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Supplementary Materials for

Inner solar system material discovered in the Oort cloud

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S1. Solar System Formation Model Predictions

In this section we briefly summarize the models that we refer to in the main text and their predictions in terms of asteroidal mass in the Oort cloud.

S1.1 The Grand Tack model

In this model (*1*), Jupiter starts to form at the snowline, near 3.5 AU. It migrates inwards while Saturn is still growing. When Jupiter reaches a distance of ~1.5 AU, Saturn achieves a mass large enough to influence the migration of Jupiter. Jupiter reverses migration direction (*33*) and the two giant planets start to migrate outwards until Jupiter reaches a final distance of ~5.4 AU.

During the inward migration phase, Jupiter and its resonances sweep approximately two Earth masses (M⊕) of material that was originally inside of it's orbit. The material in this region was likely volatile-poor (represented in today's meteorites by ordinary chondrites, enstatite chondrites, and differentiated planetesimals). The parent bodies of these volatile-poor meteorites are the S-type asteroids (*16*). Of these 2M⊕ of S-type material, 14% is scattered outward, ending up beyond 3 AU. When the planets migrated outwards they again encountered this scattered material. About 5% of this is implanted in the asteroid belt, and 13% survives beyond Neptune. This represents a total of $0.14 \times 0.13 \times 2 = 0.04$ M⊕ of S-type material mixing with the local disk of comets. Later, when the giant planets became unstable and the cometary disk was dispersed (*34*), this inner-disk material followed the same dynamical fate of the comets. About 5% of it ends in the Oort cloud and 1% in the scattered disk. So today, there should be about 0.002M⊕ of S-type material in the Oort cloud (compared to 1-2 M⊕ of comets (*35*) and 0.0004M⊕ of S-type material in the scattered disk (compared to 0.3 M⊕ of comets (*35*)). In other words, the Grand Tack model predicts that the ratio of icy comets to S-type material in cometary orbits should be about 500-1000 to 1. Notice that the bodies ejected during the Grand Tack events (i.e. those which do not end up in the trans-Neptunian disk but are expelled into orbits with a > 1000 AU or even hyperbolic orbits) are unlikely to contribute to the build-up of the Oort cloud. This is because this event occurred very early (the first few My of the Solar System history, before the removal of the protoplanetary disk), so that the Sun was likely still embedded in a stellar cluster. In presence of a cluster, the orbits of the distant objects bound to the Sun are not typical of the Oort cloud, but are similar to that of Sedna (*36*-*37*). This issue is less critical for the other models described below, because the planetesimals are scattered to distant orbits at a later time (typically during terrestrial planet formation, which took several tens of My), so that the Sun might have already escaped from its birth cluster.

S1.2 The Shannon et al. (2015) model (*2*)

This model is a fairly simple one, in which all planets are assumed to be fully formed on their current orbits; test particles are distributed uniformly through the Solar System and their evolution is simulated until their ultimate dynamical removal or the age of the Solar System is attained (*2*). Somewhat less than 1% of the test particles from the terrestrial planet region are found to reach the Oort cloud. In these simulations, the asteroid belt is stable, so its test particles do not escape and do not contribute to the Oort cloud. In order to estimate the fraction of the Oort cloud population represented by inner Solar System planetesimals, Shannon et al. (*2*) assume that the initial planetesimal surface density distribution follows $1/r^{3/2}$ law characteristic of the Minimum Mass Solar Nebula model (*38*). With this assumption, they find that 4% of the Oort cloud objects should come from the inner Solar System, almost all of which form within 2 AU from the Sun. However, the assumption that the surface density of planetesimals at the end of terrestrial planet formation followed a $1/r^{3/2}$ law neglects that part of this mass should have been used to build the terrestrial planets in first place. Thus, we can improve this estimate as follows. In Shannon et al. (*2*), about 20% of the planetesimals in the terrestrial planet region hit the Earth. We know from geochemistry of the Earth mantle that our planet accreted only ~1% of its own mass as a late Veneer (*39*). Thus, the total mass of planetesimals in the terrestrial planet region should have been of the order of 0.05 $M_\oplus$. If we apply now a 1% efficiency of implantation in the Oort cloud we conclude that at most 1/2000 of the Oort cloud population (assumed to be 1 Earth mass) should come from the inner Solar System.

S1.3 The Izidoro et al. (2013) Depleted Disk model (*4*).

