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ROSINA/DFMS capabilities to measure isotopic ratios in water at comet 67P/Churyumov–Gerasimenko

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ABSTRACT

The likelihood that comets may have delivered part of the water to Earth has been reinforced by the recent observation of the earth-like D/H ratio in Jupiter-family comet 103P/Hartley 2 by Hartogh et al. (2012). Prior to this observation, results from several Oort cloud comets indicated a factor of 2 enrichment of deuterium relative to the abundance at Earth.

The European Space Agency's Rosetta spacecraft will encounter comet 67P/Churyumov–Gerasimenko, another Jupiter-family comet of likely Kuiper belt origin, in 2014 and accompany it from almost aphelion to and past perihelion. Onboard Rosetta is the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) which consists of two mass spectrometers and a pressure sensor (Balsiger et al., 2007).

With its unprecedented mass resolution, for a space-borne instrument, the Double Focusing Mass Spectrometer (DFMS), one of the major subsystems of ROSINA, will be able to obtain unambiguously the ratios of the isotopes in water from in situ measurements in the coma around the comet. In this paper we discuss the performance of this sensor on the basis of measurements of the terrestrial hydrogen and oxygen isotopic ratios performed with the flight spare instrument in the lab. We also show that the instrument on Rosetta is capable of measuring the D/H and the oxygen isotopic ratios even in the very low density water background released by the spacecraft. This capability demonstrates that ROSINA should obtain very accurate isotopic ratios in the cometary environment.

1. Introduction

Water is one of the prime ingredients required for life. As such it is one of the major foci of past and current space missions including missions to Mars (Viking and Mars Express), to the Jupiter system with its icy moons (JUNO and JUICE), as well as missions to the poles of the moon. In the case of terrestrial water it is believed that Earth was once dry. It has been argued that some terrestrial water could have originated in hydrous minerals that were present during the early accretion phase of the Earth and the presence of these minerals helps explain different aspects of Earth's geochemistry. However, these minerals must have formed locally; this would imply that the nebula must have been cooler than the models predict Ciesla and Lauretta (2005). Therefore, at least part of the water must have originated from other places in the solar system (Oró, 1961). Primary suspects are asteroids and comets. On the one hand, asteroids are suspect in particular due to the detection of carbon-rich meteorites that have deuterium to hydrogen (D/H) ratios similar to the value found in the Earth's oceans. The Nice model (Gomes et al., 2005, Tsiganis et al., 2005 and Morbidelli et al., 2005), postulates that the gas giant planets underwent orbital migration and forced objects in the asteroid belt and/or Kuiper belt on eccentric orbits that put them in the path of the terrestrial planets. During this late heavy bombardment comets might have brought water to Earth and Mars.

On the other hand, the role of comets as a source of water on Earth was long questioned, or at least thought to be of limited importance. The observed D/H ratios of several Oort cloud comets, such as Halley (Balsiger et al., 1995, Eberhardt et al., 1995), Hale-Bopp (Meier et al., 1998a, Meier et al., 1998b), Hyakutake (Bockelée-Morvan et al., 1998), Wild 2 (Sandford et al., 2006) and 2001 Q4 NEAT (Weaver et al., 2008), were clearly higher than

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the Standard Mean Ocean Water (SMOW) D/H ratio of $(1.558 \pm 0.001) \times 10^{-4}$ on Earth Handbook of Chemistry and Physics (1974). The D/H ratio in the three samples from Wild 2 show even enritchments of up to three times the terrestrial value. Recent remote sensing measurements of a Jupiter-family comet, 103P/Hartley 2, by the Herschel Space Observatory of $HD^{16}O$ and $H_2{}^{18}O$ found an ocean-like water ratio for D/H of $(1.61 \pm 0.24) \times 10^{-4}$ (Hartogh et al., 2011). In these measurements the ratio of $^{18}O/^{16}O$ was assumed to be solar. Hence Jupiter-family comets, believed to originate in the Kuiper belt, could present another possible source for the water on Earth and Mars. However, so far, the D/H ratio for water could not be measured directly without at least the assumption of the $^{18}O/^{16}O$ ratio. This is the only D/H measurement in a Jupiter family comet. Nothing is known about the diversity among this group of comets. In addition, only four Oort cloud comets are fairly small sample.

Comet 67P/Churyumov–Gerasimenko (67P/C–G), the target of the European Space Agency's Rosetta mission, most probably also originates from the Kuiper belt region. Rosetta will accompany the comet over an extended period of time. The rendezvous with the comet will take place well beyond 3 AU and from then on Rosetta will perform observations along its inward journey to characterize the physical, chemical, and morphological characteristics of the nucleus and the surrounding coma including neutral gas, dust, and plasma.

