Investigating the Relationship between (3200) Phaethon and (155140) 2005 UD through Telescopic and Laboratory Studies

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Abstract
The relationship between the near-Earth objects (3200) Phaethon and (155140) 2005 UD is unclear. While both are parents to meteor showers (the Geminids and Daytime Sextantids, respectively) and have similar visible-wavelength reflectance spectra and orbits, dynamical investigations have failed to find any likely method to link the two objects in the recent past. Here we present the first near-infrared reflectance spectrum of 2005 UD, which shows it to be consistently linear and red-sloped, unlike Phaethon’s very blue and concave spectrum. Searching for a process that could alter some common starting material to both of these end states, we hypothesized that the two objects had been heated to different extents, motivated by their near-Sun orbits, the composition of Geminid meteoroids, and previous models of Phaethon’s surface. We thus set about building a new laboratory apparatus to acquire reflectance spectra of meteoritic samples after heating to higher temperatures than available in the literature to test this hypothesis and were loaned a sample of the CI chondrite Orgueil from the Vatican Meteorite Collection for testing. We find that while Phaethon’s spectrum shares many similarities with different CI chondrites, 2005 UD’s does not. We thus conclude that the most likely relationship between the two objects is that their similar properties are only by coincidence as opposed to a parent-fragment scenario, though the ultimate test will be when JAXA’s DESTINY+ mission visits one or both of the objects later this decade. We also discuss possible paths forward to understanding Phaethon’s properties from dynamical and compositional grounds.

Unified Astronomy Thesaurus concepts: Asteroids (72); Comets (280); Meteor showers (1034); Near-Earth objects (1092); Laboratory astrophysics (2004)

1. Introduction
1.1. Overview

The Geminid meteor shower is one of the best-studied and easily observed meteor showers, but until 1983 no parent comet had been identified. Furthermore, the orbit of the Geminids is not that of a long-period or Jupiter-family comet, with a period of only 1.4 yr and a perihelion distance inside the orbit of Mercury at \( q = 0.140 \) au. Near-Earth object (NEO) 1983 TB, later named (3200) Phaethon, was discovered in a Geminid-like orbit and was quickly deemed a plausible parent for the meteor shower (Whipple 1983). While Phaethon was originally presumed to be a dead comet (see, e.g., Belton & A’Hearn 1999), with the Geminids thought to have been produced through conventional cometary activity in the past, the story has become much less clear over the past two decades. While studies of the Geminids themselves have mostly concluded that they are fundamentally cometary in nature, studies of Phaethon have been converging on the idea that it is an (active) asteroid from the main belt as opposed to stochastically captured from the outer solar system (a review of both of these topics is presented in the next subsection). Phaethon is thus a key object to understand on the now-recognized continuum between comets and asteroids. The NEO (155140) 2005 UD (Kasuga et al. 2005; Jewitt & Hsieh 2006) is compelling for the same reasons, as it is the inactive parent of the daytime Sextantids—as well as a proposed fragment of Phaethon itself. Investigations into the modern properties and relationship between members of the “Phaethon–Geminid Complex” (PGC) are thus investigations into how meteor showers form, as well as the properties of low-albedo NEOs.

1.2. (3200) Phaethon

Phaethon’s properties are much better studied than 2005 UD’s owing to its earlier discovery date and larger size; thus, it sets the framework for which these related bodies are compared and understood. The surface of Phaethon is strongly blue at visible and near-infrared wavelengths (∼0.35–2.5 μm; see, e.g., Tholen 1984; Licandro et al. 2007), unlike the typical strongly red reflectance spectrum of traditional cometary nuclei and D-type asteroids. Phaethon’s orbit, while highly eccentric to the point where its perihelion is lower than Mercury’s at \( q = 0.14 \) au, is generally accepted to be hard to produce from a typical Jupiter-family comet orbit (Bottke et al. 2002) and probably more likely to come from the main belt of asteroids (de León et al. 2010), possibly from (2) the Pallas Collisional Family. However, there are serious issues with producing Phaethon’s reflectance spectrum and albedo from an originally Pallas-like composition (see the discussion of Karetta et al. 2018). Furthermore, the radar-derived size of Phaethon of more than 6 km across at the equator (Taylor et al. 2019) is inconsistent with much previous thermal modeling of the object, supporting a lower albedo nearer to ∼8% like that of Karetta et al. (2018), as opposed to the higher ∼12%–16% values of studies like that of Hanuš et al. (2016) or Masiero et al. (2019), for reasons not yet well understood, though many of these authors have speculated that Phaethon may have odd thermal properties in light of the discrepancy. While Phaethon’s visible-wavelength albedo might be typical for B-type asteroids...
As opposed to the strange properties of their mostly inactive parent body, the study of the orbital distribution and physical properties of the Geminids themselves has been a cleaner story. The age of the Geminids appears to be among the youngest of the large meteor showers, with a maximum age of a few thousand years (Ryabova 1999, 2016). The spatial distribution of meteoroids, especially its asymmetry about the peak, probably requires a large change in parent body orbit during stream ejection, such as by nongravitational forces (Lebedinetz 1985; Ryabova 2016). The meteors themselves appear to be denser than typical cometary meteors (Halliday 1988). They have a wide variety of sodium abundances (Kasuga et al. 2005; Borovička 2010; Abe et al. 2020), probably due to intense solar heating (Kasuga 2009), but have an overall composition consistent with cometary material (Borovička 2010; Abe et al. 2020). The higher-than-cometary densities could also be explained as a heating-related effect, with the weaker grains being preferentially removed from the stream with time by thermal stresses (Čapek & Vokrouhlický 2012). Abe et al. (2020) found that smaller meteoroids were more depleted in sodium, consistent with this idea.

