Asteroid Polarimetry & Classification with the 2-m Liverpool Telescope

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1. Polarimetry: A Tool for Asteroid Characterisation

- The reflection of sunlight from an asteroid's surface induces partial linear polarisation. In **asteroid polarimetry**, we exploit this phenomenon by characterising the change in the polarised % of reflected light with STO (Sun-Target-Observer) **phase angle**.
- This is visualised as a **phase-polarisation curve** (see Figs. 1, 3 & 7).
- Polarimetry is used to make precise measurements of asteroids' **geometric albedos** and infer their **mineral composition** and **texture**.
- **Potentially Hazardous Asteroids (PHAs)** must be understood: they pose a risk of future destructive collision with the Earth, and are defined by minimum orbit intersection distances of ≤ 0.05 AU.
- PHAs are ideal targets for polarimetry, as they traverse a wide range of phase angles over short timescales (typically a few days or weeks).

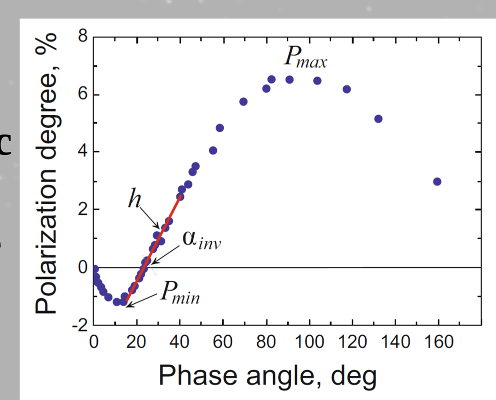

Figure 1: Typical morphology of an asteroid phase-polarisation curve. [1]

2. The Liverpool Telescope & MOPTOP

The **Liverpool Telescope (LT)** is the largest robotic telescope in the world, located at the Observatorio del Roque de Los Muchachos, La Palma. It is operated **autonomously** by Liverpool John Moores University. The LT is equipped with the **M**ulticolour **OPT**imised **O**ptical **P**olarimeter (**MOPTOP**), which uses a dual-beam, dual-camera configuration with a rotating half-waveplate.

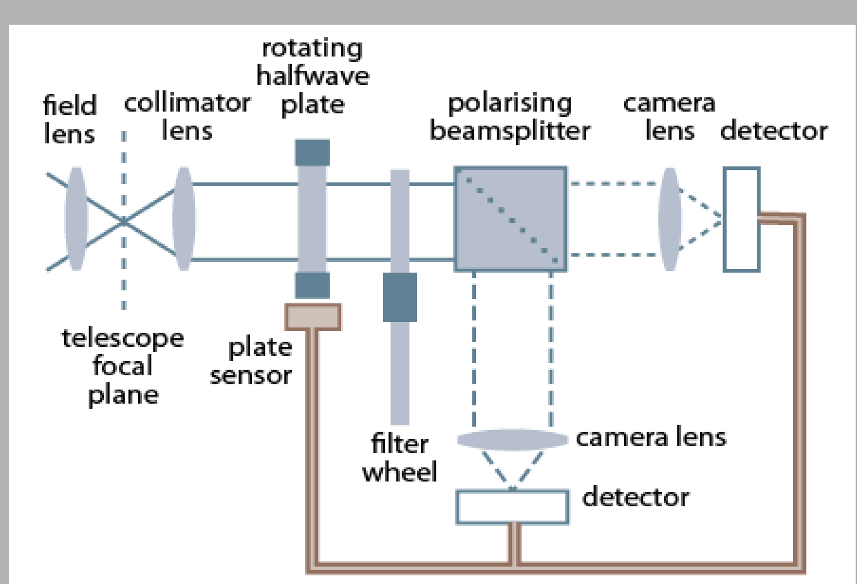

Figure 2: Schematic of the MOPTOP polarimeter. [2]

Methods

- Polarimetric R-band data was collected for 5 PHAs and 1 NEA (Near-Earth Asteroid).
- IRAF photometry was performed to extract fluxes from MOPTOP camera exposures.
- The linear polarisation degree P_r was calculated from the Stokes Q and U parameters.
- The polarisation degree and direction were transformed to the Asteroid System Definition reference frame used by the literature.

3. Polarimetric Classification Results

Asteroids are classified according to their **phase-polarisation curve morphology**. This was determined graphically from Fig. 3, through the curve that represented the closest match to each asteroid's dataset.

