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Simulated SPHEREx Spectra of Asteroids and their Implications for Asteroid Size and Reflectance Estimation

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Abstract

We describe the construction and analysis of simulated SPHEREx spectra of Main Belt and Trojan asteroids. SPHEREx will deliver the first all-sky spectral survey at 96 spectral channels between 0.75 μm and 5.0 μm . We have developed a method for correcting SPHEREx asteroid spectra for intrinsic rotational variability that does not require light curves and can enable studies before LSST light curves become available for this purpose. Using these spectra, we predict that SPHEREx will deliver meaningful flux measurements for about 100,000 asteroids, including close to 10,000 objects with high-quality spectra; this dataset will represent an increase over our current sample size by more than an order of magnitude. The main SPHEREx contribution to asteroid science will be derived from taxonomic classifications, detailed spectroscopic analyses involving a number of diagnostic spectral features associated with olivine, pyroxene,

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hydroxyl, water ice, and organics, and constraints on thermal properties. We argue that all asteroids with currently known orbits, about a million objects, should be included in the SPHEREx forced photometry object list to maximize its science impact. Our tools and the library of simulated spectra are made publicly available.

Keywords: Asteroids — Asteroids, surfaces — Near-Earth objects — Data reduction techniques

1. Introduction

Studies of asteroid compositions and size distributions across the main belt provide clues to the history of the Solar System, including its primordial composition and temperature gradient, and its subsequent physical and dynamical evolution (e.g., Jedicke et al., 2004; Nesvorný et al., 2005; Vernazza et al., 2009; DeMeo and Carry, 2013). Recent advances have revealed compositional variation with size and distance from the Sun that points to a dramatic early history of the inner Solar System, including substantial radial mixing as a consequence of giant planet migration (DeMeo and Carry, 2014). Measurements of asteroid sizes are important both in the context of studying the formation and evolution of the asteroid belt as encoded in its size distribution (e.g., Bottke et al., 2005; Parker et al., 2008), and in the context of planetary defense where the potential damage caused by an impactor scales with its size (e.g., Mainzer et al., 2015; National Academies of Sciences, Engineering, and Medicine, 2019).

Multi-wavelength wide-field surveys of the sky have produced unique data resources for the physical characterization of asteroids. While the designs of surveys like the Sloan Digital Sky Survey (SDSS; York et al., 2000) and the Wide-field Infrared Survey Explorer (WISE; Wright et al., 2010) were driven by astrophysics goals, the ability to extract magnitudes and colors for large numbers of asteroids from these survey data has greatly impacted our understanding of asteroid origins and evolution (Ivezić et al., 2001; Mainzer et al., 2015). This trend will continue with upcoming surveys such as the ground-based Rubin

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Observatory Legacy Survey of Space and Time (Ivezić et al., 2019, LSST) and space-based Gaia (Gaia Collaboration et al., 2016) and SPHEREx (Doré et al., 2018; Crill et al., 2020). In this paper, we focus on optical-infrared low-resolution spectroscopy to be obtained by the SPHEREx mission¹.

SPHEREx (the Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer) is a 2-year NASA MIDEX mission currently expected to be launched between June 2024 and April 2025. Its primary science goals include inflationary cosmology, the history of galaxy formation, and Galactic ices (Doré et al., 2018). Driven by these goals, SPHEREx will deliver the first all-sky spectral survey at 96 spectral channels between $0.75\ \mu\text{m}$ and $5.0\ \mu\text{m}$. The spectral resolving power will range from about 40 between $0.75\ \mu\text{m}$ and $3.8\ \mu\text{m}$, to about 120 between $3.8\ \mu\text{m}$ and $5\ \mu\text{m}$. SPHEREx will utilize a 20 cm telescope with a $11.3\ \text{degree} \times 3.5\ \text{degree}$ field of view, and $6.2 \times 6.2\ \text{arcsec}^2$ pixels. It will be equipped with rectangular linear variable filters, with a sensitivity per spectral/spatial resolution element reaching 5σ at $\text{mag} \sim 19$ (AB magnitudes²; assuming 4 detections for static sources). For comparison, the signal-to-noise ratio per resolution element for the faintest sources in the 2MASS PSC catalog will exceed 40σ , and even for the faintest sources in the WISE catalog it will exceed 3σ . At the end of its two-year mission, SPHEREx will provide spectra of each $6.2 \times 6.2\ \text{arcsec}^2$ pixel on the sky – about 14 billion spectra in all (Crill et al., 2020).

SPHEREx will obtain high-quality spectra (defined further below as a single-observation signal-to-noise ratio of at least 5 at $2.4\ \mu\text{m}$) for about 5,000 main-

¹<https://spherex.caltech.edu>

² Traditional astronomical magnitudes are reported as a measurement relative to some judiciously chosen celestial calibration source, e.g., Vega (Oke and Gunn, 1983). AB magnitudes are defined using specific flux, relative to flux $F_{AB} = 3631\ \text{jy}$ (an object with a specific flux of F_{AB} has $m_{AB}=0$). This flux scale is chosen so that AB magnitude and Vega magnitude are same in the Johnson's V band (i.e., approximately, 3631 jy is the flux of Vega in the standard V band). An object with $F_\nu=\text{const.}$ has an AB magnitude equal to the Johnson V magnitude at all wavelengths. For more details, please see <http://ls.st/pstn-001>.

1 INTRODUCTION

belt asteroids and about 1,000 Jovian Trojan asteroids. This SPHEREx dataset will be larger than currently available comparable samples by more than an order of magnitude. There are a number of observed diagnostic asteroid spectral features in the SPHEREx wavelength range, such as pyroxene and olivine features near 1 and 2 μm due to the presence of iron-bearing silicates, hydroxyl (OH) and water ice features around 3 μm and organics (CH stretch) in the 3–4 μm wavelength range (for details see, e.g., Edwards et al., 2019). For an example of 2.72 μm OH absorption band detection on C-type NEA (162173) Ryugu, which was the target of sample-return mission Hayabusa2, see Kitazato et al. (2019); such detections should be possible with SPHEREx for hundreds, if not thousands of objects. By binning in wavelength, measurements akin to broad-band photometry will be possible for about 100,000 objects, including over 10,000 Jovian Trojans and close to a thousand TNOs. This dataset will be used to study the variation of asteroid composition with size and position in the Solar system, and ultimately yield new clues for unraveling physical and dynamical evolution of the Solar System.

In this paper, we introduce and discuss simulated SPHEREx spectra of asteroids, including their signal-to-noise distribution. A key difficulty in data interpretation will be accounting for intrinsic rotational light curve variability because it will take SPHEREx several weeks to obtain a complete spectrum. While it is expected that LSST will ultimately deliver light curves for essentially all asteroids observable by SPHEREx, exactly how will LSST and SPHEREx data be combined has yet to be demonstrated. For this reason, we discuss here in detail how raw SPHEREx spectral data could be corrected for variability without a prior knowledge of light curves.

We describe the construction of simulated SPHEREx spectra in §2, including a discussion of SPHEREx data properties and features in near-infrared spectra of asteroids. Analysis of simulated spectra is presented in §3, and §4 provides discussion and our conclusions.

2. Simulations of SPHEREx Spectra for Asteroids

In this section we describe all the algorithmic steps in the construction of simulated SPHEREx spectra. We start with a brief introduction to SPHEREx's observing strategy and then describe the construction of a library of spectral energy distributions (SEDs) with the Asteroid Thermal Modeling (hereafter ATM) code, the augmentation of these SEDs with detailed reflectivity curves to obtain high spectral fidelity, the sampling of SEDs for a given specific orbit and SPHEREx observing plan, and simulation of measurement uncertainties due to the finite SPHEREx sensitivity and asteroid rotational variability.

2.1. Brief introduction to SPHEREx observing strategy

SPHEREx will observe the entire sky multiple times during its planned two-year mission. A given observation will yield two flux measurements because the incoming radiation is split with a dichroic at $2.45\ \mu\text{m}$ into short-wavelength and long-wavelength ranges. Three detectors will cover each wavelength range, defining six regions with the transition wavelengths at 1.10, 1.63, 2.40, 3.81, and $4.41\ \mu\text{m}$. Depending on the position of a source within the field of view, it will be detected at one wavelength from the short-wavelength range and one wavelength from the long-wavelength range. The full spectrum, at a standardized grid of 96 spectral channels, will be obtained by moving the telescope in the dispersion direction of the linear variable filters in discrete steps.

