
Direct measurement of decimetre-sized rocky material in the Oort cloud

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Supplementary Information for
Direct measurement of decimeter-sized rocky material in the Oort
cloud

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Supplementary Tables

Supplementary Table 1: Geographical coordinates of optical cameras used in this work.

Name	Field of view	Latitude (+N)	Longitude (+E)	Elevation (mean sea level)
GFO Miquelon Lake	all-sky	53.239340°	-112.889855°	785 m
GFO Vermilion	all-sky	53.338975°	-110.884085°	624 m
Cochrane	134° × 105°	51.224138°	-114.706921°	1213 m
GoPro (photometry)	140° × 90°	50.910076°	-114.038749°	1040 m

Supplementary Table 2: Fireball trajectory parameters.

	Latitude (+N)	Longitude (+E)	Height (km, WGS84)	Time (UTC)
Begin point	53.7732° ± 0.092 km	-112.0861° ± 0.036 km	130.819 ± 0.082	2021-02-22 13:23:17.683
End point	54.6182° ± 0.213 km	-113.2543° ± 0.040 km	46.498 ± 0.066	2021-02-22 13:23:20.101

Supplementary Table 3: ECI trajectory state vector.

$X =$	-1844963	±	44	m
$Y =$	-3384728	±	193	m
$Z =$	5227379	±	153	m
$V_X =$	2161	±	41	m/s
$V_Y =$	-61705	±	15	m/s
$V_Z =$	5244	±	155	m/s

Supplementary Table 4: ECI state vector covariance matrix.

	X (m)	Y (m)	Z (m)	V_X (m/s)	V_Y (m/s)	V_Z (m/s)
X	+1.778e+03	+4.430e+02	+4.577e+03	+1.499e+03	+8.165e+02	+4.720e+03
Y	+4.430e+02	+3.851e+04	-7.591e+02	+1.377e+03	+4.232e+03	+2.417e+03
Z	+4.577e+03	-7.591e+02	+2.168e+04	+4.334e+03	+2.671e+03	+2.039e+04
V_X	+1.499e+03	+1.377e+03	+4.334e+03	+1.491e+03	+9.583e+02	+4.765e+03
V_Y	+8.165e+02	+4.232e+03	+2.671e+03	+9.583e+02	+1.448e+03	+3.880e+03
V_Z	+4.720e+03	+2.417e+03	+2.039e+04	+4.765e+03	+3.880e+03	+2.163e+04

Supplementary Table 5: Orbital covariance matrix. T_p is the Julian date of last perihelion (nominal $T_p = 2459230.729594$).

	e	q (au)	T_p (day)	Ω (deg)	ω (deg)	i (deg)
e	+8.321e-06	+4.075e-06	+2.410e-04	+1.762e-08	+6.764e-04	-5.763e-04
q	+4.075e-06	+2.367e-06	+1.240e-04	+1.009e-08	+3.757e-04	-3.302e-04
T_p	+2.410e-04	+1.240e-04	+7.079e-03	+5.341e-07	+2.031e-02	-1.746e-02
Ω	+1.762e-08	+1.009e-08	+5.341e-07	+5.399e-11	+1.607e-06	-1.767e-06
ω	+6.764e-04	+3.757e-04	+2.031e-02	+1.607e-06	+6.030e-02	-5.258e-02
i	-5.763e-04	-3.302e-04	-1.746e-02	-1.767e-06	-5.258e-02	+5.786e-02

Supplementary Table 6: Modelled fragmentation behaviour. The total mass of all ejected fragments is 1.04 kg. The fragment mass percentage in the table is reference to the mass of the main fragment at the moment of ejection. The mass distribution index for all grains was $s = 2.0$. The values of the dynamic pressure are computed using the drag coefficient Γ used in the modelling for the appropriate height, as described in Supplementary Table 7.

Time ^a (s)	Height (km)	Velocity (km s ⁻¹)	Dyn pres (MPa)	Main m (kg)	Fragment	m (%)	m (kg)	Erosion coeff (kg MJ ⁻¹)	Grain m range (kg)
1.49	76.0	62.03	0.09	1.73	EF	8	0.139	0.030	10^{-7} - 10^{-6}
1.52	75.0	62.02	0.10	1.59	EF	20	0.317	0.035	10^{-6} - 10^{-4}
1.57	73.0	62.00	0.10	1.25	EM	-	-	0.030	10^{-6} - 10^{-5}
1.72	67.5	61.88	0.21	0.93	EM	-	-	OFF	-
1.79	65.0	61.78	0.30	0.87	EF	35	0.310	0.020	10^{-5} - 10^{-3}
1.84	63.0	61.66	0.38	0.54	EF	15	0.081	0.020	10^{-7} - 10^{-6}
1.90	61.0	61.49	0.48	0.42	EF	18	0.075	0.080	10^{-7} - 10^{-6}
2.12	52.7	59.84	1.28	0.17	EF	50	0.084	0.005	10^{-4} - 10^{-3}
2.17	51.2	59.07	1.52	0.06	EF	50	0.030	0.050	10^{-6} - 10^{-5}

^a Seconds after 13:23:17.683 UTC.

EM = Main fragment erosion; EF = New eroding fragment.

Supplementary Table 7: Modelled physical properties of the fireball.

Description	Value	
Initial mass (kg)	m_0	1.8
Initial speed at 180 km (km s ⁻¹)	v_0	62.10
Zenith angle	Z_c	54.885°
Bulk density (kg m ⁻³)	ρ	3300
Grain density (kg m ⁻³)	ρ	3500
Ablation coefficient (kg MJ ⁻¹)	σ	0.009
(below 60 km)	σ	0.007
Shape factor (sphere)	A	1.21
Drag coefficient	Γ	0.8
(below 75 km)	Γ	0.6