SPACE SCIENCES SERIES OF ISSI

Origin and Early Evolution of Comet Nuclei

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Springer

INTERNATIONAL SPACE SCIENCE INSTITUTE

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Origin and Early Evolution of Comet Nuclei

Workshop honouring Johannes Geiss on the occasion of his 80th birthday

Previously published in *Space Science Reviews* Volume 138, Issues 1–4, 2008

Springer

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Cover illustration: Composite image of the nucleus of comet Halley taken by the Halley Multicolour Camera onboard ESA's Giotto spacecraft during the flyby on 14 March 1986.

Library of Congress Control Number: 2008936039

ISBN-978-0-387-85454-0 e-ISBN-978-0-387-85455-7

Printed on acid-free paper.

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springer.com

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Foreword

Originally published in the journal Space Science Reviews, Volume 138, Nos 1–4.
DOI: 10.1007/s11214-008-9412-6

In 2006 Johannes Geiss celebrated his 80th birthday. His many impressive achievements as a scientist and pioneer of European and Swiss space science have been celebrated at several occasions. The Workshop on "Origin and Early Evolution of Comet Nuclei" was the last of these celebrations and for several reasons an especially appropriate one. Not only did it take place in the city—Bern—where Geiss spent the most part of his scientific life but also at the institute—ISSI—which was established after his retirement from the University of Bern according to his ideas. And finally cometary science possibly is the field that most clearly brings together all the disciplines in which Johannes Geiss has been active during his long and successful career. His contributions in geosciences, meteoritics, cosmology, origin of the solar system and the evolution of the Sun and the planets would all find new experimental nourishment if the origin and evolution of the most primitive bodies in the solar system—the comets—would be better known. Geiss was so convinced that comets were an important clue in his puzzle that he fought hard for the European Giotto mission when it was threatened to be abandoned for lack of interest by NASA and the US scientists. And he was one of the fathers of the HORIZON 2000 plan of ESA, which included the Comet Sample Return Cornerstone, a mission that was finally implemented in reduced form as Comet Rendezvous Mission Rosetta (now on its way to Comet Churyumov-Gerasimenko).

The closing session of the workshop was held as open lectures at Johannes Geiss' former home institution—the Physikalisches Institut—and was well attended by students, former collaborators, faculty and a broader public.

This reflected the fact that in Bern Johannes Geiss as a teacher and scientist has not only been one of the most well known personalities but also one of the most popular. He has built today's Department for Space Research and Planetology out of a small Group for Mass Spectrometry and developed it into the centre for experimental space physics in Switzerland. Due to many successful novel instrument designs coming out of Bern, Swiss space research achieved a leading role within the European Space Agency. A star without star manners Johannes Geiss achieved this by being an exceptionally good team player. He knew that you could request almost anything from your collaborators as long as you are an example in dedication. And dedicated to science he was and still is.

DOI: 10.1007/978-0-387-85455-7_1

With this same dedication he even led his football team of physicists to become runner-up at the University's yearly championship.

All the Workshop participants, his former collaborators at the University and at ISSI and many of his friends present wished Johannes all the best for a happy and productive future and joined in a very warm applause.

October 2006
Hans Balsiger
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9. Stephan Graf
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Introductions

Origins of Cometary Materials

W.F. Huebner

Originally published in the journal Space Science Reviews, Volume 138, Nos 1–4.
DOI: 10.1007/s11214-007-9299-7

Abstract In this introductory presentation, material is categorized according to our state of knowledge: What do we know, what do we *think* we know but don't know certainly, and what do we not know but often describe it as if it were a well-established fact about comets, their nuclei, their composition, and processes within comets and their nuclei. The material is presented not with the intend to criticize laboratory work simulating condition in comet nuclei, or observers analyzing their observations, nor modelers using data from both these sources to improve our understanding and make predictions. The intent is to provoke discussion and dialog between these groups to avoid overstating the results.

What is a Comet? A comet is a diffuse appearing celestial phenomenon moving in an orbit about the Sun. The central body, the nucleus, is composed of ice and dust. It is the source of all cometary activity, including comae and tails. We distinguish between molecular (including atoms and ions) and dust comae. At heliocentric distances of about 1 AU and less, the hydrogen coma typically has dimensions larger than the Sun. The tails are composed of dust, neutral atoms and molecules, and plasma.