SPHEREx spacecraft will be placed into a 700 km low-Earth sun-synchronous orbit with an orbital period of 90 min and a precession rate of 1 degree/day in right ascension. SPHEREx pointings will approximately follow a great circle 90° from the Sun in order to satisfy solar and terrestrial avoidance angles³. The adopted strategy will result in a minimum of four spectra at every point along the Ecliptic during the nominal survey duration of 25 months, with much greater redundancy in the deep survey fields near the North and South ecliptic poles.

³See for details <https://spherex.caltech.edu/Survey.html>

2.2 ATM SED SIMULATIONS OF SPHEREX SPECTRA FOR ASTEROIDS

SPHEREx will take approximately 2 minute long exposures, with a short slew of 12.3 arcmin after each exposure that corresponds to one spectral channel. After several exposures, a much larger slew will be undertaken to satisfy the avoidance angle constraint. Given the same relative boresight, two successive orbits have the field of view offset by about 3.8 arcmin in R.A. direction (1 deg/day orbital precession with 16 orbits per day). It takes about 3.5 days for the orbit to precess by one field-of-view width (3.5 degrees).

Asteroid fluxes will be extracted using the so-called “forced photometry” method, using pre-computed positions for objects within the field of view, at the time of each SPHEREx exposure. In other words, SPHEREx will not attempt to discover new asteroids but will measure fluxes for asteroids with already known orbits at the time of flight; measurements of these known asteroids will be included in its “forced photometry” object list. It is noteworthy that previously unknown asteroids detected by SPHEREx could be discovered at least in principle by combining multiple detections of a moving object; however, this step will not be done by the SPHEREx mission’s official data pipeline and will not be further considered here.

2.2. ATM SED library

Figure 1: Examples of asteroid SEDs simulated using ATM for the SPHEREx wavelength range. The legend in each panel shows the corresponding values of heliocentric distance (r , in a.u.), emissivity (ϵ), corresponding visual albedo (p_V), asteroid diameter (D , in km), and the temperature parameter T_1 (in K). The left panel shows the SED variation with r and ϵ , while the right panel shows the impact of T_1 variations.

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For our study, we generate simulated SEDs using ATM, a Python package designed to model asteroid flux measurements (Moeyens et al., 2020). ATM supports a number of the most popular static asteroid thermal models, such as the NEATM used here. For a given set of input parameters, ATM computes $F_\nu(\lambda)$, the specific flux (flux per unit frequency, ν) from an object. The model flux is the sum of emitted thermal flux controlled by the asteroid's surface temperature distribution, F_ν^{th} , and the portion of the incident solar flux reflected by the asteroid towards the observer, F_ν^{ref} ,

$$F_\nu(\lambda) = F_\nu^{th}(\lambda) + F_\nu^{ref}(\lambda). \quad (1)$$

The apparent measured specific flux for numerous small airless solar system bodies has been modeled in this fashion for decades (e.g., Mainzer et al., 2015, and references therein). Both $F_\nu^{th}(\lambda)$ and $F_\nu^{ref}(\lambda)$ depend on the relative positions of the Sun, the asteroid and the observer, and the asteroid's optical properties. The latter include the asteroid's diameter D , and the asteroid's emissivity, $\epsilon(\lambda)$, which controls the balance between absorbed/emitted and reflected incident flux. These relative positions are fully described by the asteroid-Sun distance, r , asteroid-observer distance, Δ , and the angle subtended on the asteroid's surface by the lines of sight towards the Sun and the observer, the so-called phase angle, α . Both flux components are proportional to D^2 .

We generated a library of model spectra for a fiducial asteroid size of $D = 1$ km, parametrized by three independent input parameters. Since SPHEREx pointings will approximately follow a great circle 90° from the Sun, Δ and α follow from a given value of the asteroid-Sun distance r for objects close to the Ecliptic. We use a grid of r ranging from 1.1 a.u. to 5.5 a.u., with a step of 0.1 a.u. In this step, we assume that asteroid's emissivity is independent of wavelength; ATM modeling supports wavelength-dependent emissivity but our approach for incorporating high-fidelity reflectivity curves described in the next section allows for simpler bookkeeping and more modeling flexibility when using a library of reflectivity curves. We use a grid of emissivity values in the range 0.72 to 0.98, with a step of 0.02. This emissivity range corresponds to

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albedo in the range 0.05 to 0.70 (see §2.4 and eq. 5 for more details). The third and final input parameter is a characteristic temperature, T_1 , defined as the subsolar temperature (the highest temperature on the asteroid's surface) at a heliocentric distance of 1 a.u., which controls the temperature distribution across the asteroid surface and it does not depend on asteroid's distance from the Sun. It depends on the solar constant, the asteroid's infrared emissivity, and the so-called "beaming parameter" (see eq. 5 and related discussion in Moeyens et al. 2020). Given this model-dependent temperature scale parameter, T_1 , the subsolar temperature T_{ss} is simply

$$T_{ss} = \left(\frac{1 \text{ a.u.}}{r} \right)^{1/2} T_1. \quad (2)$$

Detailed analysis of WISE observations by Moeyens et al. (2020) shows that T_1 for main-belt asteroids spans the range from 380 K to 420 K, and we adopt three values for our simulations: 380 K, 400 K and 420 K. The asteroid's rotation rate is assumed fast enough (>several revolutions per day, Pravec and Harris, 2000; Warner et al., 2009) that its surface temperature is stratified by longitude.

Examples of simulated SEDs are shown in figure 1. SEDs typically have a local minimum, due to $F_\nu^{ref}(\lambda)$ dominating at short wavelengths and decreasing with wavelength, and $F_\nu^{th}(\lambda)$ dominating at long wavelengths and increasing with wavelength. For given values of emissivity and T_1 , the wavelength with minimum flux increases with heliocentric distance. Except for objects at heliocentric distances below 2 a.u., such as NEAs, the flux at wavelengths below 2.4 μm is dominated by the reflected solar flux.

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The reflected flux is proportional to albedo, which follows from the adopted emissivity via energy conservation and Kirchhoff's law (see eq. 5 below). The observed dynamic range for albedo is much larger than for emissivity (i.e., emissivity is very close to unity; for the range adopted here the maximum-to-minimum ratio for albedo is ten times larger than for emissivity). Consequently, when

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emissivity and albedo are unknown, size estimates based on reflected flux component are much more uncertain than estimates based on emission component; therefore, size estimates based on infrared data are typically less uncertain than those based on optical data. However, to reach the maximum possible accuracy for size estimates based on thermal emission, the T_1 parameter must also be known. In case of infrared surveys which bracket the peak of infrared emission, such as WISE, the data directly constrain both T_1 and the size D . Unfortunately, with the SPHEREx wavelength coverage extending only to $5\ \mu\text{m}$, the degeneracy between T_1 and D cannot be broken (when emissivity is unknown). As the right panel in figure 1 shows, the plausible uncertainty of T_1 results in a size uncertainty of about 40-50%. This level of accuracy is not even competitive with asteroid size estimates based on optical color data (Ivezić and Ivezić, 2021), and we conclude that SPHEREx estimates will not be competitive with other methods without a strong prior on either emissivity or T_1 .

We now use the Markov Chain Monte Carlo fitter available in ATM to provide a more quantitative example of fitting degeneracies. We consider a simulated object at 2.5 a.u. from the Sun, observed in opposition, with a diameter of 3 km, $T_1 = 400\text{ K}$ and a constant emissivity, $\epsilon = 0.94$ (the corresponding albedo is 0.15). We assume homoscedastic Gaussian (normal) measurement errors of 0.2 mag. Precise values of these input parameters are not crucial for the following discussion.

