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Rosetta Studies of Comet 67P/Churyumov – Gerasimenko: Prospects for Establishing Cometary Biology

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Abstract

We discuss a wide range of data emerging from the Rosetta Mission that all point indirectly to biological activity in Comet 67P/Churyumov–Gerasimenko. The existence of cracks and fissures on a smooth surface terrain apparently resealed, as well as early outgassing activity are consistent with the existence of subsurface lakes in which biological activity builds up high pressures of volatile gases that sporadically ruptures a frozen icy crust. While microorganisms probably require liquid water bodies for their early colonising of a comet, they can inhabit cracks in ice and sub-crustal snow, especially if they contain antifreeze salts and biopolymers. Some organisms metabolise at temperatures as low as 230 K, explaining the coma of Comet 97P out at 3.9AU and our prediction is that they would become increasingly active in the near-surface layers as the comet approaches its 1.3 AU perihelion. The detection of an overwhelming abundance of complex organic molecules at the surface by Philae and through IR imaging by the Rosetta orbiter is most significant.

Keywords: Comets; Rosetta mission; Comet 67P; comet Churyumov–Gerasimenko; Panspermia

Introduction

"*The return of Halley's Comet; first landing by humans*. The sensational discovery of both dormant and active life-forms vindicates Hoyle and Wickramasinghe's century old hypothesis that life is omnipresent throughout space……". From Greetings, Carbon-based Bipeds! (Arthur C. Clarke) [1].

The Rosetta mission and doubtless one or more follow-up comet missions in the foreseeable future make Arthur C. Clarke's 2061 date overly pessimistic [2,3]. In the absence of a life detection experiment on Philae, similar to the 1976 Mars Viking Labelled Release Experiment [4], we can only hope for indirect pointers to the presence of microbial life on Comet 67P/C-G. In this communication we show that indications of biological activity are already available from early results of the Rosetta mission. The formation of a dust and gas coma and tail was already seen in late July 2014 when the comet was at a heliocentric distance of 3.9AU. This is clearly visible in Figure 1.

Similar to other cometary nuclei, Comet 67P/C-G has low albedo of 0.06, characteristic of its largely carbonaceous surface and regolith [5]. It has large smooth areas like 'seas' surrounded by elevated rugged terrain (Figure 2). We refer to this major smooth feature as the Cheops Sea, because the largest of the cluster of boulders (~45 m) in the upper part has been named Cheops. The 10-20 metre-wide fissure in its middle indicates a fractured coherent sheet, probably re-sealed by condensed H_2O and other volatiles emerging from layers below. Evident at the upper right corner of the sea are several impact craters with flat central regions, as from re-frozen impact melts (Figure 3). The Cheops Sea and another smooth area resemble local seas on Mars, which are thought to be the result of water flooding from below the surface, and developing an insulating regolith over ice as the near surface layer sublimates. In comets, the regolith would be sublimation lag supplemented by dust and condensed percolating gases, giving a high carbonaceous composition [6].

We conceive of transient subsurface lakes arising from bolide impacts dissipating energy at depth, typically ~10-20 m in the 40 m craters near the Cheops Sea [7]. Chemoautotrophic microorganisms released from the ice into such 'lakes' laden with high-grade organics could undergo enough doublings to exhaust available nutrients within the observed eruption times of a couple of days. (Heat loss from the surface would lead to full re-freezing, but only over a longer timescale of ~1 yr.) An initial melt of 10^4 t (10 m deep, 20 m radius) would be extended by the heat released through biochemical transformations. An average heat release of ~0.1-0.3 eV per atom implies an increase of the

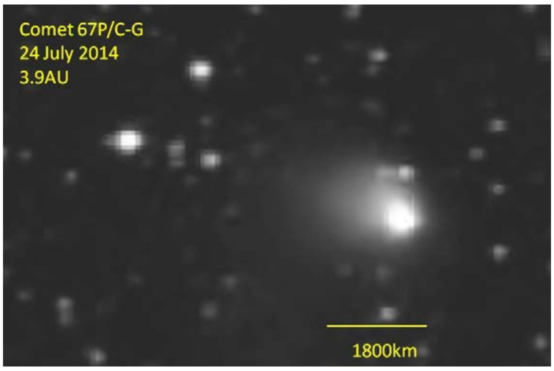

Figure 1: July 24, 2014, Image of Comet 67P/C-G at 3.9AU showing dust/gas coma and tail (Courtesy, OSIRIS/ESA).