Keywords Comet nuclei · Atomic and molecular constituent · State of matter · Physico-chemical processes

1 Comets and Solar System Objects Related to Comet Nuclei

We distinguish between various classes and families of comets. Comets with an orbital period $P < 200$ years are defined as short-period (SP) comets. They are composed of the Jupiter family and the Halley family of comets. These two families are defined by the values

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of their Tisserand parameters

$$T_J = a_J/a + 2[(1-e^2)a/a_J]^{1/2}\cos(i),$$

where a is the comet's orbital semi-major axis, e the orbit's eccentricity, i the inclination of the orbit with respect to the ecliptic, and J stands for Jupiter. Jupiter-family comets have $T_J > 2$ and are close to the ecliptic (small values of i). Halley-family comets have $T_J < 2$, and their orbital plane is typically out of the ecliptic. SP comets appear to have their origin in the trans-Neptunian region at heliocentric distances of about 10 to 50 AU (see Fernandez, this conference). Closely related to the Halley-family of comets are the Damocloids; they have comet-like orbits with $T_J < 2$, but do not show a coma.

Comets with an orbital period $P > 200$ years are defined as long-period (LP) comets. Their orbital planes and aphelia have random distributions. They appear to come from the Oort cloud, a spherical shell of comet nuclei at heliocentric distances of several times 10^4 AU (see Duncan, this conference). The Oort cloud of comet nuclei is bound to the Sun by gravity and thus forms the outer region of the solar system, just inside the boundary between the solar system and the rest of the galaxy. Since the Oort cloud is well outside of the heliopause, which modulates the cosmic ray flux, nuclei of LP comets may have been exposed over billions of years to more energetic galactic radiation than SP comet nuclei. Thus, we might expect some subtle differences between SP and 'dynamically young' LP comet nuclei, at least in their surface layers.

Closely related to comet nuclei are the trans-Neptunian objects at heliocentric distances of 30 to 50 AU. They consist of the classical Kuiper belt objects that lie in the ecliptic plane and the scattered disk objects that can be found out of the ecliptic plane. As already mentioned, Oort cloud objects have a spherical distribution with semi-major axes between 50,000–100,000 AU. Centaurs are icy bodies between Jupiter and Neptune.

Solar composition icy planetesimals (SCIPs) are a class of objects that are conjectured to have formed Jupiter (see Owen, this conference). The Galileo probe found a chemical composition for elements heavier than hydrogen that is solar, but the ratio of these elements relative to hydrogen is about three. This composition differs significantly from that of comets, particularly in the abundances of N, Ne, and isotopes.

2 The Importance of Comets

Comet nuclei were thought to be the building blocks for the outer planets. Comet nuclei in the Oort cloud form the boundary layer of the solar system, beyond which the true interstellar space of the galaxy exists. It is worthwhile to note that interstellar molecules may also be found within the solar system, beyond the heliopause. They are intruders that occupy solar system space.

Comet nuclei brought water and pre-biotic molecules into the inner solar system. Originally, most of the terrestrial planets were barren and lacked these substances because volatiles did not readily condense in the hot inner solar nebula. However, it appears that not all water on Earth came from comet impacts in the early life of the inner planets. Some water may have been brought by asteroids and much of the water may have been bound in rocks. The pre-biotic molecules brought by comet nuclei to Earth may be the source material for the origins of life. But just as comets may have contributed to the origins of life, they may also have contributed to mass extinctions. Some comets are near-Earth objects (NEOs). That is, they cross the orbit of the Earth and as potentially hazardous objects (PHOs) may cause catastrophic impacts. Potentially hazardous long-period comets are rare, but they are more dangerous since they enter the inner solar system with higher speeds and are usually more massive than short-period comets. One of the comets that came close to the Earth is C/1983 H1 IRAS-Araki-Alcock. It was detected in April 1983, and approached the Earth within 0.05 AU within two weeks of its discovery. Some NEOs may be 'stealth comets' whose nuclei have the appearance of carbonaceous asteroids.

