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# Near-infrared Spectral Homogeneity of the Didymos System Before and After the DART Impact*

Simone Ieva[1], E. Mazzotta Epifani[1], E. Dotto[1], V. Petropoulou[1], J. D. P. Deshapriya[1], P. H. Hasselmann[1], G. Poggiali[2,3], D. Perna[1], M. Dall'Ora[4], A. Lucchetti[5], M. Pajola[5], S. L. Ivanovski[6], A. Rossi[7], J. R. Brucato[2], P. Palumbo[8,9], V. Della Corte[4], A. Zinzi[10,11], C. A. Thomas[12], J. de León[13,14], T. Kareta[15], N. Moskovitz[15], N. L. Chabot[16], A. S. Rivkin[16], M. Amoroso[10], I. Bertini[8], A. Capannolo[17], S. Caporali[2], M. Ceresoli[17], G. Cremonese[5], I. Gai[18], L. Gomez-Casajus[18], E. Gramigna[18], G. Impresario[10], R. Lasagni Manghi[18], M. Lavagna[17], M. Lombardo[18], D. Modenini[18,19], S. Pirrotta[10], P. Tortora[18,19], F. Tusberti[5], M. Zannoni[18,19], and G. Zanotti[17]

[1] INAF—Osservatorio Astronomico di Roma, Via Frascati 33, 00078, Monte Porzio Catone, RM, Italy; simone.ieva@inaf.it
[2] INAF—Osservatorio Astrofisico di Arcetri, Firenze, Italy
[3] LESIA—Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, France
[4] INAF—Osservatorio Astronomico di Capodimonte, Napoli, Italy
[5] INAF—Osservatorio Astronomico di Padova, Padova, Italy
[6] INAF—Osservatorio Astronomico di Trieste, Trieste, Italy
[7] Istituto di Fisica Applicata "Nello Carrara" (IFAC-CNR), Sesto Fiorentino, Firenze, Italy
[8] Università degli Studi di Napoli "Parthenope," Napoli, Italy
[9] INAF—Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy
[10] Agenzia Spaziale Italiana (ASI), Rome, Italy
[11] Space Science Data Center—ASI, Rome, Italy
[12] Northern Arizona University, Flagstaff, AZ, USA
[13] Instituto de Astrofísica de Canarias (IAC), Santa Cruz de Tenerife, Spain
[14] University of La Laguna, Department of Astrophysics, Santa Cruz de Tenerife, Spain
[15] Lowell Observatory, AZ, USA
[16] JHU-APL, Laurel, MD, USA
[17] Politecnico di Milano—Bovisa Campus, Dipartimento di Scienze e Tecnologie Aerospaziali, Milan, Italy
[18] Alma Mater Studiorum—Università di Bologna, Dipartimento di Ingegneria Industriale, Forlì, Italy
[19] Alma Mater Studiorum—Università di Bologna, Centro Interdipartimentale di Ricerca Industriale Aerospaziale, Forlì, Italy
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## Abstract

We spectroscopically characterized the Didymos system, target of the Double Asteroid Redirection Test (DART)/Light Italian Cubesat for Imaging of Asteroids (LICIACube) space mission, close in time to the DART impact event, during six nights between 2022 August and November at Telescopio Nazionale Galileo. Here, we show that near-infrared (NIR) spectra (0.75–2.25 $\mu$m) look mostly similar within the same night and between different nights. They are in good agreement with the only spectrum previously available in the literature, observed almost 20 years before those reported in this paper. During one of the observing nights we also obtain spectroscopy information on the ejecta tail induced by the DART impact. The spectrum of the ejecta tail is also very similar to Didymos/Dimorphos itself. All of these aspects seem to suggest that the Didymos system in the NIR looks mostly homogeneous, with very subtle spectral variations.

*Unified Astronomy Thesaurus concepts:* Near-Earth objects (1092); Ground telescopes (687); Spectrometers (1554)

## 1. Introduction

The NASA Double Asteroid Redirection Test (DART) mission (A. S. Rivkin et al. 2021) on 2022 September 26 became the first to demonstrate asteroid deflection. It crashed on the secondary member of the (65803) Didymos binary asteroid system (named Dimorphos) and proved the feasibility of the kinetic impactor technique as a planetary defense tool. The mission, together with its cubesat companion ASI Light Italian Cubesat for Imaging of Asteroids (LICIACube; E. Dotto et al. 2021), was a smashing success, reaching all of its scientific goals (N. L. Chabot et al. 2024), including the change of the Dimorphos's orbit (A. F. Cheng et al. 2023; C. A. Thomas et al. 2023) and the characterization of the ejecta plume (J.-Y. Li et al. 2023; E. Dotto et al. 2024). The system will be visited in 2027 by the ESA—Hera mission (P. Michel et al. 2022). Until then, ground-based data will continue to characterize the system to comprehend the effect of the DART impact and pave the way for the arrival of Hera.

