# Estimation of the H magnitudes of near-Earth asteroids with time-resolved photometric observations at La Silla and Ondřejov Observatory

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# La Silla-Ondřejov NEA photometry project

Our long-term NEA (and MBA) photometry project:

- Primary scientific interest: NEA spin periods, vectors and states (PA vs NPA rotation), shapes, satellites (binarity), and their evolution
- Method: Time-resolved photometric (lightcurve) observations
- Our main instrument: The 1.54-m Danish telescope at La Silla
- Asteroid absolute magnitudes: A by-product of the observations

*The 1.54-m Danish telescope,*
*La Silla Observatory, Chile:*

# Accurate mean magnitude determination (1)

Observations absolutely calibrated in the Johnson-Cousins *VR* photometric system with Landolt (1992) standard stars → Absolute accuracy 0.01 mag

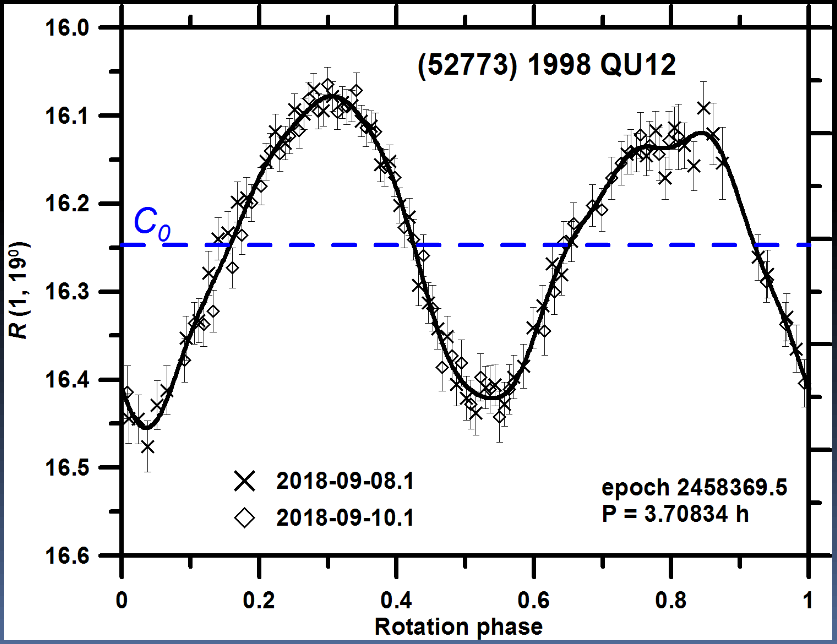
Composite rotational lightcurves – constructed from data spanning several rotations typically, reduced to unit geo- and heliocentric distances and to a reference phase angle (= the mean phase angle of the observations).

Mean magnitude – The 0th order ($C_0$) of fitted Fourier series with the period of rotation.

$C_0$ is the mean (rotationally averaged) *V* or *R* magnitude at the reference (mean) phase angle (α) of the observations, i.e., it is $V_0(1, \alpha)$ or $R_0(1, \alpha)$.

Accurate to 0.01 mag in most cases.

$$R(t) = C_0 + \sum_{n=1}^{m} C_n \cos \frac{2\pi n}{P}(t - t_0) + S_n \sin \frac{2\pi n}{P}(t - t_0),$$

