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Dielectric properties of comet 67P/CG and implications for the 2021 radar observations of its next closest approach

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Abstract

In November 2021, comet 67P/Churyumov-Gerasimenko (67P/CG) will make its next closest approach to Earth at a distance of 0.418 AU, presenting an opportunity for radar detection by the Arecibo Observatory. We report on the most up-to-date 3D dielectric model of the comet surface and interior as constrained by Rosetta mission observations primarily by the CONSERT 90-MHz radar investigation and OSIRIS optical imager. Our results suggest that any observed changes in the comet's radar backscatter reflectivity will be the result of changes in the nucleus' structure, such as surface smoothening associated with increased coverage by fine-grained material, or potential nucleus breakup.

1. Introduction

Due to comets' infrequent passes by Earth—in addition to having characteristically small diameters and low radar albedo—only a few tens of comets have been observed by Earth-based radar to date [1]. Less than half of these cometary nuclei have both (1) independent constraints on their shape and size (e.g., from lightcurve analysis); as well as (2) a detectable radar backscatter echo, which together permit reliable interpretation of the comet's physical properties [2].

Physical properties nominally inferred from radar backscatter measurements include the shape, size and spin of the comet nucleus (e.g., [3]). In addition, the power and polarization of the radar return constrain the characteristics of (1) the surface roughness at the scale of the radar wavelength (cm to m), and (2) the complex relative permittivity or dielectric constant ε_r of the material that comprises the upper meters of the shallow subsurface (e.g., [3,4])—where ε_r depends primarily on the mineralogy, bulk density, volatile content and temperature of the material at a given radar frequency (e.g., [5,6]).

Herein, we present the updated 3D dielectric model of comet 67P/CG after the Rosetta rendezvous, and assess the radar detectability of the nucleus using Earth-based radar during its next closest approach in 2021.

2. Post-rendezvous 3D dielectric model of comet 67P/CG

Table 1 lists the post-rendezvous geophysical and dielectric constraints on comet 67P/CG established by Rosetta and Arecibo observations of the nucleus, which we use to construct our updated 3D dielectric model. We define the nucleus in terms of three primary layers: (1) ~1-2 m thick fine-grained dust-ice deposits that cover about 30% of the surface—where 'fine-grained' refers to blocks ≤1 m in size—(2) ~1-5 m thick consolidated dust-ice material that is exposed over about 70% of the surface, and (3) the dust-ice bulk interior of the nucleus—considering the hypothesis of a structurally and dielectrically homogeneous interior [7,8]. We calculate the parametric range of possible $\varepsilon_r'_{eff}$ for each surface terrain type using the Maxwell-Garnett dielectric mixing law and using Hérique et al.'s [6] constraints on the density and dielectric properties of the constituent cometary dust and cometary ice materials.

Table 1: Geophysical and dielectric constraints for three primary layers of the comet 67P/CG nucleus.

Layer	Porosity	Dust-ice mass ratio [13]	ε_r'
Fine-grained deposits [9]	~85% [10]	> (4 ± 2)	≤ 1.9-2.1*
Consolidated material [9]	< 50% [11]; 30-65% [12]	(4 ± 2)	≤ 1.9-2.1*; >2.45 ± 0.20**
Dust-ice interior	75-85% [8]	(4 ± 2)	1.27 ± 0.05***

*at 2.4 GHz, averaged over the surface [14]; **at 10 Hz-10 kHz at the final Philae landing site [11]; ***at 90 MHz in the comet head interior [8]

Our resulting 3D dielectric model is shown in Fig. 1. We find that $\varepsilon_r'{}_{deposits} \lesssim \varepsilon_r'{}_{interior}$ and $\varepsilon_r'{}_{consolidated} > \varepsilon_r'{}_{deposits}$, where $\varepsilon_r'{}_{deposits} \approx$ 1.2-1.3 and $\varepsilon_r'{}_{consolidated} \approx$ 1.9-2.7 (where higher ε_r' correspond to the upper limit of possible ε_r' values for the pure cometary dust component used in the mixing law formula [6]). Unlike asteroids, which have thick, well-gardened desiccated regoliths with homogeneous dielectric properties [15], our results suggest that comet 67P/CG has an actively reworked surface with a subsequently dielectrically heterogeneous surface due to the uneven distribution of regolith material.

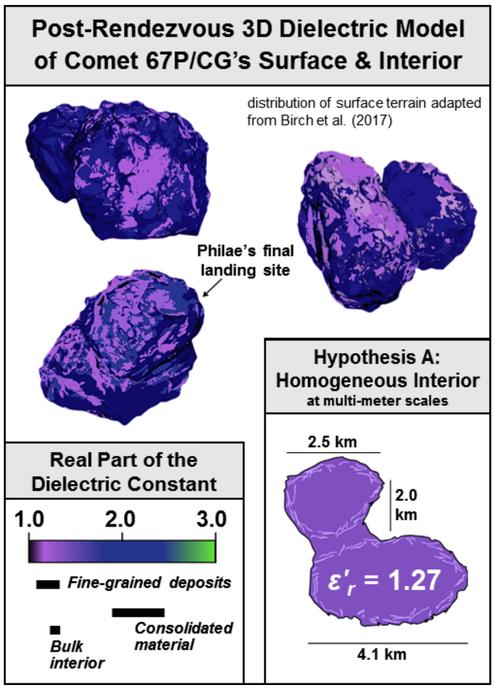

Figure 1: Three-dimensional dielectric model of comet 67P/CG's surface and interior at different perspectives. ~30% of the surface has $\varepsilon_r' \leq 1.3$ due to thick deposits of loose fine-grained dust and ice, while 70% has a higher $\varepsilon_r' \leq$ 1.9-2.7 where consolidated material is exposed.

3. Implications for future Earth-based radar observations of comet 67P/CG

The only Earth-based radar observations of comet 67P/CG were conducted by the Arecibo Observatory in 1982 [14]. While the nucleus' radar echo was not detected, Kamoun et al. [14] recently reanalyzed the 1982 data after 67P/CG's diameter was constrained using optical data (pre-Rosetta). This enabled the estimation of an upper limit on 67P/CG's surface radar cross section (by approximating 67P/CG as a sphere with a simple cosine angular scattering law) such that σ_{max} = 0.7 km^2 and $\varepsilon_r'{}_{surface} \approx$ 1.9-2.1 [14].

Our post-rendezvous dielectric model, however, suggests that ~70% of the surface has a dielectric constant of $\varepsilon_r' \approx$ 1.9-2.7, which at its upper limit corresponds to $\sigma_{max} \approx$ 1.17 km^2 (using the same scattering-law assumptions as Kamoun et al. [14]). Moreover, the Arecibo antenna was upgraded in 1997, including a gain increase of ~5 dB, and a decrease in system temperature by ~20 K (e.g., [16]). Using the latest Arecibo Observatory's antenna parameters for S-band radar observations [17], we calculate that during comet 67P/CG's next closest approach at ~0.418 AU throughout the month of November 2021, the comet will be detectable by Arecibo S-band with an SNR_{max} of ~7.6 dB above noise level.

Future work will incorporate the latest 67P/CG nucleus shape model derived from Rosetta observations to accurately simulate S-band radar scattering from the comet's surface.

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