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The chemical composition of Solar System objects

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Abstract. The Solar System is characterized by a great diversity of bodies from the hot surface of Mercury to the iced land of Pluto. Each body sharing a common origin but a unique evolution that shaped the system as we can see nowadays. This chapter will propose a brief (and not exhaustive) review on the results of the Italian scientific community in the field of the exploration of our planetary system with a focus on the investigation on the geo-chemical composition of the main objects.

Key words. Chemical composition, Solar System, planets, small bodies

1. Introduction

The study of chemical composition of Solar System objects involves a large variety of different analyses, from the investigation of elemental abundances and isotopic ratios, to the geochemical characterization of complex molecules and minerals across various Solar System bodies. Through optical and spectroscopic ground observations, in-situ measurements from spacecraft missions, laboratory analyses of analogs, meteorites and returned samples, scientists endeavor to decipher the primordial chemical reservoirs and subsequent geochemical evolution that characterized our planetary system. Comparative studies of chemical signatures among different Solar System bodies provide insights into their common origins and divergent evolutionary pathways. Therefore, only a strong interdisciplinary approach is able to reveal a wide knowledge of the Solar System and astronomers, planetary scientists, astrochemists, geochemists, and physicists should collaborate everyday to analyze the obtained data and test the their theoretical models and lab experiments. This chapter aims to offer an up-to-date, but obviously limited, overview on the chemical composition of some Solar System objects, with a particular focus on the contribution of the Italian community in this field.

2. Rocky planets

2.1. Mercury

On the Mercury surface, elements such as Potassium (K), Thorium (Th), and Uranium (U) were directly quantified via Gamma-Ray Spectrometer (GRS) measurements from

MESSENGER mission, enabling the determination of their absolute abundances. Remote sensing measurements reveal the presence of some volatile species, including H, He and other species, primarily concentrated in Mercury's exosphere (Robidel et al. 2023 and reference therein) along with other moderately volatile elements (like C, Na, S, K, and Cl). The surface of Mercury was also analyzed using spectra acquired by the MASCS instrument (McClintock & Lankton 2007). Applying principal component analysis the major terrain classes can be distinguished, as well as fresh ejecta, faculae (connected to volcanism) and red material related to impact craters (Galiano et al. 2023). Using the MESSENGER Mercury Dual Imaging System (MDIS) camera the surface of the planets can be analyzed even at higher spatial resolution (Zambon et al. 2022; Pajola et al. 2021), allowing focused studies on features of interest like the still debated hollows, shallow irregular and rimless flat-floored depressions with bright interiors and halos probably produced by devolatilization processes (Lucchetti et al. 2018, 2021; Pajola et al. 2021).

In parallel to the analysis of remote sensing data, an extensive work in laboratory is carried on to support past, present and future interpretation of the conducted observations. Several case studies has been investigated: the effect of graphite abundance and grain size in silicate mix (Bruschini et al. 2022), the presence of silicate glasses as analogs of the major component in Mercury volcanic products (Pisello et al. 2023), and the surface composition through the study of sulphide-bearing minerals (Carli et al. 2024).

Using thermophysical and exospheric circulation models, the evolution of chemical abundances can be studied as a function of the heliocentric distance. Such models has been employed to characterize the observed increase of Na (Rognini et al. 2022) and He (Yoneda et al. 2021) with temperature at perihelion.

In the near future, the BepiColombo mission (Benkhoff et al. 2021) will increase our knowledge of the smallest planet, in particular thanks to the data collected by SIMBIO-SYS (Spectrometer and Imaging for MPO BepiColombo Integrated Observatory SYStem, Cremonese et al. 2020) and SERENA (Search for Exospheric Refilling and Emitted Natural Abundances, Orsini et al. 2021) instrument suites.

