

LIGHTCURVES AND DERIVED RESULTS FOR KORONIS FAMILY MEMBER (452) HAMILTONIA

Stephen M. Slivan, Kaylee Barrera, Abigail M. Colclasure,
Erin M. Cusson, Skylar S. Larsen, Claire J. McLellan-Cassivi,
Summer A. Moulder, Prajna R. Nair, Paola D. Namphy,
Orisvaldo S. Neto, Maurielle I. Noto, Maya S. Redden,
Spencer J. Rhodes, Sandra A. Youssef
Massachusetts Institute of Technology,
Dept. of Earth, Atmospheric, and Planetary Sciences,
77 Mass. Ave. Rm. 54-424, Cambridge, MA 02139
slivan@mit.edu

(Received: 2024 January 15)

Lightcurves of (452) Hamiltonia recorded during three apparitions are presented with derived results for synodic rotation period, and analyzed together with data from other apparitions for spin vector and model shape.

Koronis family member (452) Hamiltonia was observed as a smaller target of opportunity during the study of larger Koronis members described by Slivan et al. (2008; 2023). Lightcurves have been reported by Pilcher (2010), who derived a rotation period of about 2.88 h from data spanning 23 nights in 2009, and by Aznar Macías et al. (2018) who observed lightcurves two nights apart in 2017 for a period consistent with the earlier result. The present paper begins by reporting new lightcurve observations from three apparitions, then in combination with data from Wilkin and Maier (2024), a single-apparition synodic period precise enough to count sidereal rotations is determined. Finally, a combined analysis with lightcurves from other apparitions is presented to determine the sidereal rotation period, spin vector orientation, and a convex model shape.

Lightcurves of Hamiltonia were recorded during a total of three apparitions at Whitt Observatory (WhO) in Wellesley, MA, and at the George R. Wallace Astrophysical Observatory (WAO) in Westford, MA. Observing circumstances are presented in Table I, and information about the telescopes and cameras appears in Table II. Observing and data reduction procedures were as previously described by Slivan et al. (2008); the 2022 and 2023 data were measured using synthetic aperture sizes informed by Howell (1989). Lightcurves were reduced for light-time, and standard-calibrated brightnesses were reduced to unit distances. Composite lightcurves are shown in Fig. 1, where nights of relative photometry have been shifted in brightness for best fit to their respective composites.

2006 apparition: (Fig. 1, top) Although these data at a previously unobserved aspect span 45 nights, partial lightcurves on the first two nights do not meaningfully constrain the period. Thus, the period error determination is based on a span of only 24 nights, yielding a composite lightcurve that is doubly periodic in 2.8813 ± 0.0004 h. Observations of Landolt (1983) standard star SA099-367 were used to calibrate the lightcurves to standard system R.

2022 apparition: (Fig. 1, center) The data span 28 nights, at a viewing aspect similar to that of the published data from 2017, for a derived period of 2.8812 ± 0.0004 h.

2023 apparition: (Fig. 1, bottom) These data span 23 nights at a previously unobserved aspect, for a derived period of 2.8816 ± 0.0003 h.

