

# Comet Size Distributions and Distant Activity

Karen J. Meech<sup>1</sup>, Olivier R. Hainaut<sup>2</sup>, and Brian G. Marsden<sup>3</sup>

<sup>1</sup> Institute for Astronomy, 2680 Woodlawn Drive, Honolulu HI 96822, USA

<sup>2</sup> ESO, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile

<sup>3</sup> Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

**Abstract.** We present the results of observations of distant comet nuclei as observed with the Keck II telescope during 1997 December. Our sample included 17 SP Jupiter-family comets, 3 Halley-family comets, and 1 dynamically new comet. The nucleus radii ranged between 0.6 and 12.7 km (assuming a 4% albedo), the average near  $R_N \sim 3$  km showing that, in general, the comet nuclei are relatively small. This doubles the known sample of size estimates for the comet population. These data are compared to the size distributions for the Centaurs and the Edgeworth-Kuiper Belt objects.

## 1 Introduction

The earliest stages of collapse of our solar nebula are not subject to direct observational constraints. However, comet nucleus size distributions are of great interest because they preserve a record of the outer nebula mass distributions in the late stages of planetary formation, as well as a record of collisional evolution. The rate of proto-planetary growth and scattering as a function of heliocentric distance depended on the size and mass distribution of the km-size planetesimals that have survived as today's comets, their surface density in the nebula and their velocity distributions. The estimated sizes of the Edgeworth-Kuiper Belt or Disk objects (EKO) are large compared to known short-period (SP) comet nuclei, although the statistics are still small for both populations.

The SP comets may be collisional fragments from the Edgeworth-Kuiper Belt population which have been injected into resonances to become the SP comets (Davis and Farinella (1997)). Bodies larger than 50-100 km probably retain their primordial size distributions (Farinella and Davis (1996)). As shown by Stern (1996), the present Edgeworth-Kuiper disk is probably collisionally very active – especially for smaller objects likely to evolve into SP comets. The larger disk bodies may reflect the scale of instabilities in the outer solar nebula, whereas the long-period comets (LP) that have been stored in the Oort cloud may not have been subjected to collisions, so that their size distributions may be primordial.

The size distribution of the EKOs is a critical boundary condition for understanding the formation of the solar nebula. Likewise, the size distributions of the Centaurs and the SP and LP comets will be important. However, interpreting the results will be difficult because of a large number of observational biases.

## 2 Observing Program

Observations were obtained on 1997 December 28 and 29 on the Keck II telescope using the Low Resolution Imaging Spectrometer (LRIS) in its imaging mode. The CCD was read out with 2 amplifiers with gains of 1.97 and 2.10  $e^- \text{ ADU}^{-1}$  and a read noise of 6.3 and 6.6  $e^-$ . The images were well sampled with a pixel scale of 0.215''  $\text{pix}^{-1}$  and seeing ranging between 0.5'' and 1.0'', FWHM. Both nights were photometric. Images were taken through the  $V$  and  $R$  filters on the Johnson system, and were guided at non-sidereal rates. Comets were observed over  $3 < r < 24$  AU to make estimates of their nucleus sizes. For a detailed discussion of the specifics of the data and reductions, see Meech *et al.* (1999).

## 3 Size Determination Issues

Comet nucleus sizes are currently reported in the literature from 3 observational techniques: (*i*) the coma subtraction method used by Lamy *et al.* (1996a), (*ii*) simultaneous optical and infra-red observations, and (*iii*) observations of distant, inactive comet nuclei. None of these techniques is a direct measurement – all have underlying assumptions and are model dependent. However, in most cases there is reasonable agreement between nucleus size estimates for comets measured by more than one technique (see Table 1).

**Table 1.** Nucleus Size Measurement Comparison

Comet	$R_N$	$p_v$	$R_N$	$p_v$	$R_N$	$p_v$	Ref
	Infrared		Dist. Obs.		Coma Sub.		
2P/Encke	2.5±0.5	0.08	2.8-6.4	0.04			1,2
22P/Kopff			2.46	0.04	3.3-3.8	0.04	3,4
28P/Neujmin 1	10.0±0.5	0.025	10.42	0.04			5,3
29P/SW1	20±2.5	0.13			15.4±0.2	0.04	6,7
9P/Tempel 1			2.10	0.04	3.9×2.8	0.04	3,8
10P/Tempel 2	5.9±0.4	0.02	3.07, 8×4×4	0.04			9,3,10
55P/Tempel-Tuttle	1.8±0.4	0.06	1.8±0.2	0.04			11,12
81P/Wild 2	3.0±0.3	0.02	2.0±0.04	0.04			11,13
46P/Wirtanen			0.7	0.04	0.6±0.02	0.04	14,8