The DART mission also provided a rare opportunity: to witness on a short timescale of weeks and months the effects of asteroidal impacts on surface optical and spectroscopic properties. Asteroidal impacts are supposed to be a very frequent phenomenon in the solar system's history (M. Ishiguro et al. 2011; F. Moreno et al. 2011). However, due to the unpredictable nature of these events, specific studies of a natural asteroid impact have never been carried out. The DART mission

* Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundación Galileo Galilei of the Istituto Nazionale di Astrofisica (INAF) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias (Program AOT45-TAC8 and AOT46-TAC19).

**Table 1**
Observational Conditions for the Spectra Characterized in This Work

| Spectrum ID | Date | UT Start/End | Airmass | $V_{mag}$ | $r$ | $\Delta$ | $\alpha$ | Exp Time | Sol. Ana. (airm) |
|---|---|---|---|---|---|---|---|---|---|
| #1 | 2022-08-05 | 02:56–05:20 | 1.573–1.923 | 17.0 | 1.274 | 0.286 | 21.9 | 6840 | SA115-271 (1.225) |
| #2 | 2022-08-06 | 02:44–05:14 | 1.587–1.915 | 16.9 | 1.269 | 0.279 | 21.7 | 7200 | SA115-271 (1.232) |
| #3 | 2022-10-01 | 05:30–05:53 | 1.961–2.039 | 14.6 | 1.036 | 0.072 | 59.5 | 2640 | SA93-101 (1.915) |
| #4 | 2022-11-04 | 02:39–05:34 | 1.716–1.085 | 16.0 | 1.023 | 0.118 | 71.6 | 7680 | SA93-101 (1.338) |
| #5 | 2022-11-22 | 03:30–06:07 | 1.153–1.029 | 16.3 | 1.065 | 0.155 | 56.6 | 7560 | BD+421949 (1.037) |
| #6 | 2022-11-27 | 02:12–04:38 | 1.355–1.025 | 16.3 | 1.081 | 0.166 | 51.5 | 6840 | SA98-978 (1.378) |

**Note.** $r$ and $\Delta$ are the heliocentric and geocentric distance, respectively. $\alpha$ is the phase angle.

provides the advantage of a precisely predicted time and moment for the impact, which incidentally produced a big swarm of ejecta (A. F. Cheng et al. 2023; J.-Y. Li et al. 2023).

Observations from Earth of the asteroid system are dominated by Didymos, the major body of the binary system ($761 \pm 26$ m, R. T. Daly et al. 2023). Dimorphos ($151 \pm 5$ m, ibidem) should account for roughly 4% of the light from the system. Nevertheless, some studies based on dynamical (K. J. Walsh & S. A. Jacobson 2015) and physical considerations (M. Pajola et al. 2022) suggest that Didymos and Dimorphos may be quite similar in composition. Therefore, general considerations derived here for Didymos could also stand for Dimorphos.

New ground-based observations of the Didymos system in the near-infrared (NIR) range were also pivotal, as the only spectrum available in this wavelength range prior to the DART event was taken 20 years ago (J. de León 2006), and shows shallower bands than the typical silicate asteroid. Taking advantage of the brightness of the system around the DART event, we decided to monitor Didymos and Dimorphos in the NIR to assess possible changes in their spectroscopic behavior, and look for possible inhomogeneities. Here, we report observations carried out at Telescopio Nazionale Galileo (TNG), located on La Palma, Canary Islands, during six nights before and after the impact event between 2022 August and November. These new data were obtained as a part of a larger collaboration among the DART and LICIACube team to characterize the system and monitor eventual changes induced by the DART impact. These spectroscopic data will be used to infer spectral properties of the Didymos system surface and derive general properties that will be later compared with analysis obtained using the DART and LICIACube images (see e.g., J. D. P. Deshapriya et al. 2023; E. Dotto et al. 2024; P. H. Hasselmann et al. 2024).