2.2. Venus

Attention on the second planet of the Solar System is growing in the recent years due to the preparation of no less than three space missions. The NASA Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI+) mission (Garvin et al. 2022) will perform a flyby of Venus and release an atmospheric probe to perform in-situ measurements of the Atmosphere. NASA Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) target for 2031 will map the surface of Venus using radar measurements (Campbell & Hensley 2024). Moreover, the ESA Envision mission will study in detail the planet from the inner core to its upper atmosphere with a focus on the planet activity and climate. Past mission had studied the planet atmosphere in detail, in particular ESA Venus Express spacecraft carried two Italian-led experiments, namely the Planetary Fourier Spectrometer (PFS) (Formisano et al. 2006) and the Ultraviolet/visible/near-infrared Mapping Spectrometer (VIRTIS) (Drossart et al. 2004). VIRTIS limb observation of infrared emission revealed the photochemical complexity of the planet atmosphere, characterized by the presence of O_2, OH, NO, CO_2 and CO (Soret et al. 2010; Migliorini et al. 2013; Gilli et al. 2015; Piccioni et al. 2016), along with the strong dynamic activity that controls the structure of the upper atmosphere of Venus (Drossart et al. 2007). Although past mission focused mainly on the atmosphere, some evidence of active volcanism where found on the surface. A recent review of what is known so far on the surface composition of Venus can be found in (Gilmore et al. 2023), mostly based on major element data obtained from Venera and Vega landers and pointing out to the presence of tholeiitic and alkali basalts. Moreover, it is clear that the SO_3 content and density of these rocks indicate they have been altered under the current Venus atmosphere. Venus, although very similar in some aspects to Earth, still remains a target with great unknowns that hopefully future missions will clarify.

2.3. Mars

Mars is the most explored body in the solar system to date. Almost 50 missions have been launched to study the red planet (though not all of them successful). From the very beginning of Mars ' exploration, it became evident that the planet is characterized by a complex geological and climatic evolution similar to the Earth. Both the planet's surface and atmospheric composition were investigated by instruments with strong Italian contribution onboard orbiter missions, such as OMEGA (Bibring et al. 2004; Bellucci et al. 2006) and PFS (Formisano et al. 2005) on Mars Express and NOMAD (Vandaele et al. 2018) on ExoMars TGO. These instrument investigated in detail the atmosphere of the Red Planet characterizing dust, water, methane, CO and other minor species (D'Aversa et al. 2022; Bouche et al. 2021; Sindoni 2013; Geminale et al. 2011; Brines et al. 2023) Moreover, along with allowing detailed studies on the mineralogical composition of Mars (Bibring et al. 2005; Ehlmann & Edwards 2014), also H_2O and CO_2 ices were characterized (Giuranna et al. 2007; Oliva et al. 2022). Moreover, clays and phyllosilicates minerals were also identified as a prove of a past presence of liquid water on the surface (Jakosky & Phillips 2001; Poulet et al. 2005; Ehlmann & Edwards 2014; Wordsworth 2016). Indeed the planet still host liquid water in the subsurface as detected by the Italian radar instrument MARSIS on board ESA Mars Express orbiter (Orosei et al. 2018). The past habitability of the Red Planet (Simonetti et al. 2024) and presence of liquid water, although still discussed with respect to its duration and evolution, poses some interesting constrain on the possible formation of complex organics. Two factors should be taken into account: the mineralogy available on Mars (Esposito et al. 2000) and the catalytic and/or protective role of the minerals in the interaction with organic material in presence of strong irradiation (Fornaro et al. 2018). Several studies evaluated the survival of biomarkers such as amino acids and nucleotide on the surface even in presence of a oxidant environment (Poggiali et al. 2020; Fornaro et al. 2020).

The future of Mars exploration passes through the ESA-NASA Mars Sample Return campaign that will allow access to Martian samples in laboratories on Earth, enabling unprecedented geo-chemical analysis. In the coming years, however, the in-situ scientific activity of the ExoMars rover Rosalind Franklin, which will be the first to carry out geo-chemical analyses of the Martian subsurface, will see a large participation of the Italian community, which led the realisation of the miniaturised spectrometer Ma_MISS (De Sanctis et al. 2022; Ferrari et al. 2023). In addition to the continuation of the work already underway on the study of the presence of water on the subsurface Orosei et al. (2020). Regarding Mars, it is worth mentioning that the upcoming JAXA Martian Moon eXploration mission boosted again the Italian scientific studies on Phobos and Deimos, trying to identify the composition of this enigmatic bodies. Indeed the two moons could inherit a basaltic component derived from a giant collision with Mars (in analogy with Earth's Moon) or could have the composition of a captured primitive asteroid and therefore rich in carbonaceous material and possible volatiles such as organics and water ice in the subsurface (Giuranna et al. 2021; Pajola et al. 2018; Poggiali et al. 2022b; Wargnier et al. 2023).

