ON THE IMPORTANCE OF THE CROSS-BODY APPROACH IN PLANETARY AERONOMY

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Cross-disciplinary and cross-body approaches can be applied to study universal processes occurring in the heliosphere. Magnetospheric, interplanetary, and heliospheric plasmas, all of which are low density plasmas, host similar processes. A cross-disciplinary approach is thus of great relevance for a universal understanding of processes occurring within these various plasmas. On the other hand, the upper atmosphere of planets and moons are a highly collisional medium acting differently compared to a collisionless plasma. Therefore, the comparative study between solar system bodies hosting atmospheres under different settings is a more suitable approach for assessing universal processes in aeronomy. For the past several years the aeronomy community has undertaken many initiatives in comparative studies of solar system atmospheres. We highlight the maturity of this field and illustrate its relevance by applying the comparative approach to key scientific topics. We would like to encourage aeronomers interested in comparative studies to consider participating to International Heliophysical Year (IHY) focused activities. More information on the comparative initiative can be found at the IHY website (http://ihy.gsfc.nasa.gov/) as well as at: http://www.bu.edu/csp/uv/cp-aeronomy/aeronomy-sol-sys.html.

1. Introduction

A cross-body approach is suitable for assessing universal processes in aeronomy, an interdisciplinary field aimed to study the upper atmospheric regions (of Earth, planet, moon, comet) where ionization and photodissociation processes play a role.[1] In other words, such a discipline focuses on the physics and chemistry occurring in an upper atmosphere, divided — for

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dense atmosphere — into a neutral part (mesosphere, thermosphere, exosphere) and an ionized part (ionosphere).[2] Thus, essentially the field of "*planetary aeronomy*" deals with the composition, dynamics, and energetics of the thermosphere–ionosphere system of a planetary body that has an atmosphere. The upper atmospheres encountered in the solar system are extremely diverse[3] due to differences in atmospheric constituents and densities, distance from the Sun, topology and magnitude of the magnetic environment, gravity, rotation rate, and gravity wave forcing, among others. This diversity in setting makes comparative aeronomy an exciting and enriching field of research.[4] The solar system bodies to whom this approach applies include those with a thick, permanent atmosphere (Venus, Earth, Mars, the giant planets Jupiter, Saturn, Uranus, and Neptune, and Saturn's moon Titan) and those with a thin or transient atmosphere or with a coma — defined as a gas envelop not restricted by gravity — (Mercury, Galilean moons (Io, Europa, Ganymede, Callisto), Triton (Neptune's moon), Saturn's inner, icy moons, Pluto, and comets).

Comparative aeronomy is becoming increasingly fruitful as spacecraft mission and Earth-based datasets are assimilated and interpreted using state-of-the-art multidimensional methods. The International Heliophysical Year (IHY) in 2007 which is fully encompassing the comparative aeronomy effort[5] emphasizes the timeliness of this initiative and provides a platform for such studies. In this paper we first review key scientific topics in comparative aeronomy. Next, we present some of the actions initiated from the community since 2000 for promoting comparative aeronomy and for sharing scientific findings. Finally, we conclude on the importance of the comparative approach for aeronomy and discuss future directions for this discipline.

2. Key Scientific Topics in Comparative Aeronomy

A cross-body comparison applied to aeronomical quantities highlights the range and complexity of solar system environments[4,6–8] and illustrates how comparative aeronomy contributes to a true synthesis of the solar system. For instance, while the observed average exospheric temperature of the upper atmosphere at Mercury, Earth, Jupiter, and Uranus, decreases linearly as a function of distance from the Sun, at Venus, Mars, Saturn, and Neptune, the observed values are lower than those predicted from this linear trend (see Fig. 1). The planets closer to the Sun are not always hotter. Local conditions, such as composition and heating and cooling sources,