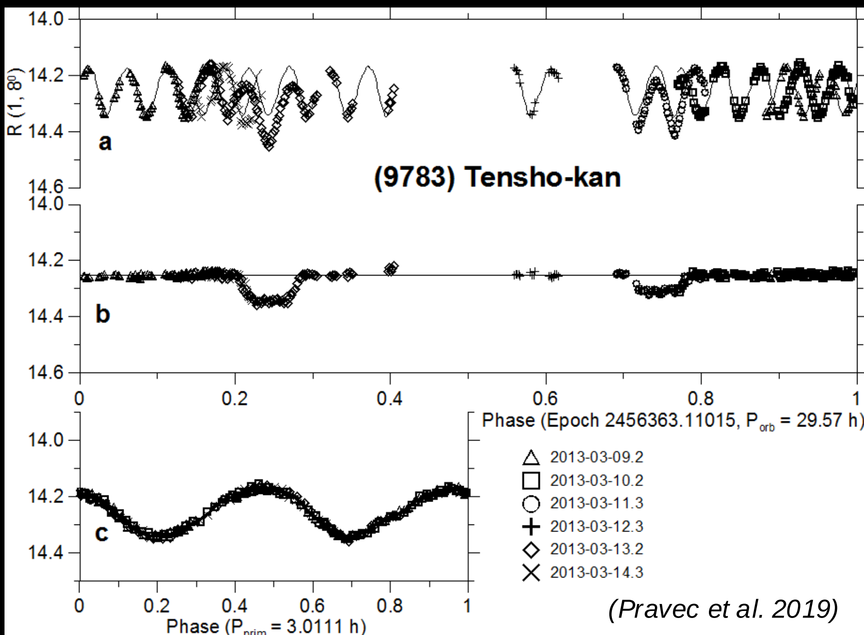


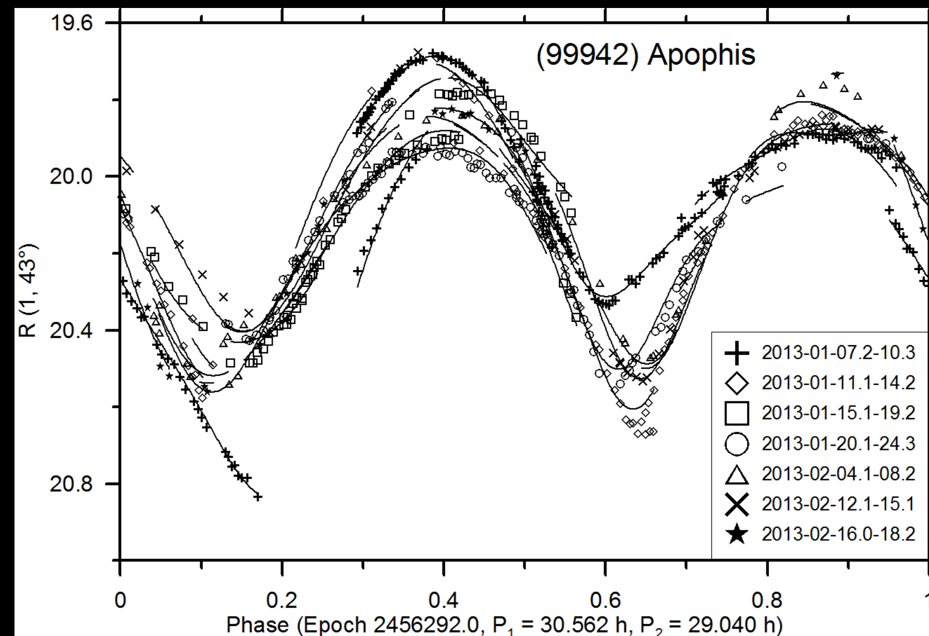
# Accurate mean magnitude determination (2)

Binary (with asynchronous primary):

Tumbler:

*(Pravec et al. 2014)*




$$F(t) = F_1(t) + F_2(t),$$

$$F_1(t) = C_1 + \sum_{k=1}^{m_1} \left[ C_{1k} \cos \frac{2\pi k}{P_1}(t - t_0) + S_{1k} \sin \frac{2\pi k}{P_1}(t - t_0) \right],$$

$$F_2(t) = C_2 + \sum_{k=1}^{m_2} \left[ C_{2k} \cos \frac{2\pi k}{P_2}(t - t_0) + S_{2k} \sin \frac{2\pi k}{P_2}(t - t_0) \right],$$

