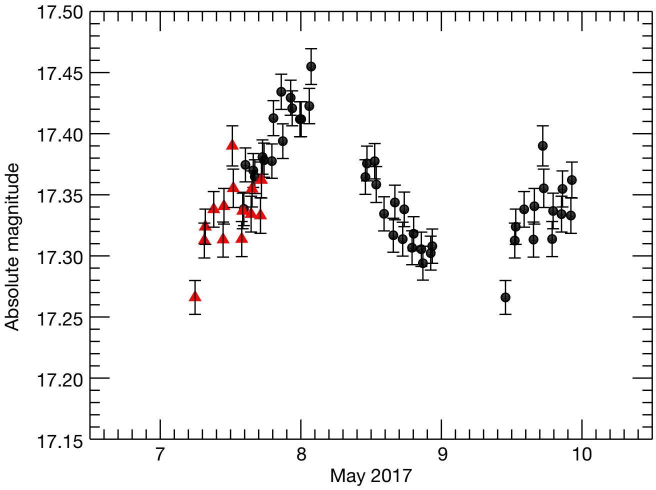

Figure 2 | Light curve of the inner coma measured by Swift/UVOT on 7–10 May 2017. The data acquired on 9.4–10 May are repeated as red triangles, phase-shifted to best match the data acquired on 7.5–8 May (black circles). Depending on the decrease in the activity of the comet with heliocentric distance (Methods), a range of periods of 46–60 h is found (Extended Data Fig. 2). The central period (53 h) is shown here. Error bars indicate 1σ stochastic uncertainties.

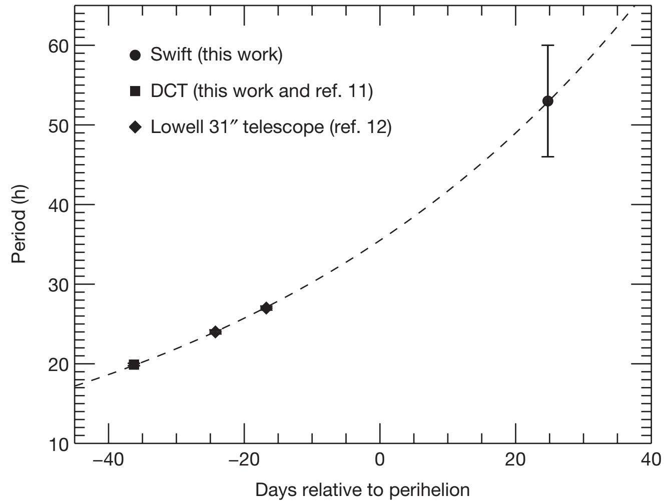

Figure 3 | Rotation periods for comet 41P measured as a function of time relative to perihelion. Perihelion occurred on 12 April 2017. The period increased at an average rate of at least 0.53 h per day over more than 60 days, an unprecedented rate of change. The different observations are indicated by symbols: Swift (circles; this work), DCT (squares; ref. 11 and this work) and results acquired[12] using the Lowell Observatory's 31″ telescope (diamonds). The dashed line is a guide to the eye. Error bars indicate 1σ absolute uncertainties; the error bar on the Swift observation (circle) indicates the range of possible solutions due to the uncertainty in the change of activity as a function of heliocentric distance.

A cyanogen morphology similar to that seen in our DCT observations was observed on 18–27 March 2017[12], but the structure took 24 h to repeat on 19 and 21 March, and increased continuously to nearly 27 h on 26 and 27 March (Fig. 3). During the densest coverage in late March, the morphology repeated at progressively later times on subsequent nights, revealing a daily trend that is consistent with our ensemble dataset from March to May. The consistent repetition of the morphology at the end of each lengthening period over such an extended time suggests that any non-principal axis component of rotation is small. Furthermore, we cannot conceive a scenario in which non-principal axis rotation could mimic the observed continuously changing period. Therefore, we assume that the nucleus was in a state of simple rotation.