## 2. Observations and Data Reduction

To characterize the Didymos system, we made use of the 3.6 m TNG (La Palma, Spain) during six separate runs between 2022 August and 2022 November. We used the Near Infrared Camera Spectrometer (NICS; C. Baffa et al. 2001), coupled with the AMICI prism, in low-resolution mode. We covered the 0.75–2.40 $\mu$m spectral range and used a $2''$ slit, always oriented along the parallactic angle (except when we observed the ejecta tail) to reduce the effects of atmospheric differential refraction. Observations were carried out using the standard technique of moving the objects along the slit between two positions denoted A and B. Cycles are repeated on ABBA sequences until the total exposure time is reached. Standard procedures were used in the reduction process. We corrected spectra for flat field; then, bias and sky removal were obtained by subtracting the two spectra and producing A-B and B-A frames. We combined and averaged all pairs to obtain the final spectrum, which was then extracted. Spectral wavelength calibration was obtained using a look-up table available on the TNG website.[20] Unfortunately, this method creates a small pixel shift and sometimes the division of asteroid and solar analog can create artifacts around the telluric emissions at 1.3 and 1.8 $\mu$m. We opted to remove these noisy regions because they are inessential to our following analysis. Extinction and solar removal was carried out by dividing the spectrum of each asteroid by the best solar analog, generally the one with the closest airmass or the one observed right after or before the asteroid. Finally, spectra were normalized at 1.6 $\mu$m. All of the images taken per night were coadded to retrieve a single daily reflectance spectrum, labeled from #1 to #6. Observational circumstances are summarized in Table 1.

## 3. Results

### 3.1. Spectral Behavior

During the 2022 observational window (OW), we observed the Didymos system during six nights, distributed in the timeframe August 4–November 26, therefore bracketing the DART impact event. Observational conditions are reported in Table 1. First, we decided to compare the daily reflectance spectrum collected during the nights, obtained over a full rotational period ($T = 2.26$ hr; P. Pravec et al. 2022) In Figure 1 we reported the whole data set of our observed NIR reflectance spectra, together with the only available data in the literature prior to the 2022 OW, i.e., the spectrum taken in 2004 by J. de León et al. (2006, hereafter indicated as JDL06). As shown in Figure 1, the spectra collected during each of the six nights are very similar and comparable to the JDL06 spectrum. Spectra are generally in agreement with a silicate composition, although the 2 $\mu$m band is confirmed to be somewhat shallower than the typical S-type agglomerate. Data obtained after the DART impact (#3, #4, #5, and #6) share a similar spectral behavior compared with the ones obtained before (#1 and #2). This can be quantitatively computed using a chi-squared test for goodness of the fit (P. R. Bevington & D. K. Robinson 1992), following the approach outlined in M. Popescu et al. (2012). See the results in Table A1.

Despite even the quite different observing conditions (airmass, phase angle...), the spectral shape appears very muck alike before and after the DART event. This result is strengthened even when we compared preimpact spectra with #3, taken during the night of September 30, four days after the impact. Unlike the others, those spectra were obtained at unusual higher airmass, as Didymos was very low on the horizon at that time from the northern hemisphere. The