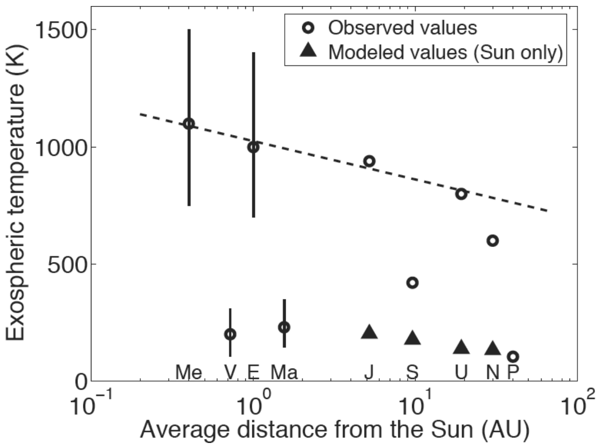

Fig. 1. Comparison of the neutral exospheric temperature of the upper atmospheres of the planets (adapted from Ref. 4, Fig. 1, p. 2). The circles represent the average, observed values and the vertical bars, the diurnal, seasonal, and solar cycle range estimates: Mercury,[9] Venus, Earth, and Mars,[10] outer planets,[11] Pluto.[12] The triangles represent the modeled values derived with solar heating alone.[11] The dashed line is a fit to the average exospheric temperature observed at Mercury, Earth, Jupiter, and Uranus.

need to be taken into account. A list of key topics and related outstanding questions is given in Table 1. This list, far from being exhaustive, provides an illustration of scientific challenges in comparative aeronomy.

A model is a key tool to assess the contribution of various processes individually to a given physical quantity. For instance, thermospheric heating associated with solar irradiance has been modeled for assessing the contribution of the solar source to the exospheric temperature of upper atmospheres. Such an approach has shown that solar heating is not sufficient for explaining the observed exospheric temperature at the giant planets — as illustrated in Fig. 1 — yielding an energy crisis which is still under debate.[11] It is also very valuable to adapt aeronomical models developed for Earth to other Solar System bodies. Such a challenge allows us to test a given model under different conditions and to assess its robustness regarding the included physical processes. As an illustration, terrestrial thermosphere (/ionosphere) general circulation models (GCM)[22,23] have been adapted to: Venus and Mars,[10,24–26] Jupiter,[27,28] Titan and Triton,[29] and Saturn.[30] Such an experience is also crucial for application to exoplanets and will provide the only constrain to the future observations of the atmosphere of other worlds.[31,32]

Table 1. Key scientific topics of relevance in comparative aeronomy and related outstanding questions.

Key topic	Sample outstanding questions
Ionospheric structures and dynamics	Is a part or the entire ionosphere under photochemical equilibrium? What are the sources of night time ionization, if any?[7,8,13]
Energy budget	Is solar heating the major heating source of a thermosphere? What are the other significant heating and cooling sources? What is the resultant thermal structure?[11]
Magnetosphere–Ionosphere coupling	How important is external control (solar wind) versus internal control (planetary rotation, satellite) of the auroral activity? What is the role of the ionosphere as a source of magnetospheric plasma and what is its influence on magnetospheric processes?[16–19]
Laboratory experiments	What are the rates and cross-sections of atomic and molecular processes which are critically needed and which require to be (re-) determined?[20,21]

The atmospheric modeling tools are critically dependent on the knowledge of cross section and reaction rates, quantities which can be derived from laboratory experiments[20] or from the analysis of atmospheric emissions.[33] Other critical physical quantities which drive aeronomical models include solar irradiance, which is still largely unknown, especially in the soft X-ray range responsible for the ionization of the lower part of upper atmospheres. Such uncertainties largely limit the modeling effort. It is crucial to improve the assessment of the solar irradiance spectral profiles in soft X-rays and extreme ultraviolet (EUV), as recently discussed at a comparative aeronomy special session at 2005 Spring AGU.[34–37] It is important to assess not only the typical solar spectrum in the soft X-ray region (0.1–few keV), but also its large variability ranging from a factor 10 between minimum and maximum solar conditions, to 10 000 during strong solar flares. This is particularly critical for the modeling of the solar soft X-ray scattered from planetary atmospheres.[38,39]