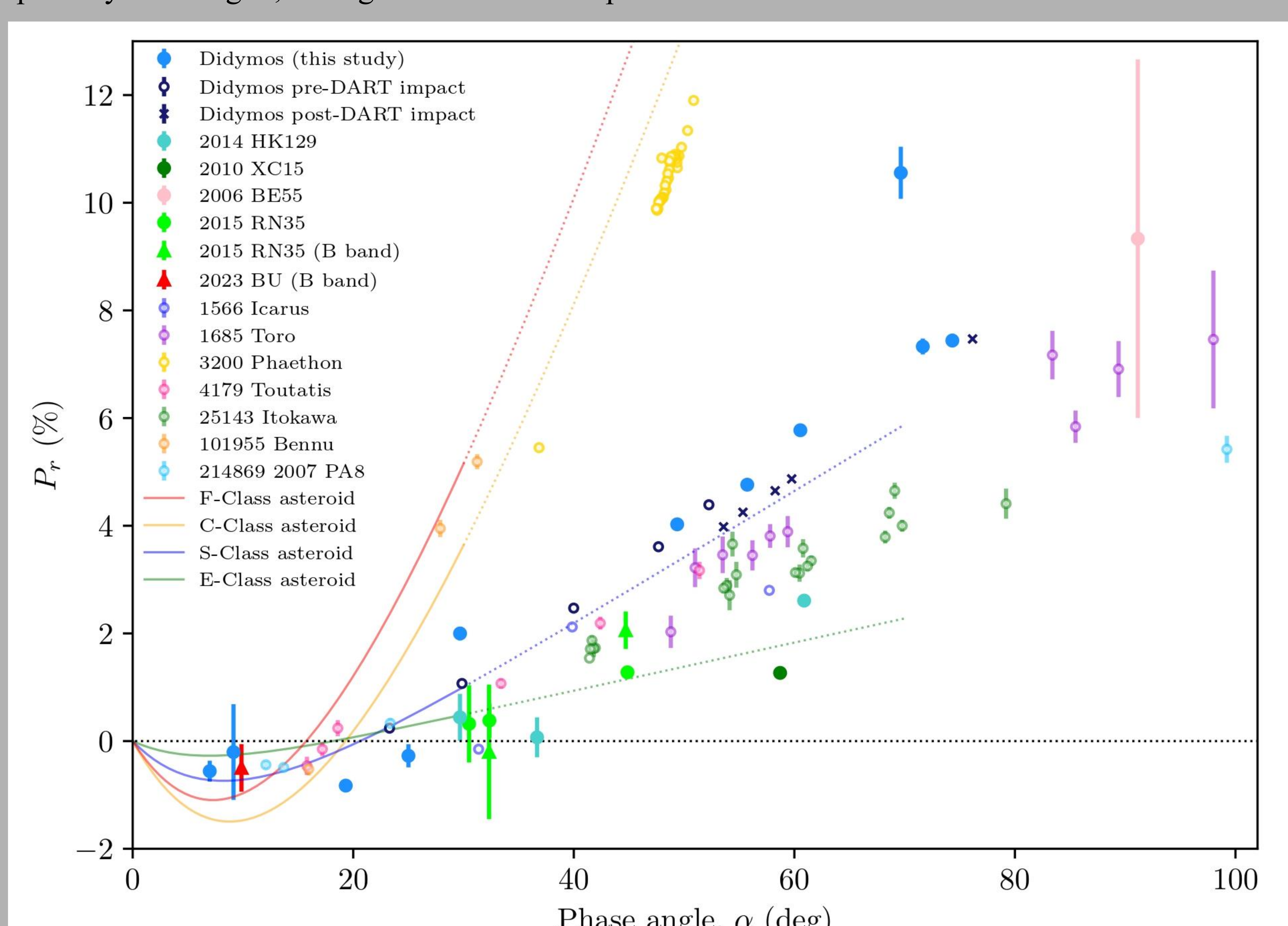

Figure 3: Phase-polarisation data for various asteroids observed in this study (solid circles) and asteroid datasets from the literature (hollow circles or crosses) [3,4]. All data is in the R band unless otherwise specified. The averaged trends from datasets of several asteroid types typical among PHAs (representing a range of albedos) are overplotted for classification purposes [5].

The **Tholen Taxonomic System** classifies asteroids according to their mineralogical composition and **geometric albedo**, i.e. the proportion of incident light they reflect. [6]

Tholen Class	F	C	S	E
Composition	Dehydrated carbonaceous	Carbonaceous	Stony, siliceous	Enstatite achondrite
Geometric albedo	Low	Low	Moderate	High
Asteroids	Bennu	Phaethon	2023 BU, 2006 BE55, Didymos, Icarus, Itokawa, Toro, Toutatis	2014 HK129, 2015 RN35, 2010 XC15, 2007 PA8

The phase-polarisation behaviour of asteroid classes **diverges significantly** at high phase angles (Fig. 3).
⇒ **A single polarimetric observation at high phase angles ($\gtrsim 40°$) is sufficient to classify an asteroid**, even with significant uncertainty.