[20] https://www.tng.iac.es/instruments/nics/spectroscopy.html

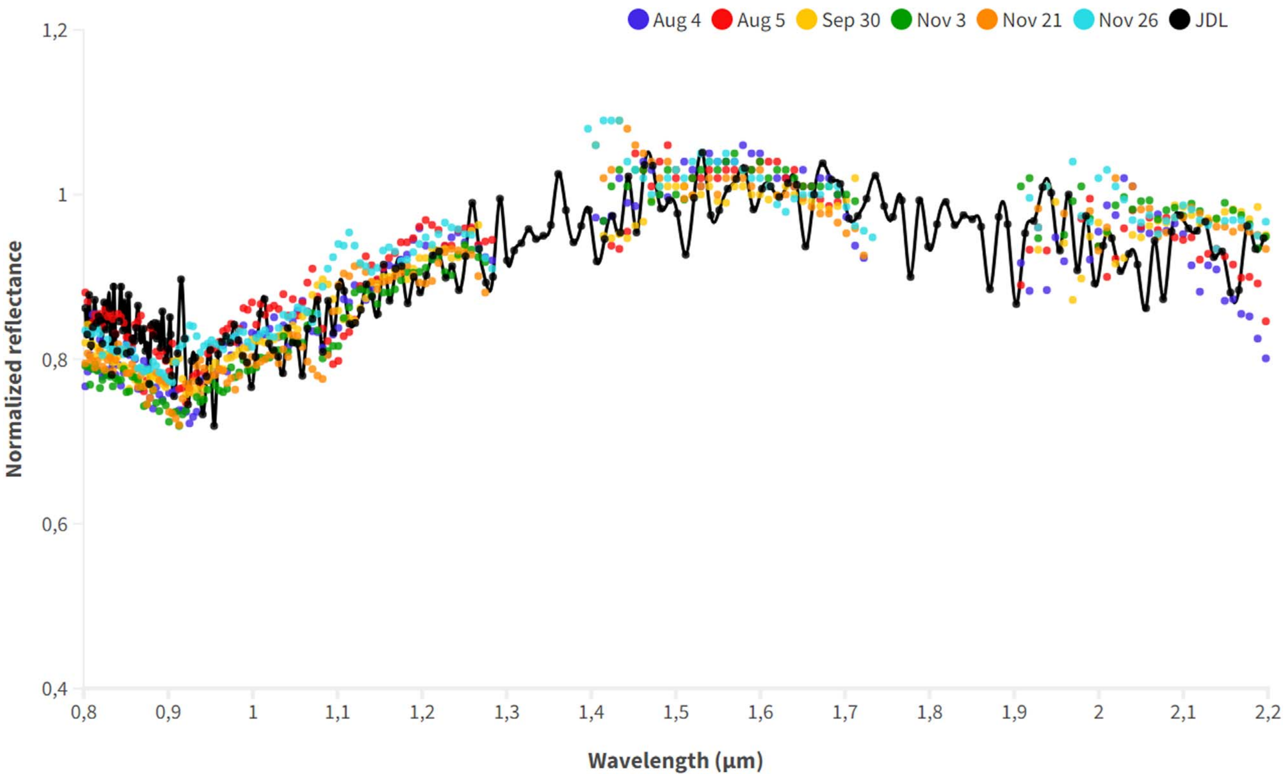


**Figure 1.** Daily reflectance spectra of Didymos acquired during each of the six nights, together with spectrum from J. de León (2006). Spectra are all normalized at 1.6 $\mu$m.

**Table 2**
Spectral Parameters (Slope, Band Center) and Fayalite and Ferrosilite Molar Composition for Data Characterized in this Work

| Spectrum ID | Slope (%/0.1 $\mu$m) | BIcen ($\mu$m) | Fa (mol%) | Fs (mol%) |
|---|---|---|---|---|
| #1 | $5.65 \pm 0.42$ | $0.959 \pm 0.017$ | 23.59 | 19.89 |
| #2 | $4.73 \pm 0.70$ | $0.964 \pm 0.008$ | 24.51 | 20.56 |
| #3 | $4.81 \pm 0.31$ | $0.955 \pm 0.011$ | 22.80 | 19.32 |
| #4 | $5.68 \pm 0.31$ | $0.955 \pm 0.008$ | 22.80 | 19.32 |
| #5 | $6.28 \pm 0.57$ | $0.964 \pm 0.013$ | 24.51 | 20.56 |
| #6 | $5.92 \pm 0.43$ | $0.955 \pm 0.011$ | 22.80 | 19.32 |
| ejecta | $5.70 \pm 0.26$ | $0.946 \pm 0.011$ | 20.87 | 17.93 |

**Note.** Slope is computed between 1.0 and 1.25 $\mu$m. The average errors for Fs and Fa originally inferred in T. L. Dunn et al. (2010) are $\pm 1.3$ mol% and $\pm 1.4$ mol%, respectively.

substantial similarity of the Didymos system spectral behavior, other than by a chi-squared comparison, is also suggested by their slope comparison, computed among the linear part of the spectrum (between 1 and 1.25 $\mu$m) with a standard linear fit. Slopes, reported in Table 2, are enclosed between $4.73 \pm 0.70$ and $6.28 \pm 0.57$ %/0.1 $\mu$m, and they are in agreement when considering the error bars, retrieved assuming the standard deviation of the linear fit.

Further, we compare spectra taken during the same observational night and ideally corresponding to different rotational phases. For the nights of August 5 and November 3, we collected a total of 15 ABBA cycles; we combined three ABBA cycles to increase the signal-to-noise ratio. Furtermore, this roughly corresponds to covering 1/5 of Didymos surface; therefore, with five spectra we can assume we are sampling all the surface. In Figure 2, we reported the combined spectra taken during the nights of August 5 and November 3 as an example for a night preimpact and a night postimpact, but similar considerations stand for all other nights. Spectra taken at different phases look very much alike among the same night for both the pre- and postimpact night (See Table A2 for a quantitative comparison). No clear compositional heterogeneity emerges with NIR investigation, suggesting a potential similarity even at different planetocentric longitudes and latitudes.

Following the DART impact, a lot of ejecta were produced (A. F. Cheng et al. 2023). In the subsequent days and weeks, these ejecta collimated in a long, thick tail, which was clearly observed from most of the ground-based telescopes and even by the Hubble Space Telescope (HST; J.-Y. Li et al. 2023). Motivated by the scientific goal to understand if the spectral behavior of the ejecta was substantially similar or different with respect to the main body (Didymos + Dimorphos), during one of the nights dedicated to this program we decided to align the slit along the ejecta tail. Around the time of our characterization, the main body and the ejecta share a substantial similar magnitude (for more details see T. Kareta et al. 2023. their Figure 1). To ensure the spectrum obtained is representative of the ejecta, we focused on regions within the slit where the ejecta's light was most prominent. The spatial profile along the slit was examined to isolate the contribution from the ejecta and minimize contamination from the main body. We are aware that because of the nature of these spectroscopic observations and how they were performed at Telescopio Nazionale Galileo (TNG), we cannot be sure that we completely removed the main body contribution. Nonetheless, spectra of the main body and the ejecta (shown in Figure 3) are almost similar, as indicated by their chi-squared test, but with larger differences with respect to the comparison of daily reflectance spectrum and rotational phases. Indeed, the averaged spectrum of ejecta seems to have a slightly shorter band center than the Didymos