$$F(\psi, \phi) = C_0 + \sum_{j=1}^{\infty} [C_{j0} \cos j\psi + S_{j0} \sin j\psi] + \sum_{k=1}^{\infty} \sum_{j=-\infty}^{\infty} [C_{jk} \cos(j\psi + k\phi) + S_{jk} \sin(j\psi + k\phi)],$$

where

$$C_0 = a_{00}, \quad C_{j0} = a_{j0}, \quad S_{j0} = b_{j0},$$
$$C_{0k} = a_{0k}, \quad S_{0k} = c_{0k},$$
$$C_{\pm j,k} = \frac{a_{jk} \pm d_{jk}}{2}, \quad S_{\pm j,k} = \frac{c_{jk} \pm b_{jk}}{2},$$

for $j, k > 0$.

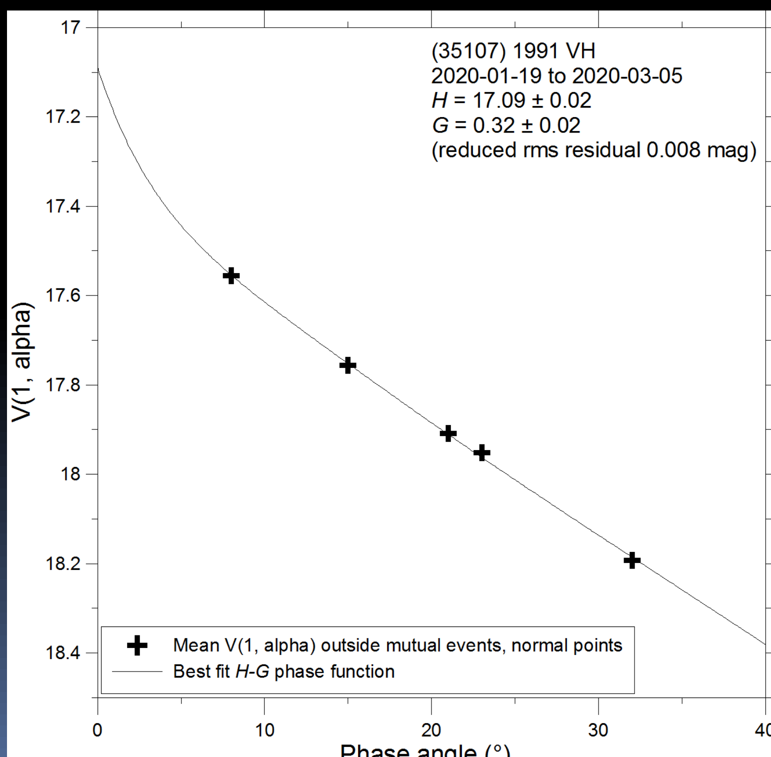
$C_0$ (= $V_0(1, \alpha)$ or $R_0(1, \alpha)$) determined using additive (for binaries) or full (for tumblers) 2-period Fourier series. Accurate to 0.01 mag in most cases, as well.

# Phase relation (1)

Absolute magnitude $H = V_0(1, 0°)$. Extrapolation of $V_0(1, \alpha)$ to zero phase angle.

We use the H-G phase relation (Bowell et al. 1989) . (Our observations typically taken at moderate solar phases.)

With good coverage in solar phase, we get a high-accuracy estimate for *H* (small formal uncertainty).




550 E. BOWELL ET AL.

$$V(\alpha) = V_{obs}(\alpha) - 5 \log r\Delta \quad \text{(A2)}$$

where $r$ is the heliocentric distance and $\Delta$ the geocentric distance of the asteroid, both in AU.