Complementary to the modeling effort, observations of the upper atmosphere of solar system objects have been very productive during the past 25 years. *In situ* aeronomical measurements are scarce. Beside the Earth, for which the dataset is acquired onboard rockets or low-altitude satellites, *in situ* aeronomical measurements include the on-going, fascinating case of Titan. Its upper atmosphere has been directly probed through flybys of the Cassini spacecraft, which arrived in July 2004 at Saturn. A total of 44 flybys will be achieved over the four-year nominal mission. The most common observations of planetary upper atmospheres are performed remotely, including optical remote-sensing as well as occultations of a star and of a radio source. Analysis of occultation data provides neutral and electron density profiles along the field of view. Optical remote-sensing from infrared[11,14] and visible[40] to ultraviolet[41,42] and X-ray[43] yields the assessment of atmospheric temperature, drift, and composition, chemical processes, and plasma interactions. Their origin is very diverse, ranging from airglow[44–46] to aurora[14,15] to reflected or fluorescent sunlight.[38,39,52] Figure 2 shows a sample of X-ray emissions observed at various solar system bodies. The origin is auroral at Earth through bremsstrahlung continuum produced by precipitating energetic electrons (Fig. 2(a)), in

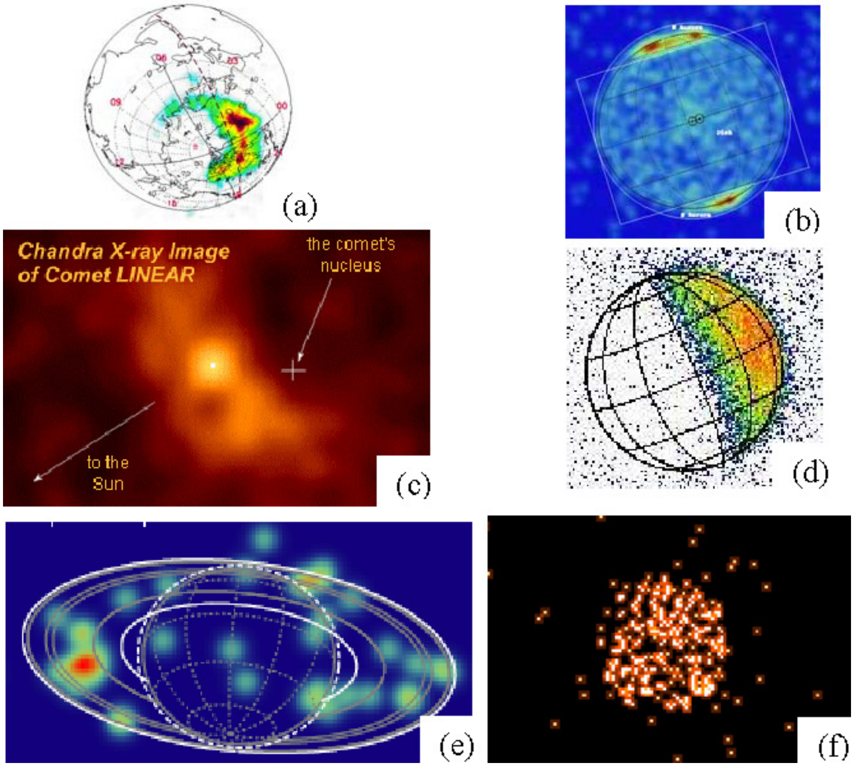

Fig. 2. X-ray emissions observed from a few objects in the solar system: (a) at Earth by Polar/PIXIE (credit to: N. Ostgaard and NASA); (b) at Jupiter by Chandra[47]; (c) at comet Linear by Chandra[48]; (d) at Moon by Rosat[43,49]; (e) at rings of Saturn by Chandra[50]; (f) at Mars by Chandra.[51]