1.4. The Phaethon–Geminid Complex and Paper Overview

A comprehensive explanation of the PGC needs to explain the modern asteroid-like properties of Phaethon (surface reflectivity, orbit, as well as the comet-like properties of the Geminid meteoroids themselves (composition, orbital distribution) as described in the previous section. One avenue for further study is characterizing other small bodies thought to be dynamically associated with Phaethon and the Geminids. (155140) 2005 UD is a ~1.6 km NEO with a blue reflectance spectrum (Jewitt & Hsieh 2006; Devogèle et al. 2020) thought to be dynamically linked to Phaethon and the Daytime Sextantids, as well as the Geminids less directly (Kasuga et al. 2005). This is a second NEO with similar (visible) reflectance properties, with a very low perihelion (q = 0.16 au), and associated with its own meteor shower, and thus it is expected to be a highly valuable target for comparison with Phaethon.

The specific of the relationship between the two bodies are debated. For example, Ryabova et al. (2019) make dynamical arguments that the two objects could not have been in close contact in the recent past given our understanding of their orbits despite their similar and rare surface properties. It is unclear whether or not 2005 UD (the so-called “mini-Phaethon”) is a fragment of its larger cousin and thus genetically related, introduced to near-Earth space through some common process, or that the two objects just coincidentally have similar orbits, surfaces, and associated meteor showers. It is imperative to understand the relationship between these objects, not just to better understand the origin of their modern properties and meteor showers, but also to make preparations and predictions for the arrival of JAXA’s DESTINY+ spacecraft to Phaethon in the mid-2020s (Arai et al. 2018), which may be able to fly by 2005 UD at a later date. There is another object proposed to be in the PGC, 225416 (1999 YC) (Ohtsuka et al. 2008), but its orbit and physical properties are even more different from Phaethon than UD’s (Kasuga & Jewitt 2008), and it has received comparatively little characterization as a result.

In this paper, we present the first near-infrared reflectance spectra of (155140) 2005 UD in Section 2 to better understand its modern properties and compare it to its better-studied cousin (3200) Phaethon. We also present new laboratory reflectance measurements of the CI chondrite Orgueil heated to Phaethon and 2005 UD relevant temperatures in Section 3 to better constrain the thermal histories of and relationship between these bodies. In Section 4.1, we discuss how these interrelated lines of evidence and inquiry change our perception of their respective properties and histories.

2. Near-infrared Observations of 2005 UD

We obtained the first near-infrared reflectance spectra of 2005 UD at the NASA Infrared Telescope Facility using the SpeX instrument (Rayner et al. 2003) on three dates in 2018 September and October, the details of which are presented in Table 1. Guiding was accomplished with the MORIS camera (Gulbis et al. 2011) owing to the high apparent motion and faintness of the target. The observations followed the procedure of Kareta et al. (2018), whereby observations of the target were “bookended” by observations of a local G-type star for immediate telluric correction and later slope-corrected further using a well-characterized solar analog G2V star (SAO 93936) observed near zenith. This method has been used to effectively and reproducibly characterize faint solar system small bodies on many occasions (see, e.g., Sharkey et al. 2019). The...
reduction was performed partially within the “spextool” environment (Cushing et al. 2004) and partially within custom-written scripts in Python (see “Software” after the Acknowledgments section).

The reflectance spectra obtained on 2018 October 2 and 3 of 2005 UD are presented and compared with the reflectance spectrum of Phaethon from Kareta et al. (2018) in Figure 1. The September 19 data are much noisier compared to the other two spectra, so they are only described here and omitted from Figure 1. The reflectance spectrum of 2005 UD is weakly red throughout the near-infrared ∼0.7–2.5 μm on all three dates, though we note that the use of MORIS as a guider with SpeX can decrease the signal in the shortest-wavelength region (<0.85 μm) owing to low throughput near the visible/near-infrared dichroic mirror (S. J. Bus 2021, personal communication). We also note that while the slit was aligned to the parallactic angle, the object’s nonsideral tracking rates were so large that moderate short-wavelength slit losses may be possible. Both of these issues would result in lost flux and thus artificially lower reflectance values in the <0.85 μm region if relevant. The lack of any large change in slope at the shortest wavelengths indicates that neither process had a significant effect on the data.

