ASTEROIDS 4092 TYR (FOLLOW UP, ANALYSIS, PRELIMINARY RESULTS) AND 699 HELA (SPIN-SHAPE MODEL)

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In this work we present the results of the photometric follow up of the asteroid 4092 Tyr carried out by the Grupo de Observadores de Asteroides throughout the months of 2020 August and September. The rotation period derived from the observations is P = 16.091 ± 0.003 h. Furthermore, 4092 Tyr has been revealed to be a synchronous binary asteroid with two main bodies of similar size. We also present a confirmation of the rotation period of the asteroid 699 Hela (0.1415100 ± 0.0000024 d), and a study of its shape and spin. We analyze dense lightcurves acquired in 2020 by the Grupo de Observadores de Asteroides, as well as those available in public databases. We have also used sparse lightcurves from USNO (Flagstaff) and the TESS mission. We find two possible solutions for the spin axis (λ1, β1) = (37°, +51°), (λ2, β2) = (189°, +14°), in agreement with previously published models.

4092 Tyr is a main-belt asteroid discovered by Jensen in 1986. The published diameter is 6.8 km and the albedo is 0.2 (LCDB; Warner et al., 2009), but the rotation period is not confirmed. A search in public databases did not find dense lightcurves prior to 2020. In the Database of Asteroid Models from Inversion Techniques (DAMIT, 2020) are published two models of the asteroid (Ďurech, 2019) made with photometry from the Gaia mission (Gaia collaboration et al., 2018) and sparse photometry from the Asteroids Dynamics Syte (AstDys-2, 2020). These models don't show the binary nature of Tyr but the inferred rotation period (16.0937 h) is in good agreement with the period presented in this work.

An analysis of the sparse photometry (Lowel, Catalina, Gaia) made by researchers from the Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA) using the Generalyzed Lomb Scargle (GLS) periogram (Zechmeister and Kürster, 2018), also shows a value for the rotation period of Tyr in agreement with that obtained from the Grupo de Observadores de Asteroides (GOAS, 2020) lightcurves.

Since GOAS observes poorly studied asteroids, or those that require revision, 4092 Tyr was included in the photometric monitoring program. Fifty-eight lightcurves were obtained in 25 nights between 2020 August 20 and September 29, with 4092 Tyr in the range of ecliptic longitudes and latitudes λ = 329.6658°, β = 3.9038°, and λ = 344.9986°, β = 4.0247°, elongation in the range 171.4° and 137.7°, and phase angle in the range 4.3° and 19.8°. V Johnson, I cousin, R cousin, Sloan g´ and Sloan i´ were used in the photometric follow up to derive and study the color indices (in preparation).

The images were calibrated in the standard way (bias, darks and flats), rejecting those with SNR < 25 for Tyr. We also reduced to geocentric date and absolute magnitude.

In order to carry out the photometric analysis, we used the *FotoDiF* (2020) and *Periodos* (2020) packages. We derive a period P = 16.091 ± 0.003 h, with a confidence interval (probability of 0.95) from 16.082244 to 16.0987385 h and an RMS of 0.028704. The amplitude is 0.53 ± 0.04 mag. In Figure 1, we show the rotation curve of 4092 Tyr, phased with the derived period. In the figure, the magnitudes are in absolute values, and light-time and phase angle corrections have been applied.

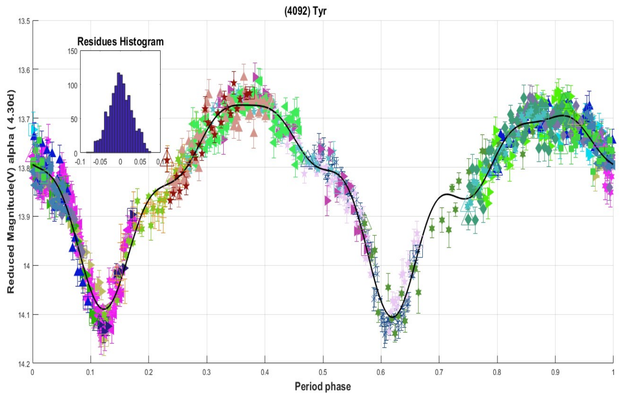

Figure 1. Rotation curve of 4092 Tyr.

