that is described later. 1: mandatory, 3: optional
*3: Both from spacecraft and from ground (mainly for Earth only).

2.4. Summary of relevant measurements

Table 1 summarizes mandatory and optional measurements requirements. Not all the measurements in the table have been possible in the past and on-going missions. However, instrument technology has significantly improved (for optical remote sensing, plasma spectrometers, mass spectrometers, and electric and magnetic field instruments). Here, "matured" does not necessarily mean the size is optimized for missions with severe mass limit. The highest-rank ("1" in the table) in-situ measurement can form a small plasma package with total payload mass of < 20 kg at present and will become < 15 kg within a decade. The detailed description how these measurements answer the questions on the listed topics (A1)-(B2) is given in §3.3 where the mission for the terrestrial observation is given as an example.

The recent and future improvements are not limited to the individual instruments, but also to the spacecraft technology such as the automated operation of multi-spacecraft including low-cost sub-spacecraft of less than 50 kg (Swedish Innosat already achieved this for 15 kg payload), combination method of in-situ and remote measurements, and to the upgraded ground infrastructure. These technologies are rapidly improving in the recent decade (e.g., Comet Interceptor was not possible to propose as ESA's M class mission 5 years ago), and we expect further improvement within a decade.

2.5. Destinations of relevant missions

Possible parameters that influence the ion-neutral interactions are: (1) Temperature (2) Density, composition, and degree of ionization (3) Gravity (4) External free energy such as radiation, cosmic rays, large-scale electric and magnetic field, and (5) Existence of catalysts such as the surfaces of the dust grains, cloud (layer of condensed molecules) or catalytic structures such as non-mixing layers. While there is room to improve the knowledge on (5) and a part of (4) through laboratory experiment, environment of (1)-(3) are difficult to achieve inside ground laboratory experiments.

Limiting the discussion just to (1)-(3), the solar system is full of different environments. **Table 2** summarizes p a number of possible missions, from farthest from the Sun to the nearest to the Sun, that may contribute to the plasma-neutral gas interaction theme. Most of these are self-explanatory. The "artificial comet" mission refers to a massive release of water or other "light materials" in the solar wind. The "planetary L2 composition" mission aims at measuring the composition of pick-up ions of planetary origin near planetary L2 points, since there might be several piggy-back opportunities for Earth L2 telescopes or for Martian missions in the 2040's. Other destinations have been under discussion by other space agencies. For each destination, temperature (T), density (n), and gravity (g) are classified from extremely low to extremely high. Therefore, each mission can address the topics only in that range.

The most comprehensive knowledge can be obtained with a comet rendezvous mission for aphelion reaching the Kuiper belt so that the spacecraft can measure both the comet environment and the space plasma near the Kuiper belt. Such mission is also useful as a step toward the Halley comet rendezvous in 2060's, and in fact at least two such missions are proposed in White Papers (cryogenic comet sample return by D. Bockelée-Morvan and comet plasma mission by C. Goetz).

On the other hand, other missions can also contribute in improving our knowledge on the plasma-neutral gas interactions to answer many of the fundamental questions on topics (A1)-(B2). By combing different target (e.g., Earth and Venus with the same instrumentation like Mars Express and Venus Express) missions to study event a high temperature or high-density environment also help understanding the solar energy conversion in the form that has different roles in the evolution of the solar system as well as understanding low-temperature stars with neutral species possibly exists.