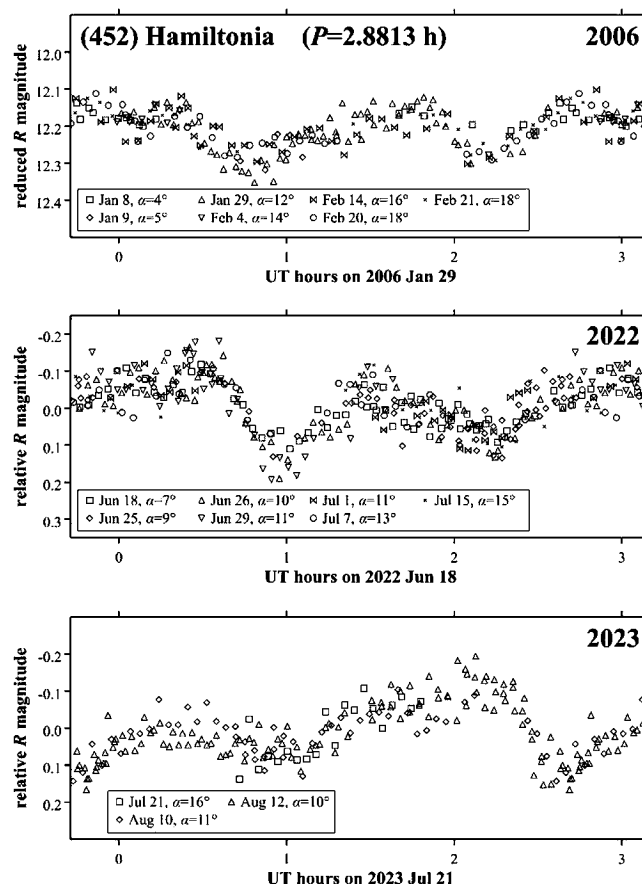


Figure 1. Folded composite lightcurves during apparitions in 2006 (top), 2022 (center), and 2023 (bottom), light-time corrected with the earliest and latest 10% of rotation repeated. Legends give UT dates of observations and solar phase angles α .

The rotation periods derived from the three independent data sets each are consistent with the previously published periods.

In 2023 Hamiltonia also was observed by Wilkin and Maier (2024), to increase the precision of the derived synodic period by extending the length of the time interval spanned by the data during the apparition. Combined, the 2023 data span 92 nights over four lunations and yield a derived synodic rotation period of 2.88130 ± 0.00006 h, which is precise enough to unambiguously count rotations between the consecutive apparitions in 2022 and 2023 (Slivan, 2012; Eqs. 3-5).

The observations reported here, together with those recorded in 2009 (Pilcher, 2010) and in 2017 (Aznar Macías et al., 2018), comprise dedicated lightcurves from a total of five apparitions. The amplitudes do not exceed 0.25 mag, and the lightcurve shapes exhibit significant asymmetric departures from sinusoids. Slivan (2013) discusses constraining an asteroid's sidereal rotation period by combined analysis of observations from multiple apparitions; in favorable cases epochs from five aspects can be sufficient to isolate a sidereal rotation count.

The epochs presented in Table III were measured from the lightcurves using the filtered Fourier series model approach described by Slivan et al. (2024). Estimating the epoch errors here was a bit more involved, because the Hamiltonia lightcurves are asymmetric with significantly different maximum slopes between

each pair of extrema. For that reason, the maximum slope in each unfiltered model at mid-brightness was used in estimating the corresponding epoch error, instead of the slope from the filtered model.

It is noted that the 2017 lightcurve data values used in the present work were estimated from the graph figure presented in Aznar Macías et al. (2018) and are incomplete, because of the 85 points indicated in the text only 72 are distinguishable on the graph, and the original measurements are unavailable.

Applying the sidereal rotation-counting sieve algorithm (Slivan, 2013) to the intervals among all five epochs finds an unambiguous integer count of half-rotations, with the unknown direction of spin yielding a pair of candidate sidereal periods (Fig. 2). Analysis of the same epochs using sidereal photometric astrometry (SPA) (Slivan, 2014; Drummond et al., 1988) indicates that the pole does not lie near the ecliptic plane (Fig. 3), but it does not otherwise distinguish the direction of spin.

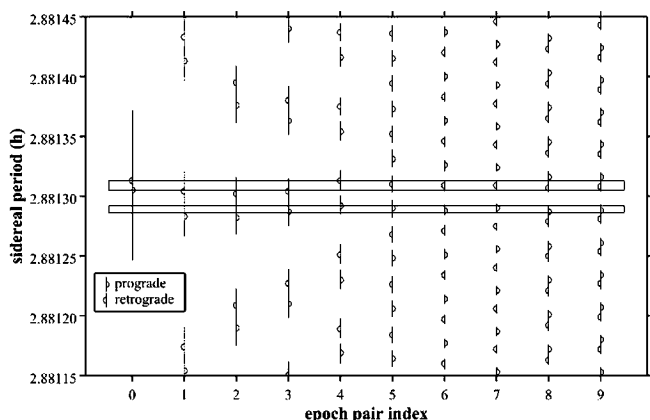


Figure 2. Sieve algorithm output for the five epochs in Table III, Part A. The number of rotations that elapsed during the longest interval spanning 2006 to 2023, excluding the fraction of a rotation induced by the aspect change, is unambiguously 53159.5 rotations. The two ranges of periods indicated by thin horizontal rectangles represent the non-overlapping constraints for the two possible directions of spin. Candidate ranges of periods for each epoch interval were calculated using epoch range half-widths of 2.5 times the epoch errors.

