Dust Properties of Double-Tailed Active Asteroid (6478) Gault

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ABSTRACT

Context. Asteroid (6478) Gault was discovered to exhibit a comet-like tail in observations from December 2018, becoming a new member of the so-called active asteroid population in the main asteroid belt.

Aims. The aims are to investigate the grain properties of the dust ejected from asteroid (6478) Gault and to give insight into the activity mechanism(s).

Methods. We use a Monte Carlo dust tail brightness code to retrieve the dates of dust ejection, the physical properties of the grains, and the total dust mass losses during each event. The code takes into account the brightness contribution of the asteroid itself. The model is applied to a large data set of images spanning the period from January 11, 2019 to March 13, 2019. In addition, both short- and long-term photometric measurements of the asteroid have been carried out.

Results. It is shown that, to date, asteroid (6478) Gault has experienced two episodes of impulsive dust ejection, that took place around 2018 November 5 and 2019 January 2, releasing at least 1.4 \times 10^7 kg and 1.6 \times 10^6 kg of dust, respectively, at escape speeds. The size distribution, consisting of particles in the 1 \mu m to 1 cm range, follows a broken power-law with bending points near 15 \mu m and 870 \mu m. On the other hand, the photometric series indicate a nearly constant magnitude over several 5–7.3 h periods, a possible effect of the masking of a rotational lightcurve by the dust.

Conclusions. The dust particles forming Gault’s tails were released from the asteroid at escape speeds, but the specific ejection mechanism is unclear until photometry of the dust-free asteroid are conducted, in order to assess whether this was related to rotational disruption or to other possible causes.

Key words. Asteroids: (6478) Gault – Techniques:image processing, photometric – Methods: numerical –
2. Observations and data reduction

Images of Gault have been obtained at various telescopes around the world in the time frame from January 11 to February 15, 2019. Table 1 shows the log of the observations. Except for the observations from SOAR 4.1m telescope, in which a broadband $V + R_c$ filter was used, either Sloan $r$ or $R_c$ (Cousins) filters were used. The images from GTC 10.4m telescope were calibrated using standard stars, while in all the other cases, field stars and the USNO-B1.0 catalogue was used in the reduction procedure. Median stacking was performed for the TRAPPIST (Jehin et al. 2011) images to improve the signal-to-noise ratio. The seeing disk varied between 0.8 and 1.5 arcsec FWHM.

The early images show a single narrow tail near $PA = 290^\circ$, and a dense nuclear condensation (Figure 1a). Since early February, a second tail started to show up near $PA = 305^\circ$ (Figure 1b).

In addition to the images, long photometric series were obtained with both TRAPPIST-North (TN) and -South (TS) on 2019 January 13, 14 and 15, in order to determine the rotation period of the asteroid. In total we acquired 5 lightcurves of about 5 hours each, taken with the $R_c$ filter and an exposure time of 120 s (Table 2). On January 14 and 15, we observed first with TN and then with TS, all with the $R_c$ filter, which allowed continuous observation during 7.3 hours, with some overlap between the two telescopes. The calibration of the images was made with IRAF scripts using corresponding flat fields, bias and dark frames. The photometry was derived using the PhotometryPipeline (Momert 2017). About 700 to 900 stars in the PanSTARRS catalogue were used for the photometric calibration to obtain the apparent $R_c$ magnitudes.

3. The Dust Tail Brightness Code

In the simulations of the tails brightnesses, we used our Monte Carlo dust tail code that has been already described in several works in the past to characterise the dust environments of comets and main-belt comets (see e.g. Moreno et al. 2016, Moreno et al. 2017), so that only a brief description is given. The dynamics of the particles (assumed spherical) are described by the $\beta$ parameter, defined as $\beta = \frac{C_{pr}Q_{pr}}{\rho d}$, where $d$ is the particle diameter, $C_{pr} = 1.19 \times 10^{-4}$ g cm$^{-2}$ is the radiation pressure coefficient, and $Q_{pr}$ is the scattering efficiency for radiation pressure, which is $Q_{pr} \approx 1$ for absorbing particles large compared to the observation wavelength (Burns 1979).

As Gault is an inner belt asteroid of likely S-type, the particle density is assumed at $\rho = 3400$ kg m$^{-3}$, which is appropriate for S-type asteroid Itokawa regolith (Tsuchiyama et al. 2011). The code computes the position in the sky plane of a large number of particles emitted isotropically from the asteroid, whose trajectories depend on $\beta$ and their terminal velocities (e.g., Fulle 1989). We assume a broad differential size distribution of particles between 1 $\mu$m and 1 cm in radius, following a power-law function.