Table 2: Possible destinations

Mission	(1) T	(2) n	(3) g	A1	A2	A3	A4	B1	B2	mission size*2
Interstellar/Oort cloud	ex low	ex low	ex low	x	-	x	(x)	x	(x)	LL or L
Ice Giant atmosphere	ex low	medium	high	x	x	x	x	(x)	(x)	LL
plumes (Enceladus, Io, Europe)	low	medium	medium	x	x	x	(x)	x	(x)	L or LL
Titan around exobase	low	medium	high	x	x	x	(x)	x	x	L or LL
comet rendezvous	**wide*1**	**wide*1**	**low**	**x**	**x**	**x**	**x**	**x**	**x**	**L**
deep inside Gas Giant	medium	high	ex high	(x)	-	(x)	-	(x)	-	L
artificial comet	medium	high	medium	x	-	x	(x)	(x)	(x)	P
Earth around exobase	**high**	**medium**	**high**	**x**	**x**	**x**	**x**	**x**	**x**	**M or P**
Venus around exobase	**high**	**medium**	**high**	**x**	**x**	**x**	**x**	**x**	**x**	**M**
planetary L2 comp.	(mixed)	low	ex low	x	(x)		(x)	-	-	P
Solar corona	ex high	low	ex high	x	-	(x)	(x)	-	-	M

*1 It ranges from very low to high along the orbit.
*2 LL: Need to collaborate with other agency for either cost or for RTG generator. P: S-class or at least much less than M-class or if piggy-back is possible.

3. Terrestrial mission case

Since the plasma-neutral gas interaction problem is very fundamental, a mission in the terrestrial environment has a large advantage because of strong support from the ground-based measurements, including EISCAT-3D. The mandatory altitude range to cover is 500–3000 km, i.e., upper thermosphere and lower exosphere, where our knowledge of even the ground state is poor for both neutral species and cold thermal ions (except hydrogen atoms) as described in §1.3.1, and is an important subject even for the ground-based observation community. Here, the apogee of > 3000 km comes from requirement to obtain the scale height for H. Since ion and neutral mass spectrometers have a dynamic range of 6 orders of magnitude, tuning the instruments for the exosphere can provide unprecedented new information.

3.1. Observation strategy using multi-spacecraft

Figure 11 shows one example of such a mission design. The apogee altitude is 1.5 RE (about 10000 km) in the figure but this is flexible between 3000 km and 30000 km (below the forbidden region for geosynchronous orbits and preferably avoiding the radiation belts). To combine the optical and in-situ measurements and to address topic (A3), a multi-spacecraft mission with three or more spacecraft is ideal. The both options in **Figure 11** (left and right), the mission is composed of a main spinning spacecraft for in-situ observation (payload 100-120 kg), a 3-axis stabilized sub-spacecraft just for optical remote observation (payload 10-15 kg), and one or two sub-spacecraft (the attitude control can be either spinning and 3-axis stabilized) for multi-point in-situ measurements flying with separation in the ion scale to fluid scale from the main spacecraft (payload 5-10 kg). A spinning platform is preferable for the main spacecraft to cover 3D for particle instruments, for which a substantial portion of field-of-view (FOV) would otherwise be blocked by the spacecraft body on a 3-axis stabilized platform, and to have good coverage of DC electric field measurements.

