Space Sci Rev (2010) 153: 5–9
DOI 10.1007/s11214-010-9664-9

Preface

Satellites of the Outer Solar System: Exchange Processes Involving the Interiors

O. Grasset · A. Coustenis · W.B. Durham · H. Hussmann · R.T. Pappalardo · S. Sasaki · D. Turrini

Received: 10 June 2010 / Accepted: 10 June 2010 / Published online: 30 June 2010

1 Introduction

Recent space missions to the outer solar system, Galileo (1996–2003) and Cassini-Huygens (2004–today), together with ground observations, have revealed that the moons of the outer solar system are enigmatic objects, introducing extraordinary challenges for geologists, astrobiologists, organic chemists, and planetologists. Chemical exchange exists through the different layers that form their interiors, and also from the interior to the surface. The most convincing evidence is certainly the discovery of water vapour and ice particles emerging from Enceladus's active south polar region (Fig. 1a). Evidence for exchange with a subsurface liquid ocean has also been provided by the inference of hydrated salts on the surfaces of Jupiter's moons, Europa (Fig. 1b) and Ganymede, as well as the detection of sodium salts in particles originating in Enceladus's plumes. Aqueous exchange with the rocky core may also be possible, considering that ^{40}Ar has been observed in the plumes of Enceladus during one flyby of Cassini and in the atmosphere of Titan. The ongoing CH_4 replenishment in Titan's atmosphere is additional striking evidence of exchange processes within the moons (Fig. 1c).

2 Observations and Measurements

Telescopic observations and, in the past few decades, spacecraft observations, from the Galileo and Cassini-Huygens missions, have led to the discovery of many surface materials, from rock-forming minerals to water ice to more exotic volatiles. The tremendous variability of surface compounds is fundamentally related to the exchange processes within the moons (variability of chemical compounds, the degree of activity, and the nature of

O. Grasset (✉)
Laboratoire de Planetologie et Geodynamique, UMR-CNRS 6112, 2 rue de la Houssiniere, 44322 Nantes Cedex 03, France
e-mail: olivier.grasset@univ-nantes.fr

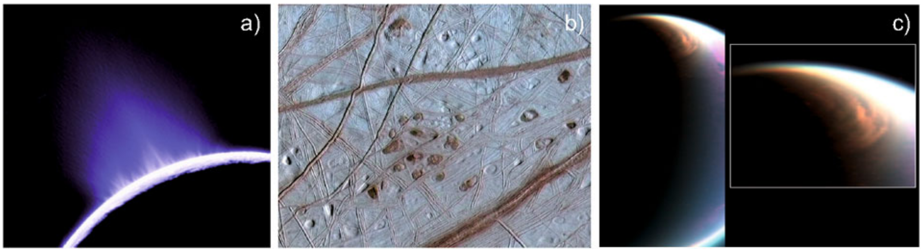

Fig. 1 Evidence of exchange processes in the icy moons: (**a**) Eruption of water vapor and ice particles on Enceladus (credits: NASA/JPL/Space Science Institute); (**b**) Brownish hydrated salt minerals associated with domes and linear ridges on Europa (credits: NASA/JPL/University of Arizona/University of Colorado); (**c**) Giant methane–ethane cloud on the north pole of Titan (credits: NASA/JPL/University of Arizona/University of Nantes)

volcanic/tectonic processes, . . .). A comprehensive description of these processes has been provided in the first section of this book.

In the first chapter, Krupp et al. describe the global magnetospheric environments of the gas giants, their global configuration with its large-scale transport processes, but also the local environments, especially the interaction processes between the magnetospheric plasma and the exosphere/atmosphere/magnetosphere of the moons. It also includes the gravity, shape, rotation, astrometric observations and orbital parameters of the icy moons.

Prockter et al. describe the variety of morphological features displayed by the surfaces of the Solar System's icy satellites. Using data from spacecraft missions, the detailed morphology, size, and topography of cryovolcanic, tectonic, aeolian, fluvial, and impact features of large moons and smaller satellites are discussed.

Identifying surface materials and mapping their distributions allows us to constrain interior processes such as cryovolcanism and aqueous geochemistry. Dalton et al. look at all the findings we have so far on the planetary surface composition as derived from remote sensing over the ultraviolet through infrared wavelength ranges. Both ice and non-ice materials are considered, as well as exospheric species. The differences among the various satellites are discussed and brought into context. Other considerations include constraints brought on the interior composition and processes, the transport to the surface and communication with putative oceans.

Coustenis et al. review the characteristics of some satellites with atmospheres like Titan, Enceladus, Io and Europa, based on observations. The authors show that the atmospheres/exospheres of icy satellites greatly vary from one to another in terms of density, composition, structure or steadiness. Looking at satellites around the giant planets, Titan appears as the only icy satellite with a dense nitrogen atmosphere comparable in many ways to that of the Earth's atmosphere. Titan's atmosphere prevents the surface from direct interaction with the plasma environment, but gives rise to terrestrial-like exchanges of energy, matter and momentum. The atmospheres of other satellites are tenuous at best, non existent for most. However, new discoveries by the Cassini-Huygens mission have shown that there is an atmosphere around Enceladus' manifesting itself in large water vapor plumes emanating from surface cracks near the South Pole. The jets extend hundreds of kilometers into space and also include organics and ammonia. Io's SO_2 atmosphere originates from volcanoes that create a torus around the satellite. Europa's tenuous O_2 atmosphere is produced by intense radiation bombardment.