*H* and *G* are the two fundamental photometric parameters for each asteroid. They may be calculated by linear least squares (see below) from the reduced observed magnitudes using

$$\begin{cases} 10^{-0.4V(\alpha)} = a_1\Phi_1(\alpha) + a_2\Phi_2(\alpha) \\ H = -2.5 \log (a_1 + a_2) \\ G = \dfrac{a_1}{a_1 + a_2}. \end{cases} \quad \text{(A3)}$$

In this equation, similar to the first member of Eq. (38), $a_1$ and $a_2$ are auxiliary constants for a given asteroid. Optimally, $V(\alpha)$ are magnitudes averaged over rotation, but in practice they may be individual magnitudes (sometimes of widely differing quality) observed without prior knowledge of an asteroid's rotational brightness variation, or a mixture of both. The $V(\alpha)$ may even pertain to more than one apparition, though it will not usually be prudent to combine observations over long intervals because of aspect changes. In wave bands other than $V$, it is conventional to subscript $H$ and $G$: for example, $H_B$, $G_B$.

To *calculate* *H* and *G* for asteroids, and to predict asteroid magnitudes that should well represent the observations, use is made of

$$\begin{cases} \Phi_i = W\Phi_{iS} + (1 - W)\Phi_{iL}; \quad i = 1,2 \\ W = \exp\left(-90.56 \tan^2 \frac{1}{2}\alpha\right) \\ \Phi_{iS} = 1 - \dfrac{C_i \sin\alpha}{0.119 + 1.341 \sin\alpha - 0.754 \sin^2\alpha} \\ \Phi_{iL} = \exp\left[-A_i\left(\tan\frac{1}{2}\alpha\right)^{B_i}\right] \\ A_1 = 3.332 \quad A_2 = 1.862 \\ B_1 = 0.631 \quad B_2 = 1.218 \\ C_1 = 0.986 \quad C_2 = 0.238. \end{cases} \quad \text{(A4)}$$

# Phase relation (2)

Most of our photometric asteroid targets observed over a small range of solar phases only, often at effectively one epoch → determination of *G* impossible (or uncertain).

To estimate *H* in such cases, we assume *G* and its plausible range based on determined or estimated taxonomic class for given asteroid. (The *G* data from Tables 3 and 4 of Warner et al. 2009.)

The plausible *G* and its range uncertain → a significant uncertainty in the estimated *H*. Typically exceeding ± 0.1 mag, sometimes even much greater.

**Table 3**
Adopted albedo and phase slope parameter ($G$) by taxonomic class groups.

| Taxonomic classes | Harris | | Warner et al. | |
|---|---|---|---|---|
| | Albedo | $G$ | Albedo | $G$ |
| C, G, B, F, P, T, D | $0.058 \pm 0.024$ | $0.086 \pm 0.088$ | $0.057 \pm 0.02$ | $0.12 \pm 0.08$ |
| M | $0.124 \pm 0.028$ | $0.214 \pm 0.057$ | $0.16 \pm 0.04$ | $0.20 \pm 0.07$ |
| S, Q | $0.184 \pm 0.059$ | $0.227 \pm 0.109$ | $0.20 \pm 0.07$ | $0.24 \pm 0.11$ |
| E, V, R | $0.403 \pm 0.064$ | $0.440 \pm 0.074$ | $0.46 \pm 0.06$ | $0.43 \pm 0.08$ |

For the Harris values, the bias-corrected dispersions were used. The Warner et al. values, which have been adopted for default values in the LCDB, have been rounded in most cases to two-decimal precision, which reflects the somewhat large "probable errors".