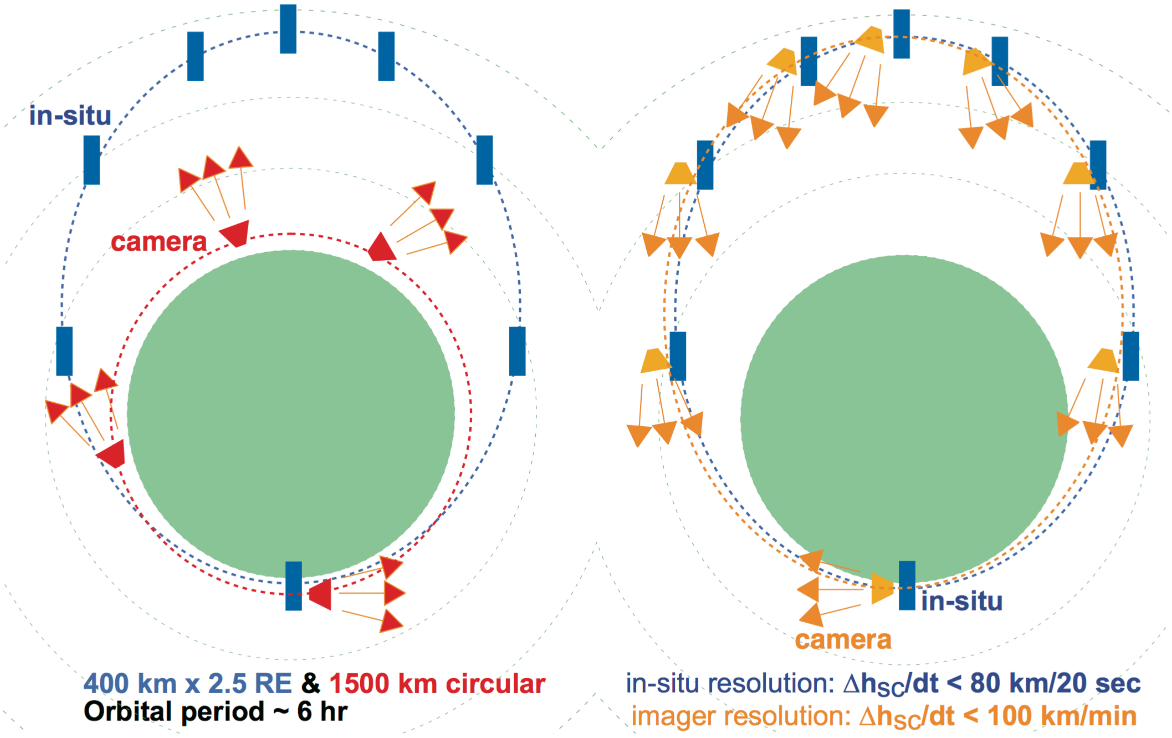


Figure 11: Orbits for the M-class or smaller class mission for the Earth and Venus.

The difference between the left and right in **Figure 11** is where to locate the remote observation spacecraft: (left) It can be placed in a completely different orbit than the in-situ spacecraft so that the camera's FOV includes the in-situ spacecraft for real-time comparison, or (right) fly together with the main spacecraft and look along the orbit so that the camera's FOV covers the region of in-situ observation with some time delay. The first option has the advantage of not looking at the high-density region, whereas the second option has the advantage of avoiding conjugacy problems. In the first option, the in-situ spacecraft is not always in good conjugacy with the remote sensing spacecraft even though the spacecraft inclination is adjusted such that the longitudinal drift velocity matches.

The telemetry for the in-situ sub-spacecraft is through the main spacecraft, both for downlink and uplink, so that the cost for ground operations can be minimized. In this sense, the second option becomes the lower cost because the telemetry for the remote sensing spacecraft can go through the main spacecraft. Using a despun platform could be less expensive than having a separate spacecraft for remote sensing, but by 2030 the cost for building and operating very small (< 50 kg) sub-satellites will be significantly reduced, so that the trade-off has to be re-evaluated. The telemetry link through the main spacecraft also opens up the possibility of having nearly identical platforms (with some difference in thermal design, the radiation protection, the antenna design, and numbers of payload or sub-spacecraft).

The other requirements for the orbit and spacecraft are:

- The 3-year radiation dose shall not be excessive so that it would require an unreasonable amount of shielding.
- Orbital parameters must be designed to require as few maneuvers as possible (e.g., free drift) to avoid contamination of composition measurements from (chemical) propulsion exhaust.
- To be able to study ion-neutral interactions properly, the spacecraft should cover the auroral regions, and thus the inclination must be as close to 90° as possible. This automatically facilitates conjugate observations with ground-based radar (e.g., EISCAT-3D) and optical instruments (e.g., Fabry–Pérot interferometer for airglow) that are mainly located in the polar region.
- At mission completion all spacecraft can be de-orbited.