3 Composition and Place of Origin of Comet Nuclei

Now we turn to the main topic of this conference. Can comets be traced by their composition or other properties to their places of origin, e.g., a planet sub-nebula in the early solar system? First we note that most comet nuclei appear to be chemically heterogeneous within their own structure and composition. These comet nuclei cannot be traced to their place of origin based on their composition and structure (see also DiSanti, this conference). If, on the other hand, some chemically nearly homogeneous comet nuclei can be identified, then, perhaps they can be traced to their places of origin. Each such nucleus may release chemical species peculiar to their place of origin. I will call such comets allopatric comets: They reveal different properties based on their place of origin (their 'fatherland').

4 Comparison of Some Comet Nuclei

To date, several spacecraft have visited and imaged four comets, all short-period comets and three of them Jupiter-family comets. The Soviet spacecraft Vega 1 and Vega 2 and the ESA spacecraft Giotto flew through the coma of Comet 1P/Halley at the subsolar side at distances of 8890 km, 8030 km (Sagdeev 1988) and 596 km (Curdt et al. 1988), respectively. Three spacecraft flew in front of Halley's comet at still larger distances from the nucleus: the Japanese spacecraft Suisei and Sakigake, and the NASA spacecraft ICE. Of all the 1P/Halley investigations, the Halley Multi-Colour Camera (HMC) on Giotto gave the most detailed images (Reinhard 1988). The Deep Space 1 spacecraft imaged 19P/Borrelly in 2001. The nucleus of Comet 81P/Wild 2 was imaged by the Stardust spacecraft in 2004, and the nucleus of Comet 9P/Tempel 1 was imaged by the Deep Impact spacecraft in 2005.

All these images present an opportunity for the most detailed comparison to date. Comet nuclei are considered to be among the most primitive bodies in the solar system. Their surfaces also have aged: They have been exposed to cosmic radiation, solar heat causing erosion from the loss of volatiles (sublimation of ice from discrete active areas), collisions in the Kuiper belt, buildup of a dust mantle, change in porosity, and refreezing of gases flowing inward into a porous nucleus (see also Thomas, this conference). All these changes can alter their strength, and detailed surface features including changes in the moments of inertia and angular momentum that can lead to vibrational distortions, stresses, and loss of structural integrity. In extreme cases, it can even lead to splitting and disintegration of the nucleus.

We note immediately that all four comet nuclei appear to be different. However, they also have some common features such as smooth appearing valleys and slopes. The nuclei of 1P/Halley (Fig. 1) and 19P/Borrelly (Fig. 2) are very elongated. They may be composed of several large sub-nuclei that may have merged to form one body. The nucleus of 1P/Halley shows several crater-like features with effective diameters of several hundred meters. There are mountainous features as well as smooth appearing valleys. The nucleus of 19P/Borrelly

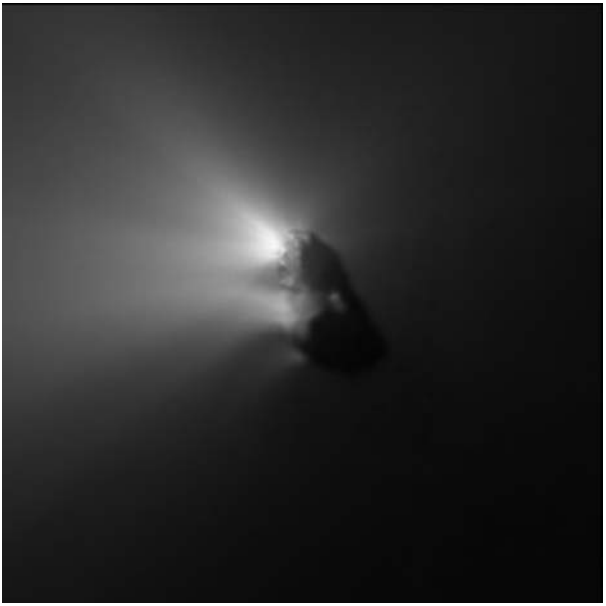

Fig. 1 Nucleus of Comet 1P/Halley. The dimensions of the nucleus are about 15.5 × 8.5 × 8 km. The spatial resolution for two pixels is 100 m at the top of the image of the nucleus. (Courtesy H.U. Keller et al., Giotto, 1986)