In 2020 August and September, an independent photometric follow up of 4092 Tyr was made by D. Romeuf, D. Augustin, E. Barbotin and R. Behrend. None of the teams was aware of the fact that the other were doing the same follow up. A measure of the rotation period ($P = 0.670313 \pm 0.000022$ d) and an announcement of the binary nature of Tyr based on the observations from R. Behrend's team have been published independently (Behrend, 2020web). Simultaneously, the GOAS data were analyzed by P. Pravec (Ondrejov Observatory) and P.J. Gutierrez (CSIC, Observatorio de Sierra Nevada) and reported the asteroid as being binary (Garcia et al., 2020).

A detailed inspection of the temporal evolution of the minimum at phase ~0.63 and the slope in certain regions of the lightcurve, reveals the binary nature of 4092 Tyr (Kwiatkowski et al., 2009).

Figure 2 shows the evolution of the eclipse corresponding to the minimum at phase ~0.63 (typical behavior of a binary asteroid in opposition); as the days go by, a step appears in the ascending size of the lightcurve (centered in the minimum at phase ~0.63), disappearing and reappearing later in the descending size. Simultaneously, the minimum goes deeper and sharpens.

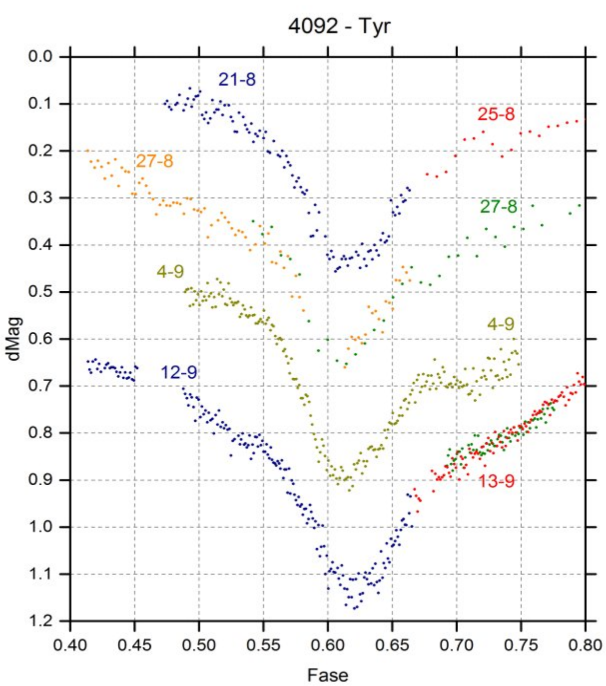

Figure 2. From top to bottom: 1) August 21th – August 25th. 2) August 27th. 3) September 4th. 4) September 12th – September 13th.

As stated in the CBET 4850, mutual eclipses are 0.17-0.23 mag deep, which implies a lower limit for the ratio of the primary to secondary diameters of 0.45. The rotations of the components are synchronous with the orbital motion, and the combined rotational amplitude of the pair is 0.3 magnitudes at a phase angle between 4° and 12°.

699 Hela has been widely observed in multiple apparitions and its rotation period is well known (Behrend, 2020web), but a unique spin-shape model has not been established yet.

Automatic surveys as ASAS-SN (Kochanek et al., 2017) or ATLAS (Tonry et al., 2018) and space missions as TESS (Ricker et al., 2014) or Gaia (Gaia collaboration et al., 2018), provide a large number of lightcurves with a wide temporal coverage to derive the main parameters of asteroids. However, since many asteroids are too faint for these automatic surveys and space missions, and also their photometry is sparse, the work of amateur astronomers is necessary. Therefore, a balance between both data sources (amateur astronomers and automatic searches) is essential.

In this work we present the first collaboration between the Grupo de Observadores de Asteroides (GOAS, 2020) and the Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), confirming the rotation period of asteroid 699 Hela and studying its shape and spin axis. For this matter we analyze observations acquired by GOAS, photometry from the TESS mission, and archival photometry.

699 Hela was observed by GOAS from 2020 July 7-24. The follow up finished with nine dense lightcurves of the asteroid. In the analysis, we used the dense lightcurves of 699 Hela available at the Asteroid Photometry Database (ALCDEF, 2020). Eleven lightcurves are available at ALCDEF, and five of them have already been obtained by GOAS in the 2020 follow up. Therefore, six dense lightcurves covering the 1999, 2016, and 2020 apparitions were used from ALCDEF. We also used the sparse lightcurves from USNO (Flagstaff), available at the Asteroids Dynamics Site (AstDys-2, 2020), as well as the sparse lightcurves reduced by Pál et al. (2020) from the TESS space mission (Ricker et al., 2014).

