MODELING THE SEASONAL EVOLUTION OF 67P/CHURYUMOV-GERASIMENKO WATER LOSS RATE.

M. Ciarniello[1], M. Fulle[2], F. Tosi[1], F. Capaccioni[1], G. Filacchione[1], A. Raponi[1], G. Rinaldi[1], A. Rotundi[3,1], S. Mottola[4], M. C. De Sanctis[1], D. Bockelée-Morvan[5], M. Formisano[1], G. Magni[1], A. Longobardo[1], M. T. Capria[1], [1]INAF-IAPS (via del Fosso del Cavaliere, 100, 00133, Rome, Italy; mauro.ciarniello@inaf.it), [2]INAF - Osservatorio Astronomico (Trieste, Italy), [3]Università degli Studi di Napoli Parthenope, Dip. di Scienze e Tecnologie (Naples, Italy). [4]Institute for Planetary Research, German Aerospace Center (DLR) (Berlin, Germany), [5]LESIA, Observatory of Paris, PSL University, CNRS, Sorbonne University, University of Paris (Meudon, France).

Introduction: Before ESA's Giotto mission to comet 1P/Halley, the thermophysical models of cometary nuclei assumed that pure water ice was exposed on the nucleus surface [1]. The water-vapor loss rates computed according to the early measurements of nuclei's cross sections often resulted much larger than the observed ones, so that the concept of active area fraction was introduced, e.g. close to 8% in case of 67P/Churyumov-Gerasimenko (hereafter 67P) [2]. After the Giotto mission, which found a nucleus much darker than expected, most of the subsequent thermophysical models of cometary nuclei were based on the assumption of a desiccated crust, mantling an interior richer in water ice. Thus, all thermophysical models depend on one or two free parameters, namely the thickness of the crust and the nucleus' active area fraction [3]. These models, however, proved to be inconsistent with the observed ejection of sub-cm dust [4], and could not reproduce the steep dependence of the 67P water loss rate versus heliocentric distance [5], requiring the ad hoc assumption that some of the free parameters varied in time [6].

Here we show that the water-driven activity model for a nucleus made of cm-sized pebbles described in [7] and that proved consistent with the observed dust ejection, also fits the observed time evolution of the 67P water loss rate within the uncertainty of the measurements assuming no free parameters. The entire sunlit surface of the 67P nucleus is here assumed to eject water, provided it experiences T>205K, as required by the model to be water-active. The model slightly overestimates the water loss rate when the expected CO_2-driven erosion [8] and fallout self-cleaning [9] mechanisms do not involve the whole nucleus surface.

Methods: We compute the illumination geometry over 67P/Churyumov-Gerasimenko surface at different orbital phases by taking advantage of the illumination maps provided by [10] over 10^5 facets. This allows us to determine the instantaneous Solar flux received by each surface element, and, by means of the activity model of [7], to compute the average temperature of each sunlit pebbles (Fig. 1), and the corresponding emitted water-vapor flux (Fig. 2). According to [7], only surface elements with temperature T>205 K can be water-active, thus being the ones that can contribute to the total water-vapor loss rate.

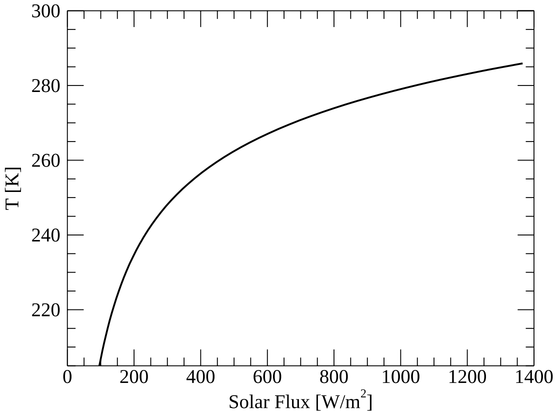

Figure 1. Average temperature of the sunlit pebbles as a function of the incident Solar flux at the nucleus surface as provided by [7]. Temperatures lower than 205 K make a comet water-inactive, so they are not shown here.

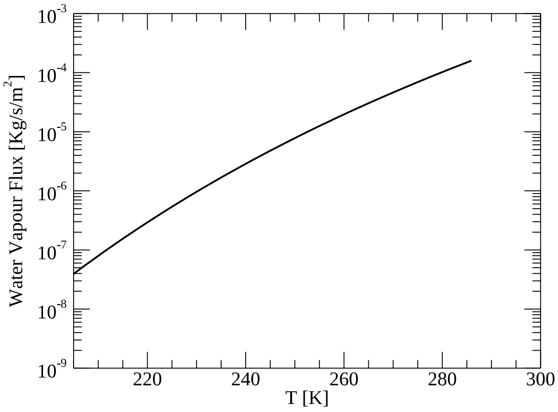

Figure 2. Water vapor flux as a function of the average temperature of the pebbles as provided by [7]. T < 205 K makes a comet water-inactive.