4. Didymos-Dimorphos Observations Post-DART Impact

NASA Double Asteroid Redirection Test (DART) Mission:
First attempt at asteroid deflection through kinetic impact.

- The DART spacecraft impacted **Dimorphos** (see Fig. 4) on 26th September 2022. Dimorphos' binary orbit was shortened by 33 minutes (4.6%).
- Most of the momentum transfer came from **ejected material**, not the impact itself [7] ⇒ Understanding Dimorphos' **texture & composition** was key to analysing the impact ⇒ Polarimetry can help to **reproduce the deflection for a future Earth-bound PHA**.
- A temporary **ejecta tail** was produced by debris ejected from Dimorphos, see Fig. 5.
- The tail produced a **depolarising signature**, i.e., a lower P_r: Reflected sunlight was polarised to a lesser extent ⇒ This material was lighter in colour, corresponding to a higher geometric albedo (Umov effect) ⇒ Unlike the pre-impact surface, this unearthed ejecta had not been exposed to space weathering.

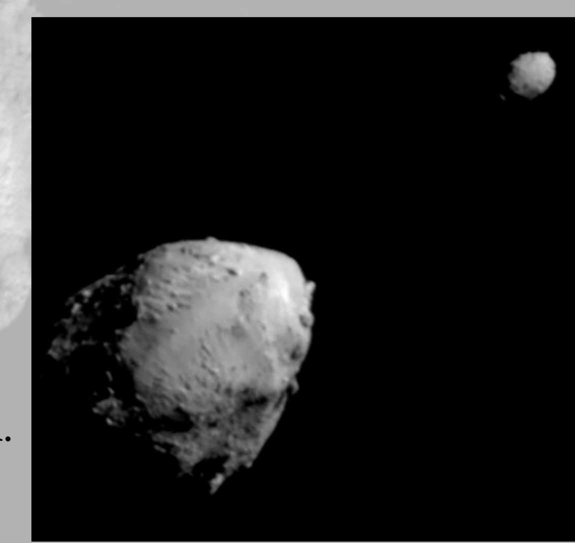
Figure 4: Dimorphos (151m in diameter, upper right) and its binary partner Didymos (~780m), imaged by the DART spacecraft. [8]

The LT cannot resolve Didymos and Dimorphos, due to their small sizes and proximity to each other. Therefore, the binary asteroid system was treated as a point source, which is referred to collectively as Didymos. Observations spanned the period October 2022 – January 2023, with the first observation being made three weeks post-DART impact.


Figure 5: Stacked images of the Didymos-Dimorphos system taken with the LT+MOPTOP on 29th October 2022. Dimorphos' ejecta tail from the DART impact is visible. Nearby stars have been removed via sigma clipping, though they remain somewhat visible as streaks. A logarithmic scaling has been used.

An anomalous data point that may be explained by surface albedo or compositional inhomogeneity. Hera will illuminate the answer!

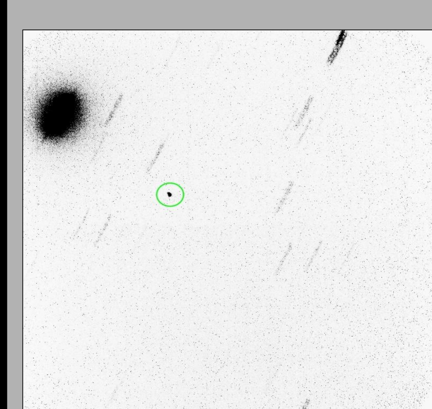
Figure 6: The Didymos-Dimorphos system (circled) on 28th November 2022, imaged in the same way as Fig. 5. The ejecta tail is no longer visible. Bright stars passed through MOPTOP's FOV, shown here by streaks and an over-saturated oval region.