This model simulates the formation of the terrestrial planets from a disk of planetesimals and planetary embryos (*4*). There are initially 2 $M_\oplus$ of planetesimals, between 2.5 and 4 AU. Jupiter and

Saturn are assumed to be fully formed and on their current orbits. In some simulations only Jupiter is considered. Most of the planetesimals (~1.7 M⊕) are dynamically removed during the simulation. Their fate is not explicitly discussed in the paper. But assuming that 50% of them suffer close encounters with Jupiter (typical of asteroid belt depletion simulations; the rest falling into the Sun or being accreted by the terrestrial planets) and that 1% of these is emplaced in the Oort cloud [as in Shannon et al. (*2*)], we expect that this model produces about 0.01 M⊕ of asteroidal material in the Oort cloud of which roughly half would be S-type objects. Compared to the total mass of the Oort cloud (1-2 M⊕), this implies that the ratio icy objects/S-type objects in the cloud is 200-400.

S1.4 The Weissman and Levison (1997) estimate (*3*)

In this work the authors assumed that the primordial mass of the asteroid belt was ~3 M⊕ and that during the primordial depletion of the asteroid belt half of this material was removed by encounters with Jupiter (*3*). They also assumed that 8% of the population encountering Jupiter ends in the Oort cloud. This amounts to 0.12 M⊕ of asteroidal material in the Oort Cloud, about half of which is in S-type bodies. Using a modern estimate for the Oort cloud mass of 1-2 M⊕ (*35*), then 3-6% of the Oort cloud objects should be S-type objects (the authors assumed an Oort Cloud mass of 16 M⊕, concluding that 1% of it should be asteroidal). However, they admitted that the 8% implantation efficiency into the Oort cloud came from numerical simulations which "did not include the effects of galactic tides or passing stars and thus should be considered preliminary". A refined estimate for the implantation efficiency is ~1% (*2, 40*), so the revised expectations from Weissman and Levison (*3*) should be in line with those from the model of Izidoro et al. (*4*)

S1.5 The Levison et al. (2015) Pebble Accretion Model (*5*)

The goal of this model (*5*) is to provide a solution to the problem of the small mass of Mars without invoking a wide range migration of Jupiter as in the Grand Tack scenario (*1*). It is assumed that planetary embryos grow due to a very efficient process known as "pebble accretion" (*41*). A few drastic assumptions are made on the protoplanetary disk structure. First, that the disk is assumed to be flared also in its inner part, which requires a radial gradient in the dust/gas ratio. Second, it is assumed that the disk exhibits a pressure bump at the snowline, so that there is no pebble drift into the inner disk from the outer disk. Consequently, the planetary embryos in the inner disk grow only from pebbles that form by condensation and coagulation within the snowline. With these assumptions, accretion is strongly favored closer to the Sun than farther out. The population of planetesimals initially in the asteroid belt does not grow in mass significantly, whereas the planetesimals in the terrestrial planet region grow much more effectively and become planetary embryos. In this way, the resulting mass distribution is strongly concentrated within 1 AU, which leads to the formation of a massive Earth and of a much less massive Mars (*42*). A characteristic of the pebble accretion model is that the small body populations are never massive, accounting in total less than 1% $M_\oplus$. Thus, the total amount implanted in the Oort cloud is at most 10^{-4} $M_\oplus$, thus predicting a ratio of icy/rocky bodies in the cloud larger than 10,000.

Basically, we can conclude that all models assuming primordial massive populations of small bodies in the inner Solar System, regardless of the specific aspects of planet evolution, expect an icy/S-type ratio in the Oort cloud of several hundreds to 2,000, whereas the new model suggesting that the asteroid belt always had a very low mass implies a ratio larger than 10,000.

S2. Details of the Observations

A log of the observing dates, orbital geometry, and observing conditions is shown in table S1. All the imaging data were obtained in the Sloan *gri* filter system (*43*).

After it became clear that C/2014 S3 was very interesting, on 2014 Nov. 14 our team requested Director's discretionary time on the European Southern Observatory (ESO) Very Large Telescope to obtain a spectrum and within 5 hours we received a positive answer. Concerned about the potential target faintness, we obtained observations on UT 2014 Nov. 16 using the Megaprime mosaic camera on the CFHT. This showed that the comet had rapidly faded and was a magnitude fainter than predicted.

