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PATT2
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APPLICATION FOR TELESCOPE TIME (OPTICAL AND INFRARED)

1 TELESCOPE *(AAT, UKST, WHT, INT or UKIRT)*	INT	Reference:	Date stamp:
2 SEMESTER	2022A	3 SCIENTIFIC CATEGORY	1

4 COORDINATED PATT PROPOSALS: *AAT:*☐ *UKST:*☐ *WHT:*☐ *INT:*☒ *UKIRT:*☐ *JCMT:*☐ *GEMINI:*☐ *LT:*☐ *MERLIN:*☐

5 PRINCIPAL APPLICANT

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Is the applicant a possible observer? Yes

6 COLLABORATORS

Name:	Institute:	Observer?
Dr Agata Rożek	Institute for Astronomy, University of Edinburgh	Yes
Dr Colin Snodgrass	Institute for Astronomy, University of Edinburgh	Yes
Dr Rosita Kokotanekova	European Southern Observatory, Garching bei München	Yes

7 SHORT TITLE OF PROPOSAL *(maximum 12 words)*

The shapes of comet nuclei

8 SUMMARY OF PROPOSED OBSERVATIONS

In situ missions to short period comets indicate that a large fraction of these objects have a bilobed morphology. Increasing the number of comets with well-constrained shapes will enable us to test whether this large contact binary fraction is representative of the population. The shapes of small bodies can be modelled using convex lightcurve inversion (CLI), which has constrained the shapes and spin states of hundreds of asteroids, making use of well-sampled lightcurves over numerous observing geometries, but to date has been used to model the nucleus of only one comet: 67P/Churyumov-Gerasimenko.This work aims to make use of existing lightcurves for three low-activity JFCs. With one INT run we will add to them temporally-dense, single-epoch photometry sufficient to model their shapes and to improve our understanding of the contact binary fraction among less active comets.

9 FOCAL STATION, INSTRUMENT AND DETECTOR

Focal station:	Instrument:	Detector(s):	Gratings/Filters:
prime	WFC	EEV	Sloan R

10 OBSERVING TIME REQUESTED THIS SEMESTER

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Time requested this semester	4			nights
Minimum useful allocation this semester		3		

UKIRT applicants requiring dark time must justify this in section 18

11 COMPLETE THIS SECTION ONLY IF THIS IS A LONG TERM PROPOSAL

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Total time requested				

12 SCHEDULING INFORMATION

Preferred dates:	25 Feb-9 Mar
Impossible dates:	10 Mar-
Give justification for impossible dates	Targets visible throughout Feb and until 9 Mar. 172P no longer visible beyond 9 Mar, 137P getting fainter.
If observations are to be simultaneous with other telescopes or satellites, give details:	N/A
Any other scheduling constraints: *Include likely clashes with other time applications, constraints on lunar position or quarter, instrument preparation requirements, etc*	All three targets are observable during the same night in the selected windows.

13 SERVICE OBSERVING

yes: [ ] no: [ ] maybe: [X]

14 SUPPORT ASTRONOMER REQUESTED AT TELESCOPE

every night: [ ] no: [ ] first night only: [X]

15 LIST OF PRINCIPAL TARGETS

Object(s):	RA(h,m):	Dec(degs):	Mag(type):	Colour:	Exp. Time:
172P	04:12 (2 Mar)	+29.6	21.3 (R)	0.5*	250s
162P	12:32 (2 Mar)	+22.1	19.4 (R)	0.5*	60s
137P	11:35 (2 Mar)	-02.7	22.4 (R)	0.5*	350s

* Mean (V-R) colour of JFC nuclei based on 16 measurements [16]

16 LIST ALL SIMILAR/SUPPORTING APPLICATIONS TO ANY PATT OR OTHER TIME ASSIGNMENT COMMITTEE

You must include a brief description of any other applications whose targets or science goals are similar to those requested here

Telescope/satellite:	Title/Description of programme:
CAHA 3.5m	Morphological links between asteroids and comets / programme with similar science goals (shapes of small bodies), but a different set of targets
INT WFC	PI Rożek: Exploring the morphological links of bilobed near-Earth asteroids to comets / Post-doctoral programme with similar science goals (shapes of small bodies), but focused on supplementing radar observations of NEAs.