3. Inner system Small bodies

3.1. Asteroids

The variety of composition of the asteroids and small rocky bodies of the inner solar system is remarkable, ranging from bodies almost entirely composed of iron to bodies with very low density and a high proportion of carbon and volatile components via monolithic rocky bodies or rubble pile bodies. It would not be possible to report a complete review here of all the detailed findings on the various types of asteroids, and besides, there is already a remarkable series of books treating this subject (Gerhrels et al. 1989; Bottke et al. 2002; Michel et al. 2015).

In the panorama of asteroid studies, the activities of the Italian community are very broad, impressive and certainly cannot be listed exhaustively here. By reviewing some of the recent main results mainly related to space missions, we can begin with the important discoveries made on the dwarf planet (1) Ceres. The relatively recent NASA DAWN mission carried on board the VIR spectrometer: the instrument, developed by INAF, detected on the surface of the asteroid the ubiquitous presence of phyllosilicates and carbonates with complex composition (De Sanctis et al. 2015; Ammannito et al. 2016; Marchi et al. 2019). Ammonium is also ubiquitous but while generally is bounded with phyllosilicates, it has been found also in salts (Singh et al. 2021). Water ice have been detected in localized regions (Combe et al. 2016; Raponi et al. 2018). Moreover, evidence of aliphatic organic material and bright carbonate deposits linked to aqueous alteration were also observed (De Sanctis et al. 2016, 2017; Raponi et al. 2020b). DAWN also visited asteroid (4) Vesta and VIR instrument mapped its surface mineralogy (Frigeri et al. 2015), strengthening the Vesta-HED meteoritic link (De Sanctis et al. 2013) as well as identified the presence of hydrated minerals (De Sanctis et al. 2012) and olivine (Ammannito et al. 2013).

Other space missions that have investigated the mineralogy and volatile components of asteroids have received strong italian scientific contributions. NASA OSIRIX-REx and JAXA Hayabusa2 studied in detail carbonaceous asteroids that are believed to be crucial for the transport of prebiotic material in the solar system. Several studies revealed the presence of hydrated minerals, organic and carbonates in the main bulk composition of the surface of these asteroids (Kitazato et al. 2019; Hamilton et al. 2019; Barucci et al. 2019, 2020; Ferrone et al. 2021) as well as the direct effect of space weathering in the alteration of the pristine material using laboratory techniques to interpret remote sensing data (Brunetto et al. 2020).

The Italian community has been strongly involved also in the recent DART and HERA missions to study the binary system (65803) Didymos. Regarding the study of the composition of these asteroids, contributions were delivered both from ground based observations (Ieva et al. 2022; Rivkin et al. 2023) and spacecraft data analysis (Poggiali et al. 2022a; Dotto et al. 2024; Hasselmann et al. 2024).

Since many years asteroid science is supported by a strong laboratory work. In this framework, the study of the effects of temperature on minerals in support of mineralogical interpretation is one of the main field brought forward by Italian leaded works (De Angelis et al. 2021; Poggiali et al. 2021; De Angelis et al. 2022) with important results on the response of minerals to temperature changes according to their composition. Moreover, the Italian community is also deeply involved in more classical mineralogical studies of both meteorites and analogue minerals in support to asteroid science for example, some recent results can be found in Ferrari et al. (2019); Folco et al. (2018); Musolino (2021); Pratesi et al. (2021); Carli et al. (2022); Poggiali et al. (2023).

3.2. Comets

Comets are among the least modified bodies in our solar system, thus covering an important role in astrochemistry research. They accumulated from the material surrounding our proto-Sun about 4.6 billion years ago and shortly after their formation they were redistributed (mainly) into the Oort cloud (OC, source of dynamically new and long period comets) and the Kuiper Belt (considered the source of Jupiter and short period comets) (Morbidelli & Rickman 2015; Gomes et al. 2005). There, the nuclei have remained frozen to this day, retaining most of the chemical and mineralogical properties associated with their formation site. A proper understanding of the composition of comets offers thus a unique window into the chemistry and physics of the early solar system (Mumma & Charnley 2011).