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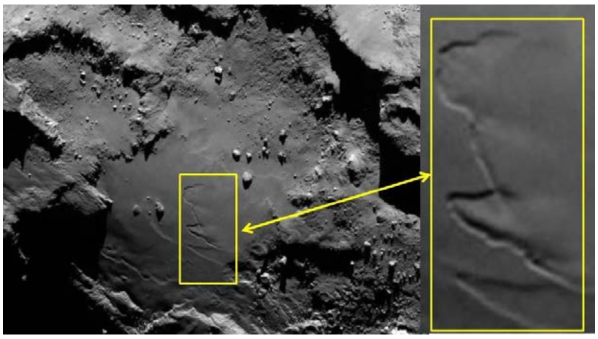

Figure 2: Rosetta imaging of Comet 67P/C-G. **Left:** The 600 x 800 m Cheops 'sea'. The image shows it curving away into shadow approaching the terminator at bottom left. The plateau at the top right corner (semi-circular) is a few 100 m higher than the sea and appears to have shed debris at the cliff-foot. **Right:** Enlargement of the major fissure, ~10 m deep and 10-20 m wide. (ESA/Rosetta/MPS for OSIRIS Team).

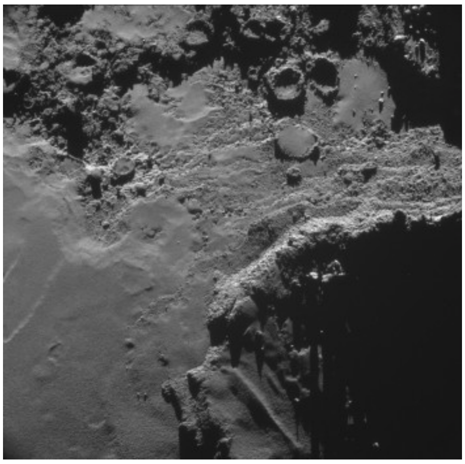

Figure 3: Flat-bottomed impact craters, showing impact-melt interiors that could be re-frozen lakes ~40 m across. The left of the image shows the corner of the Cheops sea to the upper right of the Cheops boulder cluster.

melt volume by a factor ~10 to 30. Methane and carbon dioxide can be produced by bacteria from a variety of nutrients and such gases could build up and eventually vent through fissures in the overlying ices and crust. Whereas abiotic chemical reactions leading to gas production are in general self-limiting, being impeded by pressure increase in the surrounding medium, microbial biochemistry, that takes place within the confines of exceedingly strong cell walls, is evidently unaffected by pressure to a large extent. Several examples could be cited of bacteria functioning in media subject to very high hydrostatic pressure: barotolerant or barophilic bacteria function normally at depths of 5.5 km in the sea corresponding to a pressure of 600 atmospheres (Parkes et al.). Bacteria recovered from drills of the Siljan crater at depths of 6.7 km evidently thrive in sludge subject to even higher pressures [8,9]. Such pressures of ~10^3 atmospheres are interestingly close to the limits set by the tensile strength of water-ice. Thus fractures and fissures in the cometary crust could easily develop, their formation being assisted by the more frequent impact of smaller meteorites which both dig over the surface and serve as a source of nutrients.

Cometary Activity at Large Distance

Activity of comets at perihelion distances much greater than 3AU has stretched the limits of credulity for dirty snowball models of comets. A pre-perihelion dust outburst from Comet Halley was observed in 1983/84 at a heliocentric distance of 6.2 AU [10]. Likewise, observations of CO around comet Hale-Bopp at ~6.5 AU, together with its extensive dust coma at this distance [11-13], presented further difficulties of interpretation within the constraints of conventional cometary paradigms. The data for Comet Hale-Bopp at 6.5 AU implies a CO production rate of 2 × 10^{28} molecules s^{-1} (~1 t s^{-1}) and some 15 times this rate of emission in the form of micron and sub-micron-sized dust particles along a collimated jet. The emissions from Hale-Bopp were recorded as several distinct bursts on 19 August, 24 September and 12 October 1995, with each event lasting for about 2 days [12].