Figure 2 shows fitting results for D and T_1 when it is assumed that emissivity is known a priori. As evident, the best-fit results agree with the true values within expected uncertainties. As the posterior probability density function shows, there is no strong covariance (degeneracy) between the two quantities. The reason is that size can only change the overall scaling of the predicted flux, but cannot change its shape because reflected and emitted flux components are both proportional to D^2 . On the other hand, T_1 can only influence the emitted flux component and thus it alone controls the overall shape of the predicted flux.

The fitting results dramatically change when emissivity is added as the third

2.4 Addition of SPHEREx Reflectivity Curves for Asteroids

unknown parameter, as illustrated in figure 3. There are strong degeneracies between the parameters and large biases in the best-fit values when compared to their true values. These results can be understood as follows. As emissivity increases, albedo and the reflected flux component decrease. Since the emitted flux component increases with emissivity, emissivity variation can change the shape of predicted flux (the ratio of emitted and reflected components) in a similar way as T_1 . As a result, there are combinations of emissivity and T_1 that produce very similar predicted flux shapes but with different normalizations (i.e., essentially the same within measurement uncertainties). The value of D then needs to be adjusted to produce correct flux normalization, which moves it away from the true value; in this particular example, a combination of 28% smaller emissivity and 14% larger T_1 led to 56% smaller best-fit D . If instead we fix the emissivity to its true value, as in the first fitting example, forces D and T_1 to stay close to their true values.

Therefore, the emissivity/albedo needs to be known in order to use SPHEREx data for reliable asteroid size estimation. But if either are already known, then size can be estimated at least as accurately using optical data. We conclude that while the SPHEREx data will thus provide useful independent checks on an asteroid's size, overall asteroid science will benefit most from SPHEREx's unique measurements of asteroid reflectivity spectra, as discussed next.

2.4. Addition of High-fidelity Reflectivity and Emissivity Curves

Model spectra generated with ATM assumed constant emissivity, and thus constant reflectivity, too. We first discuss how to correct ATM model SEDs to include an arbitrary reflectivity curve, and then describe a library of reflectivity curves used in subsequent analysis.

Given a reflectivity curve, $\rho(\lambda)$, normalized to unity at $\lambda = 0.55 \mu\text{m}$ (the standard V band), we correct the reflected component computed by ATM, $F_{\nu}^{ref, atm}$, as

$$F_{\nu}^{ref}(\lambda) = \frac{p_V}{p_V^{atm}} \rho(\lambda) F_{\nu}^{ref, atm}(\lambda), \quad (3)$$

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Figure 2: **Posterior probability density function for a 2-parameter fit to a SPHEREx spectrum.** The emissivity value ($\epsilon = 0.94$) was assumed known (the corresponding albedo is $p_V = 0.15$). The fitted parameters are the object diameter D and the temperature parameter $T1$, and their posterior probability density function (pdf), obtained using Markov Chain Monte Carlo, is shown in the bottom left panel. The other two panels show the one-dimensional projections of this pdf (marginal distributions). The true parameter values, marked by blue lines in the panels, are: $D = 3$ km ($\log D = 3.48$), and $T1 = 400$ K ($\log T1 = 2.60$). The best-fit values agree within expected uncertainties with their true values.

where the corresponding ATM model produced with constant emissivity and reflectivity must satisfy a condition that the absorbed energy, which is re-radiated as thermal emission, remains unchanged ($p_V^{atm} \approx p_V$ for solar radiation)

$$p_V^{atm} = p_V \frac{\int F_V^\odot(\lambda) \rho(\lambda) d\lambda}{\int F_V^\odot(\lambda) d\lambda}. \quad (4)$$

The relationship between reflectivity $\rho(\lambda)$ and emissivity $\epsilon(\lambda)$ is discussed further below.

2.4.1. The Bus-DeMeo and AKARI reflectivity curves

For main-belt asteroids, we adopt 24 reflectivity curves that define the Bus-DeMeo taxonomy from DeMeo et al. (2009). These curves extend to $2.42 \mu\text{m}$

2.4 Addition of SPHEREx Reflectivity Curves to Asteroids

Figure 3: **Posterior probability density functions (pdfs) for a 3-parameter fit to a SPHEREx spectrum.** Analogous to figure 2, except that here emissivity was also fit (its true value is $\epsilon = 0.94$). The three panels towards bottom left show two-dimensional projections of the full 3-dimensional distribution, while the three panels towards upper right show one-dimensional projections. Note the strong degeneracies and the strong bias in the best-fit values when compared to their true values (shown by blue lines).

and are normalized to unity in the V band. We focus our analysis here on three taxonomic classes: C, S and V. It would be straightforward to extend our analysis to less numerous classes. The reflectivity curves with wavelengths above $2.42 \mu\text{m}$ were obtained by the AKARI mission (C: asteroid Hygiea; S and V: asteroid Herculina) and are taken from Usui et al. (2019). The Akari curves are renormalized to approximately agree with the Bus-DeMeo curves. For Trojan asteroids, we adopt reflectivity curves for “red” and “less red” subsets from Wong et al. (2019), and extend them smoothly by low-order polynomials. We

2.5 Accounting for the SPHEREx observing plan

smooth the joined curves using the Savitzky-Golay filter⁴, extended to $5.0 \mu\text{m}$ using the value at the longest available wavelength, and finally interpolate them to the standard SPHEREx wavelength grid. The resulting reflectivity curves for C, S, and V main-belt asteroids and for “red” Trojans are shown in the top panel in figure 4. Note abundant spectral features for S, C and V curves, and extreme redness of the curve for “red” Trojans.

2.4.2. Emissivity curves

Emissivity curves can be computed from reflectivity curves via Kirchhoff’s law,

$$\epsilon(\lambda) = 1 - q(G) p_V \rho(\lambda), \quad (5)$$

where the empirically derived phase integral, $q(G)$, is purely a geometric quantity and we adopt here $q(G = 0.15) = 0.4$ (Bowell et al., 1989). For the visual albedo, p_V , we adopt values from Romanishin and Tegler (2018) for Jovian Trojans and from Ivezić and Ivezić (2021) for main-belt asteroids. The resulting curves are shown in the bottom panel in figure 4. In addition to being flat at the wavelengths dominated by thermal emission, as assumed by ATM, they also agree with the emissivity range implied by WISE data (Moeyens et al., 2020).

2.5. Accounting for the SPHEREx observing plan

Here we provide a description of our algorithms for generating measurement noise and then show the final simulated spectra.

The predicted number of SPHEREx observations, and exact asteroid position and time of observation, depend on complex details in the SPHEREx observing plan. In order to generate simulated observations, we generate orbits for seven specific objects representative of different populations. We use LSST simulation tools (Jones et al., 2018) to compute daily positions during the period used in simulated SPHEREx observing plan (June 17, 2024 to July 17, 2026) for the following objects: (3200) Phaethon (an inner solar system Earth-crossing

⁴Using astroML code publicly available at https://www.astroml.org/book_figures/chapter10/fig.wiener_filter.html

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asteroid), (434) Hungaria, (176014) Vedrana, (153) Hilda (main-belt asteroids), (1143) Odysseus (a Jovian Trojan), (19521) Chaos (a TNO) and 55P/Tempel-Tuttle (a short period comet). Their basic orbital characteristics are listed in Table 2.5 and their positions during that period are shown in figure 5.

Table 1: Orbital elements for simulated asteroids^a.

Object	a	e	i	Ns	Nobs
(3200) Phaethon	1.27	0.14	22.3	4	472
(434) Hungaria	1.94	0.07	22.5	2	436
(176014) Vedrana	3.10	0.25	10.6	3	408
(153) Hilda	3.98	0.14	7.8	3	424
(1143) Odysseus	5.25	0.09	3.1	4	520
(19521) Chaos	45.5	0.10	12.0	4	488
55P/Tempel-Tuttle	10.3	0.91	162.5	4	562

^aTable lists the object name and designation, semi-major axis (a , in a.u.), orbital eccentricity (e) and inclination (i , in degrees), the number of observing seasons (approximately corresponding to full SPHEREx spectra), and the total number of flux measurements, for the seven objects with simulated SPHEREx observations.

