Enrichment of planetary surfaces by asteroid and comet impacts

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DOI:
10.33612/diss.100695383

6. Conclusions and future prospects

In this thesis I have investigated the role of small planetary bodies, in particular asteroids and comets, in process of planetary surface enrichment. In doing so I focused on the geologically recent times (current impact rates). Impacts were more frequent in the younger Solar System. Therefore impacts were more efficient in the enrichment of the surfaces, e.g. this could be the main source of water on Earth (Morbidelli & Wood, 2015). There is large body of work on the delivery of material to planetary surfaces in the early stages of the Solar System. However, our research was focused on the current delivery rates. By performing N-body simulations, I studied these processes in our Solar System and in the exoplanetary system HR 8799. I determined the contribution of asteroids and comets to the organics budget to the surface of Mars and the water budget on Mercury's poles. Furthermore, I explored potential volatile and refractory delivery to the four giant planets in the well-known HR 8799 system. This chapter presents the highlights of the main results from the scientific chapters and briefly discusses the future outlook for each of the chapters.

6.1 Chapter 3

Delivery of organics to Mars through asteroid and comet impacts

- The discovery of methane in the Mars atmosphere and organic molecules in drill samples taken by NASA's *Curiosity* rover is surprising, as photodissociation and photodegradation would destroy most organics within hours.
- Burying in the subsurface will increase the lifetime of organics. However, it is clear that organics must have been delivered in geologically recent times by such suppliers as asteroids, comets, and/or interplanetary dust particles (IDPs).

- Our goal is to calculate the organics flux from asteroids and comets and compared it to the IDP fluxes estimated by Nesvorný et al. (2011a); Borin et al. (2017); Crismani et al. (2017).
- We have performed numerical gravity simulations of impact rates on Mars within the past few Myr and found that asteroids and comets collide with Mars at rates of 3.3 asteroids per Myr and 0.00434 comets per Myr.
- In our asteroid simulations we focused on organic-rich, C type, asteroids. To identify the asteroid type, we use the dynamical model by Greenstreet et al. and the measured distribution of taxonomic types across the Main Asteroid Belt from DeMeo & Carry (2013). For the comets we assumed a constant organic fraction.
- We found that asteroid and comet impacts deliver $\sim 0.05 \times 10^6$ kg/yr and $\sim 0.013 \times 10^6$ kg/yr, accordingly. The amount of carbon resulting from these delivery rates is comparable to that delivered by IDPs. Depending on how the IDP flux is calculated, comets deliver 4-19% of the IDP-born organics, while asteroids deliver 17-71% of the IDP-born flux.
- Finally, we have calculated carbon surface density around the impact crater for a 1 km asteroid, the most likely type of impactor. Organics from asteroids and comets dominate over IDP-borne organics at distances up to 150 km from the crater centre.

6.2 CHAPTER 4

EXOGENOUS DELIVERY OF WATER TO MERCURY

- Radar and in-situ observations have shown that Mercury's polar regions contain bright and dark polar deposits, which are associated with water ice and, possibly, volatile organic material despite the planet's proximity to the Sun.
- IDPs, asteroids and comets are possible sources of water on Mercury. We study how much water C-type asteroids, comets and IDPs can deliver to Mercury using the most recent minor bodies catalogues.
- In order to calculate the asteroid, comet and IDP impact rates on Mercury within the past few Myr we have performed numerical gravity simulations. We numerically modelled the gravitational dynamics of Mercury impactors using the N-body integrator RMVS/Swifter, and accounted for post-impact water-loss mechanisms. Immediate post-impact ejection into outer space is taken into account as is water diffusion across the surface into the polar cold traps.

- We find that water delivery is dominated by IDPs, while asteroids deliver an order of magnitude less, and comets deliver the same amount as asteroids. The exogenous water sources can easily deliver the amount of water required by the lower limits of the available radar and MESSENGER data; taken together, they require ~ 1.2 Gyr to deliver the lower limit on available water.
- In order to explain the upper limits on the observed water other sources of water are needed.