Like comets Halley and Hale-Bopp, Comet 67P/C-G also displayed unexpected activity and dust emission during its last orbit in November 2007 pre-perihelion when it was at a heliocentric distance of 4.3AU [14]. By comparing the pre-perihelion and post-perihelion behaviours at 2.99-2.22AU [15], inferred that this comet was covered with a 12 cm thick dust layer that quenched its pre-perihelion and near-perihelion activity. During the current perihelion approach the first detection of water emission from Comet 67P/C-G was made by Rosetta instruments in July 2014, which showed low activity and outgassing at 3.9AU (Figure 1). The comet was releasing the equivalent mass of 0.3 kg/s H_2O in July which increased to 1.2 kg/s in late August [16]. This low gassing rate suggests multiple small vents or sublimation through thin-crust material overlying water ice [15].

Eruptive activity

The idea of a sporadically exploding organic/biogenic comet was developed by Hoyle and Wickramasinghe, in proposing the theory of cometary panspermia (Hoyle and Wickramasinghe, 1983). It has been argued that for sufficiently large comets a substantial fraction of the comet's interior volume would have spent several Myr in a liquid state due to radioactive heating during its early history [17,18]. If microorganisms (chemotrophs and methanogens) pre-dated the formation of solar system comets, they would undergo extensive replication and effectively colonise the interior of the comet before it freezes through. This inner part becomes exposed aeons later, as the outer comet layers strip off on sojourns within Jupiter's orbit and more so around perhelia closer than 1AU from the sun.

Extremophiles and Comets

Recent microbiological studies have highlighted an almost uncanny range of space-survivability for extremophiles [19,20]. Very recently Russian scientists have reported the survival of microorganisms mounted on the surface of a Spacecraft (Foton-M) launched with a Soyuz rocket in July 2014 and collected after re-entry through the Earth's atmosphere 6 weeks later (http://en.itar-tass.com/non-political/760517).

During the past decade, new data have shown that microbial extremophiles can live in permafrost, glaciers, and ice sheets. Diatoms and many bacteria have ice-active substances and antifreeze proteins that enable them to thrive in polar environments, Cyanobacteria and many other gram-positive bacteria have lipoteichoic acid in their cell walls that induces localized melting of the water-ice if the temperature exceeds 230 K [21]. These discoveries further enhance the possibility that cyanobacteria and a variety of other microbial extremophiles would be able to thrive in the cometary habitats we have discussed [18,22].

Whilst the known list of culturable microbial species on the Earth

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is limited, an indefinitely large number (millions) of 'dormant' or uncultured species have been identified from studies of bacterial DNA in a variety of terrestrial environments including Antarctic snows and dry valleys. Junge et al. [23,24] have shown that bacterial activity in arctic sea-ice and under laboratory condition the take-up of radioactive leucine by microorganisms continuing below 20°C. Excess methane measured in ice cores shows further that methanogenic organisms are active well below 270 K [25].

Figure 4 shows microbial activity following the Arhhenius formula for the rate of metabolism, R(T) ~exp (- A/T), suggesting that archaea are active in low temperature ice at T as low as -40°C (Tung et al. [25]). Water is available for cell processes, because of dissolved salts and biopolymers and also because a few monolayers of H_2O remain mobile in cracks in impure ice at such low T. Such a process was discussed by Wallis at al. [18] in the context of microbial life retaining viability in the polar regions of Mars.

At the present time the full range of conditions within which microbiology operates remains an open question, but identified limits of life are continually receding. Modern developments, combined with the lack of any known mechanism for explaining the early beginnings of terrestrial life some 3.83 b yr ago, give a new impetus to panspermia from within the science of microbiology itself [26,27].

Activity of Comet 67P/C-G at Rosetta Encounter

When first imaged at a distance of 3.7 AU from the sun, the surface temperature of Comet 67P/C-G averaged 205 K (VIRTIS IR imaging), then had peaks of 230 K at 3.5AU [4]. The surface temperature of Comet Hale-Bopp when it was at 6.5 AU would on normal scaling have been ~155 K. In neither case can the presence of liquid water at the surface be justified.