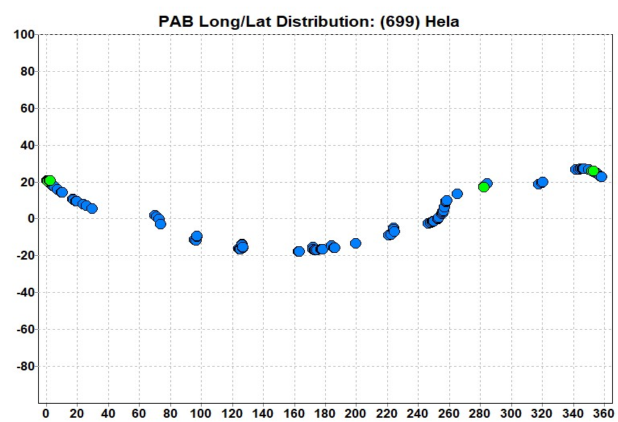

Figure 3. Ecliptic longitude and latitude of phase angle bisector for the observations used. Blue: sparse data. Green: dense data.

The analysis of the light curves obtained by GOAS in the 2020 apparition using the ANOVA method (Schwarzenberg-Czerny, 1996), results in a rotation period of 3.3959 ± 0.0022 h (Figure 4), in agreement with the value of 3.39624 ± 0.00006 h that was published by R. Behrend (2020web) with the same data. We will adopt this second value for the rotation period of 699 Hela.

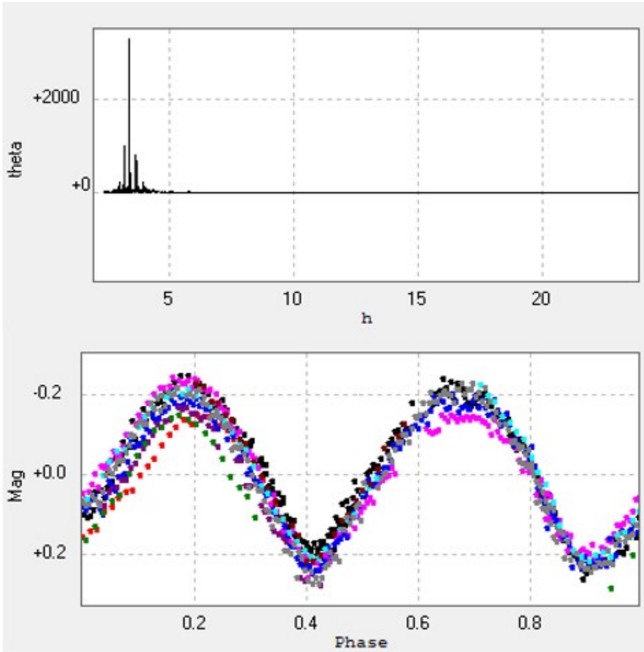

Figure 4. Top panel: ANOVA periodogram obtained with GOAS data of 699 Hela. The highest peak is at 3.3959 ± 0.0022 h. Bottom panel: photometry data phased with the period of 3.3959 ± 0.0022 h.

The lightcurve inversion was made with the *MPO LCInvert* package (BDW Publishing, 2016), which implements the procedures described in Kaasalainen and Torppa (2001) and Kaasalainen et al. (2001). We adopted a weight of 0.3 for the sparse curves (USNO and TESS) and 1.0 for the dense curves (ALCDEF & GOAS). We carried out a medium search adopting P = 3.39624 h, a value of 0.1 for the dark facet factor and 50 iterations. In this way we analyzed 312 different positions of the pole in steps of 15° in latitude and longitude. The analysis finds two regions (Figure 5) that minimize χ2, centered at (λ, β) = (30°, +45°) and (195°, +15°).

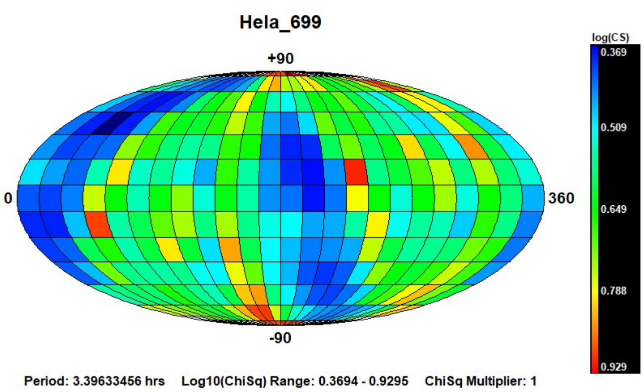

Figure 5: Initial pole search distribution. The darkest blue regions are those that minimize χ2.