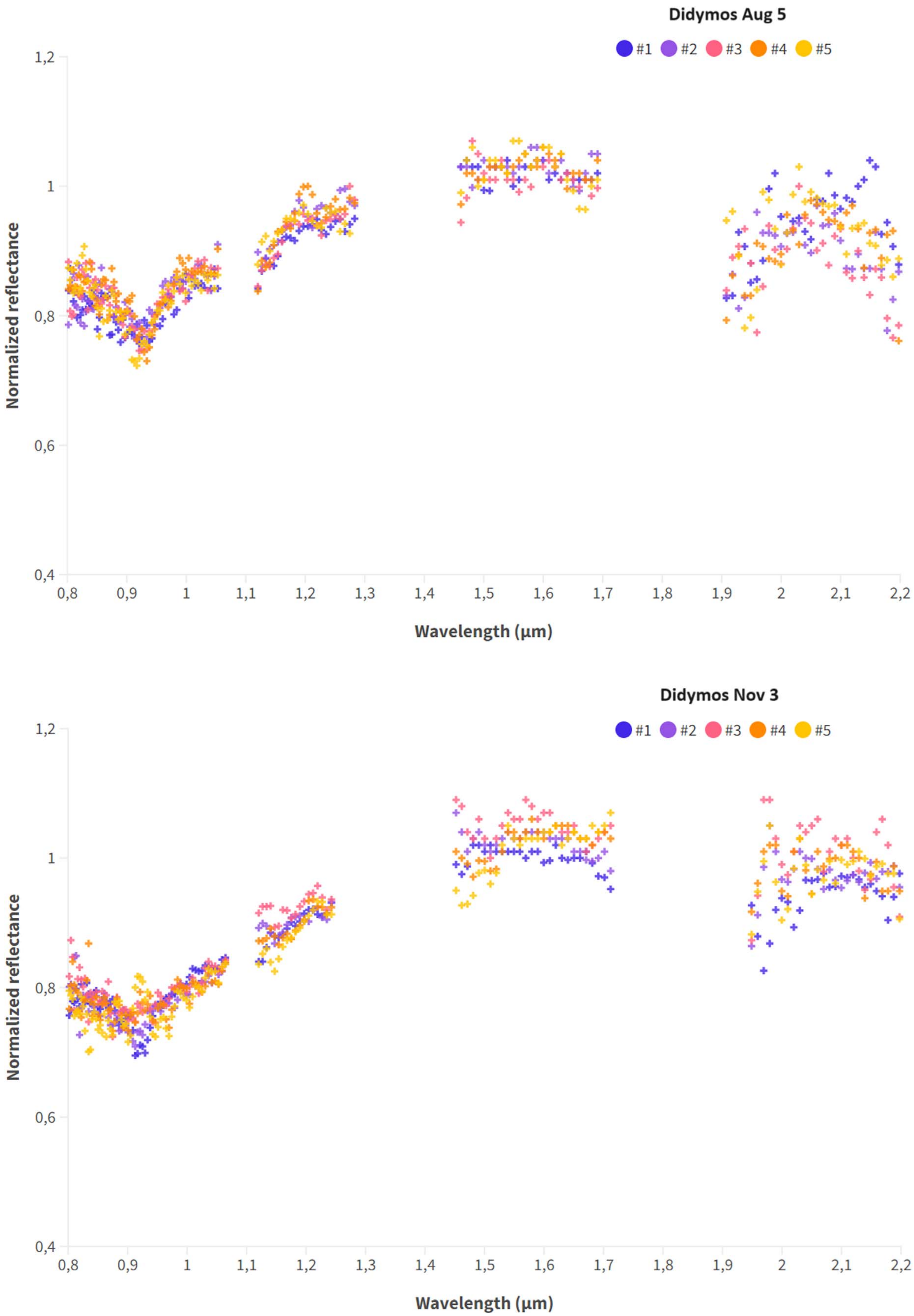


**Figure 2.** All the spectra taken at different rotational phases on the night of August 5 (a) and November 3 (b). Some wavelength regions were removed due to improper telluric correction.