Table 3: Model payload

mandatory measurements	instruments	in-situ obs.	remote obs.
Neutral/Ion composition to high mass:	mass spectrometer + optical spectrometer	Rosetta (2004)	BepiColumbo (2018)
Neutral temperature (major species)		under development	(too heavy)
Electron temperature and density	Langmuir robe + ground IS radar	Cluster (2000)	
Neutral velocity distribution (N_2 and O)		under development	(too heavy)
Ion energy (major species) >10 eV	mass-resolving ion spectrometer	BepiColombo (2018)	
Electron energy distribution	electron spectrometer	Solar Orbiter	
DC B-field (5m boom)	magnetometer + geomagnetic chain	MMS	
DC E-field (20 boom)	antenna + geomagnetic chain	Cluster (2000)	
keep SC potential < 1V	potential control	Cluster (2000)	
important measurement			
Ion temperature (average)	Langmuir robe	Solar Orbiter	(too heavy)
Ion bulk velocity (average)	ion driftmeter + ground HF radar	DE-2 (1981)*	
Ion energy (major species) < 10 eV	cold ion spectrometer	Akebono (1989)*	-
Energetic neutral energy >10 eV	ENA	BepiColombo (2018)	-
Energetic particles (> 10 keV)	solid-state detector	Solar Orbiter	-
Cosmic ray (> 100 MeV)	wide angle telescope	(too heavy)	
Electric current	magnetometers + geomagnetic chain	Cluster (2000)	
EM waves < 10 kHz	induction coil.	Solar Orbiter	-

* Technology is so old that a significant improvement is needed.

3.2. Payload

Table 3 summarizes model payloads. Compared to the Cluster mission, measurements of the neutral gas have to be added, ion spectrometers with mass separation ability have to be used, and the detection of low-energy ions has to be improved, whereas we do not require a very wide frequency range for waves. Still, most of the instruments are already available with acceptable masses and sensitivities. As of 2019, instruments for neutral gas velocity and temperature with sufficient sensitivity are not ready. However, a miniature prototype with very low sensitivity has already flown on Dellingr cubesat in 2017 (Jones et al., 2017, Nicholas et al., 2015), and IRF Kiruna is developing a different design as shown in **Figure 12**. Therefore, this challenge is can be considered solved in the near future.

The addition of a strong suite for neutral gas and composition measurements makes this mission unique compared to the past missions. The last mission that obtained density profiles of the thermosphere and exosphere is 40 year old and did not cover a very high altitude range. All recent missions to study the density profiles are using the line-of-sight integrated measurements, which strongly rely on the model (for example, the temperature of the exosphere is derived from the scale height with an assumption of nearly constant temperature). By combining in-situ measurements and remote-sensing measurements, we can construct density profiles without the assumptions that are inevitable for line-of-sight observations. In addition, no systematic measurements of isotope ratios have been made in the terrestrial exosphere, although that has been done for Mars (MAVEN) and comets (Rosetta).

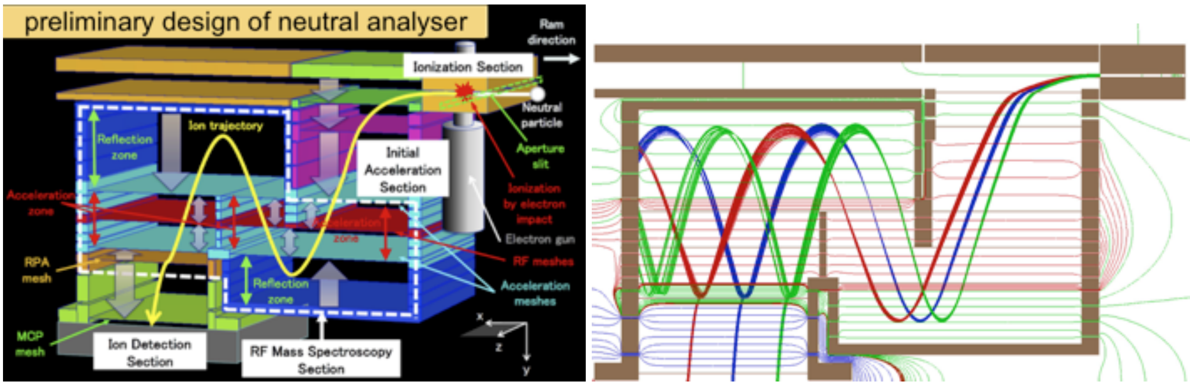


Figure 12: Preliminary design of NIVA instrument. (left) principle of measurement. (right) an example of ion optical simulations. Particle trajectories with equipotential lines are shown.