Results: The total water loss rate for comet 67P derived with the approach described in **Methods** is shown in Fig. 3, as a function of the heliocentric distance, and compared to the water loss rate estimated from the observations performed by the Double Focusing Mass Spectrometer (DFMS) and the COmet Pressure Sensor (COPS) of the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) [5,11]. Simulations have been performed from 2.15 au inbound to perihelion (1.24 au) and up to 3.74 au outbound.

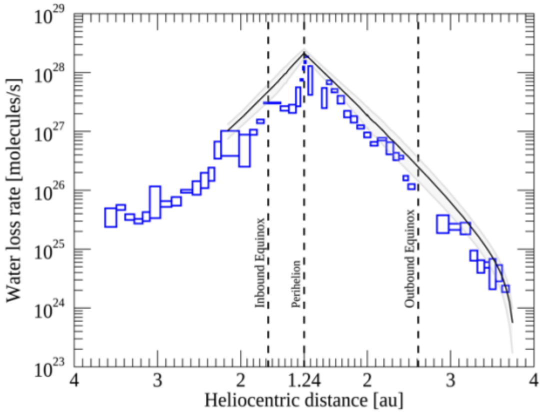

Figure 3. Computed water vapor loss rate (solid line) compared with the estimates by the DFMS/COPS observations (blue boxes). All the nucleus surface at T>205K is assumed to eject water. The gray band encompasses the maximum and minimum simulated water loss rate over one comet rotation, while the average value is represented by the black line. The blue boxes account for the uncertainties of the observed loss rate.

The simulated water loss rate is in fairly good agreement with the results from [5] within error bars although the model assumes no free parameters. Our results slightly overestimate the observed flux up to a factor 2 close to perihelion. Such overestimates are consistent, before the outbound equinox, with CO_2-driven erosion (exposing sub-surface water ice potentially contributing to the water loss rate) occurring only over part of the illuminated nucleus [7,12,13]. Further outbound, they are consistent with post-perihelion fallout [9], which increases the amount of self-cleaning as the heliocentric distance increases, [7, 12, 13], giving the best fit beyond 3.5 au.

Future work: We plan to extend our present computation at heliocentric distances > 2.15 au inbound. This would require to account for self-heating in the concave "neck" of 67P (being progressively more illuminated at larger inbound heliocentric distances), a feature that is not yet included in our approach, which considers only the energetic contribution by direct illumination in the determination of the surface temperature. Nonetheless, at ~3.3-3.6 au inbound, VIRTIS (Visual Infrared Thermal Imaging Spectrometer) [14] observations have constrained 67P surface temperatures [15], which we plan to use as input to determine the expected water vapor flux in the corresponding orbital phase.

Acknowledgments: This work made use of the illumination maps of [10], available through the Virtual European Solar and Planetary Access (VESPA) (http://vespa.obspm.fr/) with the support of CDPP (http://www.cdpp.eu).

References: [1] Delsemme A. H. (1982). In *Comets*, University of Arizona Press, 85-130. [2] Lis D. C. et al. (2019). *A&A*, *625*, id.L5. [3] Hu X. et al. (2017) *MNRAS*, *469 (Suppl. 2)*, S295-S311. [4] Skorov Y. and Blum J. (2012). *Icarus*, *221*, *Issue 1*, 1-11. [5] Lauter M. et al. (2020). *MNRAS*, *498 (3)*, 3995-4004. [6] Skorov Y. et al. (2020) *MNRAS*, *494 (3)*, 3310-3316. [7] Fulle M. et al. (2020) *MNRAS*, *493 (3)*, 4039-4044. [8] Gundlach B. (2020), *MNRAS 493 (3)*, 3690-3715. [9] Pajola M. et al. (2017) *MNRAS*, *469*, *(Suppl_2)*, 636-645. [10] Beth A. et al. (2017). *EPSC 2017*, id. EPSC2017-634. [11] Balsiger H. et al. (2007). *Space Sci. Rev.*, *128 (1-4)*, 745-801. [12] Fulle et al., (2021). *In preparation.* [13] Ciarniello M. et al. (2021). *Nature, submitted.* [14] Coradini, A. et al. (2007). *Space Sci. Rev.*, *128 (1-4)*, 529-559. [15] Tosi F. et al. (2019). *Nat Astron 3 (7)*, 649-658.

.