Great progresses have been made in studying comets through a series of spacecraft missions. The most recent and successful one is the European Space Agency (ESA) Rosetta mission, which performed with unprecedented accuracy in situ studies on the Jupiter Family comet 67P/Churyumov - Gerasimenko during its active phase, challenging our understanding of these bodies. The VIRTIS instrument (Coradini et al. 2007) allowed the spectroscopic investigation of the coma volatile and dust content (Migliorini et al. 2016), and of the nucleus' composition identifying surface CO_2 (Filacchione et al. 2016b), water ice (Barucci et al. 2016; Filacchione et al. 2016a), aliphatic organics (Raponi et al. 2020a), as well as ammonium salts (Poch et al. 2020) and Mg-rich silicates (Mennella et al. 2020).

Unfortunately, space missions are complex and limited to a few targets. On the contrary, remote space and ground-based investigations, even if less detailed, can target different dynamical types allowing a more systematic study in many comets. Over two dozen molecules have been found in cometary atmospheres, with water being the main component of a comet nucleus, followed by CO_2, CO, CH_3OH, CH_4, H_2S, C_2H_6 and NH_3. Recent reviews based on spectroscopic surveys in the mid-IR and mm spectral ranges, reveal a wide diversity among comets consistent with the numerous processes that occurred in our protoplanetary disks and the models that predict comets dispersion after formation (Mumma & Charnley 2011; Bockelée-Morvan & Biver 2017; Lippi et al. 2021; Dello Russo et al. 2016). There are no evident differences between different dynamical types, suggesting that all comets may have a similar composition, most likely inherited before disseminating in their reservoirs.

However, the statistics of comets investigated using spectroscopy in the mid-IR and millimeter are still low (less than 70 comets) and thus insufficient to draw clear inferences about population characteristics and/or physical conditions at the time of formation. Furthermore, some observational and modelling biases can be detected in the present databases and and should be addressed and revised before any conclusions can be drawn (see for example Lippi et al. 2021). Finally, the Rosetta mission's measurements do not fully correlate with IR and radio surveys (Lippi et al., paper in prep.), suggesting either a bias caused by the different methods used (mass vs flux line spectroscopy) or a possible organic depletion for this specific comet.

In the next future, it is critical to increase these statistics and to implement observing programs aimed at understanding the sources of observational and modeling biases.

4. Giant planets and their satellites

Jupiter and Saturn, the two largest gaseous giants in our solar system are characterised by an atmosphere rich in hydrogen but with the presence of many other elements and molecules such as CH4, H3+, ammonia and several others (Taylor et al. 2004; Adriani et al. 2015; Ingersoll 2020; Migliorini et al. 2023; Grassi et al. 2021).

A particular attention were dedicated by the Italian community to the icy moons of Jupiter and Saturn thanks to data collected by the JIRAM (Adriani et al. 2008) on board the Juno spacecraft and the VIMS spectrometer (Brown et al. 2004) on board the Cassini mission.

Sputtered-induced water ice grain enrichment was found on Ganymede along with several minor species such as hydrated salts, trapped H_2, CO_2, and acids (Mura et al. 2020a). Recently hydrated sodium chloride, ammonium chloride and sodium/ammonium carbonate, as well as organic compounds, possibly including aliphatic aldehydes were also detected by the instrument (Tosi et al. 2024). JIRAM observations of Io, the volcanic moons of Jupiter, found presence of SO_2 frost and the possible presence of Cl_2SO_2 and H_2O/SO_2 have mixtures. Nitrile compounds or tholins may also be present on the surface (Mura et al. 2020b; Tosi et al. 2020).

Some studies focused on Enceladus and Titan, the two most famous moons of Saturn, looking for the surface and atmosphere composition (Brown et al. 2006; Scipioni et al. 2017; Fabiano et al. 2017). These two bodies show some really intriguing features: Enceladus - a subsurface and possibly habitable ocean - and Titan - a complex atmosphere with a methane cycle similar to the water-cycle on Earth. For Titan an intense laboratory work was perfomed by the Italian community to study astrobiological implication and prebiotic chemistry in the atmosphere (Balucani 2009; Brucato et al. 2010; Balucani et al. 2010, 2023).