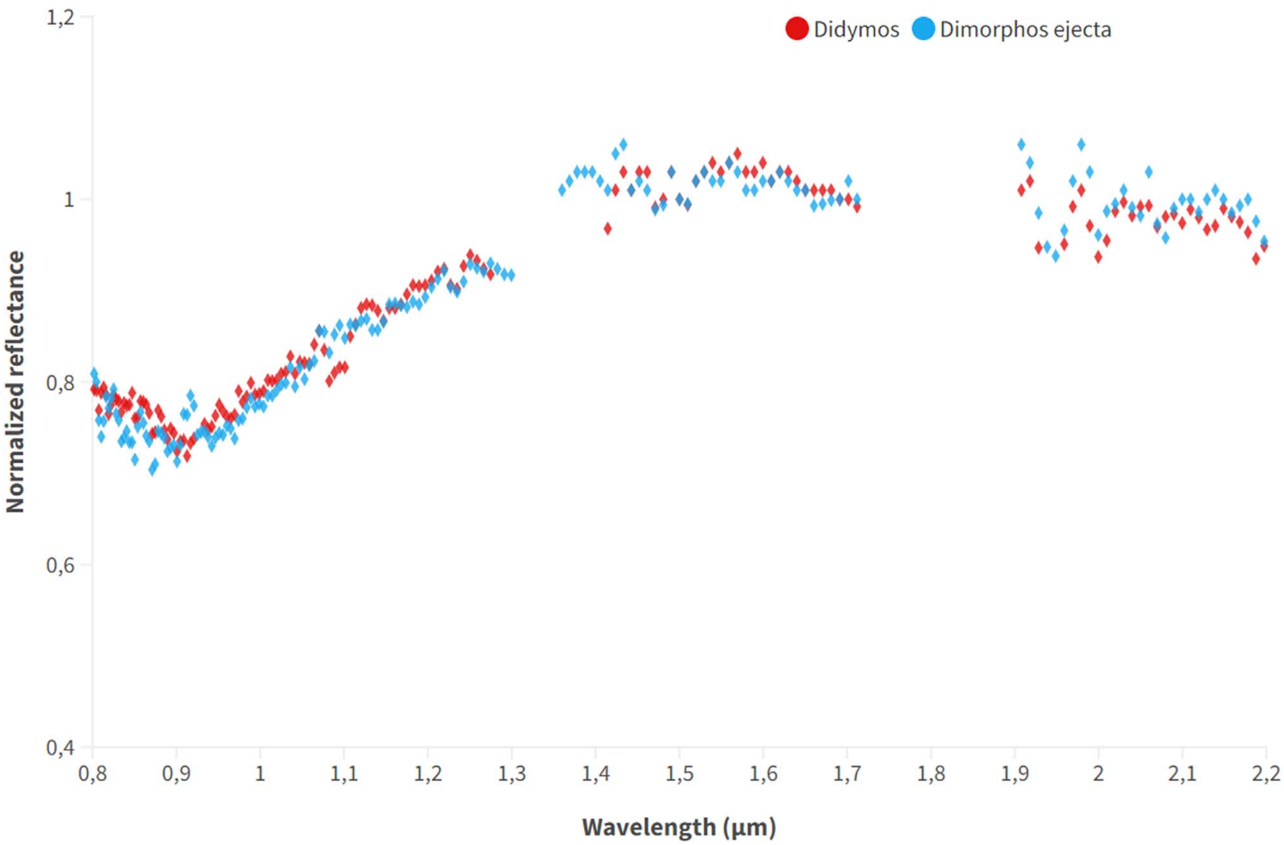


**Figure 3.** Averaged spectra taken during November 3 of main body (Didymos + Dimorphos) in red and the ejecta tail in blue.