3 Physics and Chemistry of Ices and Organics: Constraints from Laboratory Experiments

Physical and chemical properties of planetary building materials are the medium between the observables described in Sect. 1 and the modeling to be presented in Sect. 3. Thus, laboratory measurements of intrinsic properties and behaviors are key elements in constraining planetary exchange process. Papers in this section describe techniques being developed to permit the measurement of spectral properties of planetary molecules at relevant condition (Dalton), and to determine electrical properties relevant to radar observations (Kofman et al.), thus enabling the interpretation of remotely sensed data.

Critical to our understanding of surface materials are the effects of ionizing radiation, which can sputter molecules from the surface, and can change molecules in atmospheres and surfaces through photolysis and radiolysis, as described in the paper by Cassidy et al. Also described in this chapter are latest results regarding phase relationships among frozen volatile compounds as a function of pressure and temperature, with special emphasis on mixtures of water ice with methane and ammonia (Fortes and Choukroun), which thus constrains the phases present under extreme planetary conditions. Laboratory measurements of rheological properties and thermal transport properties of icy materials, a necessary part of dynamical models, are also detailed (Durham et al.).

4 Modeling and Interpretations

Based on the data from space missions the models describing the interior structure, evolution and processes operating at icy moons have improved considerably. Models of the satellites' interior structures, rotation states and orbital states are required to compute the satellites' internal energy budgets that drive internal activity. In a few cases such activity is ongoing at present. Energy sources that are in some cases linked to the orbital and rotational states by tides and heat transport models are reviewed by Hussmann et al.

Past and recent activity in the icy moons are mainly visible at the surfaces where we find evidence for tectonism and volcanism at specific satellites. However, to distinguish internal processes from the external environment, models of the latter are required. Especially, the interaction with the giant planets' magnetospheres is an important factor. The state and composition of the tenuous atmospheres of the satellites are a result of both internal processes and interaction with the environment. Furthermore, impactors have shaped the satellite surfaces. Models for the impact rates in combination with the measured number density of craters on the surface can allow for the estimate of global and regional surface ages. The external environment including atmosphere-magnetosphere interactions and models for the cratering record are reviewed by Burger et al.

The interface between interior and surface is the lithosphere which is subject to external forcing (e.g., periodic tidal stresses and impact processes). It is also affected by internal processes (e.g., cryo-volcanism and dynamics in the ice shell). In some cases liquid water or volatiles and gases can reach the surface. The activity at Enceladus' south-pole is the most prominent example of such interior-surface communication. The physics of these processes and the conditions and models for individual satellites including Io, Enceladus, Triton and Titan are discussed by Tobie et al.

5 Implications

The state of knowledge about the structure and composition of icy satellite interiors has been significantly extended by combining direct measurements from spacecraft with laboratory experiments, and theoretical modeling. The spacecraft data supplies us with precious information to constrain the models describing satellite evolution, and the possible existence of water reservoirs below the crusts of the icy moons.

The processes governing the formation of the giant planets and the accretion of their gaseous envelopes determine the environments and the initial conditions for satellite formation. Coradini et al. and Mosqueira et al. show how temperature and pressure gradients in circumplanetary disks constrain their chemical evolution and condensation profiles and influence the abundances of elements available to build the satellites. Moreover, the forming planets and their subnebulae interact with the Solar Nebula and the planetesimals that populate the outer Solar System. Gas and planetesimals are captured from the Solar Nebula and spiral toward the growing planet, allowing for different generations of satellites to form and be accreted by the giant planets. In addition, it is shown that irregular satellites did not form where we see them now but originated elsewhere and were captured by the giant planets, introducing exogenous material in their host systems.

Once formed, the satellite systems of the giant planets start their secular evolution to their present state (Schubert et al.). Radiogenic and tidal heating supply the internal energy needed to the larger satellites to differentiate. Dynamical resonances, by exciting the orbital eccentricities of the satellites, interplay with tidal forces and enhance their effects. Internal activity and differentiation shape both the interiors and, through volcanism and tectonism, the surfaces of satellites. In addition, exchange processes take place between regular and irregular satellites or satellites and planetary rings, and high-velocity impacts may expose deeper layers of the satellites. All these processes act to modify both the morphology and the composition of the surfaces of the satellites and must be accounted for in any attempt to interpret the observational data.

The existence of potentially habitable liquid water reservoirs within icy satellites depends on the amount of energy which is available and on the chemistry of the icy materials. Sohl et al. review the chemical evolution of subsurface liquid water oceans, taking into account the processes occuring in aqueous environments and related to material exchange, including processes occuring at the transitions from the liquid water layer to the ice layers above and below, and water-rock exchange when the liquid layer is in contact with the rocky ocean floor.

In the final chapter, Raulin et al. discuss how the exchange processes in the icy moons are comparable to those thought to have played an important role in the emergence of life on Earth. They show how the study of prebiotic processes on and within outer solar system moons is a key goal for exobiology, together with the question of habitability and the search for evidence of past or present life. The question of planetary protection, especially in the case of Europa, is also presented.

6 Conclusion

Despite the large amount of observational evidence that has already been obtained, it is still unclear how the release of internal materials and volatiles onto the surface operates on water-rich bodies. Exchange processes have likely changed as evolution has proceeded, and what we observe today on surfaces and atmospheres is the integrated result of several billion years of complex interactions. In the absence of a precise quantification of these chemical exchange processes, it is also extremely difficult to evaluate the exobiological potential of these water-rich environments. In this volume, a detailed and up-to-date summary is given of the various topics related to the exchange processes in and on the satellites of the outer system.

It is our pleasure to thank all those who have contributed to this volume and to the dedicated workshop. We are grateful to the authors for their contributions, but also to the reviewers who helped us to improve the quality of this book. We also wish to express our warm thanks to the directorate and staff of the International Space Science Institute, for their effort in making the workshop happen and in finalizing the book.