As Comet 67P/C-G reached closer to the Sun (3.3AU) in Sept. 2014 emissions of gas and dust as were imaged in Figure 5, emerging from a wide area of the "neck" between the two cometary lobes, where smooth but furrowed icy areas are seen (Wallis and Wickramasinghe, 2015). The furrows in the crust would probably penetrate into the underlying ice, being generated by strains due to flexing of the two lobes. The furrows and cracks provide, we suggest, a congenial habitat for micro-organisms when warmed by the sun.

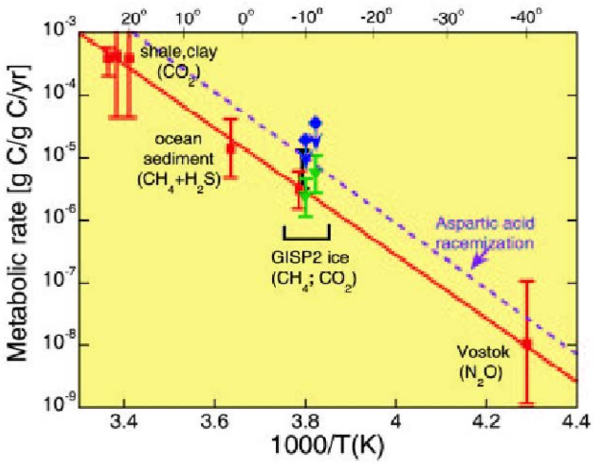

Figure 4: Metabolic rates from bacteria from Tung et al. [25] using data on trapped CH_4 and CO_2 in ice core samples. Spontaneous racemisation of aspartic acid appears to follow the same exponential law.

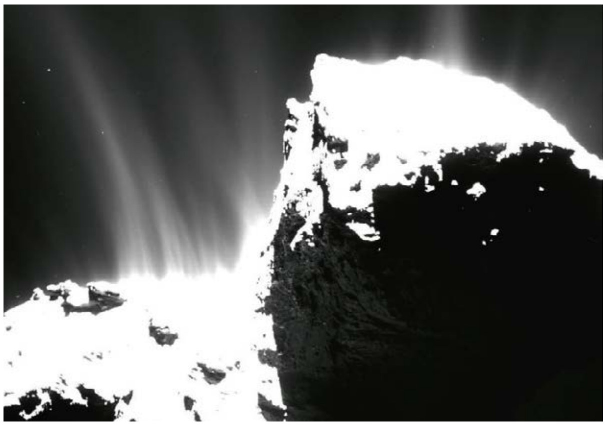

Figure 5: September, 10, 2014 imaging shows jets of cometary activity along the whole neck of the comet. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/ INTA/UPM/DASP/IDA.

The outbursts of comet Hale-Bopp and likewise of comet 67P/C-G could not result from the volatilisation of the comet's surface, but from gas pressure built up in subsurface (presumed liquid) domains. The contents of a pressurised 10^6-10^7 tonne lake flooding out with say 10% going as gases and entrained particles into the coma, could explain the outbursts of CO and dust observed in comet Hale-Bopp [28]. Although CO_2 or CH_4 may well be constituents of the driver gas at the base of ruptured vents, most of this material would recondense on grains close to the surface while liquid water would form an ice crust due to sublimation cooling. The CO production would most naturally be explained as a photo dissociation product of volatile and fragile bio chemicals that contain weakly bonded CO groups which re-evaporate from superheated (smaller) grains).

The process suggested here is analogous to repeating 'strombolian' volcanic eruptions, caused when viscous lava plugs the vent after each short-lived outburst. In a comet, any surface liquid re-freezes and gases re-condense to plug the vent, rebuilding tensile strength and providing for a repetition of the outbursts - seen in comet Hale-Bopp and now in Comet 67P/CG. Each outburst cools the source fluid along with releasing gas pressure. The repetitions are driven by input of metabolic heat dissolving new material, with each outburst effective in mixing in fresh nutrients.