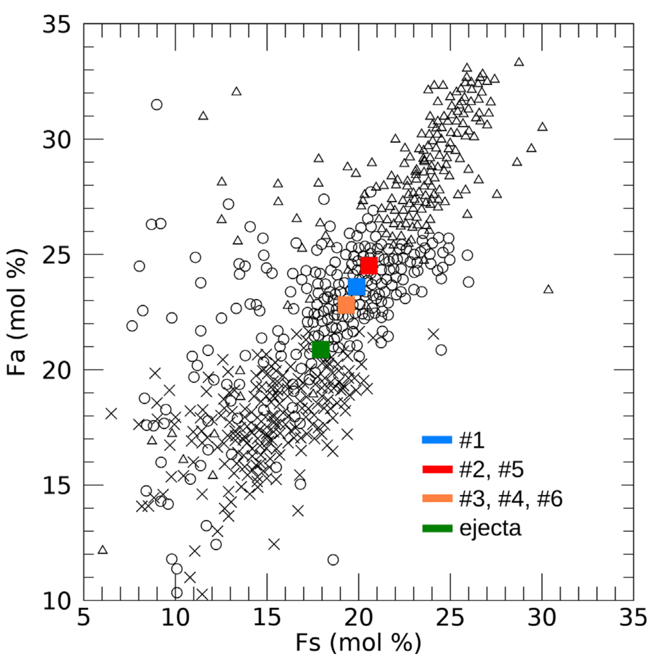


**Figure 4.** Molar content of Fa/Fs for all the average spectra of Didymos observed each night and the ejecta tail (observed on November 3), overimposed on a collection of the same values for H- (x), L- (circles), and LL-ordinary chondrites (triangles), retrieved from T. Nakamura et al. (2011). Didymos data are in agreement with L-ordinary chondrites, although ejecta data show a slightly lower value for Fa/Fs. The average errors for Fs and Fa are originally inferred in T. L. Dunn et al. (2010) and correspond to ±1.3 mol% for Fa, and ±1.4 mol% for Fs.

system, implying a slightly different molar composition (see Section 4), but do not exhibit a different band depth, a parameter usually associated with the pristine degree of the pyroxene or the grain size of the material in orthopyroxene assemblages (V. Reddy et al. 2015).

### *3.2. Iron/Calcium Molar Content*

The center of the absorption feature at 0.9 $\mu$m, due to olivine and pyroxene, is diagnostic of the composition of the asteroid, and can be used to derive mineralogical composition. Using laboratory-calibrated relations (T. L. Dunn et al. 2010), it is possible to infer a method to establish the molar composition of fayalite (Fa) and ferrosilite (Fs) in ordinary chondrite assemblages, the meteorite analogs of silicate asteroids, starting from the center position of the 0.9 $\mu$m feature. To compute the band center, we followed the standard approach (e.g., see S. Ieva et al. 2014). First, we removed the continuum, approximated as a straight line between the two maxima at 0.75 and 1.25 $\mu$mm. Then, we fitted a six-degree polynomial over the bottom third of each band. The minimum of the polynomial fit is considered the BIcen. Errors were computed using a Monte Carlo simulation, randomly sampling data 50 times and taking the standard deviation as incertitude. Final results are reported in Table 2, together with the derived molar content of Fa and Fs for each of the average spectra using T. L. Dunn et al. (2010) equations. We also report these values on Figure 4, overimposed with a collection of the same values retrieved by T. Nakamura et al. (2011) for a collection of H, L, and LL-ordinary chondrites. It is possible to see that the Didymos system is generally in agreement with a L-ordinary chondrite composition, similar to what established from comparison of Didymos visible spectra with meteoritic analogs (S. Ieva et al. 2022). It is also noticeable that the ejecta spectrum, having a shorter BI center than the other data, exhibits a lower Fa/Fs content, although still in agreement with L-ordinary chondrites.

## 4. Discussion

Ground-based observations have been crucial to characterize the Didymos system, both before and immediately after the DART impact event. In conjunction with DART/LICIACube data and prior to Hera arrival in 2027, this will be the only method to derive physical properties for the system. The spectral behavior of the Didymos system seems remarkably consistent in the NIR range. This can be seen when comparing spectra of the system taken before and after the DART impact. All the spectra characterized in the 2022 OW are similar (Table A1) and also in good agreement with JDL06, observed more than 18 yr before. This similarity can also be inferred when comparing the spectral slope for single daily reflectance spectra with the one for the ejecta, enclosed between $4.73 \pm 0.70$ and $6.28 \pm 0.57$ %/0.1 $\mu$m. Although slopes are susceptible to change due to several factors (composition, observational conditions, phase angle, space weather) the fact that the computed slope do not change appreciably is another proof of the potential homogeneity of the system.

From ground-based observations, we could also infer that the Didymos system should not be very dissimilar at different rotational phases, as indicated by the substantial similarity of the spectral behavior for the combined spectra of one night pre- and postimpact (specifically August 5 and November 3). The spectral homogeneity of the system is also in agreement with the recent results from D. Polishook et al. (2023). They had the chance to characterize the system right before and after the DART impact, noticing that while in the first ∼60 hr after the impact the slope and the Band II center change appreciably, the system return to its unaltered preimpact status starting from September 28 to 29. They attribute these changes to the ejecta cloud following the impact, that likely disperse after a week.