To test whether including epochs from additional apparitions might distinguish the spin direction, the MPC Orbits/Observations Database was checked for suitable additional photometry to fill in gaps in the dedicated lightcurves' aspect coverage (Fig. 4). Observations from the ATLAS sky survey (Tonry et al., 2018) recorded during the 2019 and 2021 apparitions (Fig. 5) supply data from aspects that reduce two of the three largest gaps (Table III, Part B). Including these two epochs does not significantly change the results, which suggests that in this case the aspect coverage is not a limiting factor. Instead, it is plausible that the combined low amplitude and asymmetry of the lightcurves are interfering with measuring the epochs accurately enough to distinguish the direction of spin. Thus, the outcome of the epochs analyses is a pair of derived candidate sidereal periods: 2.8812885 ± 0.0000018 h for prograde spin, and 2.8813078 ± 0.0000018 h for retrograde spin.

With its good aspect coverage over seven apparitions, and having already yielded an unambiguous sidereal rotation count, this data set is a good candidate for convex inversion (CI) (Kaasalainen et al., 2001). The lightcurves were analyzed using CI as described by Slivan et al. (2023), here including the sky survey data as

standard-calibrated photometry. The analysis identifies a symmetric pair of retrograde pole regions (Fig. 6) whose ambiguity is a consequence of the small 3° orbit inclination of Hamiltonia; the corresponding spin vector results are summarized in Table IV. Lightcurve fits and model shape renderings for pole solution P_3 are shown in Figs. 7 and 8, respectively. The spin vector lies near the short-period end of the spin rate vs. obliquity distribution of retrograde poles in the Koronis family, close to that of larger member (321) Florentina (Slivan et al., 2023).

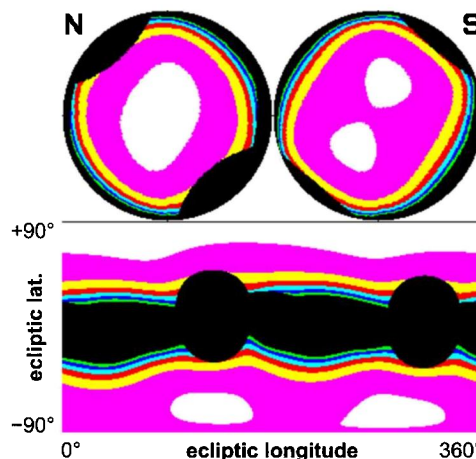


Figure 3. Contour graphs of RMS error of trial poles for the SPA analyses of the five epochs in Table III, Part A. The lower half of the figure represents the celestial sphere as a rectangular grid of ecliptic longitude and latitude; the same data in a polar format undistorted near the ecliptic poles appear in the upper half of the graph, where north and south hemispheres are plotted separately. Best-fit regions are colored white. Here the poorest-fit region (black) rules out pole locations near the ecliptic plane.

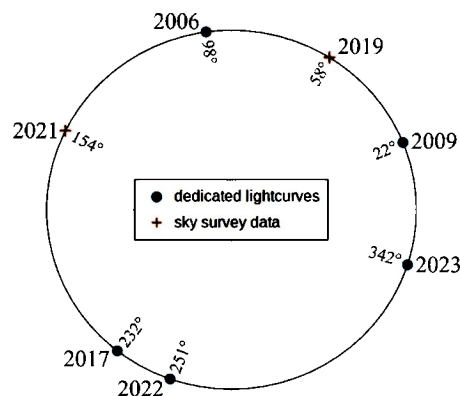


Figure 4. Angular distribution of ecliptic longitudes of phase angle bisectors (PABs) for epochs in Table III. Each apparition of sky survey data is represented by a single longitude calculated for the “median date” of the UT dates of observations.

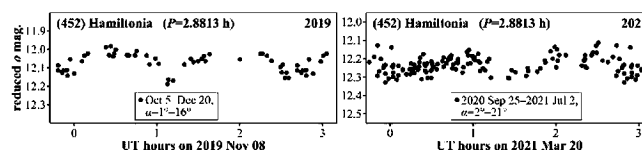


Figure 5. Photometry from the ATLAS sky survey (Tonry et al., 2018) during the 2019 and 2021 apparitions, each composited to the median date of the data. The slope parameter $G = 0.23$ for S-type objects (Lagerkvist and Magnusson, 1990) was used to reduce for changing solar phase angle.