17 SCIENTIFIC JUSTIFICATION

Case not to exceed this A4 page. Figures and/or references can be included on page 4a

As some of the least thermally processed objects in the Solar System, comets can provide us with incomparable insights into the formation of our planetary system. In situ missions to six short period comets in recent decades have led to huge leaps in our understanding of these objects. Of these comets, four were found to be *bilobed* in shape. Combined with radar observations of one additional comet, 8P/Tuttle, we know for certain that **five out of these seven comets are bilobate**. This sample is small - nevertheless, it leads us to draw some conclusions about how comets might be shaped. Given that this high contact binary fraction is not seen in the dynamically excited trans-neptunian regions [1] from which Jupiter-family comets (JFCs) are believed to originate, possibilities for the formation of these shapes have been considered at various stages of the cometary dynamical lifetime: slow growth by hierarchical agglomeration in the primordial disk [2]; re-accretion following catastrophic collisional disruption [3]; or rotational disruption of the nucleus by sublimative activity in the Centaur region (the supposed precursor population of the JFCs) [4].

One notable feature about each of the comets visited by spacecraft - the only ones for which we currently have well-constrained shape information - is that **they all exhibit considerable activity**. One of the plausible end states for JFCs is that they gradually devolatise, becoming dormant and asteroidal in appearance [5]. Sparse photometry of a small number of JFC nuclei (without the presence of a coma) collected in the past decades has led to a hypothesised evolutionary trend for these objects: active JFCs have their surfaces become increasingly dust covered, quenching their activity over time and they become darkened (in albedo) and eventually dormant [6]. We currently have no information about how such objects, potentially approaching the ends of their dynamical lifetimes, might be shaped. Does the population of nearly extinct comets feature the same fraction of contact binaries as the spacecraft-visited comets, or does sublimation-driven erosion change this shape distribution?

For this proposal, we intend to use *convex lightcurve inversion* (CLI) to make use of the existing photometry mentioned above that has been collected for inactive JFCs, in order to model their convex shapes. CLI is a well established technique routinely used to produce asteroid shape models from ground-based photometric lightcurves [7,8]. The procedure takes as input lightcurves that cover a wide range of observing geometries, and creates a convex hull representing the object. The process mathematically cannot produce concavities, and so these are often masked by large, flat facet areas in the final model. CLI yields an estimate of the object's spin state, characterised by the sidereal period and direction of the axis of rotation. CLI has been applied extensively to produce a large database of asteroid shape models, and combined with more elusive radar observations to produce nonconvex shape models of some of these objects [9], but to date has been used to produce **only one convex model of a comet nucleus:** 67P/Churyumov-Gerasimenko, target of the Rosetta mission. Lightcurves from targeted ground-based photometry during 67P's aphelion passage were used to construct a detailed spin-state model [10] (see Fig.1). The presence of large, flat facets on the model were indicators of large concavities, concealing the slim neck that separates the lobes. Physical considerations regarding the criteria for stability of any shape model can also be used to an extent to infer bilobate shapes, given that it is unlikely that single-lobed objects with highly elongated axis ratios ($\frac{a}{b}$) would have formed naturally - such objects undergo rotational fission resulting from instability when their elongation exceeds $\sim$2.3 [11,12].

Given that CLI has been used to model only a single JFC nucleus so far, we believe that now, in anticipation of surveys such as LSST coming online, is an appropriate time to advance this 'classical' method of modelling nucleus shapes. Existing lightcurves from targeted monitoring have proved invaluable for estimating sizes and rotation periods of these objects [e.g. 13,14]. Modelling the convex shapes of these objects is not only the next logical application of these lightcurves, it is the only consistent, predictable method for obtaining JFC shape information from the ground. The shapes that we can produce are limited only by the paucity of the existing lightcurve coverage, which in turn is limited by observing time. At present we are in the early stages of a project investigating how the sparse, calibrated photometry from LSST will aid in our analysis of comet lightcurves. We expect, while rotation periods and phase function slopes may be obtainable with good accuracy from such lightcurves, **the most realistic models will require temporally-dense photometry** - achievable only by targeted monitoring programmes such as this one. The combination of these dense, single-epoch lightcurves and data points from LSST covering a wide range of geometries will, we predict, enable the shapes of JFC nuclei to be as well-constrained as is possible from ground-based observations.

18 TECHNICAL INFORMATION (I)

Give details of the technical feasibility of the proposal (S/N,etc) AND any non-standard technical requirements

Target selection & technical justification

We have selected three comet nuclei as ideal targets for this analysis: **137P/Shoemaker-Levy 2** ($P_{rot} \sim 8$h); **162P/Siding-Spring** ($P_{rot} \sim 33$h); and **172P/Yeung** ($P_{rot} \sim 34$h).