More general works studied the composition of Saturn moons and rings, in particular focusing on the radial variability of icy satellites and main rings average spectral properties (Filacchione et al. 2012; Ciarniello et al. 2019).

5. Trans Neptunian Objects

Trans-neptunian objects (TNOs) are bodies located in the outer solar system, whose dimensions range from a few tens of kilometers up to the size of Pluto and Eris and that are thought to contain both refractory and frozen volatile materials accreted during the early stages of the formation of the solar system. Their color vary from neutral to very red (e.g., Barucci & Merlin 2020) and observations in the near-infrared (NIR) revealed features attributed to a variety of frozen volatiles. Water ice, either in the amorphous or crystalline state, is the most widespread ice in the TNO population (Barucci et al. 2008). Other ices are also present and among them CO, CH_4, and N_2 that are abundant at the surface of Pluto, NH_3 that is revealed on Charon (Dumas et al. 2001) and CH_3OH, recently detected on Arrokoth by the instruments onboard New Horizons (Grundy et al. 2020).

The available information on TNOs comes from remote sensing data in the Visible (Vis) and Near-InfraRed NIR. At these wavelengths, photons only probe the topmost layer of the surface (Urso et al. 2020a). Since these bodies lack of an atmosphere, or at most, they show tenuous atmospheres due to the sublimation of ices, surfaces are continuously exposed to space weathering. As a result, remote sensing data are severely affected by the alteration induced by space weathering. In this framework, laboratory analysis of pure ices or mixtures aim to inform on the optical properties of ices and their absorption features. Optical constants were calculated for CO, CO_2, and CH_4 also exposed to ion bombardment (Baratta & Palumbo 1998; Palumbo et al. 2006; Brunetto & Roush 2008), as well as refractory materials such as silicates (Brunetto et al. 2007) and complex organics (Baratta et al. 2015). Density and refractive indices were also calculated for several ice species, including CO (Urso et al. 2016), CO_2 (Baratta & Palumbo 2017), CH_4 (Brunetto et al. 2008), and several others (e.g., Fulvio et al. 2009; Modica & Palumbo 2010; Scirè et al. 2019).

Some studies focus on the behavior of IR bands of both crystalline and amorphous water, informing on how IR features would be affected by temperature changes and irradiation conditions (e.g., Palumbo et al. 2006; Urso et al. 2018). Experiments also informed on the spectral changes when water is mixed with other frozen volatiles commonly revealed at the surface of TNOs, such as N_2 and CH_4 (e.g., Fulvio et al. 2010).

The ion bombardment of ices also lead to changes in their composition. Keeping water as target ice, together with the changes in its structure we observe the formation of H_2O_2 (Gomis et al. 2004; Urso et al. 2018). The formation of new molecular species was also investigated in a variety of ices containing H-, C-, N-, O- and S-bearing molecules. Both qualitative and quantitative estimations show that both the destruction of original molecules and the formation of new compounds depend on the stoichiometry of the ice and on the irradiation dose, that is, the energy deposited by incoming ions to the sample (e.g., Urso et al. 2022).

Particular focus was dedicated to the effects of energetic charged particles on frozen C-bearing molecules. In fact, irradiated ices show the appearance of a slope in the Vis-NIR when undergoing ion bombardment. Reddening and darkening are observed in a variety of C-bearing ices and are found to increase with the irradiation dose (Brunetto et al. 2006). During irradiation, the destruction of the original compounds leads to the formation of both volatile and less volatile species (e.g., Urso et al. 2022). By warming-up the irradiated ices to simulate the sublimation process that occurs at the surface of TNOs, the increase in the molecular diffusion and reactivity leads to the formation of a complex macromolecular material referred to as organic refractory residue (Palumbo et al. 2004; Baratta et al. 2015; Urso et al. 2017; Accolla et al. 2018; Urso et al. 2020b). Experiments also pointed out the relevance of the chemistry triggered by ion irradiation in ices and the mechanism that determine changes in the final composition of organic refractory residues (Urso et al. 2020b, 2022).

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