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The nuclei of Jupiter family comets: A critical review of our present knowledge

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ABSTRACT

Of the currently over 300 identified Jupiter family comets (JFCs), we have estimated nucleus sizes and shapes for fewer than 70 and have detailed nucleus observations arising from spacecraft fly-bys for just 3: 19P/Borrelly (Deep Space 1), 81P/Wild 2 (Stardust), and 9P/Tempel 1 (Deep Impact). These observations reveal similarities but also significant diversity. In this review, we make a critical assessment of our knowledge of JFC nuclei and suggest a priority list for observations of the nucleus of the JFC, 67P/Churyumov-Gerasimenko, the Rosetta target comet.

1. Introduction

At the time of writing over 300 Jupiter family comets (JFCs) have been identified. Their nuclei have been investigated by Earth-based observations (we use this term to include both ground-based observations and those from Earth-orbiting observatories such as Hubble Space Telescope) and spacecraft.

The volume of literature discussing cometary nuclei is already extensive. Considering only the past 4 years, several significant books have been published (Festou et al., 2004; A'Hearn and Combi, 2007; Balsiger et al., 2008; Huebner et al., 2006). The main aspects of cometary research have been summarized and discussed recently in the major publication by Festou et al. (2004). Within this book, Lamy et al. (2004) have provided a detailed compilation of Earth-based measurements of cometary nuclei. Several other authors address the observations of gaseous species and dust within cometary comae (e.g. Bockelée-Morvan et al., 2004; Kolokolova et al., 2004). Also within Festou et al. (2004), Keller et al. (2004) have reviewed spacecraft observations of cometary nuclei including those of 19P/Borrelly and 81P/Wild 2.

The major new addition to our body of knowledge since these reviews come from the Deep Impact observations of 9P/Tempel 1. In this case, a compilation of papers resulting from the acquired data and their initial interpretation has been published in book form (A'Hearn and Combi, 2007). For comparison purposes, the books by Keller et al. (1994) and Szego et al. (1994) about the prototype comet in the Halley family of comets are useful references. Furthermore, many aspects of cometary nuclei have been addressed in a recent volume of Space Science Reviews which was the result of a workshop held in Berne in 2006 (Balsiger et al., 2008). Crovisier (2007) has also provided a brief review of cometary diversity emphasizing in particular the composition of their outgassing products.

It is also worth pointing out that Huebner et al. (2006) have published a detailed description of the physics of the uppermost surface layer of cometary nuclei and how the properties of these surfaces can affect the outgassing rates over the orbit.

With this vast body of recent literature concerning cometary nuclei (including several important reviews), it makes little sense to repeat or slightly update that work here. Instead, we introduce what we consider to be the most important data concerning JFC nuclei and critically discuss their interpretation. We then seek to place this in the context of the discussion concerning the origin and structure of cometary nuclei. Finally, the European Space Agency's Rosetta mission will have many tasks at the JFC 67P/Churyumov-Gerasimenko. We conclude by listing what we see, personally, as the main priorities for the investigation of the nucleus.

2. Available data

The nuclei of JFCs can be investigated by one of two means. Earth-based observations allow us to sample a significant number of the discovered population (and can of course add to the identified number). However, the nuclei are typically smaller than the resolution unit of the observing system being used. Lamy et al. (2004) and references therein have demonstrated how one can subtract the brightness of the dust and gas comae by taking advantage of accurate knowledge of the point spread function of an imaging system combined with fairly reasonable assumptions of how the dust brightness varies with radial distance from the

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source. This allows one to determine the integrated reflectance from the nucleus and to produce a light curve, thereby constraining the rotation period and the shape (through the amplitude and form of the light curve). The solidity of this technique was demonstrated by the successful prediction of the nucleus size of comet 9P/Tempel 1 prior to the Deep Impact encounter. In addition, estimates of the colour can be obtained from Earth-based observations and an assessment of the degree of inhomogeneity of activity can be made (albeit with considerable uncertainty). The composition of volatiles in the nucleus can be obtained through spectroscopic observations of emitted gas species from the infra-red (DiSanti and Mumma, 2008) to radio wavelengths (Bockelée-Morvan et al., 2000). These results are limited, however, by the spatial resolution and the knowledge that chemical reactions in the innermost coma can be rapid thereby modifying relative abundances. Because of the strong resonance fluorescence of radicals such as CN, C_2, and C_3, narrow-band imaging observations of these species can provide information on the inhomogeneity of individual regions of activity.

On the other hand, one can send spacecraft to specific targets. Until now these measurements have been acquired during fast fly-bys and therefore give only a snapshot of the nucleus and its behaviour at one specific time. However, here we can obtain a detailed picture of a nucleus at resolutions better than 100 m px^{-1}. The size, shape, and albedo can be constrained, the activity and inhomogeneity quantified, and surface temperatures measured. At the time of writing, just 3 JFCs (19P/Borrelly, 81P/Wild 2 and 9P/Tempel 1) have been studied by spacecraft (Deep Space 1, Stardust, and Deep Impact, respectively). Hence, we have a statistically limited sample. But furthermore, the data acquired from these three missions vary markedly in breadth and quality. Deep Space 1, for example, was a technology-driven mission with tests of several new devices (including the integrated camera system, MICAS) which did not always work perfectly (Nelson et al., 2004; Soderblom et al., 2004a). Stardust's primary goal at 81P/Wild 2 was the collection of dust particles (Brownlee et al., 2004). Observations of the nucleus were restricted to images with a relatively simple imaging system (Duxbury et al., 2004). On the other hand, the observations by the Deep Impact spacecraft were dedicated to the investigation of the cometary nucleus of 9P/Tempel 1 and have provided a significant advance (A'Hearn and Combi, 2007).

While this combination of in situ and remote observations appears at first sight to be an appropriate way forward, the limitations of both techniques are severe. Comets are small, dynamic objects influenced strongly by their individual history, orbit, rotation, and inhomogeneity. For the nuclei, ground-based observations are insufficient for anything but a rough characterization of their bulk properties. Spacecraft observations are too limited in time to provide detailed assessments of the evolution of the surface and too limited in number to allow a transition from the specific to the general. Within these constraints, however, some hypotheses can be constructed which might soon be testable.

3. Sizes and shapes

Lamy et al. (2004) have provided tables of measured sizes and shapes of cometary nuclei through 2006. Of the 65 ecliptic comets for which values of the effective nucleus radius were computed, 63 are JFCs. The largest is 28P/Neujmin 1 at 10.7 km with only three (4.8%) being larger than 5 km in effective radius.

Table 1 gives a revised version of Table 3 in Lamy et al. (2004) which refers to measurements made (primarily) by spacecraft. We are now able to add accurate measurements for 9P/Tempel 1 and 81P/Wild 2. Here too, the effective radii of the three JFCs are small—less than 5 km.

With respect to Table 1 and Lamy et al. (2004), it should be noted that the 1P/Halley measurements by the Giotto camera only allow determination of a projected value on the plane of sky for the length of the long axis. This must be determined from the lower resolution Vega 1 and 2 data. This leads to a combined set of semi-axes values with fairly substantial error bars. For 9P/Tempel 1, the shape model of Thomas et al. (2007) is excellent. The values given in Table 1 to represent this work are only approximations.

The triaxial ellipsoid approximation to the shape of these objects is clearly crude. Given the unusual shapes of 1P/Halley and 19P/Borrelly, it is highly improbable that other JFCs can be well approximated in these terms when viewed in detail. On the other hand, this type of description has some use for Earth-based observations. Here, a lower limit to the axial ratio can be derived through the influence of shape on the light curve and deviations from sinusoidal behaviour might then be related to shape anomalies in extreme cases. This assumes that surface albedo variations are negligible or cancel each other out. It is not obvious that such an assumption is valid although the Earth-based observations which pre-dated the Deep Impact mission provided values for the effective radius and the axial ratio (Weissman et al., 1999; Lamy et al., 2004) which were very close indeed to the final result from Thomas et al. (2007) indicating that the method has considerable merit. From Lamy et al. (2004)'s catalogue, only 7% of JFCs have a minimum axial ratio which is 2:1 or higher but 86% have minimum axial ratios of 1.2:1 or higher. Near-perfect spherical nuclei are therefore uncommon.

4. Rotation periods

The modulation of the light curve by rotation of a non-spherical nucleus allows determination of the rotation period.

Table 1
The sizes of cometary nuclei as measured by imaging systems on spacecraft.

Comet	Dimensions (km × km × km)	Typical error in 1D (km)	Spacecraft	Fly-by distance (km)	Phase angle of approach (deg)	Heliocentric distance (AU)	Date	Ref.
1P/Halley	15.8 × 7.4 × 7.4	0.25	Giotto and Vega 1/2	596 (G)	107 (G)	0.89 (G)	14 March, 1986	Keller et al. (1994), Szego et al. (1994)
9P/Tempel 1	7.5 × 6.0 × 5.0	0.1	Deep Impact		63	1.50	4 July, 2005	Thomas et al. (2007)
19P/Borrelly	8.0 × 3.2 × 3.2	0.1	Deep Space 1	3500	88	1.36	22 September, 2001	Buratti et al. (2004)
81P/Wild 2	5.50 × 4.00 × 3.30	0.05	Stardust	236	72	1.86	2 January, 2004	Tsou et al. (2004)

See text for discussion of individual values.