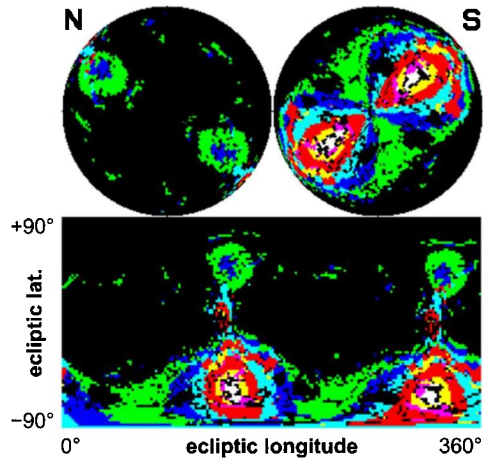


Figure 6. Similar to Fig. 3 but for the CI analysis of the seven apparitions of lightcurve data, locating a symmetric pair of retrograde pole regions.

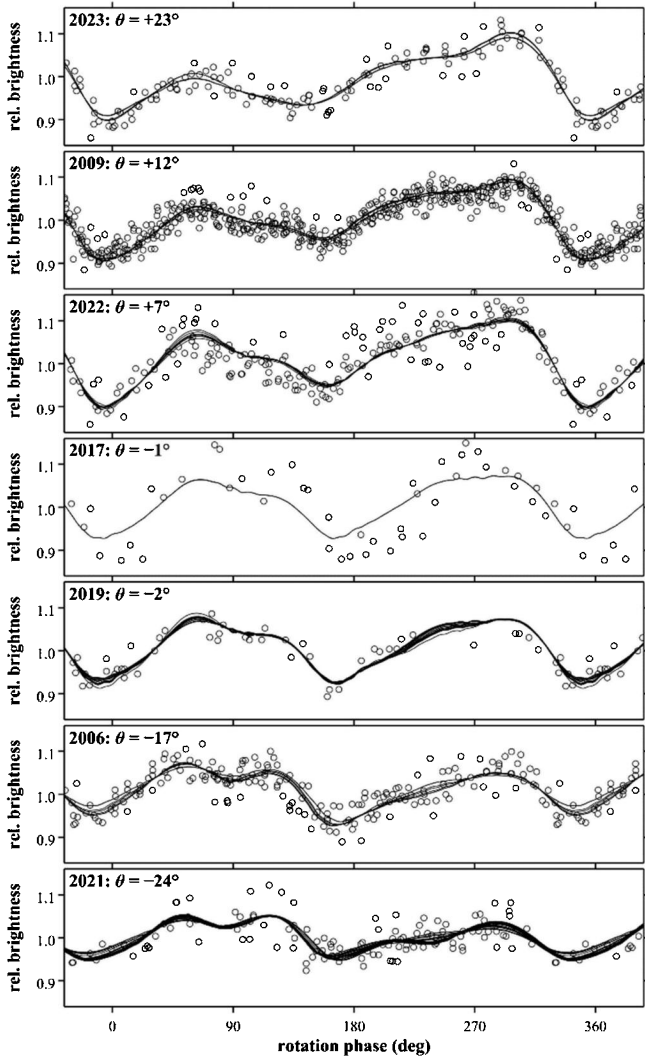


Figure 7: CI model lightcurve fits for pole P_3 as brightness vs. sidereal rotation phase. Changes in lightcurve shape during the apparition appear as non-overlapping model curves. The graphs are presented in order of decreasing sub-PAB latitude θ . The RMS error of the fit to the combined data set corresponds to 0.035 mag.

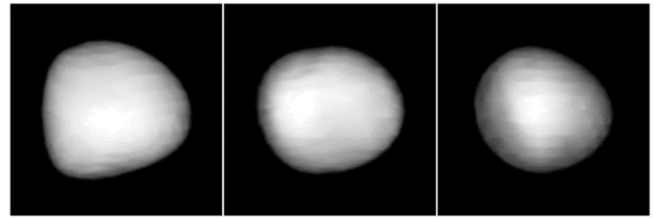


Figure 8. Renderings of convex model for pole P_3 . (left) Polar aspect, showing the rounded triangular profile that contributes to low-order asymmetry of the lightcurves. (center and right) Equatorial aspects for side-on (lightcurve maximum) and end-on (lightcurve minimum) views, respectively. The model for the symmetric pole P_4 is essentially a mirror image.