After that, we made fine searches centered in these two initial values found. The fine searches find (λ_1, β_1) = (37°, +51°) and (λ_2, β_2) = (189°, +14°), with values χ2 = 2.34 and χ2 = 2.30, respectively. These solutions, with a typical uncertainty of ±20°, seem to mirror one another. They are also in moderate agreement with the solutions published in the DAMIT database (Ďurech et al., 2010), (λ, β) = (45°, +44°) or (197°, +31°). However, more observing campaigns are necessary to adopt one of the two solutions.

In Figure 6 we present the shape model obtained corresponding to the solution (λ_2, β_2) = (189°, +14°), while in Figure 7 we present two examples of the fit between the light curves from GOAS and TESS and the theoretical lightcurves based on the derived model.

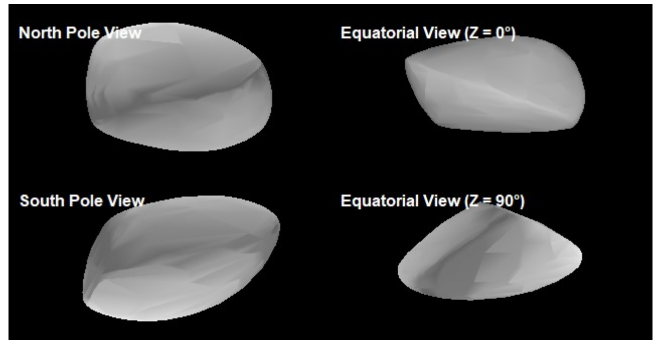

Figure 6. Shape model of (699) Hela corresponding to the solution (λ_2, β_2) = (189°, +14°).

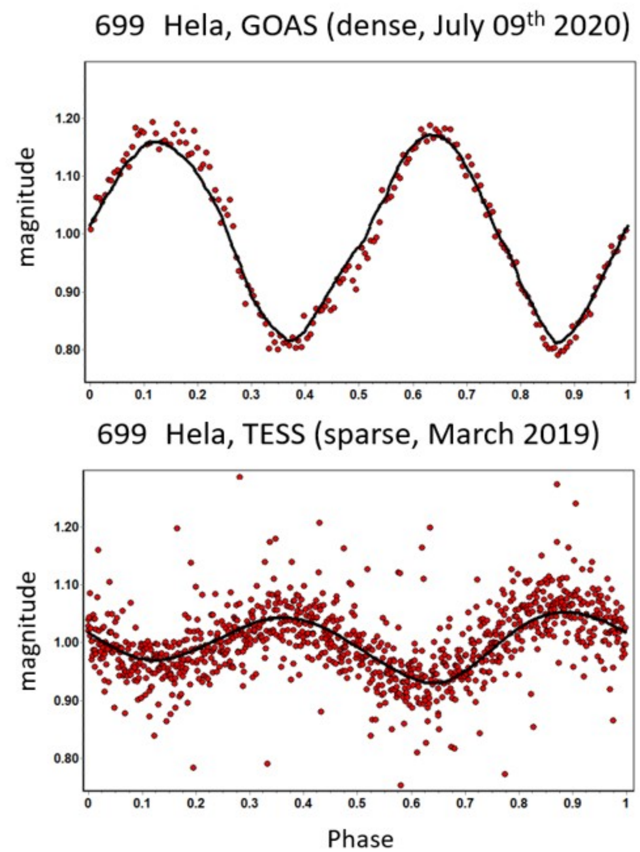

Figure 7. The fit between the experimental (red dots) and theoretical (black lines) lightcurves derived from the model for the solution (λ_2, β_2) = (189°, +14°). Top panel: red dots correspond to dense data obtained by GOAS on 2020 July 9. Bottom panel: red dots correspond to the sparse data from the TESS mission.

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References

ALCDEF (2020). Asteroid Lightcurve Data Exchange Format database. *http://www.alcdef.org/*

AstDys-2 (2020). Asteroids - Dynamic Site web location. *https://newton.spacedys.com/astdys2/*

BDW Publishing (2016). *http://www.minorplanetobserver.com/MPOSoftware/MPOLCInvert.htm*

Behrend, R. (2020web). Observatoire de Geneve web site. *http://obswww.unige.ch/~behrend/page_cou.html*

DAMIT (2020). Database of Asteroid Models from Inversion Techniques (DAMIT). *https://astro.troja.mff.cuni.cz/projects/damit/*

Ďurech, J.; Sidorin, V.; Kaasalainen, M. (2010). "DAMIT: A Database of Asteroid Models." *Astronomy & Astrophysics* ***513***, A46.