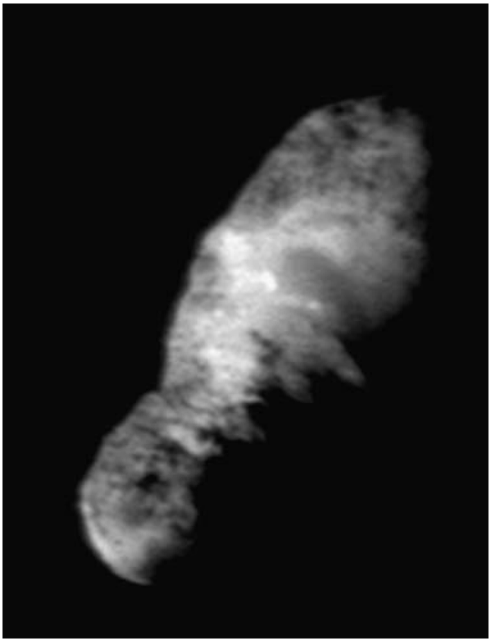

Fig. 2 Nucleus of Comet 19P/Borrelly. The dimensions of the nucleus are about 8 × 4 × 4 km. The spatial resolution for two pixels is 90 m. It is not significantly better than for Comet 1P/Halley, but is for most of the nucleus. (Courtesy L. Soderblom et al., DS1 spacecraft, 2001)

shows high ridges along a jagged terminator as well as several dark patches and a small series of parallel grooves. A smooth, broad basin contains brighter features and mesa-like structures.

The nuclei of 81P/Wild 2, (Fig. 3) and 9P/Tempel 1 (Fig. 4) appear to be more spherical. They may have accreted more uniformly from smaller bodies (sub-nuclei) in the primary

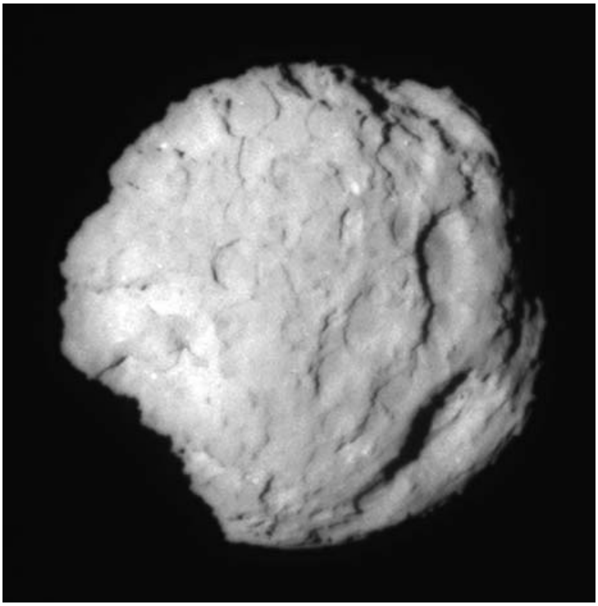

Fig. 3 Nucleus of Comet 81P/Wild 2. The dimensions of the nucleus are $2.75 \times 2.00 \times 1.65$ km. The spatial resolution for two pixels is 20 m. (Courtesy D. Brownlee et al., Stardust spacecraft, 2004)

size-distribution. The nucleus of 81P/Wild 2 is particularly strongly eroded, possibly because of prolonged exposure to the Sun. This must have occurred some time ago, because the nucleus was captured from an orbit with a distant perihelion only a few decades ago.