To check for consistency in spectral slopes between our three nights of observations, we consider the region 0.85–2.4 μm and calculate values for $S$′, where $S$′$_i$($\lambda_1$, $\lambda_2$) = ($dS/d\lambda$)$_i$/($S$$_i$ of 1.5% ± 0.2%/0.1 μm), 0.7% ± 0.2%/0.1 μm), and 0.5% ± 0.1%/0.1 μm) for September 19, October 2, and October 3, respectively. The uncertainties are those from the formal linear curve fitting. The combined October 2 and 3 spectrum has 0.6% ± 0.1%/0.1 μm. For context, the Bus-Demeo average C-type has $S$′ = 1.16 ± 0.07 over the same range, so we find that 2005 UD is less red than a C-type but still red in the near-infrared. We note that Marsset et al. (2020) analyzed decades of similar observations and found a systematic 4.2%/μm uncertainty over this whole wavelength range (0.8–2.4 μm), larger than our uncertainties derived from our linear fits. However, those same authors note that regular observations of standard stars (thus requiring regular reacquisition of the target on the slit) do mitigate much of this systematic uncertainty. We also utilized standard-star observations close in air mass (ΔX < 0.1), which is the other dominant factor in this systematic error. The rotation period of 2005 UD is 5.235 hr (Devogèle et al. 2020), so our October 2 and 3 observations are separated by almost exactly 4.0 rotation periods, and the September 19 and October 2 observations are separated by slightly more than 59 rotation periods. These three separate nights of observations do not show evidence for the previously reported possible heterogeneous surface of 2005 UD (Kinoshita et al. 2007), but that is perhaps unsurprising, as the three sets of observations span the same ∼$\frac{3}{4}$ period of the surface. The observing geometry did change significantly, so some difference might have been expected. The redder slope of the September 19 observations is statistically different, but given that the spectrum is likely phase reddened (Sanchez et al. 2012), was taken at a low enough heliocentric distance that the object likely has thermal emission contaminating the longer wavelengths (see, e.g., Delbó et al. 2003; Reddy et al. 2009; Kareta et al. 2018), and is much noisier owing to the lower total integration time on a dimmer target, we suspect that the difference is not resulting from heterogeneous surface properties. We again note that measuring slope differences at the level of subtlety discussed here is at or near the limit of what can be provided by traditional observing schemes with this instrument, so our actual knowledge of slope variations on 2005 UD is driven by systematic uncertainties, which are challenging to quantify in more detail than we have described in this section.

3. Phaethon versus 2005 UD

The revelation that (3200) Phaethon and (155140) 2005 UD might have very different near-infrared reflectance spectra is very surprising given the ample similarities of the two objects (very similar and uncommon visible reflectivities, similar and uncommon orbits, both are meteor shower parent bodies, etc.),
so two questions must be addressed: is the difference real, and if it is, what are plausible mechanisms to explain it?

As for whether or not the difference is real, there are multiple reasons that we believe the results. First, both sets of observations (of UD and of Phaethon) compared in Figure 1 were taken by the same instrument, taken by the same observers, and reduced using the same packages and methods. Second, due to the large nonsideral rates that 2005 UD moved during the portion of its 2018 apparition in which we observed it, we had to use different local telluric stars each night (but the same master solar analog), which, when combined with the almost identical retrieved reflectance spectra on each night, makes flukes of calibration due to poor choice of calibration stars seem unlikely. Third, though perhaps most important, the retrieved spectrum of Phaethon shown from Kareta et al. (2018) is very consistent with many previous observations of the object, and thus the pipeline by which both data sets has been reduced is validated. The difference between the objects seems very real, though we again remind the reader of the possible calibration issues in the 2005 UD data at shorter wavelengths due to the dichroic and parallactic angle issues mentioned previously.

There are then two kinds of scenarios to be considered when attempting to explain these objects’ discrepant physical properties: either they are genetically/dynamically related somehow, and some process has made their surfaces appear different, or they are not related and their similarities are either coincidental or simply by-products of some larger process in the inner and middle solar system.

If the two objects really are only coincidentally similar, then there should be multiple pathways into Phaethon/Geminid-like orbits. While there are serious issues to be resolved in understanding whether or not Phaethon is a heated and devolatilized member of the Pallas Collisional Family (de León et al. 2010; Kareta et al. 2018; MacLennan et al. 2021), 2005 UD’s spectrum is a very poor match for Pallas or any member of the Pallas Collisional Family (they are all strongly blue in the near-infrared, many with Phaethon-like concave-up spectra), suggesting that those problems would be even more challenging to resolve for it. Furthermore, the surface of the less studied candidate member of the PGC 1999 YC (Ohtsuka et al. 2008) is an even worse fit (Kasuga & Jewitt 2008), so the problems continue in that arena. Dynamical studies of how to implant objects into Phaethon-like orbits from source populations beyond the Pallas family (e.g., other volatile-rich asteroid families, the outer main belt, Hildas, JFCs, etc.) could be extremely useful in answering the plausibility of this scenario. The significant inclination (∼22°) of Phaethon and 2005 UD (∼29°) limits the number of areas to search.

If the two objects actually do share some sort of meaningful relationship, then some divergent process should be able to create both kinds of surfaces. We consider the five following processes:

1. Parent Body Heterogeneity: If the precursor object that disrupted into Phaethon and 2005 UD had variable composition over its surface and throughout its interior (such as if it had been fully or partially differentiated, as has been argued for (24) Themis in Castillo-Rogez & Schmidt 2010), then the daughter fragments could inherit some of these differences and appear different from each other. Considering that Phaethon itself appears to have a largely homogeneous surface (Kareta et al. 2018) and dominates the mass of the two objects combined, it seems unlikely that UD would somehow inherit different properties by chance. Furthermore, if the Geminids are a by-product or related to the breakup event, then they, too, should be heterogeneous, which they do not appear to be outside of variable sodium depletion (Borovička 2010), often but not exclusively attributed to their low perihelion distance. (In principle, we cannot rule out some stranger scenario where the progenitor object was obviously differentiated or heterogeneous, but neither daughter object nor the Geminids inherited any unambiguous heterogeneities by chance.)