Optical spectra were obtained using the VLT FOcal Reducer and low dispersion Spectrograph (FORS2) on the UT1 telescope two nights later, on 2014 Nov. 18. We used the GRIS300I+11 grism with the OG590 filter. This combination provided the highest transmission between 0.8-0.9 μm for a total wavelength range from 0.45-0.95 μm. We used a 1.0×408 arcsec slit that provided a spectral resolving power of 600 at $\lambda_{central}$ = 0.858 μm. To correct for strong telluric absorption features from the atmosphere, we observed the G2V star HD224817, which was close to C/2014 S3 in the sky. This star also served as a solar analog for determining reflectivity.

S3. Data Reduction

S3.1. Image Data Reduction

The imaging data was calibrated using field stars belonging to the PSPS export database (*44*). We converted the Pan-STARRS1 3pi mean psf magnitudes to SDSS AB magnitudes using the transformations in (*45*). Image photometry was performed using the SExtractor package (*46*). SExtractor automatic aperture photometry (MAG_AUTO) with expanded apertures was used for trailed or crowded images; for most non-trailed images a curve of growth was developed using a series of sextractor aperture magnitudes. Final object photometry was performed using the same method (MAG_AUTO or aperture) used to calibrate the image. The spectral reflectivities were computed from the photometry using the following formula

$$S'(\lambda) = 10^{-0.4[m(\lambda)-m(\lambda,\odot)]} / 10^{-0.4[m(g)-m(g,\odot)]} \quad [1]$$

Here m($\odot$) is the magnitude of the sun at the specific filter wavelength, λ, with the spectral reflectivity normalized to a value of 1 in the *g* filter. The absolute AB magnitude of the sun and colors in the *griz* system are: m(g) = +5.12, m(*g,*$\odot$) - m(*r,*$\odot$) = 0.44±0.02, m(*r,*$\odot$) - m(*i,*$\odot$) = 0.11±0.02, m(*i,*$\odot$) - m(*z,*$\odot$) = 0.03±0.02. Transformations between the Sloan Survey photometric system and other standard systems are found on the Sloan Digital Sky Survey website (http://classic.sdss.org/dr4/algorithms/sdssUBVRITransform.html).

S3.2. Spectral Data Reduction

Because of the low contrast between the bright sky and faint object, we performed two independent reductions.

Reduction 1 – Nominal data processes (i.e. bias subtraction, flat fielding and wavelength calibration) were performed using the FORS2 pipeline with Gasgano (a Data File Organiser developed and maintained by the European Southern Observatory). The first order sky removal was performed as part of the FORS2 pipeline procedure. Additional skyline removal and the extraction of one-dimensional spectra of the comet as well as the standard star were carried out using standard IRAF tasks.

Reduction 2 – The spectra were extracted in a stepwise fashion to account for the curvature in the *y*-direction of the spectrum dispersed along the *x*-direction on the CCD. The extraction box size was 9 pixels wide. The same size box is used for sampling the sky both above and below the spectrum. The sky values from the top and bottom sky are cross-correlated to see if there is any shift in the lines; there were none. We used the average of the two sky regions to subtract the sky from each of the four target spectra. We deleted the cosmic rays by linearly interpolating across them. Then the four spectra were averaged together. We used an identical procedure to process the solar-like standard star, with the exception that the extraction box width was 11 pixels. We divided the Manx spectrum by the solar standard spectrum to get the reflectivity.

The spectra have been binned into intervals representing the regions free of night sky emission lines to increase the signal-to-noise.

S4**. Conceptual Ice Sublimation Model**

We use a simple ice-sublimation model (*47*) to investigate the origin of the dust coma for C/2014 S3. This model was used to investigate the behavior of comet 67P/Churyumov Gerisamenko prior to arriving at the comet, and successfully predicted the gas flux levels when the Rosetta spacecraft first started to detect gas (*48*). The model computes the amount of gas sublimating from an icy surface exposed to solar heating. The brightness of a bare nucleus is related to its radius, R_N [m], and geometric albedo, $p\lambda$, by

$$p_\lambda R^2_N = 2.235\times10^{22}\ r^2\ \Delta^2\ 10^{[0.4(m(\odot) - m)]}\ 10^{0.4(\beta\alpha)} \qquad [2]$$

where r and Δ are the helio- and geocentric distances [AU] and $m(\odot)$ and m are the apparent magnitudes of the sun and comet. The term $\beta\alpha$ represents the simplified linear phase function, with phase angle, α [deg] and β is a constant ranging from 0.02-0.04 mag / degree.