6.3 Chapter 5

Enrichment of the HR 8799 planets by asteroids and comets

- Several exoplanetary systems are known to host analogues of the Main Asteroid Belt and the Kuiper Belt. The exoplanetary system HR 8799 is known to host both a warm and a cold debris belt and four giant planets between the belts.
- We investigated the possibility that minor bodies deliver volatile (water and organics) and refractory (metals and silicates) material to the four giant exoplanets in the HR 8799 system.
- Using the N-body integrator REBOUND/MERCURIUS we performed gravity dynamical simulations of the entire exoplanetary system HR 8799 with its giant planets and belts.
- The simulations show that after 1 Myr the system reaches steady state. After 6 Myr the belts develop a clear structure with gaps similar to the Main Asteroid Belt and the Kuiper Belt.
- During the simulations we check for impacts between the planets and the minor bodies. We find that all four giant planets are impacted with material from both belts.
- The innermost planet suffers the most impacts from the inner belt, while the outermost planet suffers the most impacts from the outer belt.
- The inner belt delivers to the planets $0.5 \times 10^{-7}\,M_{\oplus}$ of volatile material per Myr and $1.1 \times 10^{-5}\,M_{\oplus}$ of refractory material per Myr. The outer belt delivers $2.2 \times 10^{-5}\,M_{\oplus}$ of volatiles per Myr and $2.2 \times 10^{-5}\,M_{\oplus}$ of refractories per Myr. Due to its higher mass and volatile content the outer belt delivers more material to the planets even though there are fewer impacts originated from the

outer belt. These rates are much higher than what we find for the Solar System in the Chapters 3 and 4.
- The amount of delivered volatiles and refractories, $4 \times 10^{-3}\,M_{\oplus}$, is small compared to the total mass of the planets but may be observable.

6.4 Future prospects

For more than 40 years, the surface of Mars has been searched for organic molecules. In the last few years there finally have been successful detections of organics by NASA's Curiosity rover. The most recent finding was the in situ detection of organic matter preserved in three-billion-year-old sedimentary rocks near the surface (Eigenbrode et al., 2018). This discovery showed that the organics have been protected within this rock all this time. However, there has not been any detection of organics in any surface samples even though we show that organics are continuously delivered to Mars. One possible explanation is that surface organics are destroyed on much faster timescale than the calculated through models. We suggest that searching for organics in the close vicinity of recent impact craters will improve our understanding of the organics survivability on the surface of Mars.

The nature and the origin of the dark and bright deposits on the Mercury's poles remains somewhat uncertain. Our results suggest that the lower limits of the observed water ice on Mercury can be explained by the delivery through IDP, asteroid and comet impacts. We also demonstrate that to explain the upper limits on the observed water ice more sources need to be included. More observations are needed for a better understanding. Luckily, the joint ESA-JAXA mission BepiColombo has been recently launched, in October 2018. The mission is expected to arrive at Mercury in 2025. One of the instruments aboard is the Mercury Gamma-Ray and Neutron Spectrometer (MGNS). This spectrometer is similar to the Neutron Spectrometer (NS) aboard the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft but has higher resolution. One of the tasks MGNS has is to map water across the entire surface of Mercury. It will map for the first time the Southern polar regions, which were not possible to map during the MESSENGER mission. The observations by MGNS will do mapping down to a depth of 1–2 m, which will give us more understanding about the composition of the deposits, and will clarify both polar regions are water-rich in the same way.

A great variety of ground based and space observatories (i.e. Herschel, Spitzer, ALMA, TESS) led to the age of exo-asteroid and exo-comet discoveries (see, e.g., Welsh & Montgomery, 2018; Zieba et al., 2019). We just start to discover what the minor bodies around other stars can be like, since minor bodies are the byproduct of planet formation, which is expected to happen around most of the stars.

Future missions (i.e. JWST, CHEOPS and, hopefully, SPICA) will provide us a better understanding of the composition, size frequency distribution and diversity of the belts in exoplanetary systems, which are the analogues of our own Main Asteroid Belt and Kuiper Belt. Better understanding of the belts' nature will improve studies of the volatile and refractory delivery within the exoplanetary systems and possibly will lead to observations of such mechanisms, at least at the early stages of the planetary systems when the delivery processes are expected to happen at the high rates. Our investigation of the exoplanetary system HR 8799 shows that such processes may happen and that our Solar System is not the only place where asteroids and comets have an important role. We demonstrate that the refractory delivery to the giant planets may be observable. Past observations of the impact of comet Shoemaker-Levy 9 on Jupiter may be of great use for post impact enrichment observations of the giant planets in the HR 8799 system. Although the HR 8799 system hosts four giant planets (maybe HR 8799 has rocky planets as well) and volatile delivery to this kind of planets is not significant astrobiologically, a potential discovery of a minor body population in an exoplanetary system with terrestrial planets would be astrobiologically very relevant.