While valleys and hills are visible in all four images, the nucleus of Comet 9P/Tempel 1 shows a very large smooth area in the top left of Fig. 4. It implies a young surface area. The surface appears to be layered. Belton (2007) and Belton et al. (2007) argue that layering is primordial and an essential element of the internal structure of nuclei of Jupiter family comets produced in the accumulation phase of gently colliding bodies. Because the collisions were gentle, they did not significantly increase the density. The differences in observed topography may be the result of environmental changes during agglomeration phases. This layering, they suggest, is present in the interior of the nucleus. The original surface may have eroded by sublimation. The arguments are based on observations of some surface layers that are bounded by scarps estimated to be 20 m high while some other surfaces show linear outcroppings on slopes. Different layers have diverse topographic features: one is "cratered," bright spots characterize another, while still another shows very rough topography. However, overall the surface of the nucleus is uniform in brightness and color. Some layers appear to have been "exhumed." Smooth layers appear in topographic low areas (see also A'Hearn, this conference). Belton suggests that random layers of materials are superposed on the original material in the core of the nucleus. The core may consist of a gently interpenetrated fractal aggregate as suggested by Donn (1991).

How this model might affect composition is not known. However, if it does affect composition, then the surface layer may be different from the deep interior even before long-term exposure to cosmic radiation or solar heat.

Several circular features, based on their shape, form, and size distribution, appear to be impact craters. However, impact craters have not been identified on other comet nuclei; thus, this interpretation must await further examination.

The question arises whether the observed surface features on the nucleus of 9P/Tempel 1 date to the primordial origin of the nucleus or are the result of evolution. Can a connection

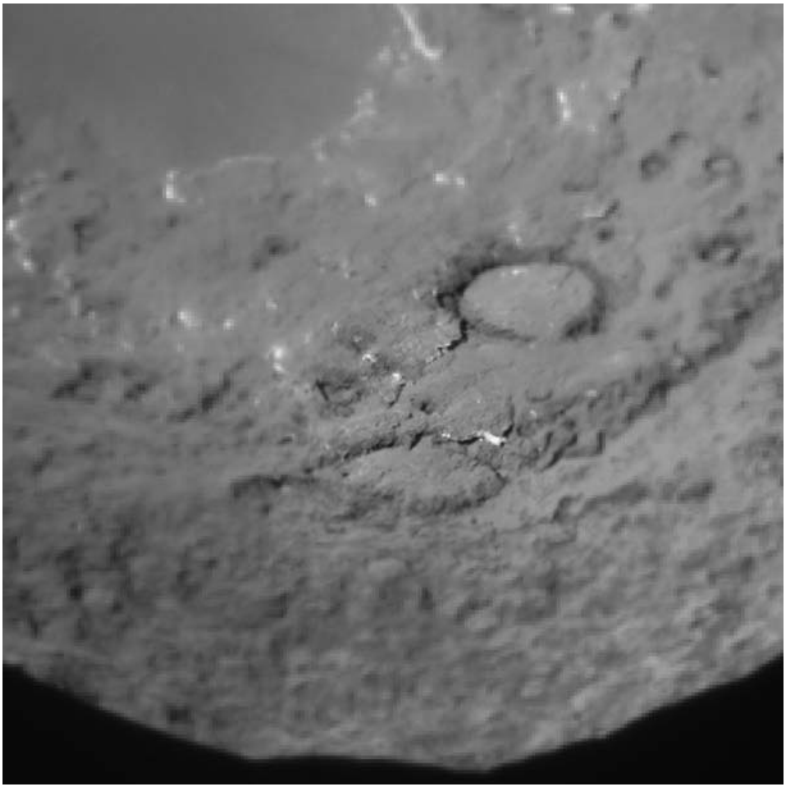

Fig. 4 Nucleus of Comet 9P/Tempel 1. The nucleus is approximately 3.1 × 2.3 km. The third dimension was not determined from spacecraft images. The spatial resolution for two pixels is 2.5 m. (Courtesy M.F. A'Hearn et al., Deep Impact spacecraft, 1995)

be made between these features and the chemical composition? Are the layered structures different in chemical composition and physical strength from each other and from the underlying core?

The layered pile model of Belton et al. (2007) is based in part on laboratory experiments of collisions between dust aggregates by Wurm et al. (2005) in which, for relative impact speeds between 13 and 25 m/s, about half of the projectile mass sticks to the target and the rest is ejected at small angles from the impact site. This "splashing" is the basis of the layered pile model. It deserves close attention and further scrutiny in conjunction with the work of Wurm et al. (2005) and Sirono and Greenberg (2000).

An opposing view is that the layered structure is the result of evolution. In active areas, gas emerges from the nucleus in jet-like features entraining dust particles. The smallest dust particles are most easily entrained; larger dust particles fall back to the surface (as we will show below) or are not entrained and remain on the surface. Volatile ices below the surface sublimate causing a gas flow outward as well as inward. The inward diffusing gas condenses again at cooler regions in the pores. The combination of coarser dust particles and refreezing gas builds a crust that is stronger (less porous) and therefore more resistant to future erosion. These layers may form the observed mesa-like structures observed on the nuclei of Comets 19P/Borrelly and 9P/Tempel 1. Since they are caused by inhomogeneities of more volatile ices in the nucleus, this would also explain the appearance of activity at their edges.

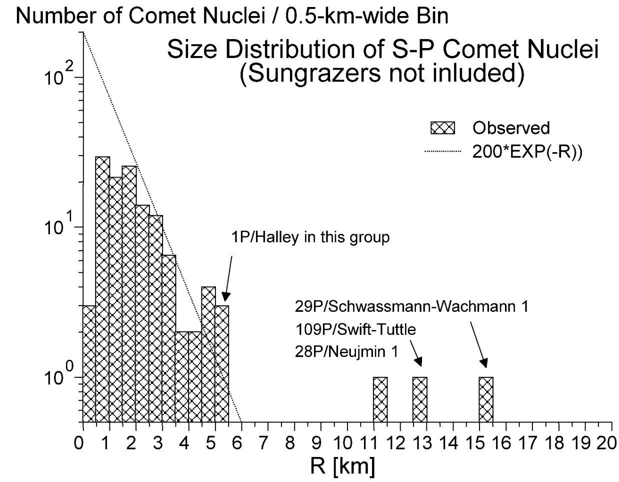

Fig. 5 Distribution of the mean radii of short-period comet nuclei, based primarily on ground-based observations. The *dotted line* is shown only to guide the eye

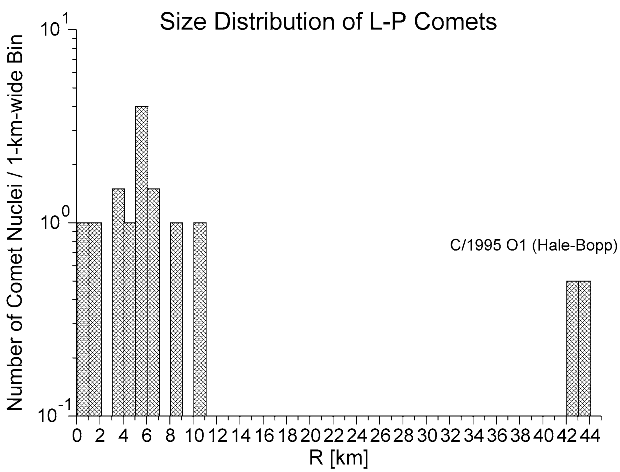

Fig. 6 Distribution of the mean radii of long-period comet nuclei, based primarily on ground-based observations. Comet Hale-Bopp (43 km) is spread over two bins

Thus, layering may be a natural result of preferential sublimation of the more volatile ice components because of thermal and gas diffusion in comet nuclei. Not only are the outer layers on a comet nucleus depleted of the more volatile ices through losses into the coma, in part these gases also diffuse inward and refreeze in pores, making a harder and possibly smoother crust (Huebner et al. 2006; see also Prialnik, this conference). Except for the four comets that were visited by spacecraft, data for the size distributions of comet nuclei are taken from websites at JPL http://neo.jpl.nasa.gov/orbits, Gonzalo Tancredi http://www.fisica.edu.uy/∼gonzalo/catalog/node17.html, and a few other sources. Only a few comets have large nuclei. The dotted line shown in Fig. 5 is shown only to guide the eye, but it might suggest an evolutionary trend. Note also that sungrazing comets are not included. These sungrazing comet nuclei would fill in the graph at the smallest mean radii. It could be argued that such comet nuclei are the result of splitting of a few larger nuclei, but we do not know the history of the other comet nuclei. They too may be fragments of larger nuclei. Note that the gap also exists when mean radii are plotted vs. perihelion distance q in Fig. 7.