Prior to this activity period, Gault absolute magnitude has been reported as $H = 14.4$ (JPL Small-Body Database). We assume a geometric albedo of $p_v = 0.15$, appropriate for a S-type asteroid (e.g. Luu & Jewitt 1989). Then, its diameter can be calculated as $D = 4.5$ km, using the equation by Harris & Lagerros (2002). Owing to its significant size, we added in the simulations the asteroid brightness contribution to the tail brightness, assuming a constant cross section with time. To produce realistic model images to be compared with the observations, we performed a convolution of the synthetic images obtained with...
a two-dimensional Gaussian function. The full-width at half-maximum of the Gaussian was set to the average seeing value at the corresponding observation date. The asteroid and the dust particles brightness were corrected for the effect of the phase angle. For the asteroid we applied a linear phase coefficient of $b=0.033$ mag deg$^{-1}$, which is computed from the relation by Belskaya & Shevchenko (2000). For the dust particles ejected, we assumed the same values of $p_i$ and $b$ as for the asteroid.

The remaining model parameters are the event times and duration, the dust masses ejected, and the terminal particle speeds. The speed is assumed to follow a law of the kind $\gamma \sigma \sim 0$. The event occurrence of the ejection events. Further photometric observations when the asteroid will have no detectable coma can give additional results on the rotation properties. Since the number of free parameters in the model is large, in order to make the problem tractable we had to perform preliminary searches of some of the input parameters. Thus, the exponent $\gamma$ in the particle ejection speed equation was set to $\gamma=0.5$. For a sublimating body in which particles are accelerated by gas drag, $\gamma \sim 0.5$. For a simple model of rotational disruption, a size-independent speed would be expected, so that $\gamma \sim 0$. The event times are preliminarily guessed by a sydnye-synchronous analysis (Finson & Probstein 1968), which applies to zero ejection dates. A recent study performed by Kleyna et al. (2019) points to a $\sim 2h$ rotation period for Gault, which would indicate a super-fast rotator and probable rotational disruption as the cause of the dust ejection. Further photometric observations when the asteroid will have no detectable coma can give additional results on the rotation properties.

5. Results and Discussion
Since the number of free parameters in the model is large, in order to make the problem tractable we had to perform preliminary searches of some of the input parameters. Thus, the exponent $\gamma$ in the particle ejection speed equation was set to $\gamma=0.5$. Although this value is appropriate to gas drag acceleration from an ice-sublimating body, we had to assume it in order to explain the observed widening of the main tail as a function of distance to the asteroid, mainly for the latest images acquired (see Figure 1b and Figures A.8 to A.10). At present, we do not find any explanation for this fact, as ice sublimation seems rather improbable.

### Table 2. Summary of Gault short-term photometric series ($R_C$ filter).

| Date (UT) | $N_p$ | $r$ (au) | $\Delta$ (au) | $\alpha$ (deg) | Site |
|-----------|-------|---------|---------------|---------------|------|
| 2019-01-13.3 | 119 | 2.46 | 1.79 | 19.9 | TRAPPIST-S |
| 2019-01-14.2 | 124 | 2.46 | 1.78 | 19.7 | TRAPPIST-N |
| 2019-01-14.3 | 134 | 2.46 | 1.78 | 19.7 | TRAPPIST-S |
| 2019-01-15.2 | 124 | 2.45 | 1.77 | 19.5 | TRAPPIST-N |
| 2019-01-15.3 | 131 | 2.45 | 1.77 | 19.4 | TRAPPIST-S |

Notes. Telescope acronyms: TCS: 1.52m Carlos Sánchez Telescope at Tenerife. GTC: 10.4m Gran Telescopio Canarias. TRAPPIST: 0.6m Transiting Planets and Planetesimals Small Telescope. SOAR: 4.1m Southern Astrophysical Research Telescope.
The overall width of the tails depend on $v_0$. We found a value $v_0 = 3 \text{ m s}^{-1}$ as appropriate, which implies terminal speeds values of $\sim 0.4 \text{ m s}^{-1}$ for $10 \mu\text{m}$ particles, and lower for larger particles. These terminal speeds are comparable to the escape velocity of the asteroid at distances where the asteroid gravity becomes negligible compared to solar gravity. Thus, if we assume for the bulk density of the asteroid a value typical for S-type ($\rho_{\text{bulk}} = 2710 \text{ kg m}^{-3}$, Krasinsky et al. 2002), the escape velocity at 100 km from the asteroid surface would be $\sim 0.4 \text{ m s}^{-1}$, where the ratio of solar gravity to asteroid gravity is larger than $10^3$. This indicates that the particles populating Gault tails were likely released at near escape speeds from the asteroid surface. This would be compatible with a rotational breakup. However, the speed dependence on particle size seems incompatible with this mechanism. A simple model of rotational disruption would yield a size-independent ejection speed.

On the other hand, the event times are preliminarily guessed by a synodyne-synchrone analysis (Finson & Probstein 1968), which applies to zero ejection velocity conditions, and then refined by the Monte Carlo dust tail model. The duration of such events is only weakly constrained by the model, provided they are shorter than $\sim 5$ days. We then fixed the duration to 1 day for simplicity, but keeping in mind that this can be in fact much shorter.