Each of these comets has existing archival lightcurves (see Fig.2). As can be seen from the figure, large regions of the lightcurves of 137P and 172P are not well sampled despite observations over multiple epochs. Collecting large lightcurve segments of these objects over the course of a single epoch, to combine with this sparse photometry covering multiple observing geometries, will enable us to model the shapes of these objects for the first time.

The lightcurve of 162P is noticeably more populated, predominantly due to a targeted run using the INT in Feb 2017. Thanks to these data, we have been able to produce a first shape model of 162P, seen in Fig.3. Based on the pole solution resulting from this model, 2022A provides us with an opportunity to acquire more high quality, dense single-epoch photometry at an aspect angle ~10° further northwards on the object. Adding this to our existing dataset will enable us to not only ensure the robustness of the modelling procedure for comets, but also to improve the preliminary shape model and to verify the tentative evidence that 162P might be a contact binary.

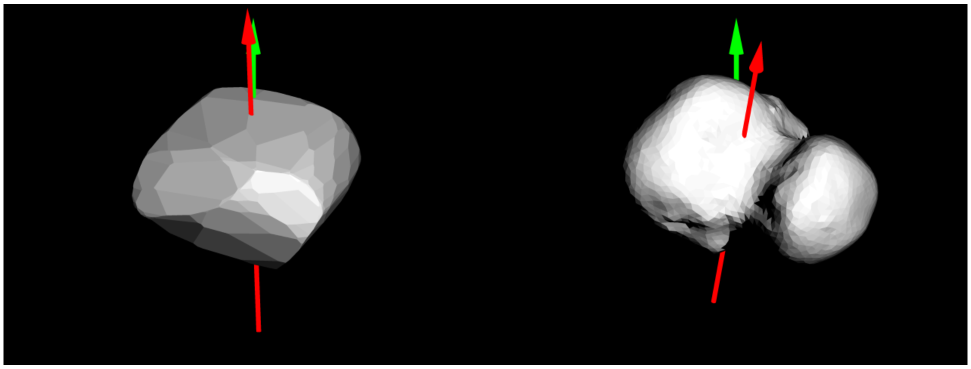
While comet 137P is faint, it is expected to reach solar phase angles lower than it has been previously observed at (existing phase angle coverage: 3-17°, possible to obtain 1-3° during early 2022A). Observations with sufficient S/N will allow us to not only to produce a shape model, but also extend the phase function slope to closer to opposition ($\alpha \sim 0°$). It would also benefit enormously from a completely-sampled lightcurve during a single epoch, to test the precision of its current phase function that has, at present, been spliced together using sparse photometry from multiple epochs.

Using the CLI method, we will improve our estimate of the objects' rotation periods (one of the software capabilities is searching for a best-fitting sidereal period), which we have tested successfully using existing lightcurves for 162P. Sufficiently well-populated lightcurves will constrain the overall shape of each object; we can then use clues from the models to infer any large-scale surface concavities which may indicate a contact binary configuration. We will also use these lightcurves to measure and update each object's phase function, enabling us to determine their precise absolute magnitudes. Combined with the known effective radii [15], we can improve the precision of the nucleus albedo measurement for each comet.

Time requested & observing strategy

We request 4 nights of optical lightcurve observations with the **INT WFC** in semester 2022A. The two primary targets, 162P and 172P, are slow rotators, meaning several hours each night will be needed to cover a different lightcurve segment. At the beginning of each night we will spend several hours on 172P, and several hours on 162P at the end of the night. At intermediate times, we will observe 137P. We therefore request 4 nights (minimum useful: 3) where we can spend several hours on each of the three targets to populate large fractions of the rotational lightcurves. We will use the Sloan R filter, to combine these observations with our existing sparse R-band lightcurves. This will enable us to perform precise absolute calibration using field stars from the Pan-STARRs catalogue. The large FOV on the WFC will allow us to perform precise calibration on even very sparse star fields.

These comets all display weak levels of activity when close to the Sun, though are at sufficient heliocentric distances (>3.5 au) during the times requested such that we do not expect to detect any coma, as has historically been the case for these objects. We will nonetheless check the PSF early in the observations of each object for any evidence of activity, and prepare suitable backup targets in the unlikely event activity is detected. The large heliocentric distances also mean they will be faint targets (R-mag ~19mag for 162P, ~21 for 172P and ~22 for 137P) and require a telescope with a large collecting area such as the INT for accurate magnitude estimates. Using the exposure time calculator for the WFC, it should be possible to obtain S/N ~20 using 350s exposures for the faintest object, 137P, during dark time. For the brightest object 162P, we can obtain S/N ~90 with 60s exposures. Within these exposures the comets shouldn't trail by more than the radius of the seeing disc.