the polar regions of Jupiter through charge exchange of highly ionized heavy ion precipitation (Fig. 2(b)) and at comet Linear through charge exchange of highly ionized heavy ions from the solar wind interacting with the cometary neutral gas (Fig. 2(c)). In the equatorial region of Jupiter the emission is dominantly through resonant and fluorescent scattering of solar X-rays.[52] At the moon, the dayside lunar soft X-rays are fluoresced sunlight scattered by elements present in lunar regolith (Fig. 2(d)), while the X-ray emission recently detected from the rings of Saturn is the result of fluorescent scattering of solar X-rays from oxygen atoms in the H_2O icy ring material (Fig. 2(e)). At Mars the emission are due to fluorescent scattering of solar X-rays from O, C, and N present in the atmospheric gases (CO_2, O_2, N_2) in the Martian upper atmosphere (Fig. 2(f)). However, an X-ray halo around the planet extending up to three Mars radii with an origin similar to that of comets has also been observed.[53]

Analysis of auroral emissions has been used to assess magnetic field configuration, to trace plasma interactions, to identify the energetic particle sources and atmospheric constituents.[14,15] For instance, the analysis of auroral X-ray emission identifies the type and characteristics — thus the origin — of the energetic particle population (Figs. 2(a)–2(c)) and is used to derive the time variability of this energy source. Multispectral analysis provides further constraints for identifying processes occurring at a given body.[47,53,54] Due to the large variety in magnetic environment, energetic particle source, atmospheric species, and chemistry, the comparative approach applied to atmospheric emissions, such as airglow and aurora, is of great relevance. It yields a synthetic — thus, more critical — view of interactions taking place at different solar system bodies, including solar–wind–magnetosphere–ionosphere coupling.[16,17,19,55,56]

3. Past and Present Actions from the Community

Year 2000 marked a renewed interest in comparative studies of solar system atmospheres, as attested by the organization of a Yosemite Conference, a workshop at the Coupling, Energetic, and Dynamics of Atmospheric Regions (CEDAR) meeting, and the creation of a discussion group dedicated to this subject. These initiatives were followed by additional special sessions at international meetings and by the publications of community paper,[57] special issue,[58] and monograph.[4] More detailed information regarding current actions, special sessions, and publications can be found at the comparative aeronomy website: http://www.bu.edu/csp/uv/cp-aeronomy/aeronomy-sol-sys.html. The information posted does not pretend to be exhaustive. Any member of the community is free to send input, sign up for the mailing list as well as consult past newsletters. It should be noted that at the initiative of the Space Physics and Aeronomy (SPA) president, Prof. M. Mendillo, comparative aeronomy is a full part of Spring AGU meetings, since 2004, through the organization of dedicated special sessions.

4. Future Directions in Comparative Aeronomy

Aeronomy is an ideal field for comparative studies of solar system bodies due to the diversity and complexity of their environments. Comparative aeronomy contributes to a better understanding and true synthesis of our solar system.[4,16,58] It provides a challenge to models and opens new horizons which allow aeronomers to be more critical toward their one-body research.

The comparative aeronomy community has been strengthening its effort over the past five years through the organization of special sessions and through topical publications. The IHY initiative would benefit from the momentum of this community, while at the same time the IHY constitutes a true platform for comparative aeronomy. Among the five universal process science themes identified (http://ihy.gsfc.nasa.gov/science_themes.shtml), theme two focusing on energy transfer and coupling processes encompasses aeronomical topics. The IHY initiative is providing a web infrastructure to carry out focused activities and facilitate international collaborations.

The on-going Cassini and Mars orbiting missions and the upcoming Venus Express are going to enrich the aeronomical database, providing dataset more comprehensive than single flybys can offer and requires more complex models to describe the observed environment. At the same time, comprehensive, 3D models have matured enough the past years for carrying out quantitative cross-body comparison of physical and chemical processes. For easy access to laboratory measurements supporting the modeling and data analysis effort, a central database of cross-sections and reaction rates — including recommended values, references, and error bars — would be of great relevance to planetary aeronomers.[21] Comparative aeronomy is now ready to move from a discovery, assessment phase — based on the identification of main differences between solar system bodies — to a more mature phase addressing key outstanding issues (Table 1) quantitatively. Comparative aeronomy also constitutes an excellent step towards the aeronomy of exoplanets,[31,59] which has already begun[32,60] and is expected to play an increasing role in the future.

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