Reference Notes: 1-Fernández *et al.* (1998), 2-Jewitt and Meech (1987), 3-This work, 4-Lamy *et al.* (1996b), 5-Campins *et al.* (1987), 6-Cruikshank and Brown (1983), 7-Meech *et al.* (1993), 8-Lamy (1998), 9-A'Hearn *et al.* (1989), 10-Jewitt and Luu (1989), 11-Fernández *et al.* (1999), 12-Hainaut *et al.* (1998), 13-Meech and Newburn (1998), 14-Boehnhardt *et al.* (1997).

### 3.1 Coma Subtraction

Lamy *et al.* (1996a) uses the Hubble Space Telescope (HST) to image the inner coma of active comets, and models the coma contribution to determine the flux from the nucleus and infer a nucleus size. The coma brightness,  $B(\rho)$ , where  $\rho$  is the projected distance from the nucleus in arcsec, is modeled by a function:

$$B(\rho) = [k_c/\rho + k_n\delta(\rho)] \otimes PSF \quad (1)$$

Here  $k_c$  and  $k_n$  are normalization constants,  $\delta$  is the delta-function of the nucleus, and PSF is the point spread function of the telescope. The brightness is modelled and compared to the observed surface brightness profiles to determine the nucleus contribution. The assumptions inherent in this technique which can give rise to systematic effects are numerous. First, many comae are not symmetric and may not be well modelled by a radially symmetric profile. In addition, this method assumes that the coma profile intensity drops as a function of  $\rho^{-1}$  which is true only for a steady-state coma unaffected by radiation pressure. Finally, the technique assumes a geometric albedo,  $p_v = 0.04$ , and a dust phase function,  $\beta = 0.04 \text{ mag deg}^{-1}$ . The phase function in particular, has only been measured on a few comets between 5-30° (Meech and Jewitt (1987)) and may not be applicable to the high phase angles at which the comets are often observed with HST.

### 3.2 Infrared Observations

Simultaneous optical and thermal infrared comet observations can give an estimate of both the instantaneous nucleus size and geometric albedo. The technique utilizes the following relations for the optical and thermal fluxes,  $F$ :

$$F_{opt} \propto R_N^2 p_v \phi(\alpha) \quad (2)$$

$$F_{thermal} \propto \epsilon R_N^2 \phi_{thermal}(\alpha) \quad (3)$$

However, just as in the previous case, assumptions must be made about the optical phase function,  $\phi$ , as well as the thermal phase function,  $\phi_{thermal}$ . Measurements of  $\phi_{thermal}$  have not been made for comets, therefore the thermal phase function measured for asteroids is used:  $\phi_{thermal} = 0.005 - 0.017 \text{ mag deg}^{-1}$  (for  $\alpha < 30^\circ$ ). Because infrared detectors are not as sensitive as optical detectors, often the comet must be fairly close to the sun for a detection, which can imply a large phase angle,  $\alpha$ , leading to greater uncertainty in these terms. The close proximity to the sun can also result in significant coma around the nucleus, and thus some sort of model must be used to account for the thermal and optical signal from this coma. Finally, a thermal model (*e.g.* the standard thermal model or the isothermal latitude model, etc.) must be used to interpret the radiometry, and this creates even more uncertainty in the final results.

### 3.3 Distant Comet Photometry

The scattered light,  $m_N$ , from the nucleus of an inactive comet is related to the size of the nucleus,  $R_N$ , and the geometric albedo,  $p_v$ , by:

$$p_v R_N^2 = 2.235 \times 10^{22} r^2 \Delta^2 10^{0.4(m_\odot - m_N)} / \phi(\alpha) \quad (4)$$

Here the heliocentric and geocentric distances,  $r$  and  $\Delta$  [AU], and the solar magnitude,  $m_{\odot}$ , are known, and the only values which must be assumed are the albedo and the phase function  $\phi(\alpha)$ . Because the comets must be at large distances to be inactive, and are therefore very faint, typically they are observed near opposition to get the maximum observing time on the object, and therefore the phase angles,  $\alpha$ , are very small. Thus any errors in assuming a phase function of  $\phi(\alpha) = 0.035 \text{ mag deg}^{-1}$ , which is common, are also very small.