2. Differential Space Weathering: Space weathering is a collection of processes (energetic particle impact, UV irradiation) that acts to change the spectral slope of an object. While in general the process is said to make the reflectivity of a planetary surface redder and darker (Pieters et al. 1993) (true for rocky surfaces like the Moon or S-type asteroids), there is evidence that some volatile-rich surfaces like those of CI or CM chondrites might become bluer (Lantz et al. 2017). Furthermore, recent laboratory (Thompson et al. 2020) and in situ measurements at (101955) Bennu (DellaGiustina et al. 2020) suggest that for carbonaceous surfaces, surfaces might initially become bluer, only to brighten and redden afterward. It is important to note that traditional space weathering products such as nanophase iron seen in lunar regolith have not been detected in abundance on CI or CM chondrites, and it is expected that the same stimuli are resulting in fundamentally different processes on carbonaceous objects, even though all of these effects are labeled “space weathering.” In general, space weathering apparently has a much larger effect at visible wavelengths that tapers off into the near-infrared, so the very similar visible reflectance spectra of Phaethon and 2005 UD (Jewitt & Hsieh 2006) make this scenario seem unlikely. Space weathering, thought to decrease strongly in importance with increasing distance from the Sun, must play some role in modifying the surfaces of these two objects. If Phaethon and 2005 UD have different surface effective surface ages, this would allow them to be at different parts of the blueing-then-reddening trends found in works like Thompson et al. (2020) and DellaGiustina et al. (2020). However, the magnitude of changes estimated from those and other works are not enough to account for the observed difference between the two objects.

3. Grain Size Effects: The distribution of grain sizes on a planetary surface can change the way that light reflects off of it significantly (see, e.g., Clark & Roush 1984). Moreover, more massive bodies should be able to retain even smaller grains on their surfaces owing to their stronger gravity—and Phaethon is much more massive than 2005 UD. However, Phaethon also seems to be losing the finest (∼1 μm) grains off of its surface owing to solar radiation pressure (Jewitt & Li 2010), so it is
showing evidence of thermal metamorphism. The in-air spectra
of the CI chondrite Ivuna after heating to 873 and 973 K were
among the best fits for Phaethon and 2005 UD, respectively,
with and without forcing the visible spectrum to be blue-
sloped. Both in-air laboratory spectra have linear blue slopes at
visible wavelengths, while the 873 K spectrum becomes linear
and red near ∼0.9–1 μm and the 973 K spectrum continues as
blue and linear in the near-infrared without any very obvious
slope break. This trend with heating, whereby the visible
reflectance remains blue but the near-infrared reflectance goes
from linear and red to blue-sloped, is the right kind of trend to
explain these objects. The matches were imperfect in key ways,
however: the 873 K spectrum was slightly too red for 2005 UD
and the 973 K spectrum was not sufficiently blue to match that
of Phaethon, and it did not have the same slight convex-upward
curvature seen throughout the same wavelength range.
Assuming an albedo like that of Kareta et al. (2018) for
Phaethon for both objects (p_v = 0.08 ± 0.01) and a standard
emissivity value (ε = 0.9), we would expect their surfaces to be
heated to approximately these temperatures. Phaethon’s sur-
f ace-averaged temperature T_{ave} ∼ 969 K and subsolar temper-
ature T_{SS} ∼ 1085 K at perihelion are similar and slightly
higher than the 973 K laboratory data, respectively, while 2005
UD’s temperatures (T_{ave} ∼ 895 K, T_{SS} ∼ 1002 K) at its perihelion
are similar to and higher than the 873 K laboratory data as
well. The explanation that 2005 UD is simply a less thermally
metamorphosed Phaethon is an exciting prospect, but the
hypothesis is largely based on a limited number of laboratory
measurements that were conducted in air and not under a space-
like vacuum. We deemed it necessary to collect more
labatory data of heated CI chondrites to confirm the spectral
trends seen and try to better understand how well they could
constrain the thermal histories—and thus relationship—
between these two objects.

4. Laboratory Reflectance Spectroscopy

4.1. Methodology

In order to test the hypothesis that Phaethon and 2005 UD
are made of the same material but heated to different degrees,
new laboratory measurements of the reflectance of CI
chondrites at higher temperatures than available in the literature
from RELAB had to be obtained, and ideally in a vacuum as
opposed to in air. In particular, the heating experiments should
be designed in such a way as to mimic both the grain sizes
thought to be relevant for Phaethon and UD (∼1–30 mm; see
Devogèle et al. 2020) and the vacuum of space. To achieve this
goal, we constructed a vacuum heating chamber (affectionately
referred to as the “Bar-B-Cube”) in the Reddy Spectroscopy
Lab at the University of Arizona. After initial sample
preparation, which might vary based on the sample and topic
being investigated (e.g., grinding and size sorting with a mortar
and pestle), the sample is placed inside a No. 200 nickel sample
cup (chosen based on nickel’s high melting point and ease with
which it can be machined) and lowered into the chamber from
above. The sample cup is placed on the center of the heating
element, and the sapphire window on the top of the chamber is
tightened. The vacuum pump is then turned on, and the
chamber is slowly lowered to ∼10^-6 torr or lower. The vacuum

5 We note for any readers interested in utilizing or inspecting these Ivuna
spectra that they are labeled in RELAB in degrees Celsius, not kelvin, e.g.,
600°C and 700°C, and seem to be from Hiroi et al. (1996a).
chamber was able to reach pressures as low as \( \sim 10^{-8} \) torr if untouched for several hours. Highly volatile-rich samples, such as CI or CM chondrites, require this process to be quite slow so as to avoid sudden outgassing disrupting the surface of the sample once the pressure inside approaches the triple point of water at room temperature (\( \sim 7 \) torr). Reflectance spectra of the sample within the chamber are obtained by first calibrating on a nearby spectral standard through an identical sapphire window and then moving the optical fibers to observe the sample. The optical fibers are held in a standard orientation for both the calibrations and the science observations using a 3D printed part that keeps the two fibers 30° apart. The fibers are held in a near-vertical orientation otherwise in both configurations to avoid differential flexure, which might introduce subtle artifacts. This procedure was successfully tested on a variety of meteoritical and artificial samples to verify that the retrieved spectra were consistent with those measured through standard in-air procedures, though the spectra are often somewhat noisier. We note that we used a lamp optimized for the near-infrared, so the reported spectra are only shown beyond 0.5 \( \mu \)m. While the retrieved spectra are consistent in spectral behavior with their in-air counterparts after calibrations, the absolute albedo (vertical scale) is likely not after heating for volatile-rich samples. As volatiles leave the samples, the surface subsides somewhat in a way that cannot be measured well enough to correct for the change. As a result, the reflecting surface is farther away from the optical fibers and thus appears artificially darker to the spectrometer.

The heating of a particular sample is done in increments of 50–150 K both to attain a fine temperature resolution to record spectral changes over and also not to cause the sample to lose too many volatiles at once and risk exploding out of the cup into the vacuum. The general procedure is to raise the temperature of the heating element to a desired temperature, wait until the temperature stabilizes at the set value (5–15 minutes depending on how high the temperature is set), and then keep the temperature at that level for 1 hr or until outgassing of the sample has been decreasing steadily for 15 minutes, whichever is longer. For the volatile-rich samples tested, this was almost always 1 hr, with the exception of temperatures near \( \sim 950–1000 \) K, where outgassing from the sample was much more significant. (This is also the highest temperature range reached for the previous study of Ivuna Hiroi et al. 1996a.) Once this time limit is reached, the sample is allowed to cool radiatively back to near-ambient temperatures (\( \sim 300 \) K), which could take up to 2 hr from the highest temperatures the samples were heated to. Blackbody emission clearly contaminated the retrieved spectra at any higher temperature than room temperature, and all reflectance spectra suspected of having a blackbody component were discarded when possible. A full heating, cooling, and observation cycle took approximately \( \sim 3 \) hr on average. The maximum temperature reliably maintained by the heating element with a filled sample cup was \( \sim 1350 \) K, or approximately \( \sim 375 \) K higher than the samples of Ivuna we compared our data to from RÉLAB.

4.2. Heating CI Orgueil

This study largely focuses around our heating of a sample of the CI chondrite Orgueil, specifically the sample 1070B from the Vatican Observatory’s Meteorite Collection. The previous CI chondrite that was heated (Ivuna, heated up to 973 K in Hiroi et al. 1996a) has somewhat different reflective properties than Orgueil, and our sample preparation routine was not identical to theirs, so differences are to be expected. In particular, Ivuna is somewhat bluer at near-infrared wavelengths than Orgueil (at least before heating), and Hiroi et al. (1996a) heated their samples as unground chips and then ground them down into a semifine powder (\( <125 \) \( \mu \)m). Their spectra were also obtained in air, as opposed to a near vacuum more analogous to the conditions on planetary surfaces. Cloutis et al. (2011) found that even slight changes in particular mineral abundances, particularly magnetite, can cause comparatively large slope changes in CI chondrites. For comparison with that study and to meet our goal of matching the estimated grain size for these bodies as best as possible considering the limited amount of the sample of Orgueil provided (\( \sim 0.5 \) grams), we divided our sample roughly in half, into an unground \( \sim 1 \) mm subsample and a \( <45 \) \( \mu \)m subsample, which largely stuck together in larger clumps after being sorted into the sample cup. While the orbital history of the CI Ivuna parent meteoroid is not known, the orbital history of the Orgueil strongly suggests that the parent was on a Jupiter-family comet or Halley-type comet orbit (Gounelle et al. 2006). The nature of the CI chondrites in the context of their parent bodies is discussed further later. In order for a particular laboratory spectrum of Orgueil to be considered good evidence that a CI-like meteorite could fit the spectrum of the small body in question, the deviation from the fit should therefore be within the range of variability expected from changes in grain size or mineral content (within reason). The reflectance spectra of large millimeter-sized pieces of the CI chondrite Orgueil heated from room temperature up to \( \sim 1350 \) K are shown in Figure 2.

The spectrum of the large grains (\( \sim \)millimeter sized) of CI chondrite Orgueil is shown to change significantly as it is heated to successively higher temperatures, but the trends observed are not identical to those demonstrated for the CI chondrite Ivuna in Hiroi et al. (1996a). At visible wavelengths, the slope of the reflectance spectra becomes increasingly linear with increasing heating (a decrease in near-UV absorption strength, as previously noted for Ivuna as well) and has variations in absolute slope while still being blue (negative) until 1123–1173 K, where the slope becomes red and linear. At near-infrared wavelengths, the slope is always overall blue (negative), though curvature (concave-up) is apparent at a handful of temperatures, most prominently between 973 and 1173 K, or approximately the range of temperatures expected for Phaethon’s surface at the present day and in the recent past near perihelion. Figure 3 shows a comparison of our Orgueil and Hiroi et al. (1996a)’s Ivuna, both heated to 973 K compared with the reflectance spectrum of Phaethon. Figure 4 shows a comparison of the derived spectral slopes for the whole data set as a function of temperature at a variety of wavelength ranges again compared with Phaethon and 2005 UD. The relationship between the visible and near-infrared slopes, and specifically how they change in the 0.8–1.0 \( \mu \)m region and the curvature at longer wavelengths, could indeed be a useful way to identify thermal metamorphism in Orgueil-like bodies, similar to that shown in the in-air Ivuna data of Hiroi et al. (1996a) and suggested in other contexts by Vernazza et al. (2017) and Marss et al. (2016). The
reflectance maximum seen near $\sim 0.6\ \mu m$ decreases in prominence with increasing heating but does not appear to totally disappear as reported for the Ivuna samples in Hiroi et al. (1996a). We see no evidence for any curvature in the $\sim 1.3\ \mu m$ region as was seen in Ivuna, and in fact the slope changes due to heating appear less obvious there. We note that the higher signal-to-noise ratio in the room-temperature in-vacuum spectrum appears to be primarily due to the fact that the sample shrank in size afterward owing to loss of volatiles. In other words, the room-temperature spectrum shown had the sample surface be physically closer to the fiber that was going to the spectrometer, resulting in higher throughput.

Part of the difference between our work on Orgueil and previous work on Ivuna is almost certainly the usage of fine-grain-sized powders in Hiroi et al. (1996a), which generally would result in redder spectra, but the overall trends are different in a way that hints at more processes in play. This is perhaps to be expected, as carbonaceous chondrites are often highly heterogeneous in composition at small scales (Bischoff et al. 2006). Another critical difference is that our data were obtained in vacuum, and thus in an environment more similar to that of Phaethon and UD, as opposed to the in-air spectra presented of Ivuna.

While the spectra of Orgueil heated to Phaethon-like temperatures show many similarities with Phaethon’s reflectance spectrum (with some key differences discussed later), the fact that none of the retrieved spectra show red or neutral slopes in the near-infrared seem to conflict with any positive match with 2005 UD. Even if the standard is broadened to “a near-infrared slope that is redder than the visible slope of the same sample,” there seem to be no retrieved spectra that meet the criterion.
Figure 4. The derived spectral slopes (black, in the $S'$ notation of Luu & Jewitt 1990) at visible (0.60–0.74 μm) and near-infrared (1.1–1.60 and 1.8–2.2 μm) of our sample of CI/Orgueil as a function of maximum temperature reached. The spectral slopes are compared with those of Phaethon (in blue, using the spectrum from Kareta et al. 2018) and 2005 UD (in orange–red).

Figure 5. A comparison of the new laboratory data of CI/Orgueil from this study (left) with the RELAB samples of CI/Ivuna (right; Hiroi et al. 1996a). The spectra shown are subsets of both data sets centered around the temperatures most relevant for the study of 2005 UD and Phaethon. The spectra were all normalized at 0.6 μm and subsequently offset vertically to facilitate comparison with Figure 2. The processes by which each of these sets of spectra was produced and reduced into their current forms are not identical; see the text for details.
5. Further Discussion

5.1. Spectral Comparisons

In this study, we have obtained the first near-infrared reflectance spectra of the proposed fragment body of (3200) Phaethon and (155140) 2005 UD and found the two objects to be strikingly different. Phaethon’s reflectance spectrum is concave-up and overall blue-sloped throughout the near-infrared, while UD’s is approximately linear and very weakly red-sloped. One process that we hypothesized could explain their discrepant spectral slopes and curvatures would be thermal metamorphism due to their highly eccentric but distinct near-Sun orbits, meaning that they were made from the same material originally but had subsequently been altered to different extents. A comparison of our newly obtained data of an increasingly heated sample of CI Orgueil and similar data from Hiroi et al. (1996a) of CI Ivuna data to (3200) Phaethon’s properties is shown in Figure 3.

Through visual inspection alone of Figures 2 and 3, it can be seen that none of the heated samples appear similar to 2005 UD at near-infrared wavelengths, while those in the temperature range expected for Phaethon (roughly 1000–1200 K) are indeed approximately linear and blue-sloped at visible wavelengths while also being blue and concave-up at near-infrared wavelengths in good qualitative agreement. Phaethon shows no near-UV decrease in reflectance above 0.35–0.4 μm, unlike the data for Orgueil shown here. If the near-UV drop-off in our data is real (and not driven by, perhaps, very low light levels and a light source optimized for the near-IR), then we conclude that Phaethon’s spectrum is better described as Ivuna-like at short wavelengths and Orgueil-like at longer wavelengths. One other key aspect to note is where the visible/near-infrared slope change occurs. In our data on Orgueil, the slope change occurs somewhere between 0.8 and 1.0 μm but cannot be discerned more clearly owing to its proximity to a changeover in detector usage in our spectrometer near those wavelengths. In the Ivuna data set of Hiroi et al. (1996a), the slope change occurs nearer to 0.6–0.7 μm. In Phaethon and 2005 UD, the location of this spectral slope change is near to ~0.8 μm but, again, is often the area where two separate data sets (one from a visible-wavelength instrument and one from a near-infrared instrument) are stitched together. Again, the Orgueil data set seems “closer” than Ivuna does to matching Phaethon, but the location of the spectral slope change needs to be tied down more tightly with future work. Neither Orgueil nor Ivuna fits 2005 UD well, but a combination thereof seems to share many similarities with Phaethon. The rarity of CI chondrites like Orgueil and Ivuna can reproduce all the key features of Phaethon’s visible and near-infrared spectrum while not reproducing 2005 UD given the currently available spectra.

In Figure 4, we show a comparison of the derived slopes S′ (Luu & Jewitt 1990) of the laboratory data at three wavelength ranges (0.60–0.74 μm, 1.1–1.60 μm, and 1.8–2.2 μm) compared against the slopes of Phaethon and 2005 UD calculated over the same wavelengths. These ranges were chosen to try to encapsulate the changing curvature of the spectrum while avoiding the noisier parts of the laboratory data where there was a change in detectors. Where the laboratory data intersect the colored areas corresponding to each NEO is where their slopes agree (within errors) at those wavelengths. In agreement with visual inspection, Phaethon’s spectrum appears most similar to the Orgueil samples heated to 973–1073 K. 2005 UD’s apparent agreement in slope at longer wavelengths is not indicative of an actual spectral match, but instead due to the increasing curvature of the sample of Orgueil throughout the near-infrared. The 1.1–1.60 μm slope shows much less variability than the other two regions, with slopes near S′ ~ -1.25 to ~1.50 for most temperatures. The 0.6–0.74 μm region generally blues from ~623 to ~703 K before sharply becoming more red, and a similar trend is shown for the 1.8–2.2 μm, though the bluest slope is achieved at ~973 K. The fact that these changes are centered around the 973–1073 K region is unsurprising, as many materials common in CI chondrites (namely phyllosilicates) begin to break down at these temperatures into other substances. Despite the fact that the laboratory data appear to intersect the spectral slopes of Phaethon for all three spectral regions within the range of temperatures expected for this body, we argue that this is indicative of a similarity between the sample and the NEO as opposed to a direct spectral match considering the imperfections in the comparison detailed in the previous paragraph, as well as in Figure 3.

In other words, our new laboratory data and preexisting laboratory data support the hypothesis that Phaethon’s surface resembles that of a CI-chondrite-like material that has been heated significantly owing to its orbit. However, the same cannot be said for 2005 UD. While a red slope in the near-infrared and a blue slope in the visible can be achieved with the Ivuna data of Hiroi et al. (1996a), the change in slope is at altogether the wrong location, and no red-sloped spectrum is ever seen in our Orgueil data set. In summary, we conclude that a heated CI chondrite origin for Phaethon is compatible with the laboratory data, while the same does not appear to be true for 2005 UD given the currently available spectra.

5.2. The Relationship between Phaethon and 2005 UD

In Section 2, we argued that parent body heterogeneity, differential space weathering, grain size effects, and phase reddening are each unlikely to be able to explain the different spectra of Phaethon and 2005 UD. If the objects were related, then we argued that their spectra could be resultant from differential space weathering of their surfaces due to their different orbits, but our laboratory data do not appear to support that hypothesis.

While it is possible there may be some carbonaceous material (either not yet recognized or not available among terrestrial sample collections) for which this hypothetical scenario could have more traction, the fact that CI chondrites like Orgueil and Ivuna can reproduce all the key features of Phaethon’s visible and near-infrared spectrum while not reproducing 2005 UD’s spectrum suggests that the difference might be more than evolutionary and instead related to different origins for the two bodies.

While the orbital relationship between the two bodies is indeed debated (see, e.g., Ryabova et al. 2019), the objects are similar in so many ways that a shared origin is often assumed in spite of contrary orbital evidence. Blue-colored objects are fundamentally rare in the inner solar system (perhaps ~1 in 23 objects; see Bus & Binzel 2002), and inactive meteor shower parent bodies even more so. The other best-studied inactive parent body, (196256) 2003 EH1, has a more common organic-rich red surface and a typical cometary orbit (Kasuga & Jewitt 2015; Kareta et al. 2021), both of which lend themselves to more easy explanations than the situation of Phaethon, 2005 UD, and the Geminids. In the absence of other unknown processes operating on these bodies now or in the recent past,
we conclude that the least complicated interpretation of the data is simply that the objects are only similar by chance. Should they choose to do so, the DESTINY+ team (Araki et al. 2018) could thus visit two meteor shower parent bodies that have undergone similar processes yet discrepant origins, thus facilitating a greater understanding of near-Sun objects and meteor shower creation in general, as opposed to studying one interconnected system in great detail. Of course, DESTINY+ could also find more compelling evidence for the relationship between the two bodies than we have found here! Future characterization of both bodies is an incredibly compelling task, both before and after they are characterized in situ.

5.3. The Origin of the Geminids?

While an unexpected by-product of trying to explain the difference in spectral properties between Phaethon and 2005 UD, we have also provided more evidence in this study that Phaethon’s surface is consistent with that of a heated CI chondrite from the near-UV through to at least 2.5 μm. This is consistent with the composition of the Geminoid meteorites themselves (Kasuga et al. 2005; Borovička 2010; Abe et al. 2020). Considering that the CI chondrites have been suggested as derived from comets, could the story just be as simple as “Phaethon really is a dormant comet, and the Geminids are just a normal meteor shower”? As appealing as that prospect might be, the problem of Phaethon’s modern noncometary orbit remains, even if its other properties could likely be squared with an outer solar system origin. (There is also still the question of how best to interpret the origins of the CI chondrites, as while many of their properties are consistent with comets, the existence of hydrothermally altered minerals is outside of the expected material properties of comets significantly.) We consider two scenarios to explain the given telescopic, meteoric, dynamical, and laboratory data.

The first scenario is that Phaethon’s progenitor region or parent in the main belt was also made out of CI-chondrite-like material, but instead of being recently scattered in from the outer solar system, it had been emplaced there through a “Grand Tack”-like scenario (Walsh et al. 2011) billions of years ago. Considering the fact that outer solar system material has to be in the main belt, and a large fraction of the NEOs have to come from there (see, e.g., Bottke et al. 2002; Morbidelli et al. 2002), there almost certainly have to be members of the NEO population that do have CI-like properties. However, given Phaethon’s nonzero inclination and high eccentricity, the number of plausible parent bodies or families is not extremely high. The recent work by MacLennan et al. (2021) shows that the high-inclination inner main belt Svea family might be a better match than previous candidates like the family of (2) Pallas (de León et al. 2010), so further characterization of objects in that family is of interest.