As the ice sublimates, either from the nucleus surface or near subsurface, the escaping gas entrains dust in the flow, which escapes into the coma and tail thus increasing the effective cross section for scattered light. This is observed as a brightening in the heliocentric light curve, which can be compared to observed photometry. In the absence of gas fluorescence, the total comet brightness has a contribution from the nucleus and the scattered light from the dust. The latter is proportional to the total dust cross section, $p\lambda R_{dust}$, where R_{dust} is the radius of a disk of cross section equal to the total grain cross section. This can be related to a coma brightness using a variant of Eq. (2). Assuming uniform mass loss from the nucleus, the total mass of grains within a projected photometry aperture is a product of the mass loss rate times the time spent in the aperture. This is related to the total grain cross section in an optically thin coma. The total coma brightness can be expressed as a function of mass loss, dM/dt, via

$$m_{coma} = 30.7 - 2.5 \log10 [\ p\lambda\ (dM/dt)\ t / \rho\ a\ r^2\ \Delta^2\ ] \qquad [3]$$

where the time, t, is a function of the projected aperture size and grain velocity and a and ρ are the grain radius and density, respectively. The mass loss is computed using the energy balance at the nucleus

$$F_{\odot} (1 - A) / r^2 = \chi \left[\varepsilon \sigma T^4 + L(T) (dm_s/dt) + \kappa(dT/dz)\right] \quad [4]$$

The left side of the equation is the incident solar flux, $F_{\odot}$, absorbed (where *A* is the bond albedo), which is partitioned into blackbody energy, sublimation and conduction into the interior. The term χ is related to the rotation-modulated distribution of incident solar energy; ε is thermal emissivity (ε=0.9), and *T* is the temperature. The mass loss per unit area, (dm_s/dt) is related to the sublimation vapor pressure *P(T)* and the average speed of the gas molecules leaving the surface; *L(T)* is the latent heat of sublimation (*49*). The thermal conductivity, κ, is known to be low (*50*).

The model free parameters are: ice type, nucleus radius, albedo, emissivity, density, dust sizes, density, phase function, thermal conductivity and fractional active area. Because we had very few distinct data points, we did not allow all the variables to vary independently. Rather, we ran models for water ice for an S-type asteroid (25% albedo, density 3000 kg m^{-3}, phase function 0.03 mag/deg) and a typical comet (4% albedo, density 400 kg m^{-3}, phase function 0.04 mag/deg). We further assumed a slow rotation, and small micron-sized grains. The S-type model was best fit with a nucleus radius of 0.26 km and the comet model with a nucleus of 0.71 km. The inferred fractional active area was small, with satisfactory fits for 0.04% to 0.1% of the body's total area, and the inferred gas production rate was around 10^{23}-10^{24} molecules s^{-1}.

S5. Finson Probstein Dust Models

In order to investigate the morphology of C/2014 S3's coma, we used the Finson-Probstein method (*51*), which considers dust grains released from the nucleus with zero velocity, at various epochs in the past, and computes their position at the time of the observations accounting only for the solar radiation pressure and gravity. The ratio between these two forces is a function of the size and density of the dust grains, and of the radiation pressure efficiency. We used a density of 3000 kg m^{-3} (typical for S-type asteroids, (*52*)), and the particle size was set to scan the range from 1 to 1000 μm. All the grains released at a given epoch will have spread over a line connecting the nucleus (representing a giant particle unaffected by radiation pressure) to the smallest grains, forming a “synchrone” line. The line connecting the dust grains of a given size emitted at various epochs is a “syndyne”.

Syndynes and synchrones often form a very narrow fan, and the various epochs and sizes degenerate into a single inextricable line. Observationally, this corresponds to the typical long and narrow tail of a comet. Fortunately, during 2014 Sep. and Oct., the viewing geometry of the comet was very favorable, with the syndynes and synchrones broadly fanning out. In the ideal case where the dust is emitted with negligible velocity and the comet observed with superb image quality, overlaying the syndynes and synchrones on the image of the comet allows us to directly read the emission time and the grain size for any pixel of the image. The atmospheric turbulence blurs the images, and the gas resulting from the ice sublimation driving the cometary activity can push the dust grains out with a high velocity. Because of both these effects, the syndynes and synchrones cannot be used directly, but are still useful to guide the analysis of the images. Conversely, the presence of dust outside the region covered by the curves unequivocally indicates that the dust must have been released with some velocity.