We used ground-based data to infer some physical properties of the ejecta. While it is possible to see some differences in the BI center position, the spectral shape of the main body (which is dominated by Didymos) and the same one for the ejecta data is substantially similar (as shown by a chi-squared comparison), indicating that at least Dimorphos ejecta and Didymos share a similar composition. This could confirm indirectly that Didymos and Dimorphos are roughly of the same material, as suggested by indirect considerations and dynamical models. The similarity of the band depth for the main body (Didymos + Dimorphos) and the ejecta data (with an inevitable contribution of the main body) could also imply that the grain size distribution of the ejecta are not very much different from grain size properties of the Didymos surface itself, although ejecta could represent fresher, newly excavated material. Indeed, the ejecta characterized showed a band center at slightly shorter wavelength, which could be indicative of a lower calcium and iron content (T. L. Dunn et al. 2010). This could indicate that the mixing of surface and subsurface material ejected in the plume have a slightly different molar composition than the whole system. However, this result must be taken with caution, as the nature of these spectroscopic observations spectra for the ejecta (with the slit oriented along the ejecta tail) necessarily explain Didymos and Dimorphos also. The Hera mission, that will characterize in greater detail Dimorphos and its cratered area, will eventually confirm the homogeneity among different rotational phases and between Didymos, Dimorphos, and its ejecta.

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*Facility:* TNG (DOLORES).

## Appendix

Here we report a quantitative comparison of different spectra using a chi-squared test for goodness of the fit. In Table A1 we compare daily-averaged spectra, while in Table A2 we show spectra obtained during a single pre- and postimpact night, August 5 and November 3, respectively.

**Table A1**
$\chi^2$ Test Between Daily Averaged Spectra

| | #2 | #3 | #4 | #5 | #6 | Ejecta |
|---|---|---|---|---|---|---|
| #1 | 0.003 | 0.002 | 0.002 | 0.003 | 0.003 | 0.004 |
| #2 | | 0.002 | 0.004 | 0.003 | 0.002 | 0.006 |
| #3 | | | 0.002 | 0.002 | 0.002 | 0.004 |
| #4 | | | | 0.001 | 0.003 | 0.002 |
| #5 | | | | | 0.002 | 0.005 |
| #6 | | | | | | 0.006 |

**Table A2**
$\chi^2$ Test Between Combined Spectra Obtained on August 5 and November 3

| August 5 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|
| #1 | 0.004 | 0.007 | 0.004 | 0.006 |
| #2 | | 0.003 | 0.003 | 0.003 |
| #3 | | | 0.004 | 0.005 |
| #4 | | | | 0.004 |
| **November 3** | **#2** | **#3** | **#4** | **#5** |
| #1 | 0.002 | 0.003 | 0.002 | 0.009 |
| #2 | | 0.002 | 0.001 | 0.006 |
| #3 | | | 0.002 | 0.007 |
| #4 | | | | 0.005 |

## ORCID iDs

Simone Ieva https://orcid.org/0000-0001-8694-9038
E. Mazzotta Epifani https://orcid.org/0000-0003-1412-0946
E. Dotto https://orcid.org/0000-0002-9335-1656
J. D. P. Deshapriya https://orcid.org/0000-0002-5758-1286
P. H. Hasselmann https://orcid.org/0000-0003-1193-8945
G. Poggiali https://orcid.org/0000-0002-3239-1697
D. Perna https://orcid.org/0000-0002-4545-3850
M. Dall'Ora https://orcid.org/0000-0001-8209-0449
A. Lucchetti https://orcid.org/0000-0001-7413-3058
M. Pajola https://orcid.org/0000-0002-3144-1277
S. L. Ivanovski https://orcid.org/0000-0002-8068-7695
A. Rossi https://orcid.org/0000-0001-9311-2869
J. R. Brucato https://orcid.org/0000-0002-4738-5521
P. Palumbo https://orcid.org/0000-0003-2323-9228
V. Della Corte https://orcid.org/0000-0001-6461-5803
A. Zinzi https://orcid.org/0000-0001-5263-5348
C. A. Thomas https://orcid.org/0000-0003-3091-5757
J. de León https://orcid.org/0000-0002-0696-0411
A. S. Rivkin https://orcid.org/0000-0002-9939-9976
M. Amoroso https://orcid.org/0000-0003-2603-165X
I. Bertini https://orcid.org/0000-0002-0616-2444
A. Capannolo https://orcid.org/0000-0002-4917-287X
G. Cremonese https://orcid.org/0000-0001-9021-1140
I. Gai https://orcid.org/0000-0002-5367-3650
G. Impresario https://orcid.org/0000-0001-8984-4231
M. Lavagna https://orcid.org/0000-0003-4361-1437
D. Modenini https://orcid.org/0000-0002-1517-3938
S. Pirrotta https://orcid.org/0000-0003-0377-8937
P. Tortora https://orcid.org/0000-0001-9259-7673
M. Zannoni https://orcid.org/0000-0002-4151-9656
G. Zanotti https://orcid.org/0000-0002-3157-7588

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