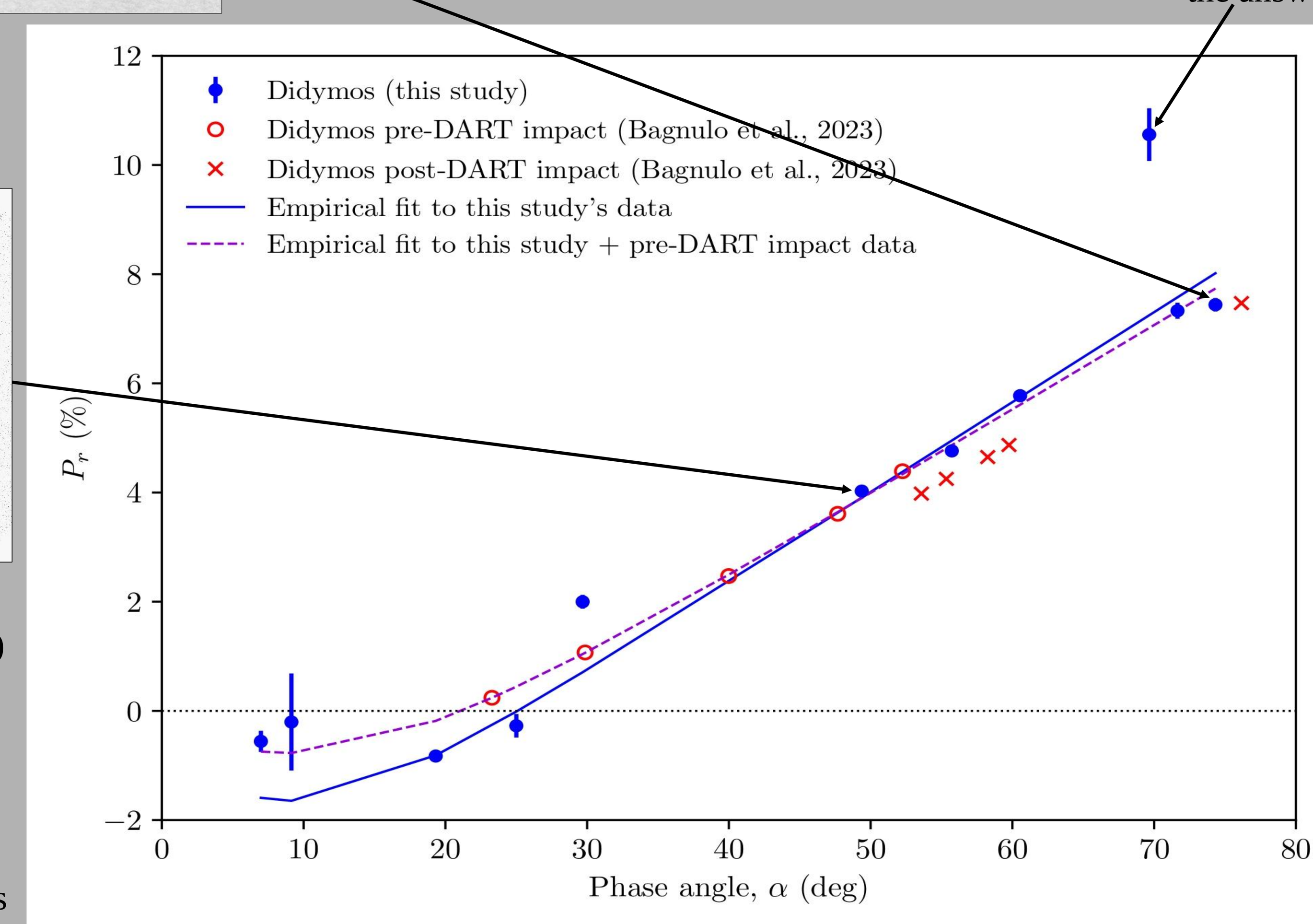

Figure 7: Phase-polarisation curve for Didymos (i.e. the Didymos-Dimorphos binary asteroid system). R-band data from Bagnulo et al. (2023) [4] is plotted as red symbols for comparison. An empirical fit of the data to the relation $P_r = A\left(e^{-\frac{\alpha}{B}} - 1\right) - C \cdot \alpha$ was performed.

Results

- From Fig. 3, it was determined that Didymos and Dimorphos are most consistent with the **S class** of asteroids - their compositions are stony and siliceous, in agreement with the majority of literature. [4]
- Their combined **geometric albedo** was calculated from the gradient at the inversion angle ($\alpha_{inv} = 21.4°$ at $P_r = 0$) to be 0.203 ± 0.012. This again agreed with established values that were not previously verified through polarimetry.
- This study's earliest observations on 29th October appear to be compatible with the regime of **reduced post-DART impact polarisation** seen by Bagnulo et al. (red crosses in Fig. 7).
- However, all subsequent observations appear to agree with the **pre-DART impact trend** (red circles)
  ⇒ The LT **did not detect a lasting change** in Didymos' polarisation behaviour due to DART. Any changes faded along with the ejecta tail.
  ⇒ The ejecta tail's polarimetric signature had predominantly **dissipated within a few weeks** of the DART impact, as its depolarising effect is not evident in the trend of our findings.

5. Conclusions & Future Work

- Asteroids can be classified from **small, uncertain polarimetric datasets** at high phase angles. This allows their mineralogical compositions to be determined easily.
- These observations **expanded** the literature dataset of PHAs characterised by high-phase angle polarimetry **by ~50%**.

What's next?

- The Liverpool Telescope and MOPTOP are effective instruments to **expand the sparse dataset** of high-phase angle PHA polarimetry.
- Observations in other filters (B, V) can be compared.
- Time-resolved polarimetry over an asteroid's rotational period may reveal **patches of varying composition** and albedo over its surface.

6. References

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