			Tel.		Integration	
UT date			α (°)	ID	Filter	time (s)
2006	Jan	08.1	4.2	WhO	R	240
2006	Jan	09.0	4.6	WhO	R	240
2006	Jan	29.1	12.1	WhO	R	240
2006	Feb	04.1	14.0	WhO	R	240
2006	Feb	14.1	16.5	WhO	R	240
2006	Feb	20.2	17.7	WhO	R,c	240
2006	Feb	21.0	17.9	WhO	c	240
2022	Jun	18.1	6.8	WAO-P24	R	180
2022	Jun	25.1	9.4	WAO-P24	R	500
2022	Jun	25.2	9.4	WAO-3,4	R	180
2022	Jun	26.1	9.7	WAO-3	R	180
2022	Jun	29.1	10.8	WAO-3	R	180
2022	Jul	01.1	11.4	WAO-3	R	180
2022	Jul	07.1	13.3	WAO-4	R	240
2022	Jul	15.1	15.4	WAO-4	R	300
2023	Jul	21.3	16.2	WAO-4	R	200
2023	Aug	10.3	10.7	WAO-4	R	200
2023	Aug	12.3	10.0	WAO-3,4	R	200

Table I: Nightly observing information, rows grouped by apparition. Columns are: UT date at lightcurve mid-time, solar phase angle α , telescope ID (Table II), filter used (R , Cousins R ; c , colorless), and image integration time.

Tel. ID	Dia. (m)	CCD camera	FOV (')	Bin	Scale ("/pix)
WhO	0.61	Photometrics TK 1K	16×16	2×2	1.84
WAO-3	0.36	FLI ML1001	20×20	1×1	1.18
WAO-4	0.36	SBIG STL-1001	21×21	1×1	1.25
WAO-P24	0.61	FLI PL16803	32×32	1×1	0.46

Table II: Telescopes and cameras information. Columns are: telescope ID (WhO, Sawyer Boller & Chivens 24-in; WAO-3 and WAO-4, shed piers #3 and #4 Celestron Classic C14; WAO-P24, Elliot PlaneWave 24-in CDK), telescope diameter, CCD camera, detector field of view, image binning used, and binned image scale.

UT date	Epoch (UT h)	PAB $\lambda, \beta(^{\circ})$	Data ref.
Part A: Dedicated lightcurves			
2006 Jan 29	0.10 ± 0.07	$97.9, +0.8$	a
2009 Sep 26	1.29 ± 0.04	$22.0, -3.9$	b
2017 May 17	1.33 ± 0.07	$231.9, +2.6$	c
2022 Jun 18	0.20 ± 0.06	$250.6, +1.3$	a
2023 Jul 21	0.46 ± 0.05	$342.1, -3.4$	a, d
Part B: Sky survey lightcurves sparse-in-time			
2019 Nov 08	0.48 ± 0.11	$58.0, -2.5$	e, f
2021 Mar 20	0.83 ± 0.12	$153.9, +3.7$	e, f

Table III: Summary of lightcurve epochs, in each case locating a maximum from the second harmonic of a Fourier series model fit to the lightcurves. PAB λ, β are the J2000.0 ecliptic longitude and latitude of the phase angle bisector. Data references are: a, this work; b, Pilcher (2010); c, Aznar Macías et al. (2018); d, Wilkin and Maier (2024); e, ATLAS-MLO α -band; f, ATLAS-HKO α -band.

Sidereal period: 2.8813085 ± 0.0000005 h					
Spin poles	λ_0	$\sigma(\lambda_0)$	β_0	$\sigma(\beta_0)$	ε
P3:	148°	5	-62°	5	155°
P4:	315°	5	-68°	5	156°
Model axial ratios: a/b: 1.1 b/c: 1.1					

Table IV: Spin vector results. λ_0 and β_0 are the pole solutions' ecliptic longitudes and latitudes, respectively; σ are the estimated pole errors in degrees of arc; ε are the spin obliquities. The axial ratios are very coarse estimates with uncertainties of at least ± 0.1 .

Acknowledgments

At Wallace Observatory we thank Dr. Michael Person and Timothy Brothers for allocation of telescope time, and for observer instruction and support. We also thank F. Wilkin and J. Maier for providing their lightcurve data prior to publication. The student observers at Wallace were supported by grants from MIT's Undergraduate Research Opportunities Program. This work uses data obtained from the Asteroid Lightcurve Data Exchange Format (ALCDEF) Asteroid Lightcurve Photometry Database, which is supported by funding from NASA grant 80NSSC18K0851. This work has made use of data and services provided by the International Astronomical Union's Minor Planet Center; specifically, the brightnesses accompanying astrometry from the Asteroid Terrestrial-impact Last Alert System (ATLAS) survey observing program.

References

Aznar Macías, A.; Cornea, R.; Suciú, O. (2018). "Photometric Analysis and Physical Parameters for Six Mars-crossing and Ten Main-belt Asteroids from APT Observatory Group: 2017 April-September." *Minor Planet Bull.* **45**, 92-96.

