Near-infrared Spectroscopy of the Nucleus of Low-activity Comet P/2016 BA₁₄ during Its 2016 Close Approach

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Abstract

The near-Earth comet P/2016 BA₁₄ (PanSTARRS) is a slow-rotating, nearly dormant object, a likely dynamical twin of 252P/LINEAR, and was recently shown to have a mid-infrared spectrum very dissimilar to other comets. Comet BA₁₄ was also recently selected as one of the backup targets for the ESA’s Comet Interceptor, so a clearer understanding of BA₁₄’s modern properties would not just improve our understanding of how comets go dormant but could also aid in planning for a potential spacecraft visit. We present observations of BA₁₄ during its 2016 Earth close approach taken with the NASA Infrared Telescope Facility on two dates, both of which are consistent with direct observations of its nucleus. The reflectance spectrum of BA₁₄ is similar to 67P/Churyumov–Gerasimenko, albeit highly phase-reddened. Thermal emission contaminates the reflectance spectrum at longer wavelengths, which we correct with a new Markov Chain Monte Carlo thermal modeling code. The models suggest that BA₁₄’s visible geometric albedo is $p_V = 0.01–0.03$, consistent with radar observations; its beaming parameter is typical for NEOs observed in its geometry; and its reflectance spectrum is red and linear throughout the $H$ and $K$ bands. It appears very much like a “normal” comet nucleus despite its mid-infrared oddities. A slow loss of fine grains as the object’s activity diminished might help to reconcile some of the lines of evidence, and we discuss other possibilities. A spacecraft flyby past BA₁₄ could get closer to the nucleus than with a more active target, and we highlight some science questions that could be addressed with a visit to a (nearly) dormant comet.

Unified Astronomy Thesaurus concepts: Comets (280); Short period comets (1452); Spectroscopy (1558)

1. Introduction

The study of low-activity or fully dormant comets is critical to understanding how comets age and deplete their volatiles, as well as learning how to identify them among other low-albedo small bodies in the inner solar system. The problem is identifying them. While some orbits might allow for more definitive conclusions about whether or not a particular object is a dormant comet (e.g., lower Tisserand parameters), many objects cannot be so conclusively identified as such without additional information. One scenario where a cometary origin can be more clearly identified is if a candidate dormant comet is dynamically linked to a traditionally active comet, such as with the dormant comet 2003 EH₁₄ and active comet 96P/Machholz (Jenniskens 2004; Wiegert & Brown 2005). (Comet EH₁₄ is also the parent of the Quadrantsid meteor shower, so their dynamical relationship was not the only clue.) Dynamically similar or linked objects have likely experienced similar thermal conditions over the past few thousand years due to their similar orbits, and if they are genetically related (e.g., descended from a common progenitor object), one can assume that their bulk compositions are quite similar as well. The problem is then to constrain which scenarios can explain their modern differences so as to better understand how comets age and turn off more directly than would otherwise be possible. When did they split, and why are they so different now? Studies of dormant and not dormant comet pairs or groups are thus of great interest to those studying the life cycles of comets in particular and the divide between comets and asteroids in general.

The close approach of comet 252P/LINEAR (hereafter 252P) to the Earth on 2016 March 21 was followed closely ~26 hr later by the approach of P/2016 BA₁₄ (PANSTARRS; hereafter BA₁₄) on March 22. Comet BA₁₄ had only been discovered in late January of that year (Linder et al. 2016) as an apparently inactive near-Earth object (NEO) on the orbit of a Jupiter-family comet extremely similar to that of 252P. Observations of BA₁₄ prior to the close approach revealed that it too was undergoing cometary mass loss (first reported by Knight et al. 2016), and it was subsequently given the cometary P/ designation, completing its modern name (Naves et al. 2016). Postencounter, 252P has a perihelion distance of $q = 0.996$ au and an eccentricity of $e = 0.673$, while BA₁₄ has $q = 1.008$ au and $e = 0.666$.

The two comets, despite their similar orbits, appear to be quite different. Li et al. (2017) characterized 252P with the Hubble Space Telescope and both 252P and BA₁₄ with the Lowell Discovery Telescope (LDT; then named the Discovery Channel Telescope) during and around their close approach and found that while 252P is small ($D \sim 0.6$ km) and was very active for its size (a water-derived active fraction of 40% to more than 100%), BA₁₄’s active fraction was on the order of ~0.01% or so, or a factor of $\sim 10^4$ less, despite its larger nucleus. Li et al. (2017) estimated BA₁₄’s nucleus to be approximately $D \sim 1$ km in size based on its JPL Horizon reported absolute magnitude of $H_V = 19.2$ and an assumed albedo of 4%. Radar observations presented by Naidu et al. (2016) found the size of the object to likely be more than 1 km in diameter (implying an optical albedo of ~0.03 or less) and an extremely slow rotation period of ~40 hr with hints of an
angular and blocky surface. While Hyland et al. (2019) did not detect gas emission from BA14, Li et al. (2017) did detect CN emission on 2016 April 17 consistent with a production rate of \( Q(\text{CN}) = (1.4 \pm 0.1) \times 10^{22} \text{mol s}^{-1} \). The visible reflectivity of BA14’s nucleus or coma is minimally constrained, with Li et al. (2017) only observing BA14 in a single nongas filter \((r')\), and Hyland et al. (2019) obtaining a red slope beyond \( \sim 0.58 \mu m \). Their results hinted at a possible blue slope at shorter wavelengths \(<0.54 \mu m \), but calibration issues hampered their ability to ascertain how reliable that measurement was.

Perhaps most relevant to the current study is the recent work of Ootsubo et al. (2021), which presented and analyzed mid-infrared observations of BA14 just prior to its close approach. Those authors argued that their observations were dominated by emission from BA14’s nucleus, as opposed to grains in its coma. The direct detection of cometary nuclei during close approaches is possible due to the larger apparent area of the sky that the coma is spread over, which in this case would be assisted by the overall minimal activity of the object. A similar scenario of somewhat-unplanned direct mid-infrared observations of the nucleus of a comet during close approach is described in the seminal Hanner et al. (1985). Ootsubo et al. (2021) presented mid-infrared photometry and low-resolution spectra of BA14 that do not look similar to typical mid-infrared observations of cometary comae (see, e.g., Kelley & Woolen 2009) or the nuclei of more active comets observed at larger heliocentric distances (see, e.g., Kelley et al. 2017). Instead of an emission spectrum dominated by emission features from silicates (perhaps most notably the 10 \( \mu m \) excess), the retrieved spectrum appears dominated instead by absorption features due to phyllosilicates and organics. While Lisse et al. (2006) did find evidence for phyllosilicates in the ejecta of the Deep Impact experiment (A’Hearn et al. 2005), the dominant materials (by areal fraction in the retrieved spectral modeling, at least) were amorphous and crystalline silicates. Ootsubo et al. (2021) argued that if they did indeed observe the nucleus of BA14, then a phyllosilicate-rich surface might be a common surface composition for comets, or at least those on the verge of going dormant. Considering the lack of information about the surface of BA14 at the wavelengths where comet nuclei are increasingly able to be studied (visible and near-infrared, NIR), it is challenging to ascertain which of these scenarios is more likely, or if BA14 is an outlier for a reason yet to be considered.

We thus have one primary question we aim to address in this study and a second that will require additional work at a later date. Primarily, what is the actual nature of the surface of BA14, and how could it inform our understanding of the surfaces of low-activity comets and how comets go dormant in general? Secondly, what is the relationship between BA14 and 252P, and what would explain their differences if they are genetically related? We do not present new observations of 252P or address this question in great detail in this work, but we highlight part of the path forward at the end of Section 6. It is particularly critical to address these questions now, as BA14 has recently been selected as a potential backup target for the ESA’s Comet Interceptor mission (Snodgrass & Jones 2019; Schwamb et al. 2020). It is critical to understand these two objects in great detail now so that the best-informed choice can be made nearer to the end of the decade when the Comet Interceptor team is choosing a target.

In this work, we present low-resolution NIR \((0.7–2.5 \mu m)\) spectra of BA14 taken with SpeX (Rayner et al. 2003) on the NASA Infrared Telescope Facility (IRTF) from approximately 11 and 14 days prior to the observations of Ootsubo et al. (2021) to attempt to diagnose the surface reflectivity and albedo of this object and place it in context among the broader population of comets whose nuclei have been studied directly. In Section 2, we present a journal of observations and describe our data reduction procedure. In Section 3, we present and describe the reflectance spectra we obtained of BA14 on March 7 and 10 UTC and make comparisons to other comets observed at the same wavelengths. We also present spatial profiles of BA14 at visible and NIR wavelengths for context about any possible coma contamination. In Section 4, we describe and utilize our efforts to remove the thermal excess from the longer-wavelength portions of our spectrum to analyze the underlying reflectance there and constrain its albedo. Finally, in Section 5, we synthesize all of these results and those in the literature to better understand how to interpret the properties of BA14 and address what potential spacecraft exploration could do for the target.

2. Observations

Object BA14 was observed on 2016 March 7 and 10 UTC with the SpeX instrument (Rayner et al. 2003) on the NASA IRTF as part of an observational program centered on time-sensitive observations of small and/or close-approaching NEOs. The observational details are summarized in Table 1. All observations were obtained with the low-resolution “Prism” mode on SpeX, providing simultaneous coverage from 0.7 to 2.5 \( \mu m \) at an effective resolution of \( R \sim 100 \) with a 0′8 wide slit. Observations of the target were “bookended” by observations of a G-type star nearby on the sky at a similar airmass for proper telluric correction, and observations of a proper solar analog star (SAO 93936 on both nights) was later observed near 1.0 airmass for further slope correction of the final output spectrum. Observations of the target and calibration stars were all obtained at the local parallactic angle to mitigate wavelength-dependent slit losses. The observational circumstances were such that all observations of BA14 were between airmasses of 1.55 and 1.70. The reduction, extraction, and telluric correction of the spectra were accomplished using the IDL-based “spectool” package (Cushing et al. 2004) using the default (optimal) settings for an unresolved point source, while the final solar analog correction was accomplished using a custom-written script in Python.

2.1. Comparison of Visible and NIR PSFs

While the reduction was completed shortly after the observations, the SpeX observations are (thankfully) available on the IRTF Legacy Archive,4 and we present a comparison of the point-spread functions (PSFs) of local telluric stars observed before and after observations of the target were taken to assess whether or not any dust coma might be visible in Figure 1. The data shown are from 2016 March 7, where seeing was much better \((\sim 0′′51)\) at visible wavelengths as measured by the visible-wavelength guide camera. The spatial profiles shown were derived by combining the A and B profiles after doing an A – B subtraction on paired sequential frames (labeled

4 http://irfdata jika.hawaii.edu/search/
2016-03-07 05:26 1.015 0.125 77.0 \sim 0^\circ 51 \sim 22 2400.0
2016-03-10 05:12 1.011 0.102 76.1 \sim 155 \sim 6 2400.0

Notes.
a UTC at start of sequence.
b Relative humidity as measured at the IRTF at the start of the sequence.

Figure 1. The along-slit spatial profiles are shown for BA14, as well as the telluric star observed immediately before and after as obtained on 2016 March 7. The profiles shown are medians over the wavelengths corresponding to the J-band (1.17–1.33 \mu m). The visible seeing was quite good (\sim 0^\circ 51), and the resulting profiles are quite narrow, but the profile of BA14 is still significantly wider than the star was before or after. Worse seeing (such as that obtained on March 10) would not have shown this clear hint of activity, however weak it might be. See text for more details.

as a “folded spatial profile” on the Figure 1 x-axis, as it effectively shows only half the slit due to their combination), such that the BA14 profile shown is the aligned and stacked average of all 12 200 s exposures on that night. The spatial profiles of the star are from single combined A–B pairs due to the much higher signal-to-noise ratio (S/N) on the brighter calibration star. The profiles were extracted at wavelengths corresponding to the J filter, or between 1.17 and 1.33 \mu m. The FWHM of a best-fit Gaussian profile to the stars retrieved FWHM = 0^\prime 28 \pm 0^\prime 01 before and 0^\prime 28 \pm 0^\prime 01 after observations of BA14, which was measured to have FWHM = 0^\prime 39 \pm 0^\prime 01. Performing the same analyses at the H or K band retrieved the same FWHMs for the stars (0^\prime 26–0^\prime 28) and comet (0^\prime 38–0^\prime 39) as for J to within \sim 1.0\sigma.

The extended PSF of BA14 in our IRTF observations could be due to an actual detection of its coma in the NIR (despite the generally much lower visibility of typically sized cometary dust at those wavelengths) or slight guiding imperfections that might not be noticed under ordinary seeing conditions. An object being tracked at nonsidereal rates (1\arcmin 4 minute \(^{-1}\) on March 7) with long exposure times will inevitably lead to some drift within the slit over the course of the exposures; both of these issues do not apply to the sidereally tracked short exposures on the nearby standard stars. If the detection is indicative of the coma’s size, given the geocentric distance of \Delta = 0.125 au, we estimate the dust coma BA14 to have an FWHM of \sim 35–36 km and a maximum detectable extent of \sim 240 km at the J-band on March 7 UTC. If the coma was the same size on March 10, we estimate its FWHM to have been \sim 0^\circ 49, though we note that this is considerably smaller than the seeing limit on that date.

To assess the appearance of the coma at optical wavelengths around the same time, we queried the Mission Accessible Near-Earth Object Survey’s database and found visible-wavelength imaging observations from the SOAR telescope and LDT on 2016 February 21 and 22, respectively, when the heliocentric and geocentric distances of BA14 were \rho_H = 1.055–1.059 and \Delta = 0.229–0.237 au. The SOAR observations utilized the Goodman High-Throughput Spectrograph (Clemens et al. 2004) in imaging mode with the Sloan r filter, while the LDT observations utilized the Large Monolithic Imager (Massey et al. 2013) with a “VR” filter. The SOAR observations consisted of one 10 s exposure and five 60 s exposures, while the LDT observations were six 60 s exposures. We applied standard corrections to each set of images (debiasing, flattening) and then calibrated them astrometrically and photometrically using the Photometry Pipeline (Mommert 2017), with the photometric calibration being derived exclusively from Sun-like stars within the fields of view. (The “VR” filter was calibrated as if it was a Sloan r filter due to their similar central wavelengths.)

In the LDT observations, the FWHM of BA14 was 0^\prime 95 \pm 0^\prime 02 along the direction perpendicular to its apparent motion and 1.07 \pm 0.02 along the direction of its motion compared to a uniform 0.91 \pm 0.01 for nearby field stars. For the SOAR observations, the cross-track profile has 0^\prime 51 \pm 0^\prime 01, the along-track profile has 0.59 \pm 0.02, and nearby stars have 0^\prime 49 \pm 0^\prime 01. The images were all taken with exposure times short enough to prevent the along-track extension being due to trailing. These quoted numbers are measured from the composite images composed of the individual frames stacked at the object’s nonsidereal rates, but the same results were found through inspection of individual frames as well. Through these analyses and visual inspection of all frames individually and stacked, it seems rather firm that we detect BA14’s small coma in these images. The magnitude of BA14 was \textit{m}_r = 18.71 \pm 0.02 on February 21, and \textit{m}_{VR-r} = 18.64 \pm 0.02.

The visible coma of BA14 was two to three times the size of the NIR spatial profile at twice the geocentric distance and when the comet was slightly further from the Sun and thus presumably slightly less active. If any of the slightly larger-than-stellar spatial profiles in our IRTF observations are from reflected or thermally emitted light from the coma of BA14, it is sampling a small areal fraction of an already small coma at wavelengths where dust should be less prominent. In Section 3, we discuss the very limited possible coma contamination of our NIR spectra.
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3. BA14 in the NIR

3.1. Retrieved Reflectance Spectra

The retrieved reflectance spectra of BA14 are shown in Figure 2. The spectra obtained are similar on both dates, with an overall red slope becoming more neutral with wavelength and an upturn in reflectivity at wavelengths longer than ~2.25 μm that is likely excess thermal emission “on top” of the reflected light from the solid coma and nucleus. However, the spectrum obtained on March 10 is noticeably redder at shorter wavelengths, becoming similar to the March 7 observations by ~the Hband; the possible slope break near 1.4–1.5 μm appears somewhat sharper; and the region ≲1.35 appears slightly more linear. Both stars were slope-calibrated to the same well-studied solar analog (SAO 93936), and inspection of the ratios of the spectra of each star’s local G-type telluric would not have introduced the change either. We also note that any wavelength-dependent slit losses would be smooth functions of wavelength, unlike the difference in the retrieved spectra, so we think this is an unlikely cause of the discrepancy as well, especially considering that our observations were all at the local parallactic angle to mitigate just this effect. Considering that conditions on both nights were rather good (low and stable humidity), the phase angle did not change appreciably, and the target was observed at a similar airmass on both nights, it seems like the difference is real, or at least mostly so.

To quantify the slopes of the two spectra, we use the S’ framework of Luu & Jewitt (1990) and report slopes for the J, H, and K spectral ranges in units of %/0.1 μm for both nights. For the March 7 data, we find S’j = 4.6 ± 0.8, S’h = 3.4 ± 0.7, and S’k = 4.3 ± 1.5. For March 10, we find S’j = 7.7 ± 0.3, S’h = 3.0 ± 0.3, and S’k = 5.9 ± 0.6. The Kslopes are contaminated from the thermal emission, and we report slopes measured over the range (1.95–2.20 μm) to attempt to mitigate this. At wavelengths away from the thermal excess, the slopes of the two spectra agree at the 1σ level at the Hband, but March 10 is significantly redder at the Jband, as expected.

Furthermore, it is worth stating explicitly that our spectra are almost certainly quite phase-reddened (Sanchez et al. 2012), meaning that the retrieved reflectance spectra appear redder than they would if observed at a lower phase angle. However, estimating the magnitude of this effect is challenging, as we do not know the phase function of the nucleus or the dust coma, the relative contribution of either to the reflectance spectrum, or how that would vary with the phase angle itself.

3.2. Did We Observe the Nucleus?

Perhaps the most obvious factor to consider, given the claimed direct observation of the nucleus by Ootsubo et al. (2021), would be the ~20% drop in geocentric distance between the two dates from Δ = 0.125 au on March 7 to Δ = 0.102 au on March 10. One would expect, a priori, that if the coma was more spread out on the sky, then the brightness of the nucleus would dominate more in the later, closer observations. Quantitatively predicting how a dust coma’s surface brightness would change with distance might be simpler at larger distances, but for the current case (a close flyby of a barely active object) it would be much more complicated and less reliable. Given the rather long rotation period (P ~ 40 hr; Naidu et al. 2016) and the small scales probed, it seems reasonable to assume that the innermost coma of BA14 is highly anisotropic unless the nucleus’s surface is uniformly active, which seems rather unlikely given its extremely low active fraction (Li et al. 2017). The visible light curve of the object presented in Li et al. (2017) shows that the object’s overall brightness trend is dominated by the nuclear signal, though this does not necessarily preclude some contamination.

The slight change in spectral behavior between the two observations also provides insight into the issue. The spectrum obtained on 2016 March 10, when coma contamination should have (in principle) been lower and the nucleus more prominent, shows a slope break near 1.4–1.5 μm. A population of small grains comparable to the wavelengths of note (as expected for cometary comae) reflects light according to Mie theory, which should produce reflectance spectra that do not have discontinuities or sudden slope changes with wavelength but instead more gradual continuous ones. By contrast, light reflected by solid surfaces or by particles much larger than the wavelength of light in question, which are out of the Mie regime and better modeled with Hapke photometric theory (Hapke 1993), can produce such sudden slope breaks. In fact, Sharkey et al. (2019) found a slope break at a nearly identical wavelength on the Jupiter Trojan and Lucy (Levison & Lucy Science Team 2016) mission target (21900) Orus. A review of the limited number of nuclear spectra of confirmed low-activity or dormant comets in DeMeo & Binzel (2008) and Kareta et al. (2021) shows that some but not all comets in those studies have slope breaks in the same wavelength region. Furthermore, the change in slope is very apparent on comet 67P/Churyumov–Gerasimenko (Filacchione et al. 2019). As to whether or not the slope break derives from large grains or the surface of the nucleus itself, a nucleus with as low an active fraction as BA14 (~0.01%; Li et al. 2017) would make ejection of large grains ir physically challenging. Furthermore, if the shorter-wavelength section of the March 7 data set is more curved and slightly less red than the March 10 spectrum, but the two spectra converge at longer wavelengths, one possible explanation is that the shorter wavelengths of the March 7 reflectance spectrum contain some light from grains similar in size to the wavelengths being studied here, e.g., micron-sized, within the Mie regime and outside of the Hapke regime. We
thus conclude that the most likely scenario to explain our observations is that the nucleus is a majority of the reflected light contained in the spectra collected on March 7 and 10, and that the March 10 spectrum is likely even more dominated by the nucleus itself.

4. Thermal Excess Modeling

4.1. Modeling Description and Initial Results

Understanding, modeling, and correcting for the exponential-like upturn at wavelengths longer than ~2.25 μm in spectra of low-albedo NEOs is critical to understanding both their reflectivities at those wavelengths and the thermal properties of their surfaces and near surfaces. The go-to method for these kinds of studies is the Near-Earth Asteroid Thermal Model (NEATM; Harris 1998), a modification of the earlier Standard Thermal Model (STM; Lebofsky et al. 1986) to better suit observations of small NEOs. The specifics of applying NEATM to thermally contaminated reflectance spectra at these and similar wavelengths is outlined in Rivkin et al. (2005) and Reddy et al. (2009). The NEATM (and STM, for that matter) assumes that all thermal emission from the object in question is blackbody emission from the dayside of the object. The surface temperature at a particular point is calculated as

\[ T(\theta, \phi) = \left( \frac{1 - A) \times S_0}{\eta \epsilon \times R_H^2} \times \cos(\theta) \times \cos(\phi) \right)^{1/4}, \]

where \( A \) is the Bond albedo of the object (which, in turn, is a function of \( p_V \)), \( S_0 \) is the solar constant (1370 W m\(^{-2}\) at \( R_H = 1 \) au), \( \eta \) is the infrared beaming parameter, \( \epsilon \) is the (bulk) emissivity of the object (assumed to be the canonical 0.9), \( \sigma \) is the Stefan–Boltzmann constant, and \( R_H \) is the heliocentric distance of the object at the time of observation in au. Here \( \theta \) and \( \phi \) are the angular coordinates on the body itself moving away from the subsolar point, such that the temperature of the object is modeled as \( T = 0 \) at the terminator and on the whole of the nightside. The infrared beaming parameter \( \eta \) is essentially the “fudge factor” that allows the model to overcome its rather large assumptions. A body with “normal” (e.g., regolith-covered and moderate-to-slow rotation speed around its principal axis) thermal parameters observed at a rather small phase angle should have a value of \( \eta \approx 0.9–1.1 \) — only a small deviation from a traditional graybody, but at larger phase angles or with less common thermal states (less regolith, non-principal-axis rotation, etc.), the value of \( \eta \) should get increasingly large, up to a (theoretical) maximum near \( \pi \). While a more detailed description of the model and its serious limitations in this capacity is included in Kareta et al. (2018), we note that as the model is really constraining \( T_{SS} \), the fit parameters \( p_V \) and \( \eta \) are expected to be somewhat degenerate.

In order to account for this degeneracy and better understand the errors on our fit parameters, we update the model of Kareta et al. (2018) by changing it from a least-squares fitting technique into a Markov Chain Monte Carlo (MCMC) technique using the package emcee (Foreman-Mackey et al. 2013). The best fit from the least-squares technique is used as an initial guess for the distribution of walkers in emcee. We utilized 32 walkers and 2000 iterations as an initial attempt due to the low number of parameters and the length it took for each iteration. The results are presented in Figure 3.

The fit parameters are constrained to be in the range of \( p_V = 0.016^{+0.004}_{-0.011} \) and \( \eta = 1.560^{+0.424}_{-0.441} \) at the 99.7% confidence level, with the maximum-likelihood values being \( p_V = 0.0135 \) and \( \eta = 1.627 \). The shapes of the distributions of the parameters are as expected, with the bottom left panel of the corner plot (the right side of Figure 2) showing a curve. Essentially, this is the curve of constant peak subsolar temperature. While the marginalized distribution of the \( \eta \) values is symmetric about its approximate maximum-likelihood value, the distribution of \( p_V \) values is highly skewed, with the maximum-likelihood value being on the absolute lowest end of the confidence interval.

These values for the infrared beaming parameter \( \eta \) are quite reasonable for a typical NEO, in fact almost exactly what would be estimated from the Delbò et al. (2003) empirical relationship between phase angle and beaming parameter. The ranges of allowed visible albedos are all really quite low; if taken at face value, this would make BA14 among the darkest objects in the solar system. The radar data do mandate that the object’s albedo has to be below 3%, so our range of values does satisfy the one preexisting constraint. The distribution for NEOs as found by the all-cryogenic phase of the WISE mission (Wright et al. 2016) finds that approximately 5% of objects have geometric albedos of 0.02 or less, so our nominal range of values places the albedo of BA14 in the “quite rare but not implausible” range. The radar albedo upper limit and an absolute magnitude of \( H_V = 19.2 \) result in a diameter estimate of \( D \sim 1.1 \) km, and our maximum-likelihood albedo of \( p_V = 0.0135 \) results in a diameter of \( D \sim 1.6 \) km. In the next two subsections, we discuss complications of this albedo estimate that would likely result in it being a slight under-estimate and thus our estimated diameters being a slight overestimate.

4.2. Phase-reddening Complications and Correction

In order to estimate the ratio \( f_{IR} = p_{IR}/p_V \), we extrapolated downward to 0.55 μm by way of a linear fit to all data points short of 0.9 μm. This is the data-driven way to estimate \( f_{IR} \) but is susceptible to over- or underestimating the actual ratio should there be slope changes in the visible. A linear extrapolation of the March 10 data results in \( f_{IR} = 3.24 \). In many cases, one can check this estimate by comparing the retrieved value against typical values for the taxonomic class of the object, most commonly the Bus–Demeo system (DeMeo et al. 2009), but our spectrum is even redder than the very red A and D types (before phase reddening is accounted for, at the very least.) For context, the low-activity Halley-type comet P/2006 HR36 (Siding Spring) had \( f_{IR} \sim 1.92 \) (Kareta et al. 2021), and the more active Jupiter-family comet 67P/Churyumov–Gerasimenko had \( f_{IR} \sim 2.0 \), depending on which area of the surface was studied (Quirico et al. 2016). The retrieved spectrum of BA14 itself is almost certainly significantly phase-reddened, which we first highlighted in Section 3. The reflectance spectra of solar system objects appear redder at larger phase angles than they would at zero phase (e.g., opposition). While the magnitude of this change per degree can be quite small (often smaller than the other measurement uncertainties at hand), at the large phase angles sometimes occupied by NEOs, it can be critical to account for it to estimate what the “real” spectrum looks like.

In the case of phase-reddened and hot NEOs, the thermal emission at longer wavelengths is being added onto a reddened
underlying continuum, making guesses at the underlying reflectivity at longer wavelengths challenging. Phase reddening is not constant with wavelength, so there is some question of how much of the thermal upturn is actual thermal emission and how much is the phase-induced redness of the object underneath the thermal photons. There has been some work done to how much of the thermal upturn is actual thermal emission and is not constant with wavelength, so there is some question of underlying continuum, making guesses at the underlying reflectivity at longer wavelengths challenging. Phase reddening is not constant with wavelength, so there is some question of how much of the thermal upturn is actual thermal emission and how much is the phase-induced redness of the object underneath the thermal photons. There has been some work done to correct NEATM’s imperfections at larger phase angles (e.g., Momment et al. 2018) calculated corrections to NEATM for high phase angles, but their work assumes that all light being collected is flux-calibrated observations at longer wavelengths than studied here), but we are not aware of a preexisting prescription in the literature for dealing with this particular issue.

Given the lack of additional information, we attempt to “undo” the phase reddening’s impact on our thermal modeling by rerunning our MCMC modeling routine with a lower $f_{IR} = 1.92$, implicitly assuming that BA14’s surface is similarly red (measured in bulk from the visible to the $K$band) at zero phase angle to P/2006 HR30 (Siding Spring)’s. These results are plotted in red in Figure 3. The distribution of $\eta$ is essentially unchanged ($\eta = 1.553^{+0.409}_{-0.330}$), but the distribution of the visible geometric albedo $p_V$ is shifted higher ($p_V = 0.029^{+0.046}_{-0.016}$) by approximately the ratio of the $f_{IR}$ values (3.24 / 1.92 $\sim$ 1.7 $\sim$ 0.28/0.016). This is the expected behavior for small enough changes in $f_{IR}$; the actual thermal model can fit the data just as well (in this case, it overlaps nearly exactly), and it is the distribution of plausible visible albedos that is modified.

So which distribution of albedos is more “likely” for this object? There is no obvious answer without a complementary visible spectrum or broadband color measurement or phase-reddening study of this object. It seems likely that BA14’s visible colors are similar to those of HR30 or 67P, and it seems inevitable that BA14’s spectrum is at least somewhat phase-reddened, so some correction is definitely in order, but the “correct” magnitude of such a correction is unknowable at present. In any case, the quality of the data does not allow obvious discrimination between such small changes in albedo anyway. The albedo of BA14 is almost certainly between 0.01 and 0.03, but precision beyond that would require higher-S/N thermal observations at longer wavelengths—or, of course, a visit by Comet Interceptor. More constraints from other techniques would not allow us to constrain the albedo better, but they would allow us to model the thermal emission more accurately and better understand the underlying reflectance spectrum with more confidence.

Figure 3. In the left panel, the maximum-likelihood thermal model with $p_V = 0.014$ and $\eta = 1.627$, or $p_V = 0.023$ and $\eta = 1.622$ after a correction for phase reddening, is shown as a dark red line, while the uncorrected data are shown as black open circles. The thermal model-corrected all-reflectance spectrum is shown as blue open circles. In the right panel, a corner plot shows the distribution of fit parameter values for $p_V$ and $\eta$ for both models. The albedo constraint from radar observations (Naidu et al. 2016) is plotted as a vertical line. As expected, the albedo and beaming parameters show some degeneracy, as the model constrains the peak subsolar temperature, which is a function of both parameters. (See text for more details.)

In summary, our thermal models of BA14’s thermal emission naturally agree with the $p_V \leq 0.03$ of Naidu et al. (2016) regardless of a phase-reddening correction, the distributions of the beaming parameters $\eta$ seem entirely typical for an NEO observed in this geometry, and the underlying spectrum appears to be featureless and linear from 1.4 $\mu$m onward like many other comets, including 67P.

4.3. Possible Thermal Contamination By Dust

Despite BA14’s thin and small coma, the dust grains that are there would still be quite warm at $R_H = 1.01$ au, suggesting that some of the thermal emission that we model as coming from the surface of the object could be coming from the coma instead. If the coma of BA14 is composed at least partially of rather small grains only a few microns in size—which seems natural for an object with such weak activity—the grains in the coma might appear “hotter” than the nucleus, as they cannot effectively emit at wavelengths larger than their physical size (see, e.g., Sitko et al. 2004). This process, often called “superheating,” would further bias the retrieved thermal fits toward higher temperatures and thus lower albedos and beaming parameters. However, BA14’s activity is quite weak, the quality of the fits is rather good, and the retrieved range of values for the infrared beaming parameter $\eta$ is quite reasonable for a small NEO. If there were significant “extra” thermal emission, then the shape of the blackbody would change and become steeper; the fact that we were able to fit it reasonably implies that the subsolar temperature our reflected-light and thermal models used was reasonable to correct the data, assuming that the thermal emission and reflected light were coming from the same source. In principle, we might be unable to differentiate our all-nucleus model from a stranger situation, such as one with a higher albedo nucleus and a darker albedo dust that balances such that their composite thermal emission looks like the curve we have modeled here. However, we would expect the dust coming off the nucleus’s surface to look...
similar to the surface itself; thus, we argue that, again, this is likely not a huge factor for this data set. We also note that if the contamination by dust was a large factor, it seems likely that our model would not be able to satisfy the albedo constraint imposed by the radar albedo. As with phase reddening, this might result in a slight underestimate of the true albedo of BA14 if it were significant.

5. Discussion

The first reason that we were interested in reexamining our spectra of BA14 was to compare with the recent work of Ootsubo et al. (2021). If BA14 looked strange or anomalous at mid-infrared wavelengths, what would it look like at other wavelengths? Do the reported mid-IR phyllosilicate and organic absorption features reported for BA14’s nucleus manifest with any signatures in the NIR? If BA14 looks like a “typical” comet using these other approaches, how does one interpret the general applicability of the Ootsubo et al. (2021) result? The second reason was the selection of BA14 as a backup target for Comet Interceptor (Schwamb et al. 2020) should a suitable long-period comet (or interstellar object) not be found in time. In this section, we first compare and contextualize our results with those of Ootsubo et al. (2021); then, we discuss its viability as a spacecraft mission target.

5.1. Comparison to the Mid-infrared

The reflectance spectra we obtained of BA14 in this work on both nights appear very much typical for comets observed in the NIR when phase reddening is considered. We interpreted our observations in Section 3 as both being primarily dominated by light from the nucleus itself, with the March 10 spectrum being even more so. The different spectral behaviors on the two nights are consistent with a thin dust coma around the object composed of micron-sized grains, which is what would be expected for such a weakly active object (Li et al. 2017). Our thermal model estimates the visible-wavelength albedo of BA14 to be quite low, at \( p_V = 0.016_{-0.011}^{+0.009} \) at the 99.7% formal confidence interval, though the large phase angle and continuing low-level dust contamination both likely result in this being a slight underestimate of the albedo of the nucleus. A simple phase-reddening correction results in a slightly higher modeled albedo distribution of \( p_V = 0.028_{-0.018}^{+0.046} \) (99.7% confidence interval). Radar data from that apparition (Naidu et al. 2016) suggest that the albedo has to be below 0.03, and there are cometary nuclei whose albedos are within this range, like 19P/Borrelly (Soderblom et al. 2002) or 103P/Hartley 2 (Lisse et al. 2009). If our albedo estimates are accurate, then we estimate a diameter between 1.1 and 1.6 km, again consistent with the current understanding of the radar data and very much a typical size for a Jupiter-family comet nucleus (Bauer et al. 2017). In the unlikely case that the object’s albedo really is on the low end of our modeled albedo distributions, the diameter of BA14 could be up to \( \sim 2 \) km. The infrared beaming parameter modeled here \( (\gamma = 1.560_{-0.041}^{+0.424}) \) is a typical range of values for an NEO observed at similarly high phase angles as is the case in this study (Delbò et al. 2003). In summary, BA14 very much appears to have the properties expected for a normal comet at these wavelengths, though it might be of slightly lower albedo than many cometary nuclei (pending the previous discussions of phase reddening and dust, of course). The only truly rare traits it seems to have are its low activity levels, slow rotation state, and anomalous appearance at mid-infrared wavelengths.

While the mid-infrared spectrum of BA14 suggests a surface incorporating more processed substances, like phyllosilicates, the NIR nuclear spectrum does not appear different than other comets expected to have a more typical composition. Ootsubo et al. (2021) attributed several features that they could not identify to being from a matrix of organics, which is thought to be a dominant surface material in comets like 67P/C-G and others (Filacchione et al. 2019). One possibility is simply that the matrix of complex organics is the dominant factor in determining the visible and NIR spectral properties of the nucleus (considering that cometary nuclei are dark and red at those wavelengths, this seems plausible) but the balance changes as one observes at longer and longer wavelengths. Could BA14 have a different surface composition compared to other objects, even if NIR spectroscopy cannot discern it? Ootsubo et al. (2021) argued based on the apparent similarity of their spectrum to heated micrometeorites that the difference is evolutionary and likely driven by previous high-temperature conditions brought on by a past orbit with a lower perihelion. However, Karetta et al. (2021) found some evidence that cometary objects should have spectral changes in the visible/NIR range if they had been heated significantly, so the fact that BA14 looks like a “typical” comet in the NIR does not necessarily support a heating origin; more data are needed on these kinds of objects to say with any more certainty. A future detailed study of BA14’s and 252P’s dynamical evolution is certainly warranted, both to understand their mutual dynamical relationship, should it be robust, and to better understand BA14’s past thermal state to assess the viability of the hypothesis that its modern surface is thermally altered.

Comets with decreasing activity levels (e.g., lowering gas production rates) can only lift smaller and smaller grains with time, in principle leading to a preferential loss of small grains from the surface. If this is a reasonable description of the recent evolution of BA14’s surface, then it might be the loss of these small and porous grains that might normally produce the 10 \( \mu \)m excess that allowed the observers to see through to the underlying material, which is usually buried in the mid-IR data. The study of Karetta et al. (2021) found that the nearly dormant Halley-type comet P/2006 HR30 (Siding Spring) had retained a classic comet/D-type slope despite whatever processes were ongoing as it became less active. That object and BA14 both have perihelia similar to or greater than 1 au, suggesting that they are also in similar thermal regimes, at least in their current and recent orbits.

One key problem going forward is the lack of clear mid-IR observations of many cometary nuclei and associated objects to compare and contextualize BA14 and related objects in. Even low-level comae might be able to hide the kinds of surface features that Ootsubo et al. (2021) observed, assuming that they (and we) were successful in actually observing the nucleus. One path forward is to obtain more 10 \( \mu \)m observations of dormant comet candidates and low-activity comets in general to compare to and better estimate which attributes of objects like BA14 are evolutionary and which parts are simply challenging to observe because of coma interference (a preliminary study reported in McAdam et al. 2018 suggests that this might be quite fruitful). The recent (successful) launch

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5 We remind the reader here that there are shortcomings of NEATM in general, summarized in Karetta et al. (2018) and elsewhere.
of the James Webb Space Telescope JWST will facilitate a generational breakthrough in our ability to measure NIR and mid-infrared reflectivities and emissivities of the surfaces of solar system small bodies. This is doubly true for cometary surfaces, for which observations at larger heliocentric distances are usually required to mitigate the confusing effects of dust and gas emission and discern the properties of the surface more directly. The NIRSPEC (up to 5 μm) and MIRI (5.0–28.5 μm) instruments are likely to be the instruments of choice, though the infrared imager NIRCAM might be better suited to fainter targets. At present, we are not aware of any currently approved JWST programs to use these mid-infrared wavelengths to better understand the composition of low-activity/dormant comet nuclei, but it seems like a highly fruitful avenue for future research. Approved studies of the Trojan asteroids and the Centaurs, both populations thought to share significant similarities with the objects discussed here, should be highly useful for planning future low-activity comet studies, in addition to their obvious scientific benefits. Another hopeful note is that the L’TES instrument on the Lucy mission will be able to measure in more detail the surface properties of more Trojan asteroids, which have previously been shown to have mid-infrared spectra like those of “typical” (non-BA14-like) comets. Lastly, we also note that many data sets obtained of BA14 during its 2016 close approach have yet to be fully analyzed and could provide key insights to help better understand how this object fits into the population of the comets in general.

5.2. Comet Interceptor

Among the backup targets for Comet Interceptor listed in Schwamb et al. (2020), BA14 is one of two low-activity targets, along with 289P/Blanpain. Low-activity targets naturally allow for safer flybys with the possibility of closer approaches to the nucleus of the chosen comet but also would result in less material being encountered and identified by remote-sensing instruments, as well as (presumably) a less complex plasma environment. Object BA14 does put off some gas (Li et al. 2017), so there is no reason to think this object would be strictly a bare nucleus, but the focus of a spacecraft visit would simply have to be more focused on studies of the surface of the comet. The slow rotation of the object as determined by radar when combined with the lower activity state could allow for higher-resolution imaging and mapping of the nucleus than many of the other targets. There are a variety of interesting questions that could be addressed through detailed imaging and spectroscopy of a nearly dormant comet, such as “how does the bulk topographic roughness evolve as comets age?” or “can the activity history of a nearly dormant comet be determined through detailed mapping of its surface?” Discriminating between surface properties (reflectance spectra, topography, thermal characteristics) between the small fraction of the surface that is active at present and the inactive fraction can only be accomplished through spatially resolved studies. If an understanding can be developed of why certain areas are still active but others are not (and how that might affect other observable features), then a more general-purpose understanding of how comets age can be developed in a much more nuanced way than just assuming that their gas production rates trend toward zero with time. The dormant comets constitute at least a few percent of the NEO population, and understanding their material and structural properties would thus benefit studies of similar objects from a planetary defense point of view, in addition to developing a broader understanding of cometary life cycles. The flyby of BA14, a “traditional” comet that has gone dormant, would provide a fascinating counterpoint to the upcoming flyby of (3200) Phaethon, an extremely low activity object that is quite unlikely to be a “traditional” comet, as opposed to a former more active asteroid, by JAXA’s DESTINY+ (Arai et al. 2018).

The MIRMIS instrument (Bowles et al. 2020) on board Spacecraft A of Comet Interceptor could produce exceptionally interesting results at characterizing BA14. MIRMIS is an NIR and mid-IR spectrograph that would facilitate detailed mapping of the cometary surface and be able to near-simultaneously observe at the wavelengths of the data presented here and the mid-IR observations of Ootsubo et al. (2021) in a spatially resolved way across much of the nucleus. This could more clearly reveal what compounds are most dominant in determining the typically featureless red spectra of cometary nuclei at visible and NIR wavelengths through detecting their absorption features directly throughout the mid-IR as in Ootsubo et al. (2021). The sensitivity of the instrument to multiple absorption features of water ice would also allow a more direct and sensitive measurement of its modern near-surface volatile content than would be capable from the ground. A comparison between the thermal stability of the surface materials, their distribution across the surface, and the orbital history of the object could then also directly assess how each of those materials responds to heating and thermal degradation once the cooling effect of sublimation is minimized. This would be a more direct test of Ootsubo et al.’s (2021) suggestion that BA14’s nucleus shows signs of past more intense heating than we were able to achieve with our observations.

6. Summary

We observed the low-activity Jupiter-family comet BA14 on 2016 March 7 and 10 using SpeX on the NASA IRTF some days before its closest approach to the Earth later that month as part of an ongoing program to obtain reflectance spectra of close-approaching and notable NEOs. We were prompted to reread and reinspect the data set after the recent publication of Ootsubo et al. (2021), who found BA14 to have an atypical spectrum at mid-infrared wavelengths compared to other comets. In particular, they interpreted their observations as being directly of the nucleus of the object and for it to be covered primarily by phyllosilicates, as opposed to the anhydrous materials more commonly found in cometary dust comae. The selection of BA14 as a backup target for the ESA’s Comet Interceptor (Schwamb et al. 2020) provides another pressing reason to reinvestigate this intriguing object now. In particular, we sought to infer whether or not our NIR observations also probed the properties of the nucleus and how it compared to other comets observed in the NIR in general. We found the following.

1. The reflectance spectrum of BA14 on both nights is steeply red and shows a significant thermal upturn at longer wavelengths. The March 7 spectrum, observed at a geocentric distance of $\Delta = 0.125$ au, has a more slowly varying spectrum, while the March 10 spectrum ($\Delta = 0.102$ au) has a sharper change in slope near $\sim 1.4–1.5 \mu m$. We interpret both spectra as being nucleus-
dominated through studies of their spatial profiles compared to visible observations from the same apparition. The latter spectrum is likely even further dominated by the nucleus due to the lower surface brightness of the coma being spread out over a larger area of the sky and the challenges with producing such a spectrum from a population of grains as opposed to a solid surface. The slope break at 1.4–1.5 μm is spectrally similar to 67P (Quirico et al. 2016) but at a longer wavelength than the slope break on comets like P/2006 HR30 (Siding Spring) (Kareta et al. 2021).

2. We employ the NEATM using a new MCMC-based implementation to our March 10 spectrum to constrain the visible-wavelength albedo (pV) and the NIR beaming parameter (η). At the 99.7% confidence level and assuming typical values for emissivity, slope parameter G, etc., we retrieve pV = 0.016±0.049 and η = 1.560±0.424. This visible-wavelength albedo is low but in line for some comets visited by spacecraft and ~a few percent of NEOs. The beaming parameter values are what would be expected for an object observed at these phase angles. Thermal contamination by dust and the large phase reddening expected for this object make these albedo estimates slightly too low. As a result, we reran our thermal models accounting for phase reddening by assuming it had a typical cometary surface and retrieved pV = 0.028±0.018 also at a 99.7% confidence interval. Radar observations (Naidu et al. 2016) constrain the albedo to be pV ≤ 0.03, which our models naturally reproduce.

3. Assuming our nominal albedo range is accurate, we estimate the diameter of BA14 to be D ≈ 1.1–1.6 km, which would be a typical size for a Jupiter-family comet. The reflectance properties at NIR wavelengths of BA14 (e.g., similar to many previously observed cometary nuclei) are seemingly at odds with a rare surface composition suggested by the mid-infrared observations of Ootsubo et al. (2021). The two could be reconciled if the visible and NIR spectral response of BA14 is minimally affected by the phyllosilicates that appear more prominent in the mid-infrared and more dominated by the low-albedo featureless matrix of organics that appears to be a common surface material on other comets.

4. While it is tempting to infer that BA14’s mid-IR derived surface composition is evolutionary, we note that the observational circumstances comparable to those for BA14’s close approach are rare, and high-S/N observations of cometary nuclei even more so, so it cannot be ruled out that more “typical” comets might look as BA14 did in the NIR and mid-IR should a similar circumstance present itself. If its properties are evolutionary, we argue for a slow loss of smaller grains with diminishing gas production as a more plausible mechanism to explain its surface composition, as opposed to thermal alteration from a past hotter orbit, but more observations are needed.

We encourage observers who obtained data on BA14 and its purported sibling 252P during their 2016 close approach but have yet to present it formally somewhere to reanalyze their observations to help understand these compelling objects and where they fit within the continuum of low-activity and nearly dormant comets and their higher-activity (possible) siblings.

We also support continued observation of low-activity and dormant comet candidates at NIR and mid-infrared wavelengths to add to the limited number of well-studied objects. Finally, a full dynamical study of the orbital evolution of BA14 and 252P would be critical to understanding the mutual relationship between the two bodies and the role that orbital evolution might have played in BA14’s modern near-dormancy. All of these observations would also help the Comet Interceptor team make an informed decision if their ideal comet is not found in time.

The MCMC thermal model described and implemented here is available upon reasonable request to the authors and is being developed for public release in 2022.

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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Facility: IRTF(SpeX).

Software: NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), AstroPy (Astropy Collaboration et al. 2013, 2018), spextool (Cushing et al. 2004), emcee (Foreman-Mackey et al. 2013).

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