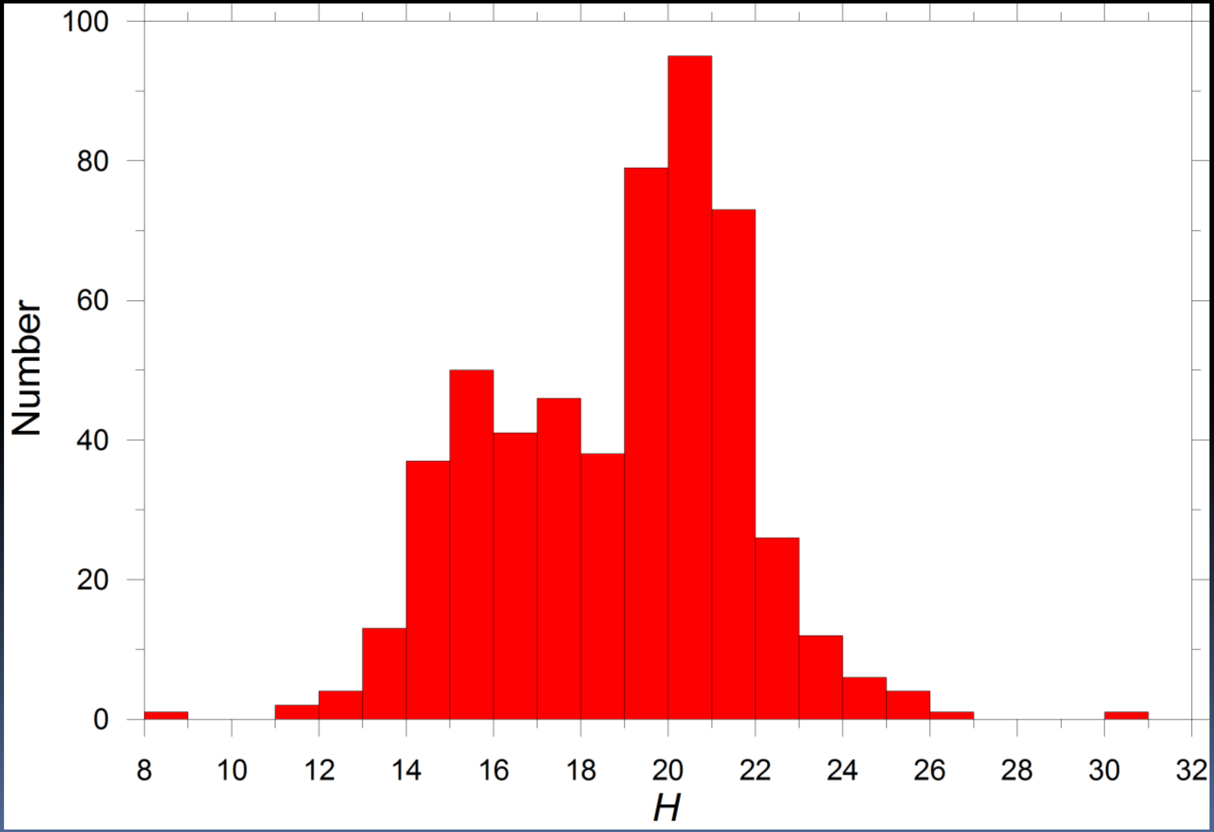
**Table 4**
Derived albedos and phase slope parameters ($G$) based on taxonomic class.

| Primary class | Subclass | Count | Albedo | $G$ |
|---|---|---|---|---|
| *Low albedo* | | | | |
| All | | 359/37 | $0.057 \pm 0.020$ | $0.119 \pm 0.080$ |
| B | | 29/5 | $0.057 \pm 0.020$ | $0.116 \pm 0.081$ |
| C | All | 260/31 | $0.057 \pm 0.020$ | $0.116 \pm 0.081$ |

# Asteroid absolute magnitudes data set (1)

The La Silla-Ondřejov photometric data set – the summary data file linked at https://www.asu.cas.cz/~ppravec/newres.htm