In the next step, we find the time-position intersections of these orbits with the SPHEREx observing plan. The survey planning software tool delivers all-sky coverage in each spectral channel, taking into account all orbital constraints (Solar, Lunar, and Earth avoidance) and operational constraints such as down-links and spacecraft slew rate. For each predicted observation, we record the exact time of observation and the two wavelengths that would have measured fluxes (one shorter than 2.42 μm dichroic mid-wavelength and one longer). The observed positions⁵ along the orbits are shown in figure 6.

⁵These data files are available from both <https://github.com/SPHEREx/Public-products> and <https://github.com/ivezicV/2share>.

2.6. ADDITION OF PHOTOMETRIC NOISE AND PHOTOMETRIC VARIABILITY TO SPHEREx SPECTRA FOR ASTEROIDS

Figure 7 further illustrates the variation of wavelength of observation with time. Typically, each object is observed in 3 to 4 “seasons”, with each season contributing a full spectrum (at least 48 pairs of flux measurements) collected over several weeks. These observing seasons correspond to four surveys for static objects and are separated by about 6 months. The total number of flux measurements exceeds 400. Details are listed in Table 2.5.

Figure 8 illustrates the variation of main physical quantities needed to compute simulated spectra in case of asteroid (176014) Vedrana. As evident, the solar elongation stays very close to 90 degrees and thus the range of observed phase angles for a given object and season is also very narrow. The asteroid-Sun distance, which controls the asteroid temperature changes by at most 1% during an observing season, and this small variation can be neglected. The only substantial variation that cannot be neglected, in addition to photometric variability, is the change of Earth-asteroid distance, and it can be trivially corrected for.

Given many days to obtain a spectrum, and with typical asteroid rotation rates of a few hours, the photometric variability due to non-spherical shapes will not be negligible. The root-mean-square uncertainty of a single photometric asteroid measurement due to rotation, both in optical and infrared, is about 0.15-0.20 mag (Pravec and Harris, 2000; Szabó and Kiss, 2008; Moeyens et al., 2020) and thus will dominate the measurement uncertainty for all but the faintest objects. We describe the addition of variability to simulated SEDs in the next section, and discuss how to correct for this effect in §3.2.

2.6. Addition of Photometric Noise and Photometric Variability

The SPHEREx team has made their predicted sensitivity vs. wavelength curves public⁶. The wavelength grid includes 96 nominal wavelengths between 0.75 μm to 5.0 μm that define a standard SPHEREx spectrum. The listed sensitivity corresponds to four coadded surveys and we subtract 0.75 mag from

⁶Available from <https://github.com/SPHEREx/Public-products>

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5σ limiting magnitudes to account for four times shorter integration time for single detections. The adjusted mean 5σ depth per spectral resolution element is about 18.8 mag AB below $2.42\ \mu\text{m}$, and ranges from 19.0 to 17.3 from 2.42 to $5.0\ \mu\text{m}$. We note that these publicly available SPHEREx sensitivity estimates correspond to “best current estimates” and thus may be a bit optimistic; it is possible that achieved sensitivities will be up to 0.5 mag brighter (James Bock, priv. comm.).

To generate photometric uncertainty (approximately the inverse of the photometric SNR), we follow Ivezić et al. (2019) and use

$$\sigma_1^2 = \sigma_{\text{sys}}^2 + \sigma_{\text{rand}}^2, \quad (6)$$

where σ_{rand} is the random photometric error and σ_{sys} is the systematic photometric error (due to, e.g., imperfect modeling of the background). We adopt $\sigma_{\text{sys}} = 0.01$ mag and compute the random photometric error (for non-trailed sources) as a function of magnitude⁷ using

$$\sigma_{\text{rand}}^2 = (0.04 - \gamma)x + \gamma x^2 \text{ (mag}^2\text{)}, \quad (7)$$

with $x \equiv 10^{0.4(m-m_5)}$. Here m_5 stands for adjusted SPHEREx 5σ limiting magnitudes and we adopt $\gamma = 0.039$ (γ depends on background noise, readout noise, etc.).

We model variability using a simple sinusoidal variation

$$\Delta m(mjd) = A \sin[2\pi(mjd - mjd_0)/P], \quad (8)$$

and adopt amplitude $A = 0.3$ mag, period $P = 0.2$ day and set mjd_0 to the time of the first simulated SPHEREx observation. The adopted value of amplitude corresponds to root-mean-square scatter of 0.2 mag, supported by observations (Moeyens et al., 2020). For a discussion of how to account for this variability in observed spectra, see §3.2 below.

⁷Equation 7 can be derived from $\sigma_{\text{rand}} = N/S$, where N is noise and S is signal, and by assuming that $N^2 = N_o^2 + \alpha S$. The constants N_o and α can be expressed in terms of a single unknown constant γ by using the condition that $\sigma_{\text{rand}} = 0.2$ for $m = m_5$.

3 ANALYSIS OF SIMULATED SPECTRA

Finally, we generate noisy “observed” magnitudes as

$$mag^{obs} = mag^{sim} + \Delta m(mjd) + N(0, \sigma_1), \quad (9)$$

where mag^{sim} are noise-free simulated magnitudes and $N(\mu, \sigma)$ stands for Gaussian distribution.

A few examples of simulated spectra are shown in figures 9 and 10. Simulation parameters in figure 9 are chosen to show typical spectra for different taxonomic classes and object sizes that correspond to approximately 5σ detections at $2.4 \mu\text{m}$ ($\text{magAB} \sim 18.8$). Simulations of NEAs shown in figure 10 are produced for much smaller heliocentric distances and thus the emission part becomes dominant at shorter wavelengths than in figure 9 ($<3 \mu\text{m}$ vs. $>4 \mu\text{m}$). We further discuss simulated spectra, the impact of variability and this choice of signal-to-noise ratio in the next section.

Figure 11 illustrates how photometric noise increases rapidly with apparent magnitude. The taxonomic type, visual albedo, and heliocentric distance are kept constant, and the same as in the top left panel in figure 9, while the object diameter is varied from 2 km to 8 km. The object diameters were chosen so that apparent V-band magnitudes are approximately 17, 18, 19 and 20.

3. Analysis of Simulated Spectra

We proceed with an analysis of SPHEREx spectra, simulated as described in the preceding section. In this discussion, we address the problem of correcting spectra for the effects of photometric variability, predict counts of SPHEREx spectra for dominant asteroid populations as a function of achieved signal-to-noise ratio (SNR), and discuss how low-SNR spectra can be binned in wavelength to generate measurements akin to broad-band photometry. We begin by introducing a signal-to-noise ratio criterion used for sample definitions.

3.1. Definition of SPHEREx signal-to-noise ratio for asteroid spectra

An appropriate definition of the SPHEREx signal-to-noise ratio (SNR) is required for a comparison of different subsamples, and to estimate fiducial lim-

3.2 Corrections for variability 3 ANALYSIS OF SIMULATED SPECTRA

iting object sizes (see §3.3 below). We adopt an SNR requirement expressed at $2.4\ \mu\text{m}$, the longest wavelength for the blue half of SPHEREx spectra (split by dichroic). Since the flux in observed asteroid spectra is generally expected to increase towards shorter wavelengths faster than the increase of SPHEREx noise per bin (for the latter, there is <0.2 mag change between $1\ \mu\text{m}$ and $2.4\ \mu\text{m}$), it is guaranteed that SNR at all shorter wavelengths will be higher than the adopted limit. The $2.4\ \mu\text{m}$ flux which produces 1σ detection in a single (as opposed to four for standard SPHEREx sensitivity curves) SPHEREx observation corresponds⁸ to AB magnitude of 20.6. The corresponding AB magnitudes for 0.5σ , 2.5σ and 5σ detections, used below, are 21.35, 19.6 and 18.85, respectively.

3.2. Corrections for variability

Due to their non-spherical shapes and rotation, asteroids show photometric variability with a root-mean-square (rms) scatter of about 0.15-0.20 mag (Pravec and Harris, 2000; Moeyens et al., 2020). The rms for color variability observed in SDSS data is well below 0.1 mag (Szabó et al., 2004). Above the size limit of a few hundred meters relevant here (see §3.3 below), asteroids have rotational periods extending down to about 2 hours (Pravec and Harris, 2000). Therefore, several pairs of SPHEREx observations from the same orbit, that are separated by a few minutes can be considered simultaneous, while observations from different orbits will be subjected to non-negligible scatter due to rotational variability.

