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Terrestrial deuterium-to-hydrogen ratio in water in hyperactive comets

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Abstract

The D/H ratio in cometary water has been shown to vary between 1 and 3 times the Earth's oceans value, in both Oort cloud comets and Jupiter-family comets originating from the Kuiper belt. This has been taken as evidence that comets contributed a relatively small fraction of the terrestrial water. We present new sensitive spectroscopic observations of water isotopologues in the Jupiter-family comet 46P/Wirtanen carried out using the GREAT spectrometer aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA). The derived D/H ratio of $(1.61 \pm 0.65) \times 10^{-4}$ is the same as in the Earth's oceans. Although the statistics are limited, we show that interesting trends are already becoming apparent in the existing D/H cometary data. A clear anti-correlation is seen between the D/H ratio and the active fraction, defined as the ratio of the active surface area to the total nucleus surface. Comets with an active fraction above 0.5 typically have D/H ratios in water consistent with the terrestrial value. These hyperactive comets, such as 46P/Wirtanen, require an additional source of water vapor in their coma, explained by the presence of subliming icy grains expelled from the nucleus. We also show that hyperactivity is only observed for comets with small nuclei, with effective radii less than 1.2 km, whereas all non-hyperactive comets have larger nuclei. Possible interpretations of these trends are discussed.

1. Introduction

The D/H ratio provides key constraints on the origin and thermal history of water molecules. The large variations in the D/H ratio in cometary water, from 1 to 3 times the Earth's oceans value, have been interpreted as reflecting their formation in different regions of the solar nebula. Indeed, models considering isotopic exchanges in an evolving accretion disk predict an increase in the D/H ratio with increasing distance from the star [4]. The same isotopic diversity observed in both Oort cloud and Jupiter-family comets could then be explained by the recent evidence that the formation zones of the two families largely overlapped and extended over a broad range of heliocentric distances.

We present a new measurement of the D/H ratio in the Jupiter-family comet 46P/Wirtanen carried out using the Stratospheric Observatory for Infrared Astronomy (SOFIA) [5]. Comet 46P/Wirtanen belongs to the category of hyperactive comets, for which water molecules are mainly produced by sublimating water-ice-rich particles within the coma. Using a sample of comets with known D/H ratios in water and nucleus sizes, we show that a remarkable correlation is present between the D/H ratio and hyperactivity [5].

2. SOFIA observations of comet 46P/Wirtanen

The 547 and 509 GHz $1_{1,0} - 1_{0,1}$ transitions of $H_2^{18}O$ and HDO, previously observed in several comets by *Herschel*, are now accessible from SOFIA. Observations of comet 46P/Wirtanen were carried out during five SOFIA flights between 2018 December 14 and 20 UT. The resulting D/H ratio in water is $(1.61 \pm 0.65) \times 10^{-4}$. Comet 46P/Wirtanen is the third Jupiter-family comet with a D/H ratio consistent with the Earth's ocean value.

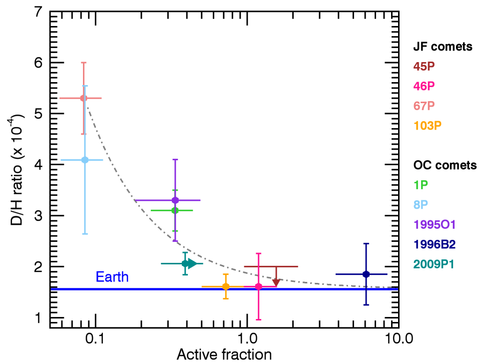

Figure 1: D/H ratio in cometary water as a function of the active fraction computed from the water production rates measured at perihelion. The dash-dotted line shows the expected D/H assuming two sources of water: D-rich (3.5×VSMOW) from the nucleus and D-poor (VSMOW). Comets with an active fraction equal to 0.08 are assumed to release only D-rich water.

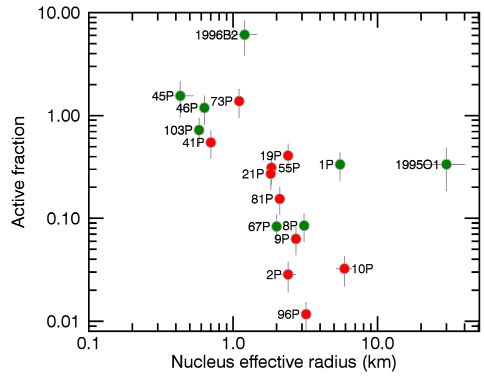

Figure 2: Active fraction at perihelion as a function of the nucleus size. Green symbols refer to comets for which the D/H ratio in water has been measured.

3. Anti-correlation between the D/H ratio and hyperactivity

When both the water production rate and the nucleus size are known, it is possible to compute the active fractional area of the nucleus (or active fraction). In the sample of comets with D/H determinations (or significant upper limits), only eight comets have a known nucleus size, most of them from spacecraft images or radar measurements. The active fraction was computed using a sublimation model and water production rates derived from Lyman-α observations by the SWAN instrument aboard SOHO [3]. Values for the D/H ratios are taken from the review of [1], except for comet C/1996B2 (Hyakutake), for which we revised the value to $(1.85 \pm 0.6) \times 10^{-4}$ using updated $Q(H_2O)$ values [2].

Figure 1 shows a striking anti-correlation between the D/H ratio and the active fraction computed at perihelion. Comets with high active fractions (hyperactive comets) have terrestrial D/H values.

4 Discussion

The observed correlation may suggest that hyperactive comets belong to a population of ice-rich objects that formed just outside the snow line, where a large enhancement in the ice surface density is expected [6], or in the outermost regions of the solar nebula, from water thermally reprocessed in the inner disk that was transported outward during the early disk evolution. The observed anti-correlation between the active fraction and the nucleus size (Fig. 2) seems to argue against the first interpretation, as planetesimals near the snow line are expected to undergo rapid growth.

Alternatively, isotopic properties of water outgassed from the nucleus and icy grains may be different due to fractionation effects at sublimation. The observed anti-correlation can be reproduced with two sources of water contributing to the measured water production rate and the active fraction: D-rich water molecules released from the nucleus and an additional source of D-poor water molecules from sublimating icy grains (see dash-dotted line in Fig. 1). In this case, all comets may share the same Earth-like D/H ratio in water, with profound implications for the early solar system and the origin of Earth's oceans.

References

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