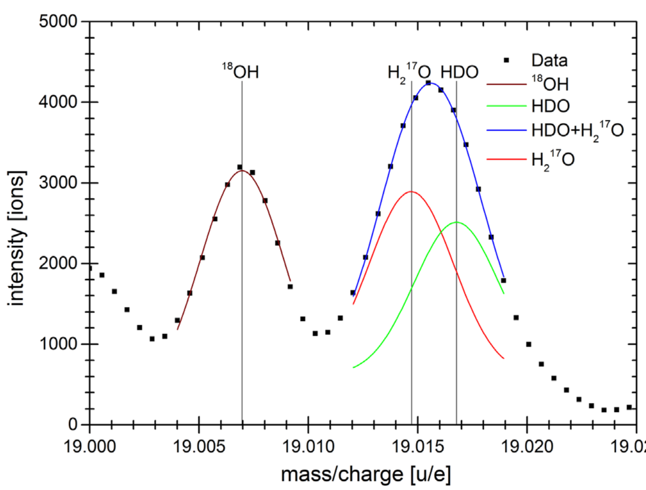

Fig. 1. HR spectrum of mass 19 u/e, whereas $H^{18}O$ is clearly separated from $H_2{}^{17}O$ and HDO. The Full Width at Half Maximum (FWHM) of the peak to the right is significantly broader than that for $H^{18}O$ and implies two overlapping peaks. To resolve the latter, two Gaussian fits were applied; taking the FWHM from $H^{18}O$ as fixed for all three mass peaks and the amplitudes of $H_2{}^{17}O$ and $HD^{16}O$ as the free parameters to be fitted. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA), consisting of the Double Focusing Mass Spectrometer (DFMS), the Reflectron-type Time of Flight mass spectrometer (RTOF), and the COmet Pressure Sensor (COPS), is well suited to determine relevant isotopic ratios (Balsiger et al., 2006).

In particular DFMS with it's high mass resolution of $m/\Delta m$~3000 at the 1% level is able to distinguish between the major fragments of water including atoms and molecules containing various combinations of the isotopes of hydrogen and oxygen. The high mass resolution allows derivation of cometary hydrogen and oxygen isotopic ratios without any assumptions on the $H_2{}^{18}O$ to $H_2{}^{16}O$ ratio as required for interpreting optical observations (Hartogh et al., 2011). In comparison to the to date only in situ measurements in a comet coma, the result should be clearly superior: The ion mass spectrometers on the Giotto spacecraft had limited resolution and the D/H ratio was determined from the hydronium ion and not from the water molecules directly (Balsiger et al., 1995 and Eberhardt et al., 1995). No attempts were made so far to determine the oxygen isotopes in water in comets apart from the very coarse determination by the Ion Mass Spectrometer- High Intensity Sensor (IMS-HIS) on Giotto (Balsiger et al., 1995) which resulted in a solar value for $^{18}O/^{16}O$ with a large uncertainty.

Therefore the observations by ROSINA at comet 67P/C–G are an important step in confirming (or dismissing) the role of Kuiper belt objects as a major source of the water on Earth.

2. DFMS

DFMS is a mass spectrometer designed according to the Nier–Johnson geometry (Johnson and Nier 1953 and Balsiger et al., 2007). This configuration is a combination of a 90° electrostatic analyzer as an energy analyzer and a 60° magnet as momentum analyzer. In this configuration, neutral gas is ionized by electron impact and the resulting ions are focused in energy and in direction. Therefore DFMS stands for double focusing mass spectrometer. DFMS uses electron impact ionization to produce ions from the incident cometary neutrals. Upon electron impact on a molecule, the molecule is not only ionized but can also dissociate into fragments. The parent neutral water molecule H_2O can form H_2O^+, OH^+, O^+, and H^+ ions inside the source when bombarded with electrons (Rao et al., 1995). Fig. 2 shows all the detected isotopes of water as well as the fragments thereof.

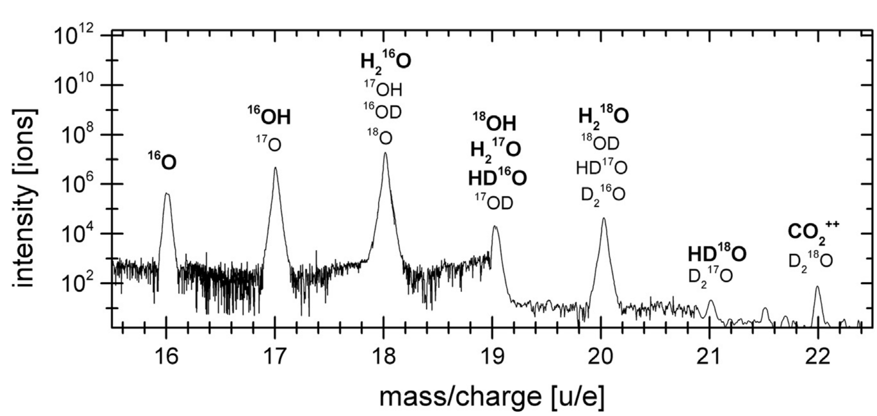

Fig. 2. LR scan (raw data) of all H_2O isotopes and the fragments thereof. In bold are detected species whereas not highlighted species are too weak e.g. $D_2{}^{17}O$ and $D_2{}^{18}O$, or obscured by other prominent high signals as e.g. ^{17}O (^{16}OH) and for ^{18}O ($H_2{}^{16}O$). The amplitude of the noise between the peaks is varies due to different detector gains, whereby the rare isotope $HD^{18}O$ is recorded with a higher detector gain and $H_2{}^{16}O$, ^{16}O and ^{16}OH with a much lower one.