There already exist light curves for a few thousand asteroids that might be robust enough to produce sufficiently accurate predicted magnitudes to correct SPHEREx spectra for rotational variability (e.g., Waszczak et al., 2015; Warner et al., 2009). The ultimate source of light curves for this purpose will be LSST, which will obtain a few hundred photometric measurements per object for over 5 million asteroids during its 10 year survey (see Section 5 in LSST Science

⁸We have used the July 2020 version of SPHEREx sensitivity files available at <https://github.com/SPHEREx/Public-products>

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Collaboration et al. 2009). Given the small color variability, all LSST bands can be combined together with a judiciously chosen model in order to estimate the rotational period and fit light curve (for a detailed discussion of multi-band periodograms, see VanderPlas and Ivezić 2015). If a good fit can be found, the resulting photometric accuracy should be of the order 0.01 mag for sufficiently bright asteroids.

Nevertheless, these forecasts assume the existence of the entire LSST dataset while, according to current estimates, the SPHEREx 2-year survey will start within a year or two from the start of 10-year LSST. Therefore, it will take at least a few years until the SPHEREx-based analysis projects will be able to fully utilize LSST light curve predictions for correcting spectra. For this reason, we describe here a different correction method, which can enable early SPHEREx asteroid science even in a complete absence of light curves (which of course is an unrealistically conservative assumption⁹).

Our method benefits from the following three facts: i) SPHEREx flux measurements are obtained in pairs, one at a wavelength below 2.42 μm , and another one at a wavelength above 2.42 μm , ii) the rather uncertain thermal emission component (in comparison to reflected component) becomes dominant at wavelengths substantially longer than 2.42 μm , typically longer than 3.5 μm , and iii) observed spectra of asteroids in the SPHEREx wavelength range display only a finite number of different reflectivity curves. Given these facts, we developed the following algorithm for correcting SPHEREx spectra:

1. Choose a reflectivity curve template, such as those discussed in §2.4.
2. Use this template and known observing geometry to evaluate reflected solar flux for an arbitrary asteroid size; rescale the resulting magnitude vs. wavelength curve to have the same mean value as the observed “raw” (uncorrected) SPHEREx spectrum to produce the “normalized template”.
3. For each set of pairs of observations from the same orbit, find the mean

⁹We do not explicitly study the case of asteroids with already existing rich datasets simply because there are no SPHEREx data yet for performing a comparison analysis.

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offset of observed magnitudes from the normalized template for all data points at wavelengths below $2.42 \mu\text{m}$; correct the observed magnitudes by this mean offset (so that they agree on average with the the normalized template while preserving their relative scatter).

4. Use the same offset to also correct all observed magnitudes at wavelengths above $2.42 \mu\text{m}$ (from the same pairs of observations).
5. Compute χ^2 per degree of freedom using 12 wavelengths between $2.42 \mu\text{m}$ and $3.4 \mu\text{m}$ in the standard SPHEREx grid.
6. Repeat this χ^2 computation for all the templates in template library (e.g., 24 templates from the Bus-DeMeo library) and choose the template with the smallest χ^2 .

Figure 12 shows the application of this algorithm to simulated SPHEREx observations of asteroid (176014) Vedrana during the first observing season. In that particular noise realization, for the chosen signal-to-noise ratio at $2.4 \mu\text{m}$ (SNR) of about 10, the correct template (S type) is the unambiguous winner. At the same SNR level, it is equally easy to distinguish the correct template from other templates when it is V or C type. The success rate for choosing the correct template from a library of trial templates depends on SNR. The left panel in figure 13 compares the distribution of differences in χ^2 per degree of freedom between the two best performing templates for 10,000 realizations of random noise. As evident, even at SNR=5, the success rate is as high as 85%.

The success rate, at a given SNR, is even higher for Jovian Trojan asteroids because there are only two known templates, and they are more different from each other than differences observed for main-belt templates. An example based on object (1143) Odysseus is shown in figure 14. The distribution of differences in χ^2 per degree of freedom between the two templates is shown in the right panel in figure 13. The success rate is as high as 95% even at SNR=5.

We note that the χ^2 per degree of freedom distribution is not following exactly the theoretical expectation for 11 degrees of freedom (well approximated as a normal distribution centered on unity and with a standard deviation of

3.3 Predicted counts of asteroids with usable SPHEREx spectra

0.426) but it gets quite close. The reason for the minor discrepancy is that there are only 3-5 points used when estimating the offset in step 3 above and thus the statistical noise of this estimate is not negligible when compared to noise due to rotational variability. We also note that it does not matter much if two templates are very similar to each other, e.g. CB, CG and CH in the Bus-DeMeo library – they will yield the same corrected spectra.

We conclude that this algorithm has a great potential for delivering early SPHEREx asteroids science, before sufficiently accurate light curves are delivered by LSST. Nevertheless, it does have at least a couple of shortcomings. First, it has low potential for discovering new spectral types because it assumes that the reflectivity template library is complete. A missing template would be recognized only when a good fit (in χ^2 sense) could not be obtained for a very high-SNR object. Second, for NEAs at heliocentric distances much shorter than those for objects in the Main Belt, the emission part of their SEDs becomes dominant at shorter wavelengths ($<3 \mu\text{m}$) than assumed for “contamination-free” wavelength region used in χ^2 computation (see figure 10). For these reasons, we anticipate that analysis of SPHEREx asteroid spectra will be built in iterative steps where light curve information for some objects will be combined with existing infrared spectra and object size estimates to iteratively build an overall self-consistent model that ultimately will resemble hierarchical Bayesian modeling (for a detailed discussion of hierarchical Bayesian modeling, see § 5.9 in Ivezić et al. 2014). In the remaining sections, we will assume that the effect of rotational variability on SPHEREx spectra has been by and large corrected.

3.3. Predicted counts of asteroids with usable SPHEREx spectra

We now proceed to estimate predicted counts of asteroids with usable SPHEREx spectra. We define four samples for which we estimate sample sizes expected from SPHEREx by adopting four values of limiting SNR at $2.42 \mu\text{m}$. First, we define high-quality spectroscopic sample by adopting $\text{SNR}(2.42 \mu\text{m})=5\sigma$ limit. This limit guarantees that fractional flux errors are below 20% for all 48 wavelengths shorter than $2.42 \mu\text{m}$.

3.3 Predicted counts of asteroids with simulated SPHEREx spectra

SPHEREx spectra can be used for “photometric” measurements by binning several wavelengths together. For example, if one defined four wavelength regions that roughly correspond to the LSST *izy* and (widened) *J*, *H* and *K* bandpasses (for more details, see §3.4), they would include between 10 and 14 data points whose binning would increase the effective SNR by a factor 3-4. The SNR for estimating the spectral slope from 0.7 μm to 2.4 μm would be about five times higher than the SNR per data point, motivating the second limit, $\text{SNR}(2.4 \mu\text{m})=1\sigma$, that defines “photometric” sample.

Finally, it could be argued that the adopted 1σ limit is too conservative because SPHEREx will obtain multiple spectra, typically four per object. When it can be assumed that these spectra do not appreciably change with time (e.g., due to activity or poorly understood phase angle effects; the impact of distance variation, on the other hand, can be easily accounted for), they can be co-added (i.e., “averaged”) and the sample depth would thus be extended by about 0.75 mag, yielding the third SNR limit $\text{SNR}(2.42 \mu\text{m})=0.5\sigma$. For an analogous reason, we define the fourth sample by adopting $\text{SNR}(2.42 \mu\text{m})=2.5\sigma$.

For a given SNR limit, simulated spectra can be used to obtain the corresponding size limit for each spectral class. Table 3.3 lists the limiting sizes (object diameters) corresponding to $\text{SNR}(2.42 \mu\text{m})=1\sigma$ limit for S and C main-belt asteroids (MBA), “red” and “less-red” Jovian Trojans, and TNOs. For TNOs, we used reflectivity for “red” Trojans to generate simulated spectra. The limiting size is then used with the adopted visual albedo, p_V to estimate an absolute magnitude H as

$$H = -5 \log_{10} \left(\frac{D \sqrt{p_V}}{1329 \text{ km}} \right) \quad (10)$$

The resulting values are listed in Table 3.3.