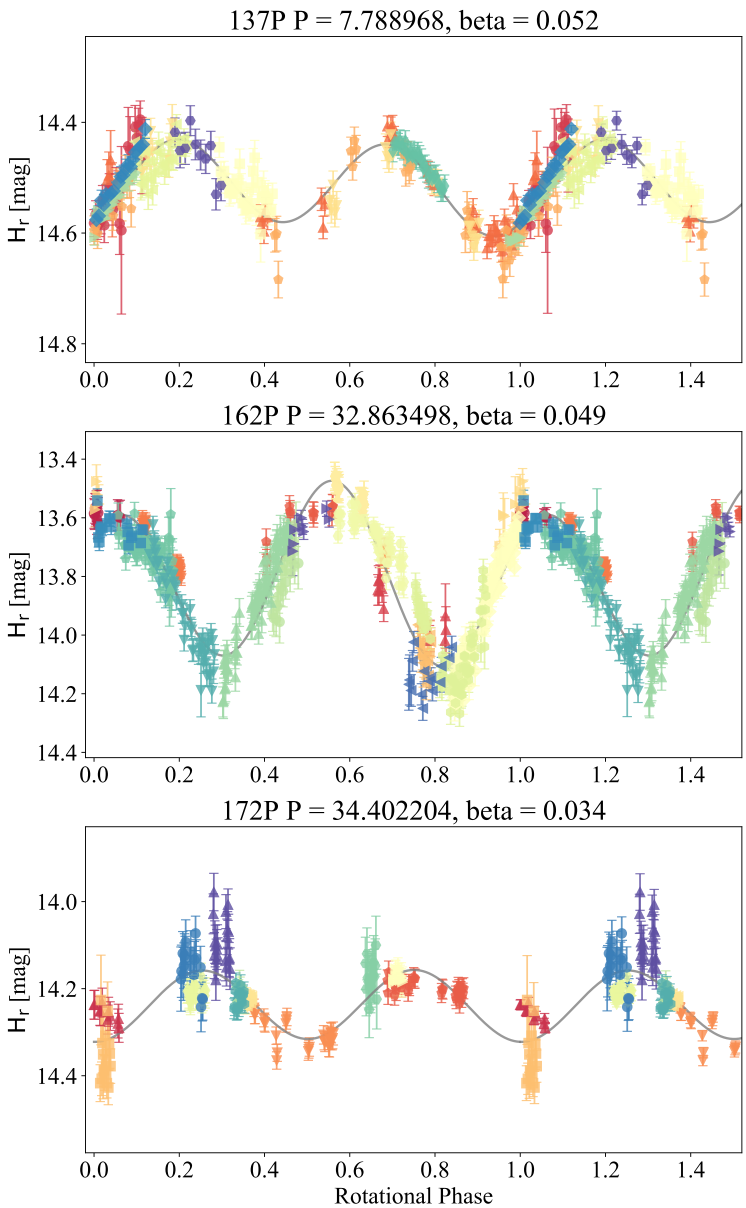


Figure 1: (Above) Projection of two models of the nucleus of 67P corresponding to the same observing conditions. Left is the CLI model from [10], right is an early model based on resolved spacecraft data from Rosetta. While there are clear differences between the two, CLI still manages to reproduce basic characteristics of the shape, particularly the elongation.

Figure 2: (Left) Summary of the existing lightcurve data for the three objects selected for this analysis: 137P (top), 162P (middle) and 172P (bottom). Each curve is plotted to 1.5× the rotational phase on the x-axis to allow for a clearer picture of the comets' lightcurve coverage.