Rotation periods have been measured for scores of comets, many with extensive coverage, but 41P is only the eighth comet for which a conclusive change in period has been measured. Furthermore, the fractional change and rate of change in period for comet 41P far exceed those observed in other comets (Extended Data Table 3). Changes in rotation period depend on the size, shape, internal structure, activity and rotational state of the nucleus of the comet[1,2,4,5]. The radius of the nucleus of comet 41P is[13] 0.7–1.0 km, which is less than 70%–90% of all measured radii of Jupiter-family comets[14]. The water production rate of comet 41P peaked around 2×10^{29} molecules per second in 2001 and 2×10^{28} molecules per second in 2006[15]. Our Swift observations suggest that production rates in 2017 were similar to those in 2006 (Extended Data Fig. 1). This result implies that more than 50% of the surface of the comet could be active, whereas most comets have less than 3% surface activity[16]. Finally, although the 20-h rotation period of comet 41P in March was long compared to most comets, the rotation period of more than 46 h that was measured in May is among the longest known[13]. It is this combination of slow rotation, high activity and a small nucleus that contribute to the rapid changes of the rotation state of comet 41P.

However, these characteristics are not unique to comet 41P. In 2010, comet 103P/Hartley 2 had an initial period of 16.5 h, a peak water production rate three times higher than that of 41P and a smaller effective radius[10] of 0.57 km. Even with the more extreme combination of these characteristics, its primary rotation period changed by only 2 h in the three months around perihelion[16] (Extended Data Table 3), more than an order of magnitude less than that of 41P. Therefore, other factors must also have a role in producing the net torque in comet 41P, which is much more efficient than that in any other known comet. The Deep Impact fly-by of comet 103P allowed a close examination of the activity of its nucleus[10], and the details that were observed enable us to explore possible differences between comets 103P and 41P. The visible jets from comet 103P are primarily along the long axis, with little moment arm for producing torques; some of the water from 103P comes from icy grains in the coma, reducing the amount of gas that contributes to torques[18,19]; and finally, the non-principal axis rotation of 103P acts to randomize the direction of the torques, reducing their efficiency.

Using the results from the four then-available comets that exhibited changes in period, an empirical parameter X has been suggested to relate cometary activity and changes in angular momentum[18]. This parameter was found to be nearly constant within a range of 1–2, leading to the conclusion that net torques are nearly the same irrespective of the effective active fractions of the nucleus. From our observations of comet 41P, we compute an X parameter of more than 50, inconsistent with that conclusion. (X parameters for comets 19P/Borrelly[20] and 67P/Churyumov–Gerasimenko[21] also lie well outside the 1–2 range; see Extended Data Table 3.) The deviation from this range implies that the torques, when integrated over all active areas, do not necessarily cancel out and that the physical characteristics of nuclei greatly affect the net efficiency of the torques. The effects of non-uniform activity and local topography are well illustrated by the results of the Rosetta mission to comet 67P/Churyumov–Gerasimenko, which demonstrated that the rotation period first increased, then decreased as new parts of the surface of the comet became illuminated[2]. The active regions on the surface of comet 41P are probably oriented in such a way that its torques are highly optimized in comparison to many other comets.

We extrapolated the rotation period of the comet in time to investigate its possible past and future behaviour (Fig. 4). Our model assumes that activity levels and effective torques are constant from apparition to apparition; for example, it assumes that the orientation of the spin axis and the water production did not change substantially. It suggests that, in the near future, the rotation period could exceed 100 h. At such slow rotation rates the stabilizing gyroscope effect disappears and off-axis torques can tip the nucleus into an excited rotation state. If strong torques persist, then the rotation period of the nucleus can begin to shorten again, but with a different orientation of its rotational angular momentum vector. Such behaviour is consistent with simulations of the long-term evolution of spin states of small cometary nuclei, which