Another scenario is motivated by dynamical studies of the Geminid meteors themselves. First raised in Lebedinets (1985) and recently discussed further in Ryabova (2016) is the idea that the Geminid-forming event changed the orbit of the parent body significantly. This particular aspect of the stream-forming event is thought to be necessary to explain particular aspects of its duration and spatial extent in the modern day given its young age. If Phaethon’s orbit did change significantly around the time of Geminid formation, then all previous backward orbital integrations of the body likely are not capturing what really happened, and as a result different past dynamical scenarios are possible. In addition to possibly opening up new possible source regions (other parts of the main belt, the Jupiter-family comets, etc.), it could also change how we interpret the “similar” orbits of 2005 UD and Phaethon in the modern day. If even a rough estimate of how much the Geminid parent orbit would need to change were available, then a suite of dynamical integrations could be investigated to see how much of our current understanding of Phaethon’s orbital history is valid. Given the chaotic nature of the inner solar system and fairly small minimum orbital intersection distance with Earth (<0.02 au, JPL Horizons), we suspect that even a small change in Phaethon’s orbit could result in a large change in its modeled dynamical history, and thus a large change in our understanding of the history of the object.

6. Summary

The relationship between (3200) Phaethon, the (semi-) inactive parent of the Geminids meteor shower, and (155140) 2005 UD, the inactive parent of the daytime Quadrantids, is of great interest for several reasons. The bodies appear to have similar visible reflectivities and orbits, neither object either is active in a cometary way or looks obviously like a dormant comet, and they are the primary and possible secondary targets of the upcoming JAXA DESTINY+ mission scheduled for the late 2020s. In this work, we have synthesized new telescopic observations and new laboratory data to attempt to better understand the relationship between these two objects and their individual properties.

1. We obtained the first near-infrared reflectance spectrum of 2005 UD utilizing three nights of observations in 2018 September and October, each time finding a primarily linear red-sloped spectrum. Phaethon’s spectrum is blue and concave-upward throughout the same wavelength range (even utilizing the same instrument and reduction scripts), indicating that the difference between the two objects is real despite their very similar properties at shorter wavelengths.

2. Either the two objects have similar properties by chance, or some process or effect has altered them from some common starting point. We make arguments against parent body heterogeneity, differential space weathering, grain size effects, and phase reddening as likely origins of the different spectra in Section 2, but we argue that differential thermal alteration could be a plausible method. The two objects are in highly eccentric near-Sun orbits with surface temperatures where many likely surface materials begin to thermally alter and decompose drastically, and Phaethon’s surface (and the Geminids!) has previously been interpreted as showing signs of previous or ongoing intense heating. CI chondrites that have been heated to Phaethon/UD-like temperatures seemed promising, but the existing laboratory data did not extend to high enough temperatures to assess the likelihood of this scenario.

3. We heated a sample of the CI chondrite Orgueil from the Vatican Meteorite Collection to incrementally higher temperatures up to 1350 K with a novel laboratory apparatus described in detail in Section 4. We measured the reflectance spectra from ∼0.5 to ∼2.3 μm at each stage after the sample had cooled back to ambient temperatures to compare to the spectra of 2005 UD and
Phaethon. Our heating sequence of the CI Orgueil is similar in some ways and different in others from the heating sequence of the CI Ivuna of Hiroi et al. (1996a), again described in more detail in the text. The spectrum of Phaethon shares many characteristics with both CI chondrites (though neither is a perfect match), but UD is not a high-quality match to either object, which argues against the differential thermal alteration hypothesis.

4. We thus propose that the two objects only have similar spectra by chance, though similar processes likely have acted upon them both. Excitingly, DESTINY+ might be able to visit two unrelated but similar meteor shower parents, or it might find evidence for their relationship that is not easily attainable from remote sensing. We also highlight several areas of future inquiry to better understand Phaethon’s modern properties motivated by its apparent similarity to multiple CI chondrites and recent studies of the Geminid meteors themselves.

The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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Facilities: IRTF (SpeX, MORIS).

Software: NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), AstroPy (Astropy Collaboration et al. 2013, 2018).

Appendix

Photos of the Vacuum Heating Chamber and Samples

This appendix provides labeled images and descriptions of our laboratory apparatus such that the reader can better understand its usage, both for a more thorough understanding of this work and in case they one day pursue a similar experimental program. Figure 6 shows a view of the full experimental apparatus and explains its parts, and Figure 7 shows how the samples were stowed and heated within the chamber.

Figure 6. The vacuum heating chamber set up (“the Bar-B-Cube”) on a laboratory bench at the University of Arizona with individual components labeled. A: the vacuum pressure gauge, which shows the current pressure inside the chamber, as well as a graphical summary of recent pressure changes. B: the vacuum pump. C: the light source (a common heating bulb) shining into the input of an optical fiber that is connected to E. D: a residual gas analyzer mass spectrometer, attached to diagnose leaks during the initial testing phase. E: the output of the light-emitting fiber, as well as the input of the fiber that leads to the VISNIR spectrometer held in a constant orientation with a 3D printed black ABS plastic holder.
Figure 7. (a) Close-up view from above the chamber looking through the sapphire viewing window into the interior, showing a filled sample cup ($D \sim 0.5$ mm for scale) on top of the circular heating element. “Below” the picture is an identical sapphire window mounted at the same height inside of which a spectral standard is mounted. (b) Similar to panel (a), but showing the thermal glow of the nickel sample cup that was obviously visible at the highest temperatures reached. The bright white-yellow crescent is the edge of the underlying heating unit, which is slightly larger in area than the footprint of the sample cup.

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