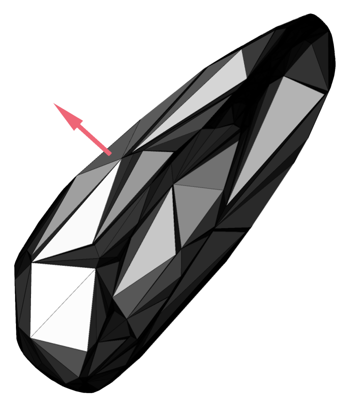


Figure 3: (Above) Plane of sky projection (Feb 2017) of our preliminary convex model of 162P, first target of this CLI analysis. This shape has elongation $\frac{a}{b}$ = 1.6, and rotation pole direction (λ, β)=(300,38)°, indicated here by red arrow. The shape model was only possible thanks to targeted INT time in semester 2017A (geometry of which illustrated by illumination of model in this figure). Making use of a new geometry available in 2022A, we would like to test the robustness of the application of the CLI procedure to comets, and improve on this shape.

References: [1] K. Noll Set al. Icarus, 194 (2), 758-768 (2008) • [2] B. J. R. Davidsson et al. A&A 592, A63 (2016) • [3] S. R. Schwartz et al. Nature Astronomy 2 (2018), 379 • [4] T. K. Safrit et al. Planetary Science Journal 2.1 (2021), 14 • [5] D. C. Jewitt Comets II University of Arizona Press (2004), 659–676 • [6] R. Kokotanekova MNRAS 479:4 (2018) 4665; [7] M. Kaasalainen and J. Torppa. Icarus 153 (2001), 24 • [8] M. Kaasalainen, J. Torppa, and K. Muinonen. Icarus 153 (2001), 37 • [9] J. Ďurech, V. Sidorin, and M. Kaasalainen. A&A 513 (2010), A46 • [10] S. C. Lowry et al. A&A 548 (2012), A12 1 • [11] A. McNeill et al. AJ 156:6 (2018) 282 • [12] J. Jeans, *Problems of cosmogony and stellar dynamics* (2019) • [13] C. Snodgrass et al. MNRAS 414 (2011) 458-469 • [14] R. Kokotanekova et al. MNRAS 471 (2017) 2974 • [15] Y.R. Fernández et al. Icarus 226:1 (2013) 1138 • [16] D. Jewitt AJ 150:201 (2015) 18

19 SUMMARY OF BACKUP PROGRAMME FOR POOR OBSERVING CONDITIONS

If instrumentation or setup differs from main programme, give full details

In the unlikely event of any of these targets being active, or in case poor conditions render our faint target unobservable, we will prepare backup targets - either NEOs to supplement AR's programme, or brighter short period comets - that would benefit from targeted photometric monitoring.

20 RELATED PATT APPLICATIONS OVER THE LAST FOUR SEMESTERS *(including unsuccesful applications)*

PATT reference:	Award:	Clear nights:	Comments:
XPL21B13	20h	-	Liverpool Telescope (2021B): Programme providing sparse lightcurve coverage of 162P over ∼4 months to obtain photometry at highest solar phase angle yet (12$^\circ < \alpha <$16°)

21 PUBLICATIONS BASED ON PATT TIME PUBLISHED DURING THE LAST FOUR SEMESTERS *(maximum 6)*

Zegmott T.J., Lowry S.C., Rożek A., Rozitis B., Nolan M.C., Howell E.S., Green S.F., Snodgrass C., Fitzsimmons A., Weissman P.R., Detection of the YORP Effect on the contact-binary (68346) 2001 KZ66 from combined radar and optical observations, 2021, MNRAS (accepted)

Rożek A., Lowry S. C., Nolan M. C., Taylor P. A., Benner L. A. M., Fitzsimmons A., Zegmott T. J., Weissman P. R., Green S. F., Rozitis B., Snodgrass C., et al., Shape model and spin-state analysis of PHA contact binary (85990) 1999 JV6 from combined radar and optical observations, 2019, A&A, 631, A149

22 EXPERIENCE OF INTENDED OBSERVERS WHO HAVE NOT PREVIOUSLY USED THIS TELESCOPE

CS and RK are experienced INT observers

AD PhD student with minimal experience, who will be accompanied if awarded time

AR is an experienced observer at other telescopes

23 COMPLETE IF THE OBSERVATIONS ARE PRIMARILY FOR A STUDENT RESEARCH TRAINING PROGRAMME

Name of student:	Abbie Donaldson
Project title:	Comet evolution: JFC nuclei

24 COMPLETE IF THE OBSERVATIONS ARE ASSOCIATED WITH A CURRENT STFC RESEARCH GRANT

Name of principal investigator:	
Grant title:	
Grant number:	

25 NON-STANDARD TRAVEL AND SUBSISTENCE REQUIREMENTS *(UK observers only)*

Justify requests for travel and subsistence for more than one person:

Details of any other expenditure (eg freight, remote observing):