S6. Statistical Assessment: Manx Observations and Dynamical Models

We use a statistical basis to determine how many Manx objects need to be observed in order to discriminate between the dynamical models which make different predictions for the amount of inner solar system S-type material that should be in the Oort cloud.

We assume four competing models with S-type fractions of A) 0.01% B) 0.05%, C) 0.13%, and D) 0.33%. We further assume that destruction of LPCs leads to a 13-fold suppression of LPCs in the in-scattered sample (*53*). Then, we note that our observational definition of a Manx selects only those objects on long-period comet orbits that are inactive or nearly inactive. Assuming that pre-selecting for low-activity objects will increase the fraction of S-types in the sample by a factor of three over randomly chosen Oort-cloud objects (based on recent active LP comet discoveries compared to Manx discoveries), we obtain a total enhancement of 3×13=39 of S-types over the above Oort cloud S-type fraction for each model.

We then use cumulative binomial statistics to examine which models are ruled out at a 2-sigma level given a particular observed number of S-types. If we observe 10 Manx objects, we can rule out hypothesis A if among them we see even a single S-type, B if we see two or more, C if we see three or more, and D if we see four or more. If we manage to observe 100 Manx objects, we can then rule out C if we do not see between 2 and 9 S-types; and D if we do not see between 8 and 19. It is important to note that even in regions where competing hypotheses are permitted at the 2-sigma level, it is still possible to assign relative likelihoods.

table S1. Observing circumstances.

Tel[a]	UT Date	Start UT	JD[b]	r^c	Δ^c	α^c	TA[c]	Fil[d]	#[e]	t[e]	*Mag*[f]	σ^f	Refl[g]	σ^g
Imaging - Photometry														
CFHT	2014/09/23	14:56:36	6924.122645	2.106	1.543	26.61	19.2	r	3	180	20.941	0.028		
CFHT	2014/09/24	15:02:31	6925.126751	2.110	1.522	26.23	19.6	r	2	300	21.026	0.025		
CFHT	2014/09/26	13:59:04	6927.082686	2.115	1.484	25.39	20.4	r	4	720	20.979	0.015		
CFHT	2014/10/22	12:52:42	6953.036593	2.210	1.227	5.27	31.5	g	3	180	20.861	0.033	1.00	0.042
CFHT	2014/10/22	12:38:34	6953.026786	2.210	1.227	5.27	31.5	r	3	180	20.261	0.021	1.16	0.048
CFHT	2014/10/22	12:45:48	6953.031806	2.210	1.227	5.27	31.5	i	3	180	20.082	0.024	1.23	0.057
CFHT	2014/10/22	12:59:31	6953.041331	2.210	1.227	5.26	31.5	z	2	120	20.193	0.062	1.15	0.085
CFHT	2014/10/24	12:32:30	6956.022566	2.224	1.240	5.07	32.7	g	3	180	20.892	0.026	1.00	0.034
CFHT	2014/10/24	12:40:15	6956.027951	2.224	1.240	5.07	32.7	r	3	180	20.892	0.026	1.14	0.041
CFHT	2014/10/24	12:47:27	6956.032959	2.224	1.240	5.07	32.7	i	3	180	20.163	0.031	1.18	0.052
CFHT	2014/10/24	12:57:25	6956.039868	2.224	1.240	5.07	32.7	z	5	400	20.294	0.035	1.07	0.046
CFHT	2014/11/16	05:26;10	6977.726500	2.332	1.588	19.48	41.0	r	1	120	22.23	0.16		
VLT	2014/11/18	01:37:08	6979.567454	2.343	1.632	20.25	41.7	r	2	120	21.786	0.040		
Spectroscopy														
VLT	2014/11/18	02:18:16	6979.596013	2.343	1.632	20.26	41.7	h	4	3600				

[a] Telescope: CFHT=Canada-France-Hawaii 3.8m, VLT=Very Large Telescope 8.0m

[b] JD-24500000 at start of observation.

[c] Heliocentric, geocentric distances [AU], solar phase angle [deg], and true anomaly [deg].

[d] Filter ($\lambda_{Central}/\Delta\lambda$ [μm]: g (0.475/0.154), r (0.640/0.148), i(0.776/0.155), z (0.925/0.153)) or grism.

[e] Number of exposures, and total exposure time [sec].

[f] *r* mag and error.

[g] Spectral reflectivity normalized to a value of 1 at λ=0.65 μm and error.

[h] 300I+OG590