Introduction to Icarus special issue "From Mars Express to Exomars"

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In February 2018, the international community working on the investigation and exploration of the atmosphere and surface of Mars met at ESAC near Madrid for a few days conference, organized and funded by the project UPWARDS ("Understanding Planet Mars With Advanced Remote-sensing Datasets and Synergistic Studies", www.upwards-mars.eu) of the EU Horizon 2020 program. This project, and that conference, were devoted to promote the scientific exploitation of Mars Express data and to revisiting and sharing results from this mission, in preparation for the upcoming new European mission to Mars, the Exomars 2016. The meeting approximately coincided in time with the end of the aerobraking phase of the Trace Gas Orbiter (TGO), which is the orbital element of Exomars 2016. The TGO science phase started on 21 April 2018.

This special issue of *Icarus* contains eleven papers which report original research results presented at the meeting or based on those presentations. This is obviously not an exhaustive representation of what was presented in Madrid, as other results have been published elsewhere. But they all share the motto of the meeting - from MEX to TGO - by presenting highlights of almost 15 years of Mars EXpress science legacy and new tools and methods for data analysis, thus paving the way for TGO observations and collaboration between two spacecraft. We think this is a valuable approach which, if properly and timely coordinated, can be very fruitful and should be promoted on every new space mission. The UPWARDS project could be considered as a bridge facilitating transition between two ESA missions, building team connections and enhancing science return from both missions.

The second goal of the UPWARDS project, now more in the scientific than in the programmatic realm, was to exploit synergies between different teams in a cross-disciplinary approach, looking for an integral vision of the planet in an attempt to unveil couplings between different regions. In the meeting mentioned above, there were investigations from the subsoil and the surface, to the lower atmosphere's composition and dust, to the water cycle and up to the thermospheric structure and escape to space. In this framework, this issue presents its 11 contributions ordered in this bottom-to-top vision of the atmosphere.

This collection starts with three papers focused on subsurface investigations. The first work by Jimenez-Diaz and colleagues (Jiménez-Díaz et al. (2020)) in the Universidad Complutense de Madrid (UCM) is a contribution to the ongoing interesting debate on the crustal composition of Mars and its impact on the thermal state and evolution of the Martian lithosphere. A second paper by Egea and colleagues (Egea-Gonzalez et al. (2019)), from the same team as the previous work, tackles the precise calculation of heat flows in two special regions on Mars, Elysium Planum, where the Insight mission landed, and Oxia Planum, the proposed landing site of Exomars-2022. Both regions are located near the Mars dichotomy, i.e., the geological transition region between the Northern lowlands and Southern highlands, characterized by significant variations in crustal properties. They studied how the regional context affects the thermal fluxes in these two planitiae. And the third paper by Gloesner et al., 2020, explores a difficult problem, the stability and composition of CH4-

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rich clathrate hydrates in the subsurface. They present global maps of stability depths of these clathrates incorporating the latest thermal fluxes from the UCM team.

This issue includes a series of four articles on the current climate of Mars, with a focus on the thermal structure, dust content and water ice clouds in the troposphere and the lower mesosphere. The first of these, by Giuranna et al. (2019) presents an analysis of an outstanding dataset by the *Planetary Fourier Spectrometer* (PFS) on board Mars Express which spans 12 years of nadir infrared spectroscopy. The set, comprising more than 2.5 million spectra collected between January 2004 and December 2015 describes in detail the latitudinal, local time and longitudinal, as well as seasonal and interannual variations of atmospheric temperatures and aerosol opacity. Improving the wide spectral range of PFS, the broad absorption bands of dust and water ice around 9.3 and 12 μm, respectively, were used to effectively separate these two components, while the fairly transparent window around 7.7 μm was used to derive surface temperatures. This 12-years PFS dataset reproduces and describes well a variety of well known meteorological patterns, and of particular value is the characterization of the water ice clouds in the North and South polar hoods with unprecedented detail and revealing clear differences between the two hemispheres. Another interesting result regards the aphelion cloud belt at low latitudes, where the authors attempted to study the water ice daily variations and the annual cycle.

A very related and difficult topic, the daily variation of the atmospheric dust opacity on Mars, is tackled by Wolkenberg and Giuranna (2020), within the same PFS team and using a similar dataset as in the previous work, covering 7 Mars Years. They describe a daily cycle of the column opacities, with a deep minimum at late night and small variations during the day, during the non-dusty season. They also studied dust storms, local and global, and we recommend the interested reader to take a look at this piece of work.

Other two papers are devoted to the hot topic of water ice clouds on Mars, in particular describing their distribution and variability using observations by *Observatoire pour la Minralogie, l'Eau, les Glaces et l'Activit* (OMEGA/Mars Express) observations. Olsen et al. (2019) and by Szantai et al. (2020) used ratios of reflectances observed at two wavelengths in a nadir geometry as proxies of the water-ice column. The first paper presented extensive analysis of the capability of their inversion method to retrieve different parameters of the cloud, like the effective radius of the particles. This in particular can only be obtained with confidence in optically thick clouds. The second work, with a modified proxy, studies the diurnal life-cycle of the clouds, improving the local time variations permitted by the Mars Express orbit. They compared the results with previous TES/MGS analysis, and with global climate model simulations, confirming the role played by the diurnal thermal tides.

Regarding the uppermost atmospheric region, two interesting papers are included in this special issue. The first one, by Jimenez-Monferrer and colleagues (Jiménez-Monferrer et al. (2020)), tackles the retrieval of CO2 abundance profiles at high altitudes from OMEGA limb sounding. This is performed by inverting a particularly strong emission of CO2 in the daylight thermosphere, at 4.3 um, due to a well known non-LTE (local thermodynamic equilibrium) situation. To solve the challenging task of atmospheric profile inversion, the team adapted a non-LTE forward model used in Earth limb observations to Mars conditions and were able to retrieve CO2 with good vertical resolution between 120 and 160 km. This is the first time to our knowledge that such an approach was applied to a CO2 atmosphere. The second paper by Chaufray et al. (2019) analyzes the escape of Hydrogen at the Martian exobase during MY28 and MY29, based on comparisons between measurements of Lyman-alpha emissions by SPICAM/Mars Express and their simulation with a 3-D GCM. They found important discrepancies between the model and the data, which they attributed to a few possible causes. These could be altitude variations in the hygropause, not included correctly in the model, and/or a possible supersaturation at lower altitudes, in the mesosphere.

From the perspective of the analysis tools mentioned above, some of the efforts in the UPWARDS project were devoted to promote new analysis techniques, like synergistic retrievals (presented elsewhere) and non-LTE retrievals (Jiménez-Monferrer et al. (2020), this issue). There is a third paper

in this special issue which explores the impact of gradients at the Martian terminator on the retrieval of species, in particular ozone. Piccialli et al. (2019) made an attempt to evaluate the usual assumption of spherical symmetry in most retrieval codes, and in particular on a gas which is predicted to present significant variations with local time at high solar zenith angles, i.e., around the terminators. The impact found, using predictions from a GCM, are significantly larger at sunset. We encourage the interested researcher to read it for more details.

The last contribution in this special issue, by Cardesín-Moinelo et al. (2020), is an overview of the possibilities for coordinated observations between Mars Express and Exomars TGO, illustrating the orbital spatial and temporal characteristics, as well as opportunities during the first year of TGO in its science phase. They presented potential synergies between observations and data sets of both missions and offered the experties of the team to anyone who would like to prepare for such opportunities in the coming years.

We hope readers find this global vision of Mars interesting and stimulating for their research.

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