After these preliminary searches of the mentioned parameters, we then solved for the total mass of dust ejected, and the power-law index of the differential size distribution. It soon became apparent that a single power-law function was inadequate to describe the variation of the brightness of the main tail with distance to the asteroid. It comes from the fact that the brightness along the tail first slightly increases or keeps constant tailward, and finally decreases (see Figure 1, and Figures A.1-A.10). In order to fit properly the observed brightness profile we adopted a broken power-law with two bending points. This left us with a total of seven fitting parameters: the two bending points, the three power-law indexes, and the dust mass released during each event. The resulting best-fitted differential size distribution was characterised by power-law indexes of $-2.28$ (between $1 \mu\text{m}$ and $15 \mu\text{m}$), $-3.95$ (between $15 \mu\text{m}$ and $870 \mu\text{m}$), and $-4.22$ (between $870 \mu\text{m}$ and 1 cm). This probably reflects the asteroid regolith size distribution. Broken power-law functions are common when describing the size distributions of asteroid dust bands (Nesvorný et al. 2006), the boulder distribution in asteroid regoliths (Tancrèdi et al. 2015), or in cometary dust (Fulle et al. 2016, Moreno et al. 2016), always with a tendency to increase slope with size.

The total dust mass released were of $1.4 \times 10^7$, and $1.6 \times 10^6$ kg, for the 2018 November 5, and 2019 January 2 events, respectively. We need to emphasise that these masses are lower limits to the actual total dust mass ejected. Thus, should a few large and massive boulders have been ejected, they would not contribute significantly to the brightness, but would do to the mass. We underline that the same differential size distribution is assumed for the two ejection events.

It is very interesting to note the remarkably similar size distribution, ejected masses, and velocities recently reported by Ye et al. (2019).

The fits to the data are shown in Figures A.1-A.10 in Appendix 1. These fits are provided as a synthetic image which best fits the observed image at a given date, an isophote map showing the measured and the modelled isophotes near the asteroid location, and the brightness along the tail, for both the observation and the model. The “bumps” along some of these measured profiles (most evident in Figures A.4, A.5, A.7, A.9, and A.10) are due to contamination by field stars. The asteroid contribution to the brightness profile near the optocenter is more and more important as time progresses, as the dust is being blown away by radiation pressure.

The total mass ejected, $1.56 \times 10^7$ kg, is negligible compared to the asteroid mass ($1.3 \times 10^{14}$ kg), and would correspond to a spherical volume of just $\sim 10$ m radius.
6. Conclusions

We have carried out observations and models to characterise the dust properties and event timelines of the double-tailed active asteroid Gault. The following conclusions can be drawn:

1. Asteroid Gault has experienced two short-lived activity periods of a maximum duration of 5 days, but might be much shorter, separated by a period of inactivity of nearly two months. A similar activity pattern has been previously observed for inner belt asteroid 311P.

2. The total dust masses ejected for particles in the 1 μm to 1 cm radius were $1.4 \times 10^7$ and $1.6 \times 10^6$ kg, for the November 5, 2018, and January 2, 2019 events, respectively. These masses represent a negligible fraction of the asteroid mass, estimated at $1.3 \times 10^{14}$ kg.

3. To fit the brightness distribution along the main tail, the differential size distribution function can be described as a broken power-law function, with power indexes of $-2.28$, $-3.95$, and $-4.22$, and bending points near $15$ μm and $870$ μm.

4. The ejection speeds are found to be close to the escape speed of Gault, a fact compatible with rotational disruption phenomena. However, the model results point to a $\beta^{0.5}$ dependence of the speeds, typical of sublimation-driven processes. This mechanism is, however, very unlikely owing to the inner belt character of the object. Only a detailed lightcurve of the naked, dust-free, asteroid in combination with dynamical modelling might shed additional light on the ejection mechanism.

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Appendix A: Monte Carlo dust tail model fits to the images

In this Appendix we show the model fits for all the images shown in Table 1.
Fig. A.1. Results of the model fit for the image obtained with TCS on 2019 January 11. Panel (a) is the observed image. Panel (b) is the model image, using the same brightness scale as in (a). Panel (c) shows the isophote field near the asteroid location (observation in black contours, and model in red contours). In Panel (d), a comparison between the observed intensity along the main tail (black line), and the model (red line), is given. Axes are labelled in km projected on the sky at the asteroid distance. In panels (a)-(c), North is up, East to the left.

Fig. A.2. As Figure A.1, but for the GTC image on 2019 January 13.
Fig. A.3. As Figure A.1, but for the GTC image on 2019 January 14.

Fig. A.4. As Figure A.1, but for the TRAPPIST image on 2019 January 21.
Fig. A.5. As Figure A.1, but for the TRAPPIST image on 2019 January 29.

Fig. A.6. As Figure A.1, but for the TRAPPIST image on 2019 February 5.
Fig. A.7. As Figure A.1, but for the TRAPPIST image on 2019 February 7.

Fig. A.8. As Figure A.1, but for the SOAR image on 2019 February 15.
Fig. A.9. As Figure A.1, but for the TRAPPIST image on 2019 March 5.

Fig. A.10. As Figure A.1, but for the TRAPPIST image on 2019 March 13.