Drummond, J.D.; Weidenschilling, S.J.; Chapman, C.R.; Davis, D.R. (1988). "Photometric geodesy of main-belt asteroids. II.

Analysis of lightcurves for poles, periods, and shapes." *Icarus* **76**, 19-77.

Howell, S.B. (1989). "Two-dimensional Aperture Photometry: Signal-to-noise Ratio of Point-source Observations and Optimal Data-extraction Techniques." *PASP* **101**, 616-622.

Kaasalainen, M.; Torppa, J.; Muinonen, K. (2001). "Optimization methods for asteroid lightcurve inversion. II. The complete inverse problem." *Icarus* **153**, 37-51.

Lagerkvist, C.I.; Magnusson, P. (1990). "Analysis of asteroid lightcurves. II. Phase curves in a Generalized HG-system." *Astron. Astrophys. Suppl. Ser.* **86**, 119-165.

Landolt, A.U. (1983). "UBVR Photometric Standard Stars Around the Celestial Equator." *Astron. J.* **88**, 439-460.

Pilcher, F. (2010). "Rotation Period Determinations for 81 Terpsichore, 419 Aurelia, 452 Hamiltonia, 610 Valeska, 649 Josefa, and 652 Jubilatix." *Minor Planet Bull.* **37**, 45-46.

Slivan, S.M.; Binzel, R.P.; Boroumand, S.C.; Pan, M.W.; Simpson, C.M.; Tanabe, J.T.; Villastrigo, R.M.; Yen, L.L.; Ditteon, R.P.; Pray, D.P.; Stephens, R.D. (2008). "Rotation rates in the Koronis family, complete to $H \approx 11.2$." *Icarus* **195**, 226-276.

Slivan, S.M. (2012). "Epoch Data in Sidereal Period Determination. I. Initial Constraint from Closest Epochs." *Minor Planet Bull.* **39**, 204-206.

Slivan, S.M. (2013). "Epoch Data in Sidereal Period Determination. II. Combining Epochs from Different Apparitions." *Minor Planet Bull.* **40**, 45-48.

Slivan, S.M. (2014). "Sidereal Photometric Astrometry as Efficient Initial Search for Spin Vector." *Minor Planet Bull.* **41**, 282-284.

Slivan, S.M.; Hosek Jr., M.; Kurzner, M.; Sokol, A.; Maynard, S.; Payne, A.V.; Radford, A.; Springmann, A.; Binzel, R.P.; Wilkin, F.P.; Mailhot, E.A.; Midkiff, A.H.; Russell, A.; Stephens, R.D.; Gardiner, V.; and 5 colleagues (2023). "Spin vectors in the Koronis family: IV. Completing the sample of its largest members after 35 years of study." *Icarus* **394**, A115397.

Slivan, S.M.; Barrera, K.; Colclasure, A.M.; Cusson, E.M.; Larsen, S.L.; McLellan-Cassivi, C.J.; Moulder, S.A.; Nair, P.R.; Namphy, P.D.; Neto, O.S.; Noto, M.I.; Redden, M.S.; Rhodes, S.J.; Youssef, S.A. (2024). "Lightcurves and Derived Results for Koronis Family Member (5139) Rumoi, Including a Discussion of Measurements for Epochs Analysis." *Minor Planet Bull.* **51**, 6-10.

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." *PASP* **130**, 064505.

Wilkin, F.P.; Maier, J.J. (2024). "Synodic Rotation Period for Koronis Family Object (452) Hamiltonia." *Minor Planet Bull.* **51**, 174-175.

Number	Name	yyyy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
452	Hamiltonia	2006 01/08-02/21	4.2, 17.9	98	1	2.8813	0.0004	0.14	0.04
452	Hamiltonia	2022 06/18-07/15	6.8, 15.4	251	1	2.8812	0.0004	0.23	0.06
452	Hamiltonia	2023 07/21-08/12	16.2, 10.0	343	-4	2.8816	0.0003	0.23	0.06
452	Hamiltonia					2.88130	0.00006		

Table V. Observing circumstances and results. The first three lines give the results derived from only the lightcurves reported in the present paper. Solar phase angles are given for the first and last dates, and L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range. The last line gives the synodic rotation period derived from analysis of a combined single-apparition data set, comprised of the 2023 lightcurves reported here together with data reported by Wilkin and Maier (2024).