Ďurech, J.; Hanuš, J.; Vančo, R. (2019). "Inversion of Asteroid Photometry from Gaia DR2 and the Lowell Observatory Photometric Database." *Astronomy & Astrophysics* **631**, A2.

Fotodif (2020). *http://astrosurf.com/orodeno/fotodif/index.htm*

Gaia Collaboration; Brown, A.G.A.; Vallenari, A.; Prusti, T.; de Bruijne, J.H.J.; Babusiaux, C.; and 448 colleagues. (2018). "Gaia Data Release 2 Summary of the Contents and Survey Properties." *Astronomy & Astrophysics* **616**, A1.

Garcia, F.; Farfan, R.G.; Pravec, P.; Ruiz, J.; et al. (2020). *CBET* **4850**.

GOAS (2020). Grupo de Observación de Asteroides. *https://sites.google.com/view/goas2*

Kaasalainen, M.; Torppa, J. (2001). "Optimization Methods for Asteroid Lightcurve Inversion: I. Shape Determination." *Icarus*, **153**, 24-36.

Kaasalainen, M.; Torppa, J.; Muinonen, K. (2001). "Optimization Methods for Asteroid Lightcurve Inversion: II. The Complete Inverse Problem." *Icarus* **153**, 37-51.

Kochanek, C.S.; Shappee, B.J.; Stanek, K.Z.; Holoien, T.S.; Thompson, T.A.; Prieto, J.L.; Dong, S.; Sheilds, J.V.; Will, D.; Britt, C.; Perzanowski, D.; Pojmanski, G. (2017). "The All-sky Automated Survey for Supernovae (ASAS-SN) Light Curve Server. v1.0." *Publications of the Astronomical Society of the Pacific* **129**, 104502.

Kwiatkowski, T.; Kryszczyńska, A.; Polińska, M.; Buckley, D.A.H.; O'Donoghue, D.; Charles, P.A.; Crause, L.; Crawford, S.; Hashimoto, Y.; Kniazev, A.; Loaring, N.; Romero Colmenero, E.; Sefako, R.; Still, M.; Vaisanen, P. (2009). "Photometry of 2006 RH120: An Asteroid Temporary Captured into a Geocentric Orbit." *Astron. Astrophys.* ***495***, 967-974.

Pál, A.; Szakáts, R.; Kiss, C.; Bódi, A.; Bognár, Z.; Kalup, C.; Kiss, L.L.; Marton, G.; Molnár, L.; Plachy, E.; Sárneczky, K.; Szabó, G.M.; Szabó, R. (2020). "Solar System Objects Observed with TESS - First Data Release: Bright Main-belt and Trojan Asteroids from the Southern Survey." *Ap. J. Suppl. Ser.* **247**, id.26.

Períodos (2020). *http://www.astrosurf.com/salvador/Programas.html*

Ricker, G.R.; Winn, J.N.; Vanderspek, R.; Latham, D.W.; Bakos, G.A. and 53 colleagues (2014). "Transiting Exoplanet Survey Satellite." *Journal Astron. Telescopes, Instruments, and Systems* **1**, p. 014003.

Schwarzenberg-Czerny, A. (1996). "Fast and statistically optimal period search in uneven sampled observations." *Ap. J. Letters* **460**, L107.

Tonry, J.L.; Denneau, L.; Heinze, A.N.; Stalder, B.; Smith, K.W.; Smartt, S.J.; Stubbs, C.W.; Weiland, H.J.; Rest, A. (2018). "ATLAS: A High-cadence All-sky Survey System." *Publications of the Astronomical Society of the Pacific* **130**, 064505.

Warner, B.D.; Harris, A.W.; Pravec, P. (2009). "The Asteroid Lightcurve Database." *Icarus* **202**, 134-146. Updated 2020 June. *http://www.minorplanet.info/lightcurvedatabase.html*

Zechmeister, M.; Kürster, M. (2009). "The generalised Lomb-Scargle periodogram-a new formalism for the floating-mean and Keplerian periodograms." *Astron. Astrophys.* ***496***, 577-584.