To estimate counts of objects brighter than a given absolute magnitude limit H , we adopt the procedure used in the LSST Science Book (LSST Science Collaboration et al., 2009) to estimate counts of asteroids with LSST data. For main-belt asteroids (MBAs), the adopted shape of the cumulative counts curve

3.4 Broad-band “photometry” with ANALYSIS OF SIMULATED SPECTRA

is based on SDSS data and given by Equation 12 of Ivezić et al. (2001),

$$N_{cum}^{MBA} = N_o \frac{10^{ax}}{10^{bx} + 10^{-bx}}, \quad (11)$$

where $x = H - r_C$ and the values of best-fit parameters r_C , N_o , a and b for S and C taxonomic classes are listed in their Table 4. For Jovian Trojans, we adopt the Szabó et al. (2007) result

$$N_{cum}^{Tr5} = 794 \times 10^{0.44(H-12)}, \quad (12)$$

and assume that the “red” to “less red” counts ratio is 3:1 (Wong et al., 2014). Finally, for TNOs we adopt results obtained by Trujillo et al. (2000, 2001)

$$N_{cum}^{TNO} = 71,400 \times 10^{0.63(H-9.1)}. \quad (13)$$

The resulting counts for the four SNR-defined subsamples are listed in Table 3.3. Their uncertainty cannot be smaller than about 10% and might be several times larger. For example, we only consider dominant taxonomic classes at each heliocentric distance while a higher-fidelity simulation could use a mixture model (note, however, that at this time the count uncertainties for such a simulation would be dominated by uncertain SPHEREx performance). To summarize the main results, we forecast about 6,000 objects in the highest-quality spectroscopic sample, and close to 100,000 asteroids with usable SPHEREx photometric measurements. The former sample could grow to about 14,000 objects when assumed that four individual spectra can be co-added.

3.4. Broad-band “photometry” with low-SNR spectra

As mentioned in the preceeding section, SPHEREx spectra can be used for “photometric” measurements by binning several wavelengths together to increase the signal-to-noise ratio. Here we discuss this method in more quantitative detail.

We define five wavelength regions that roughly correspond to the LSST iz , y and (widened) standard J , H and K bandpasses. The boundary wavelengths are listed in Table 3.4. We assume flat bandpass curves within these boundaries;

3.4 Broad-band “photometry” with ANALYSIS OF SIMULATED SPECTRA

Table 2: Predicted counts of asteroids with SPHEREx spectra^a.

Population	r (AU)	$D_{1\sigma}$	p_V	$H_{1\sigma}$	N(5σ)	N(2.5σ)	N(1σ)	N(0.5σ)
S MBA	2.4	2.1	0.25	15.5	4,288	10,887	33,440	69,293
C MBA	3.2	8.0	0.06	14.1	489	1,328	4,739	11,526
red TR5	5.2	9.2	0.05	14.0	784	1,678	4,623	9,885
less-red TR5	5.2	10.8	0.05	13.7	186	397	1,095	2,341
TNO	40	557	0.05	5.1	17	52	222	661
Total counts					5,764	14,343	44,120	93,706

^aTable lists cumulative counts of dominant asteroid populations for three values of the single-spectrum signal-to-noise ratio at $2.4 \mu\text{m}$: 5σ limit defines the highest-quality spectral sample, 1σ limit will enable “photometric” studies by binning in wavelength direction, and 2.5σ and 0.5σ limits assume that such studies can be extended deeper by co-adding four spectra obtained at different epochs. For a chosen heliocentric distance, the limiting size $D_{1\sigma}$ is obtained using simulated SPHEREx spectra, and then used with the visual albedo, p_V , to estimate absolute magnitude H , and finally corresponding cumulative counts, as described in text.

that is, we simply take weighted mean of all the fluxes within a band, with the weights given by inverse variances. Table 3.4 also lists the number of data points in the standard SPHEREx wavelength grid that fall within each band.

The mean colors, using various combinations of bandpasses, and their predicted uncertainty assuming a single-spectrum SNR=5 measurement at $2.4 \mu\text{m}$, for main-belt C, S and V taxonomic classes and for “red” and “less red” Trojans are listed in Table 3.4. We find that the $J - K$ vs. $izy - J$ color-color diagram appears as the most powerful combination of colors for classifying main-belt asteroids, while the $J - HK$ vs. $iz - J$ diagram appears as the best combination for separating “red” vs. “less red” taxonomic classes of Trojans. We illustrate such diagrams with main-belt and Trojan samples expected from SPHEREx in

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figures 15 and 16.

Due to very different reflectivity curves for “red” and “less red” Trojans (a reflectivity ratio of 1.6 at $2.4\ \mu\text{m}$), they can be efficiently distinguished even when SNR at $2.4\ \mu\text{m}$ is as low as 2.5. The diagram shown in figure 16 is analogous to figure 1 from Emery et al. (2011), except for more than an order of magnitude more objects. We predict that SPHEREx will deliver spectra for about 2,000 Trojans that will have SNR at least that high. Assuming that four individual spectra could be co-added, such performance can be expected for about 5,000 Trojan asteroids. These sample sizes are at least an order of magnitude larger than available today.

Table 3: Boundary wavelengths for defining rectangular bandpasses^a.

Bandpass	$iz : y$	$y : J$	$J : H$	$H : K$
Wavelength (μm)	0.92	1.05	1.50	1.90
Num. of data points	9	5	14	10

^aThe bandpass names listed in Table only approximately correspond to the LSST izy and standard JHK bands. The listed wavelengths correspond to the transition wavelengths between two adjacent bands, e.g., is the boundary wavelength between the i and z bands. The minimum ($0.75\ \mu\text{m}$) and maximum wavelengths ($2.42\ \mu\text{m}$) are set by the SPHEREx system. Multiple names correspond to simple flux summing; e.g. the izy “band” extends from $0.75\ \mu\text{m}$ to $1.05\ \mu\text{m}$. The second line lists the number of wavelengths in the standard SPHEREx wavelength grid that fall within the boundaries of each band. There are 10 wavelengths within the K bandpass (with a total of 48 wavelengths below $2.42\ \mu\text{m}$).

4. Discussion and conclusions

We have used a suite of existing and new tools to simulate SPHEREx spectra of asteroids. Our tools and the library of simulated spectra are made publicly

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Table 4: Predicted colors of asteroids with SPHEREx spectra^a.

Population	$iz - J$	$izy - J$	$J - H$	$H - K$	$J - K$	$J - HK$
Solar colors	-0.136	-0.135	-0.286	-0.314	-0.600	-0.407
S MBA	0.00 ± 0.05	0.01 ± 0.04	-0.19 ± 0.05	-0.35 ± 0.07	-0.54 ± 0.07	-0.28 ± 0.05
V MBA	0.26 ± 0.05	0.30 ± 0.05	-0.34 ± 0.06	-0.50 ± 0.08	-0.85 ± 0.07	-0.45 ± 0.05
C MBA	-0.12 ± 0.05	-0.12 ± 0.05	-0.21 ± 0.06	-0.24 ± 0.08	-0.45 ± 0.07	-0.29 ± 0.05
red TR5	0.15 ± 0.06	0.10 ± 0.05	-0.13 ± 0.06	-0.23 ± 0.07	-0.36 ± 0.07	-0.20 ± 0.05
less-red TR5	-0.03 ± 0.05	-0.04 ± 0.05	-0.21 ± 0.06	-0.25 ± 0.07	-0.47 ± 0.07	-0.30 ± 0.05

^aTable lists colors (using AB magnitude scale) based on fluxes obtained from simulated SPHEREx spectra by binning several wavelengths together (the first row lists colors for the solar spectrum). The “band” names only approximately correspond to LSST *izy* bands and (widened) *J*, *H* and *K* bands, with boundaries listed in Table 3.4. Listed color uncertainties correspond to objects with a single-spectrum $SNR = 5$ measurement at $2.4 \mu\text{m}$. We predict that close to 6,000 asteroids will have SNR at least that large in a single SPHEREx spectrum. When both color differences and color uncertainties are taken into account, the $J - K$ vs. $izy - J$ color-color diagram appears as the most powerful combination of colors for separating main-belt C, S and V classes, while the $J - HK$ vs. $iz - J$ diagram appears as the best combination for separating “red” vs. “less red” taxonomic classes of Trojans. For illustration, see figures 15 and 16.

available¹⁰. Together with expected SPHEREx sensitivity, these spectra allowed us to produce detailed quantitative forecasts for asteroid sample sizes as a function of signal-to-noise ratio. We expect that SPHEREx will deliver meaningful flux measurements for about 100,000 asteroids, including close to 10,000 objects with high-quality spectra; this dataset will represent an increase in sample size by more than an order of magnitude. We note that these sample size estimates

¹⁰<https://github.com/ivezicV/2share>

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are dependent on assumed SPHEREx sensitivity (see § 3.1). The variation of sample size with sensitivity can be gauged from Table 3.3.