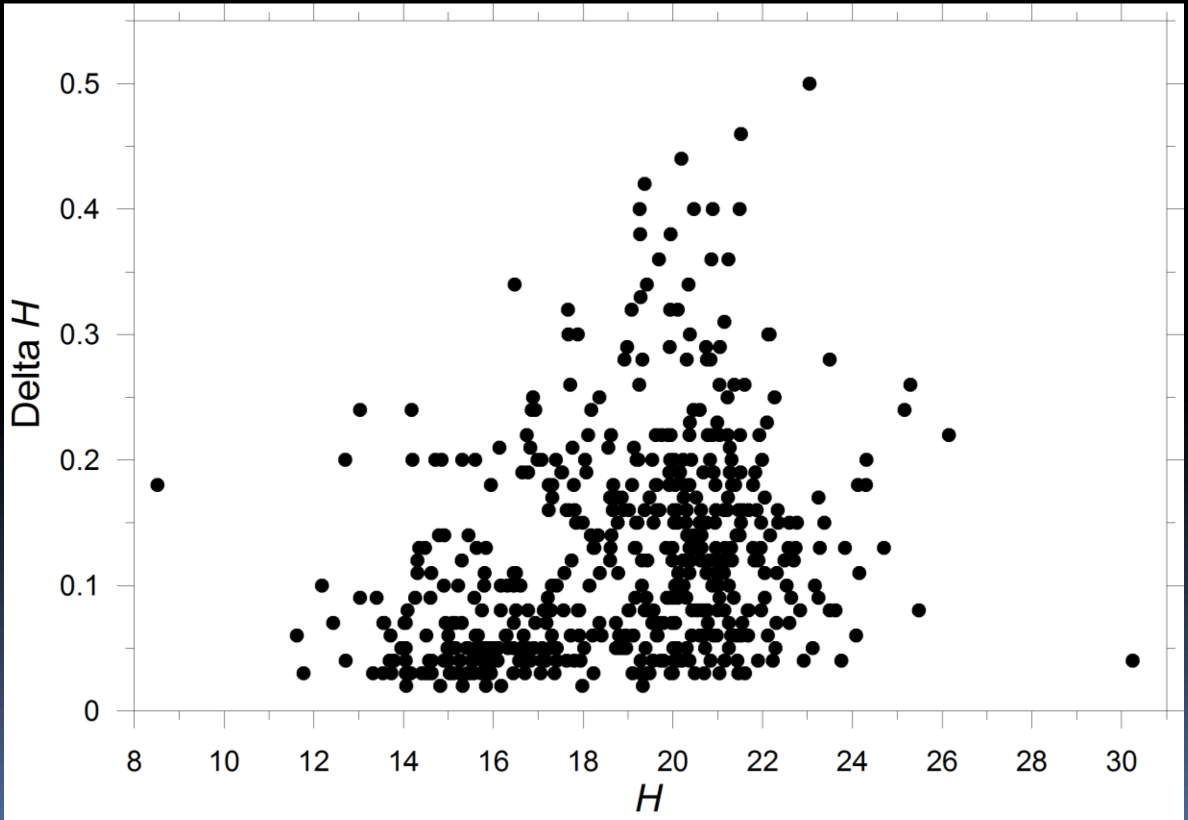
Contains 544 *H* estimates up to the date. Most of them (70%) are NEAs (mostly *H* > 17), the rest are small MBAs and MCs (mostly *H* < 17).



# Asteroid absolute magnitudes data set (2)

Uncertainties of the *H* estimates – between ± 0.02 and ± 0.50 mag. Median: ± 0.10 mag.

The data for NEAs (*H* >~ 17) are more noisy (observed at typically larger solar phases than MBAs/MCs): Median uncertainty ± 0.13 mag, but with a tail to substantially higher uncertainties.



# Concluding remarks

Our sample of unbiased asteroid *H* data useful, e.g., as reference for statistical analyses of larger but less accurate *H* data sets. (See the talk by T. Hoffmann.)

Our dataset covers primarily NEAs with sizes from 0.1 to 1 km and MBAs+MCs with sizes from 1 to 10 km.

Recently, we determine on average 44 new *H* values per year, most of them are NEAs with sizes between 0.1 and 1 km. (The target selection and observing strategy is led by the scientific interests in our research projects aimed on studying asteroid spin states, binarity, etc.)

Most recently we focus on sampling (within our new grant project) also more smaller NEAs with $H > 22$. So, in the near future we will obtain more data also for NEAs with sizes $< 0.1$ km.