The main uncertainty in this technique is ascertaining whether the nucleus is really inactive or if there is some residual dust coma which may be unresolved or at too low a surface brightness to be detected. Low-level activity can be ruled out if the comet has been observed over a range of  $r$  and the reduced magnitude,  $m(1, 1, 0)$ , has remained constant (with possible rotational modulations). This, unfortunately, requires observations over a long time base (*e.g.* years).

From the above discussion, it is clear that all of the methods of comet nucleus size determination have assumptions and/or depend on models, so that none are direct measurements. We have a direct measurement only for 1 comet which was visited by spacecraft: 1P/Halley. Nevertheless, it appears that the distant comet photometry technique is the least prone to assumptions.

## 4 Discussion and Results

In a study of the sizes of SP comets which have appeared in the literature, Fernández *et al.* (1996) have found that most comets have absolute nuclear brightnesses lying in the range of 15-19 mag, implying radii between 0.5-3.3 km for  $p_v = 0.04$ . However, given that the present work has found that there is often coma seen on comets at very large  $r$ , *i.e.* well beyond  $r = 6$  AU where water-ice sublimation is a strong driver of activity, observations must be made at even larger  $r$  to ensure that the radius estimates are not contaminated by coma. For example, a bare comet nucleus with  $m(1, 1, 0) = 19$  will reach  $m \approx 25$  near  $r = 4.5$  AU, so beyond this distance observations to determine the true distributions of nucleus sizes will require very large aperture telescopes.

This work has shown that observations from 1-2 nights of large telescope time can significantly increase the number of nucleus size estimates. The data presented here have increased the number of sizes to 36 – a 50% increase. The nucleus radii range over  $0.6 < R_N < 12.7$  km, with the most common size between 1-3 km. How many nucleus sizes are needed to make valid statistical comparisons between the different dynamical classes? Figure 1 shows a comparison of the size distributions for the observed SP comets, the LP and dynamically new (DN) comets, the EKOs and the Centaurs. There is a clear difference in the size distributions between the SP comets and the EKOs, but there are many observational biases unaccounted for. Because of the difficulty in obtaining direct SP nucleus measurements owing to their faintness, the sample is very incomplete, especially for small sizes. This incompleteness is even more severe for the EKOs. Also, in order to interpret the comparison of the distributions in terms of the early solar system, we must understand the collisional evolution of the SP

comets, the dynamical transport mechanisms into the inner solar system, and the evolutionary effects on the SP comets (*e.g.* sublimation and splitting). This leaves us with the important question – to what extent will the understanding of the SP comet sizes help towards understanding the small EKO distribution?

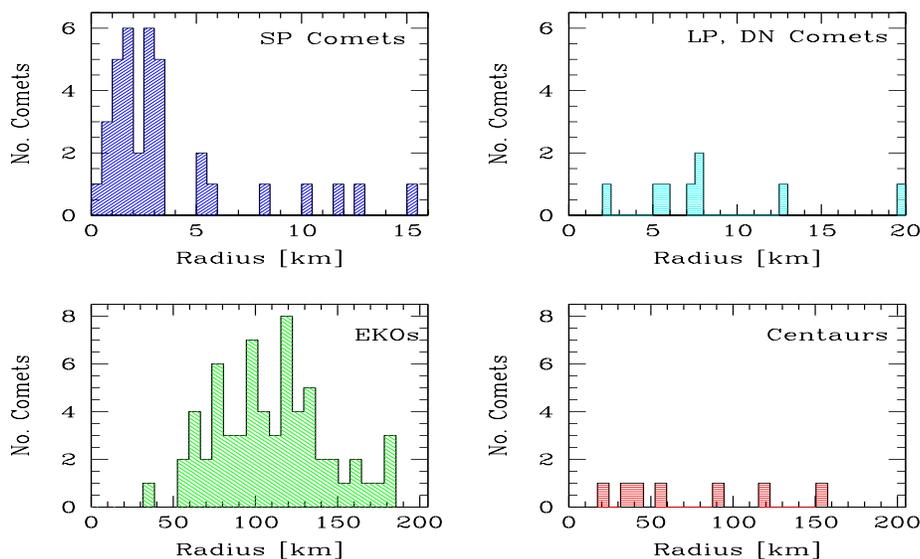


Fig. 1. Comparison of the size distributions of comets in different dynamical classes.

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