It is unlikely that SPHEREx will discover many new asteroids due to its relatively bright flux limits – most brighter asteroids are already discovered. The main SPHEREx contribution to asteroid studies will be its spectral data for already known objects. That said, there will be some NEOs and comets, and perhaps even main-belt asteroids, that SPHEREx could discover with adequate software tools (e.g., Holman et al., 2018; Moeyens and Jurić, 2019).

Our analysis showed that without prior information about object emissivity, SPHEREx size estimates will have uncertainties of about 40-50%. While certainly useful in cases when no other size estimates are available, it is unlikely that SPHEREx will make a unique impact in this context given the existing WISE-based size estimates, anticipated size estimates by the NEO Surveyor (Mainzer et al., 2019, formerly known as NEOCam), and the potential of LSST data. We anticipate that the main new SPHEREx contribution to asteroid science will be derived from taxonomic and detailed spectroscopic information because the 0.7-5.0 μm wavelength range includes a number of diagnostic spectral features, such as those created by the presence of olivine, pyroxene, hydroxyl, water ice and organics in asteroid surfaces.

A key difficulty in interpretation of SPHEREx data for asteroids will be accounting for intrinsic rotational variability. While eventually Gaia and LSST will deliver light curves for essentially all asteroids observable by SPHEREx, according to current estimates the SPHEREx 2-year survey will be completed many years before the completion of 10-year LSST. In order to enable the analysis of SPHEREx spectra before the full potential of LSST can be utilized, we developed a method for correcting SPHEREx spectra that does not require light curves. This spectral-template-based method is possible because i) SPHEREx flux measurements are obtained in pairs, ii) for most objects, the thermal emission component can be neglected at wavelengths below 3.4 μm , and iii) observed spectra of asteroids in the SPHEREx wavelength range display only a finite number of different reflectivity curves. Once SPHEREx data become available, it

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will be possible to compare the results obtained by our method in this work with light-curve-based corrections for the subset of objects that will have adequate light curve data available. We anticipate that analysis of SPHEREx asteroid spectra will be built in iterative steps where light curve information¹¹ for objects will be combined with existing infrared spectra and object size estimates to iteratively build an overall self-consistent model akin to hierarchical Bayesian modeling, building on the work presented here and improving it.

Asteroid fluxes measured by SPHEREx will be extracted using the so-called forced photometry method, using pre-computed positions for objects within the field of view, at the time of each SPHEREx exposure. There are currently about a million asteroids with known orbits that could be included in the SPHEREx forced photometry object list. We predict that for only about 100,000 of those, SPHEREx data will have signal-to-noise ratio (SNR) at $2.4\ \mu\text{m}$ exceeding 0.5. Nevertheless, we believe that **SPHEREx should deliver all measurements for all asteroids with sufficiently accurate orbits**. The two main reasons for doing so are that i) it is clear that such data will be scientifically useful for asteroid size determination and spectral characterization, and ii) it is relatively easy to do so.

First, the scientific utility of very low SNR measurements can be greatly increased by data co-addition (or in other words, “data averaging”). We already quantitatively explored the co-addition of 4 spectra *for a given object*, that yields a factor of two increase of SNR. Analogous co-addition can be applied to spectra of *different objects* too, when it can be assumed that they are similar. For example, it is well known that objects from a given asteroid family have rather homogenous taxonomy and colors (Ivezić et al., 2002; Parker et al.,

¹¹In addition to Gaia and LSST, there are a number of other relevant sources of light curve data for asteroids, such as Pan-STARRS (Kaiser et al., 2002), Zwicky Transient Facility (Bellm et al., 2019) and ATLAS (Jedicke et al., 2012), to name but a few. A worthwhile project would be to merge all these datasets and produce a tool for predicting asteroid brightness and its uncertainty at arbitrary times.

2008). If spectra for, for example, 2,500 objects from the same family are added, the SNR would increase by a factor of 50. The faintest objects in the “million asteroid” SPHEREx sample would have SNR of about 0.1 – with such an SNR boost of a factor of 50, the resulting spectra would have fidelity as high as spectra shown in figure 9. As a proof of concept, such “image stacking” for a large sample of different objects has been successfully used in radio astronomy: Glikman et al. (2004) stacked images of $\sim 12,000$ quasars with very low SNR (much below detectability threshold, on average about 0.1) and obtained a coadded flux measurement with an SNR of ~ 12 (see their figure 1). Secondly, it is relatively easy to do so because the data volume of even a million spectra is still a negligible contribution to data volume and compute requirements compared to 14 billion spectra expected from SPHEREx.

The resulting SPHEREx data product could be rather simple: for each orbit, report the time of SPHEREx observation, forced flux measurement, its uncertainty, corresponding wavelength, the background level and some other judiciously chosen metadata. The resulting list would include about 400 individual time ordered measurements per object on average ($96 \text{ channels} \times 4 \text{ measurements per object}$), for about a million objects, or less than half a billion rows of archive data.

4.1. Acknowledgments

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Software: numpy (Oliphant, 2006), matplotlib (Hunter, 2007), scipy (Jones

et al., 2001–), astropy (Astropy Collaboration et al., 2013, 2018), astroML (VanderPlas et al., 2012), ATM (Moeyens et al., 2020).

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Figure 4: The adopted reflectivity (top) and emissivity (bottom) curves for the four main taxonomic types (C, S and V for main-belt asteroids, and “red” for Jovian Trojans, as marked in each panel). The color-coded background illustrates wavelength ranges for the blue and red SPHEREx dichroic ranges, separated at $2.42 \mu\text{m}$. The standard SPHEREx 96-wavelength grid is shown as short vertical marks at the bottom of the bottom panel. The reflectivity curves with wavelengths below $2.42 \mu\text{m}$ correspond to classes from the Bus-DeMeo taxonomy and are taken from DeMeo et al. (2009) for C, S, and V asteroids, and from Wong et al. (2019) for “red” Trojans (the curve for “less red” Trojans is not shown for clarity; it looks similar to the S curve except for no “wiggles”). The reflectivity curves with wavelengths above $2.42 \mu\text{m}$ were obtained by the AKARI mission (C: asteroid Hygiea; S and V: asteroid Herculina) and are taken from Usui et al. (2019). The latter are renormalized to approximately agree with the former, normalized to unity in the V band ($0.55 \mu\text{m}$). The curves are then joined, smoothed using the Savitzky-Golay filter, and interpolated to the standard SPHEREx wavelength grid. The resulting curves are extended to $5.0 \mu\text{m}$ using the value at the longest available wavelength, and shown as dotted lines. The emissivity curves in the bottom panel, $\epsilon(\lambda)$, are derived using the reflectivity curves from the top panel, $\rho(\lambda)$, as $\epsilon(\lambda) = 1 - 0.4 p_V \rho(\lambda)$, with adopted values of the visual albedo, p_V , shown in the bottom panel. The emissivity curve for “less red” Trojan asteroids is almost identical to the curve for C asteroids and is not shown for clarity. The two wavelength ranges marked W_1 and W_2 in the top panel correspond to the two shortest bandpasses for the WISE survey. The best-fit infrared emissivity range at these wavelengths obtained by Moeyens et al. (2020) is shown by the vertical two-side arrow on the right side in the bottom panel; it agrees well with the emissivity range implied by the AKARI reflectivity curves and adopted characteristic values of p_V .