In a recent review of early Rosetta data, Thomas et al. [29] conclude:

"The buildup of supervolatile (eg CO and/or CO_2) subsurface gas pockets to pressures exceeding overburden and cohesive strength appears to be a plausible mechanism that would also explain evidence of flows."

Biological activity would provide organic gases, readily distinguishable from supervolatile CO and readily frozen CO_2.

Rosetta and Organic Materials

Spectroscopy carried out by the VIRTIS instrument on board the Rosetta spacecraft has revealed a surface overwhelmingly dominated by carbon bearing macromolecules exhibiting a broad integrated CH structure [5]. This spectral feature is said to be "compatible with opaque minerals associated with non-volatile organic macromolecular molecules" for which hypothesis some laboratory experiments are cited. The reflectance spectrum obtained by Capaccioni et al. is shown in Figure 6.

Figure 7 shows the transmittance spectra of bacteria and diatoms in a sample of local river water obtained by S. Al-Mufti [5]. The similarity between the spectra in Figures 6 and 7 (red boxes) cannot go unnoticed. The bio-interpretation of the VIRTIS data in Figure 6 suggests that microorganisms (bacterial, algal and fungal) and their decay products could coat much of the comet's surface, being left behind in eroding crust or from solids loosened and wafted out by weak outgassing. Such regolith would suffer micrometeorite impacts and soar irradiation over the lengthy orbits between perihelia. The characterisation of the organic molecules at the surface by Philae would be important for resolving the alternative interpretations.

The COSIMA instrument on Rosetta has collected and imaged smoke-like particles (~500 microns diameter composed of ~10 micron grains) released from the coma. Stratospheric collections of dust have already given us similar if smaller examples carbon rich particle clumps (Harris)[7]. The results of Schulz et al. [30] are intriguing. Figure 8 (left panels) show images of a particle collected in late October 2014 at a distance of 10-20 km from the surface of the comet. It was found that this is an example of an exceedingly porous aggregate that disintegrated on striking the target plate at speeds of 1-10 m/s. The aggregates have high porosity and very low tensile strength. Schulz et al. see them as "organic grains that are not mantled by water-ice", but rich in sodium like the dehydrated salt components found earlier. We interpret them as condensates of largely organic material on small dust cores and coagulating in a low-gassing environment. With increased gassing, fragments of crust built up tover a 4-year orbital period are now being shed.

Similarity to some of the "biomorphs" collected by Wainwright et al. in the stratosphere, although the resolution of 14 microns per pixel does not give scope for proving this. It would be of particular interest to know if these dust particles are made up of carbon and oxygen and therefore have a biological connotation.

In this connection perhaps the most interesting results in the Rosetta mission may emerge from the 3-D imaging of dust in the nm-μm size range from the MIDAS instrument aboard Rosetta. The first MIDAS results are already referred to in an ESA blog [31]; http://blogs.esa.int/rosetta/2014/12/17/midas-and-its-first-dust-grain/). A ten-micron particle from the comet scanned with an atomic force microscope is found to be a complex irregular aggregate of much smaller particles, perhaps as small as tens of nanometres in size. The image is reproduced in the background of Figure 9.

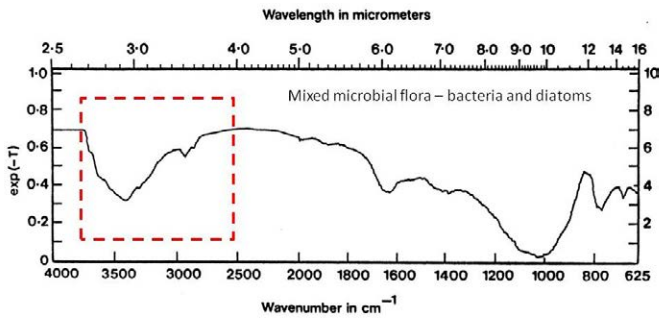

Figure 7: Transmittance curve for a mixed microbial flora (bacteria and diatoms) from a sample of water from the River Taff, Cardiff. (Experiments conducted by Al-Mufti [5]).

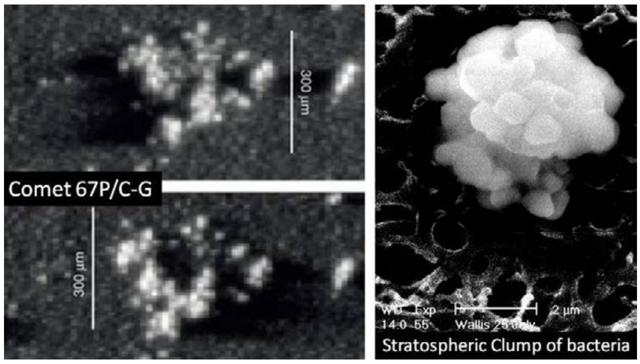

Figure 8: Coarse (14 micron resolution) image of disintegrating cometary dust clump (L) compared with a clump of stratospheric particles, (Wallis et al. [7]) recovered from a height of 41 km.

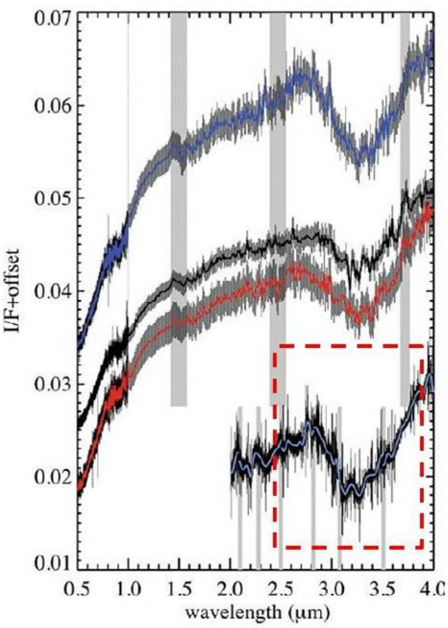

Figure 6: Reflectance spectra of 3 regions of the surface. The boxed curve is to be compared with reflectance/transmittance spectra of candidate materials (Capaccione et al. [5]).

The possibility of significant fluxes of nanometre-sized particles (of viral sizes) emanating from comets is one that merits serious study. Hoyle and Wickramasinghe [28] interpreted the X-ray fluxes obtained from comet C/1996B2 (Hyakutake) on the basis of small angle scattering of solar X-rays by 10-100 nm-sized particles, inferring a mass of a few tenths of a megatonne was present in the comet coma on March 26-28 1996. The interpretation of virus-like organic particles is tempting in view of recent findings that the total biomass of the Earth is overwhelmingly dominated by viruses; the total number of virions in the biosphere is estimated as 10^{31} [27,32]. In this context the analysis to be conducted by MIDAS as Comet 67P/G-G approaches perihelion would be highly interesting for bio-interpretations of the comet.

Concluding Remarks

The evidence of refrozen lakes, low albedo (<0.06), the overwhelming dominance of life-like organic molecules at the surface and the activity of comet 67P/C-G at large perihelion distances give credence to the theory of cometary panspermia first proposed by Fred Hoyle and one

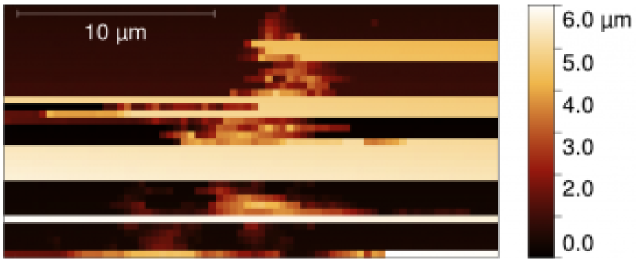

Figure 9: Atomic Force Microscope scan of the first MIDAS particle reported by Bentley [31].

of the present authors over 3 decades ago [33,34]. According to this theory comets carry not only organic molecules that could serve as chemical building blocks of life (an idea that is now widely conceded) but life itself in the form of freeze-dried microorganisms - bacteria and viruses. As Comet 67P/C-G approaches its 1.3AU perihelion in August 2015, Rosetta should be searching for further signs of life - ice-living micro-organisms becoming active as their habitats warm up - in the furrows, cracks in ice (sea or craters) or at the feet of exposed rocks/boulders. It is to be hoped that the cultural resistance to these ideas that currently prevails will eventually yield to the ever increasing weight of evidence.

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