3.3. Support from the ground-based observations

In Table 3, the ground-based observations are included for many measurements. In principle, the mission is closed without such support, but accuracy and particularly the three dimensional (3D) spatial coverage improves significantly with the ground-based conjugate observations. The relevant facilities that already exist and planned to be installed near future are:

Incoherent scatter (IS) radars: located in different regions (e.g., Europe, North America, and Asia) these radars at 200-1000 MHz range can measure some key parameters described in §2.2 (electron temperature, electron density, ion temperature, and line-of-sight ion velocity) at different altitudes nearly simultaneously.

EISCAT_3D (http://www.eiscat3d.se): the next generation IS radar will be able to cover a large 3D volume of space in very short time thanks to it using phased-array antenna arrays as opposed to a large parabolic dish, which can scan through a volume of space only very slowly. With high-power 5-10 MW transmitting and receiving antennas at core site and high sensitivity 10000 receiving antennas at remote sites, EISCAT_3D covers very wide area (>300 km diameter at 500 km altitude with 3 sites), and is under construction toward operation in 2022 for the first three sites, and additional 2 sites are planned afterward. Even with a spacecraft velocity of 10 km/s (perigee velocity of highly elliptic orbit), the spacecraft is continuously within this volume over 30 sec for the diameter traversals (instead of passing at some distance from the radar line of sight in current systems). Since the Earth is magnetized, only the geomagnetic conjugacy is often required, which allows much longer time of continuous conjugate observations.

SuperDARN: With much lower power than IS radars, and optimizing the array direction nearly horizontal, HF radars (8-22 MHz) can provide ion line-of-site velocity in a wide region in Earth's upper atmosphere and ionosphere. SuperDARN is a network of such HF radars from more that 30 sites, and continuously provides ionospheric convection. Although the detection altitude is lower than 150 km altitude, this gives important information on the plasma motion.

Fabry–Pérot interferometer: The mid thermosphere (around 240 km altitude) is region where the airglow intensity is maximum. Optical interferometry measurement of the Doppler spectrum is a standard method to obtain the neutral motion and temperature at the altitude where the airglow emission is maximized (Conde et al., 2001). Although this altitude is lower than the spacecraft perigee, this gives another important information on the momentum transfer and convection in the upper thermosphere. Scanning Doppler Imager (SDI) is capable of measuring 2D wind and temperature field from a snap shot of the all-sky image. The wide field-of-view can increase opportunity to meet simultaneous measurements with satellites. International team is working for deploying multiple SDIs in the Northern Scandinavia

Magnetometers: Global and regional networks of the magnetometers are most traditional ground-based support to indicate the ionospheric dynamic and electric current that is important in evaluating the external energy, although there is no altitude resolution and the estimate is not perfect (Kamide et al., 1981, Friis-Christensen et al., 1988). In recent years, Iridium satellites also provide extra information of magnetic activity, making the accuracy of the estimation of the electric current system.

OH airglow imager: The upper mesosphere-lower thermosphere temperature can be permanently monitored based on OH airglow measurements around the globe. This will provide input data on temperature variations due to plasma-neutral gas interactions in the upper atmosphere.

3.4. Science Closure

By covering the energy distribution of both background neutrals and ions, together with their macroscopic parameters (n, v, T), energy transfer can be measured on the distribution function level, e.g., whether a double-peak distribution is formed or not when the velocity is different between ions and neutrals under low collision frequency. The effect of the external energy is given in wide range. This addresses (A1) and (A4). By adding extra measurement points using small sub-satellites, such measurements can even address (A3). A combination of the in-situ measurements and the remote measurements (remote measurements from both the spacecraft and from the ground) will reveal the layer structure in the global context, addressing (A2). The composition data can give the chemical interaction including photochemistry, addressing (B1). Combining with the observations of layer structure, this is also addressed (B2).

3.5. Requirement for the spacecraft

For Earth missions, power and telemetry are not an issue at all. Since the mission is oriented to neutral species and ions rather than waves and fields, the magnetic cleanliness and EMC requirements do not exceed the Cluster level, e.g., a linear regulated power system, and distributed single-point-ground power system. The other requirements for the orbit and spacecraft are:

- Cold Xenon propulsion is preferable for orbit maneuvers or attitude control to avoid propulsion that contains nitrogen (N) or propane (CH_4) because nitrogen atom and nitrogen molecule, including ionized forms, are the major components in the thermosphere and exosphere, and propane has major fragments on mass 28 ($^{14}N_2$) and mass 29 ($^{14}N^{15}N$).
- External conductive surfaces are needed to keep the spacecraft potential as constant and as low as possible, together with active spacecraft potential control.
- The required pointing accuracy is 1° (0.1° knowledge) for both the main spacecraft and the remote sensing sub-spacecraft.
- A Sun-pointing constant attitude is preferable in order to maintain a constant spacecraft surface exposure to sunlight. This helps to avoid evaporation of eventual condensed volatiles, i.e., outgassing from the spacecraft (lessons from Rosetta) (Schläppi et al., 2010, Altwegg et al., 2012).
- All particle instruments shall be placed with unobstructed FOV so as not to harm the 3D observations.

With these requirements, a spacecraft with dry mass 350 kg is sufficient for the main spacecraft when the required power for payloads is less than 200 W (reasonable requirement). For the sub-spacecraft, a dry mass of 50-60 kg for remote sensing and a dry mass of 20-30 kg/each for multipoint measurements is feasible. This means that total launch mass for all spacecraft would be < 700 kg for the Earth.

A similar mission could be devised for Venus. In that case, some on-board processing of the data before sending to the Earth would be needed. Such processing could be done by each payload. The requirement on the spacecraft would be that it has sufficient memory (> 10 GByte). A main spacecraft dry mass of < 900 kg would be sufficient.

4. Summary of Technological challenges

As described in §3, new development or improvement of the light-weight instruments and low-cost small spacecraft is required to makes the proposed observations closer to be realistic. For the instrument-wise, following developments and improvements are the technological challenge that must be solved for both the terrestrial mission and the solar system missions:

- Develop a new instrument to measure the temperature of the background neutral gas for at least two major components except H. For the exobases of the Earth and Venus, it should be able to measure N_2 and O with accuracy for 10 sec integration should corresponds to the largest variation of temperature: ΔT=300K (or 30% for heated events with >1000K). For velocity, accelerometer can give accuracy up to tens m/s.
- Develop a new instrument to measure the 2D-velocity distribution of background neutrals for at least two major components except H, with 10% sensitivity compared to the Maxwellian peak. The need this because the extra ordinary interaction out of the theoretical prediction means multiple-peaks in the velocity distribution.
- Improve the old instrument or newly develop an instrument to measure the velocity and energy distribution of the background cold ions.
- Improve the low energy ENA for < 100 eV toward high angular resolution. This improves significantly the estimate of the substantial cross section that produces ENA at energy range of 10-100 eV, for which our knowledge even in laboratory is poor.

These tasks are under challenge at many places and the design shown in **Figure 12** is one of such attempt. In addition, spacecraft and operation side have some technological issues for reliability and cost to make the proposed multi-spacecraft missions as mentioned in §3. In additions to the requirement of further optimization for the inter-spacecraft telemetry and the low-cost manufacturing (including managing cost) of small sub-satellites, we have another challenge:

- The sun-pointing constant attitude requirement means frequent maneuver operation because a maximum off-pointing from the solar direction cannot be kept due to Earth's rotation around the Sun (1% per day). Therefore, autonomous maneuver using sun-sensor should be developed to keep to cost low. If not, as alternative, a cold trap should be developed for the controlled condensation and re-evaporation of volatiles. This will avoid interferences from the spacecraft background.
- Another autonomous system to be developed is for radiation belt detection so that all instruments can be turned on/off automatically. This is possible by using the on-board data (energetic particle detector and background noise in particle instruments that use a microchannel plate) combined with a radiation belt model and space weather predictions.

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