Figure 5: **The orbital segments of seven characteristic orbits during the two years of simulated SPHEREx survey (June 17, 2024 to July 17, 2026), projected to the orbital plane.** The orbits (see Table 2.5) are color-coded as shown in the legend in the right panel. The left panel is a zoomed-in version of the right panel. The dashed circle is Earth's orbit and the small yellow dot in a black circle is the Sun (not to scale).

Figure 6: **The orbital segments of seven characteristic orbits during the two years of anticipated SPHEREx survey, in ecliptic coordinates.** The orbits (see Table 2.5) are color-coded as shown in the legend. The symbols show anticipated SPHEREx detections.

Figure 7: **The variation of the SPHEREx observation wavelength with time for seven characteristic orbits** (see figure 6), color-coded as shown in the legend in the right panel. The horizontal dashed line in the left panel at $2.42 \mu\text{m}$ is the dichroic wavelength that splits the SPHEREx wavelength range. The right panel is the zoomed-in first “observing season” for the orbit of asteroid (176014) Vedrana, with 71 pairs of observations. At each observing time, one observation is obtained at a wavelength shorter than $2.42 \mu\text{m}$ and one at a wavelength longer than $2.42 \mu\text{m}$; their positions (ranks) within each wavelength range are perfectly correlated (e.g., the blue edge of the blue region corresponds to the blue edge of the red region).

Figure 8: **The variation of observing parameters for the orbit of asteroid (176014) Vedrana during SPHEREx observations.** Top left: solar elongation; top right: the Sun-Earth angle as viewed from the asteroid; bottom left: asteroid distance from Earth; bottom right: asteroid distance from the Sun. The three segments in each panel correspond to three “observing seasons”. Within each season, there are 65-75 pairs of observations at two different wavelengths, obtained in about 20 “orbits” separated by 2-3 weeks. During each orbit, 1-5 pairs of observations are separated by about 2 minutes between successive data points (up to about 8 minutes between the first and last measurement).

Figure 9: **Simulated SPHEREx spectra for several asteroid taxonomic classes.** The taxonomic type, visual albedo, heliocentric distance and object diameter are listed in each panel. The red lines show noise-free spectra and the dots are scattered with gaussian noise using uncertainties computed with predicted SPHEREx sensitivity, and shown as error bars. Magnitude offsets due to variability are **not** included. Object sizes are chosen to approximately reproduce a signal-to-noise ratio of 5 at the wavelength of $2.4 \mu\text{m}$. About 6,000 asteroids will have SPHEREx spectra of similar quality. Note that for main-belt asteroids thermal emission dominates at wavelengths longer than about $4 \mu\text{m}$, while it is negligible for simulated Trojan at 5.2 a.u. (bottom right panel).

Figure 10: **Simulated SPHEREx spectra for several NEAs at relatively small heliocentric distances.** The taxonomic type, visual albedo, heliocentric distance and object diameter are listed in each panel. The red lines show noise-free spectra and the dots are scattered with gaussian noise using uncertainties computed with predicted SPHEREx sensitivity, and shown as error bars. Magnitude offsets due to variability are **not** included. Note that the emission part of SEDs becomes dominant at shorter wavelengths ($<3 \mu\text{m}$) than for simulated spectra shown in figure 9 ($>4 \mu\text{m}$).

Figure 11: **Simulated SPHEREx spectra for an S type asteroid with a varying signal-to-noise ratio due to varying size.** Analogous to figure 9 except that the taxonomic type, visual albedo, and heliocentric distance are kept constant, and correspond to the top left panel in figure 9, while object diameter is varied, as listed in each panel. The object diameter was chosen so that apparent V-band magnitude (approximately equal to the AB magnitude at the blue end of the spectrum) is approximately 17, 18, 19 and 20. Note that photometric noise increases rapidly with apparent magnitude, and that magnitude scale is different from that in figure 9.

Figure 12: **Illustration of the correction algorithm for rotationally induced variability for main-belt asteroid (176014) Vedrana.** The red line in the top left panels shows noise-free simulated SPHEREx spectrum for asteroid (176014) Vedrana, assumed to belong to S spectral type and have a diameter of 10 km, and “observed” at a heliocentric distance of 3.0 a.u. The points with “error bars” show the impact of noise due to finite SPHEREx sensitivity, and due to sinusoidal rotational variability with an amplitude of 0.3 mag and a period of 0.2 days (see eqs. 8 and 9); the shown error bars include only the measurement noise (and thus the scatter of points around the curve appears larger than implied by error bars). The chosen size yields a signal-to-noise ratio at $2.4 \mu\text{m}$ of about 10. The other three panels show “corrected” spectra using the algorithm described in text and templates shown as blue lines (and marked by S, V and C). Red lines are same as the red line in the top left panel – the true S-type template). The resulting χ^2 per degree of freedom, evaluated for data points in the $2.4\text{--}3.4 \mu\text{m}$ range is also shown in each panel.

Figure 13: **Distributions of $\Delta\chi^2_{dof}$ differences for two best spectral templates and 10,000 trials.** The left panel is based on SEDs for main-belt asteroid (176014) Vedrana, such as shown in the two right panels in figure 12, and the right panel is based on SEDs for Trojan (1143) Odysseus, such as shown in the top right and bottom left panels in figure 14. In the left panel, the right histogram corresponds to SNR $\sim$ 10 used in figure 12, while the left histogram is produced with similar SEDs, except that the object diameter is decreased from 10 km to 7 km, resulting in a change of SNR at 2.4 μ m from about 10 to about 5. The fractions of trials with $\Delta\chi^2_{dof} < 0$ are 2.3% for SNR $\sim$ 10 case and 15% for SNR $\sim$ 5 case. In the right panel, the right histogram corresponds to SNR $\sim$ 5 used in figure 14, and the left histogram is produced with similar SEDs, except that the object diameter is increased from 20 km to 30 km, resulting in a change of SNR from about 5 to about 10. The fractions of trials with $\Delta\chi^2_{dof} < 0$ are 0.02% for SNR $\sim$ 10 case and 5.1% for SNR $\sim$ 5 case. Note the different x axis range for the two panels.

Figure 14: **Illustration of the correction algorithm for rotationally induced variability for Jovian Trojan asteroid (1143) Odysseus.** Analogous to figure 12. Odysseus is at 5.2 a.u. and assumed to have a diameter of 20 km and “red” taxonomic type. The chosen size yields a signal-to-noise ratio at $2.4 \mu\text{m}$ of about 5. The templates are marked as RT (“red”), LT (“less red”) and C (carbonaceous).

Figure 15: **Simulated optical-infrared colors for main-belt asteroids.** The left panel shows a sample of $\sim 5,000$ objects with SNR at $2.4 \mu\text{m}$ at least 5, while the right panel shows $\sim 12,000$ objects with SNR at least 2.5. Different symbol colors correspond to different taxonomic classes; red: S type, magenta: V type, blue: C type. The SNR distribution follows counts from Table 3.3, with 10% of counts for S type asteroids assigned to V type. It is assumed that rotational variability has been corrected for prior to integration of spectra over chosen bandpasses. Quantitative summary of observed distributions is given in Table 3.4.

Figure 16: **Simulated optical-infrared colors for “red” and “less red” Trojan asteroids.** The left panel shows a sample of $\sim 1,000$ objects with SNR at $2.4 \mu\text{m}$ at least 5, while the right panel shows $\sim 2,000$ objects with SNR at least 2.5. Different symbol colors correspond to different taxonomic classes; red: “red” type, blue: “less red” type. The SNR distribution follows counts from Table 3.3. It is assumed that rotational variability has been corrected for prior to integration of spectra over chosen bandpasses. Quantitative summary of observed distributions is given in Table 3.4.

- simulated SPHEREx spectra (0.75-5.0 micron) of Main Belt and Trojan asteroids
- a method for correcting SPHEREx asteroid spectra for intrinsic rotational variability
- a prediction that SPHEREx will deliver meaningful flux measurements for about 100,000 asteroids
- all the tools and a library of simulated spectra are made publicly available on GitHub.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: