Determinaton of Size, Albedo, and Thermal Inertia of 10 Vesta Family Asteroids with WISE/NEOWISE Observations

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Abstract

In this work, we investigate the size, thermal inertia, surface roughness, and geometric albedo of 10 Vesta family asteroids using the Advanced Thermophysical Model, based on the thermal-infrared data acquired by mainly NASA’s Wide-field Infrared Survey Explorer. Here, we show that the average thermal inertia and geometric albedo of the investigated Vesta family members are 42 J m−2 s−1/2 K−1 and 0.314, respectively, where the derived effective diameters are less than 10 km. Moreover, the family members have a relatively low roughness fraction on their surfaces. The similarity in thermal inertia and geometric albedo among the V-type Vesta family members may reveal their close connection in origin and evolution. As the fragments of the cratering event of Vesta, the family members may have undergone a similar evolutionary process, thereby leading to very close thermal properties. Finally, we estimate their regolith grain sizes with different volume filling factors.

Unified Astronomy Thesaurus concepts: Main belt asteroids (2036)

Supporting material: machine-readable table

1. Introduction

An asteroid family is usually supposed to be formed from the fragmentation of a parent body in the main belt. The family members may share similar composition and physical characteristics with their parent body. To identify and study the asteroid families, one of the classical methods is to evaluate the proper elements and characterize the distribution of asteroids in proper element space by applying a clustering algorithm (e.g., the Hierarchical Clustering Method; Zappalà et al. 1990). In addition, Nesvorny et al. (2015) provided an asteroid family catalog that contains 122 families calculated from synthetic proper elements. The Vesta family, as one of the largest asteroid populations, consists of over 15,000 members and is located in the inner region of the main belt with proper orbital elements 2.26 ≤ a_p ≤ 2.48 au, 0.075 ≤ e_p ≤ 0.122, and 5°6 ≤ i_p ≤ 7°9, where a_p, e_p, and i_p are the proper elements of the semimajor axis, eccentricity, and inclination, respectively (Zappalà et al. 1995). Taxonomically, basaltic asteroids are classified as V-type asteroids that have photometric, visible-wavelength spectral and other observational relationships with (4) Vesta (Hardersen et al. 2014). For example, their optical spectra are similar to that of (4) Vesta, displaying a strong absorption band attributed to pyroxene centered near 9000 Å (Binzel & Xu 1993). In the Vesta family, most of the members are believed to be V-type asteroids. But some V-type asteroids have been discovered outside the Vesta family recently, which may indicate the presence of multiple basaltic asteroids in the early solar system (Licandro et al. 2017). The Vesta family was inferred to originate from (4) Vesta through a catastrophic impact event approximately 1 Gyr ago (Marzari et al. 1996). Carruba et al. (2005) further investigated the dynamical evolution of V-type asteroids outside the Vesta family and showed that it is possible that the members of the Vesta family migrated via the Yarkovsky effect and nonlinear secular resonance. Hasegawa et al. (2014b) investigated the rotational rates of 59 V-type asteroids in the inner main-belt region and showed that the rotation rate distribution is non-Maxwellian. This may be caused by the long-term Yarkovsky–O’Keefe–Radzievskii–Paddock (YORP) effect, which can change the direction of asteroids’ spin axis and rotation periods (Delbo et al. 2015). Additionally, by numerically integrating the orbits of 6600 Vesta fragments over a timescale of 2 Gyr, Nesvorny et al. (2008) demonstrated that a large number of family members can evolve out of the family borders defined by clustering algorithms and constrained the age of this family to be older than 1 Gyr. Also, Bottke et al. (2005) determined that the cratering event may have occurred in the last 3.5 Gyr. According to Dawn spacecraft’s observation, the two largest impact craters on Vesta were estimated to have formed about 1 Gyr ago (Marchi et al. 2012). Such an early formation event of the family could provide a sufficient time to yield the rotational distribution obtained by Hasegawa et al. (2014b) under the influence of the YORP effect. Moreover, visible and infrared spectroscopic investigations imply that (4) Vesta may be the parent body of near-Earth V-type asteroids (Migliorini et al. 1997) and Howardite–Eucrite–Diogenite meteorites (HEDs; Cruikshank et al. 1991; Migliorini et al. 1997; Burbine et al. 2001). The HEDs are believed to have come from melted basaltic magma ocean crystallization on large asteroids (De Sanctis 2012; Mandler & Elkins-Tanton 2013). Fulvio et al. (2012) performed laboratory irradiation experiments on HED meteorites to simulate space weathering on Vesta and Vesta family asteroids by using different ions. Their experimental results indicate that the space weathering effect can give rise to the spectral differences between (4) Vesta and other V-type bodies. Vesta is known as one of the most frequently observed bodies (Reddy et al. 2013; Hasegawa et al. 2014a). Thomas et al. (1997) explored the pole orientation, size, and shape of
Vesta by using images from Hubble Space Telescope (HST). HST’s observations unveil an amazing impact crater with a diameter of 460 km, which is supporter of the collision site (Thomas et al. 1997). In 2011, the spacecraft Dawn arrived at Vesta and further discovered that the giant basin observed by HST is, in fact, composed of two overlapping huge impact craters, Rheaasilvia (500 km) and Veneneia (400 km), respectively. Excavation of these two craters confirmed that they were capable of supplying the materials of the Vesta family asteroids and HEDs (Schon et al. 2012). The Rheaasilvia crater appears to be younger and overlies the Veneneia. Moreover, further study by the Dawn mission revealed a wide variety of albedos on the surface of Vesta (Reddy et al. 2012) and a deduced core with a diameter of 107 ~ 112 km, indicating sufficient internal melting to segregate iron (Russell et al. 2012).

As mentioned above, V-type asteroids and HEDs provide key clues to the formation and evolution scenario for the main-belt asteroids (MBAs) as well as essential information about the early stage of our solar system, from the viewpoint of their similar orbits and the spectral properties. Therefore, the primary objective of this work is to investigate the thermophysical characteristics of the thermal inertia, roughness fraction, geometric albedo, and effective diameter etc., to have a better understanding of these Vesta family members. This can help us establish the relation between Vesta family asteroids and other MBAs from a new perspective. In fact, thermal inertia plays an important role in determining the resistance of temperature variation over the asteroid surface, which is associated with the surface temperature and materials. As a result of the major fragmentation of the parent body or the impactor, although they may have similar features in orbital evolution or spectral feature, each member of the Vesta family can have a distinguished appearance in size, surface topography, and roughness due to surface evolution over secular timescales in space, thereby causing diverse thermal inertia on the asteroid’s surface. Moreover, the geometric albedo holds significant information about the asteroidal composition. Therefore, by comparing thermal inertia and geometric albedo of the family members with those of the parent body, we can gain a deep understanding of the origin of the Vesta family.

In this work, we extensively investigate the thermal properties of 10 Vesta family asteroids whose polyhedron shape models and thermal-infrared observational data can be acquired via the Advanced Thermophysical Model (ATPM; Rozitis & Green 2011; Yu et al. 2017; Jiang et al. 2019). Moreover, we derive the thermophysical parameters for the Vesta family asteroids on the basis of ATPM and the mid-infrared data, and we further explore the correlations of various thermal parameters to provide implications for the impact history of Vesta. Furthermore, we explore the homology of these Vesta family asteroids by comparing their thermal parameters with those of Vesta. The 10 family members are: (63) Ausonia, (556) Phyllis, (1906) Neaf, (2511) Patterson, (3281) Maupertuis, (5111) Jacliff, (7001) Neother, (9158) Plate, (12088) Macalintal, and (15032) Alexlevin. Their shape models can be obtained from the Database of Asteroid Models from Inversion Techniques (DAMIT),6 whereas thermal-infrared observations can be acquired from the Wide-field Infrared Survey Explorer (WISE)/NEOWISE, Infrared Astronomical Satellite (IRAS), and AKARI. Table 1 summarizes the detailed parameters of the targets under study.

The structure of this paper is as follows. Section 2 gives a brief description on the modeling of thermal processes as well as the convex shape models, mid-infrared observations, and ATPM. The radiometric results for each Vesta family asteroid and their analysis are presented in Section 3. Section 4 presents a discussion on the relationships of the thermal inertia, effective diameter, and geometric albedo and the evaluation of regolith grain size. The conclusions are given in Section 5.

### 2. Thermal Modeling

#### 2.1. Shape Model

As mentioned above, here, we adopt 3D convex shape models for 10 Vesta family asteroids (Kasalainen & Torppa 2001) from DAMIT. In ATPM, the asteroids are considered to be composed of N triangular facets; hence, we employ a fractional coverage of hemispherical craters to describe the surface roughness of asteroids, where each crater is assumed to be composed of M smaller triangular sub-facets (Rozitis & Green 2011). Table 1 lists the parameters of the asteroids’ shape models, which include the number of facets, number of vertices, and pole orientations. The shape models for the 10 Vesta family asteroids are plotted in Figure 1, where the red arrows represent the spin axis of each asteroid.

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**Table 1**

| Asteroid    | a(au)   | e      | i(°)   | \(P_{\text{orb}}\)(yr) | \(Abs_{\text{mag}}\) | \(N_{\text{facets}}\) | \(N_{\text{vertices}}\) | Orientation(°) | \(P_{\text{rot}}\)(hr) | Spectral Type |
|------------|---------|--------|--------|-----------------|----------------|----------------|----------------|----------------|----------------|---------------|
| (63) Ausonia | 2.395   | 0.1269 | 5.7756 | 3.71            | 7.55           | 3192           | 1598           | (120, −15)    | 9.282          | Sa,Sw         |
| (556) Phyllis | 2.464   | 0.1037 | 5.2461 | 3.87            | 9.56           | 3192           | 1598           | (209, −41)    | 4.923          | S             |
| (1906) Neaf  | 2.375   | 0.1345 | 5.6977 | 3.66            | 9.11           | 1016           | 7192           | (72, −70)     | 11.010         | V             |
| (2511) Patterson | 2.298   | 0.1037 | 5.0479 | 3.48            | 12.7           | 7144           | 574            | (194, 51)     | 4.141          | V             |
| (3281) Maupertuis | 2.350   | 0.0975 | 5.9904 | 3.60            | 12.7           | 1098           | 574            | (253, −45)    | 6.730          | ...            |
| (5111) Jacliff | 2.355   | 0.1264 | 5.8043 | 3.61            | 12.7           | 1144           | 574            | (194, −45)    | 2.839          | R>V           |
| (7001) Neother | 2.378   | 0.1508 | 7.0250 | 3.63            | 13.3           | 2040           | 1022           | (13, −66)     | 9.581          | ...            |
| (9158) Plate | 2.300   | 0.1509 | 7.6954 | 3.49            | 13.6           | 1140           | 572            | (119, −52)    | 5.160          | SQ>           |
| (12088) Macalintal | 2.355   | 0.0739 | 6.2439 | 3.63            | 14.0           | 1144           | 574            | (265, 50)     | 3.342          | V             |
| (15032) Alexlevin | 2.373   | 0.1179 | 5.5082 | 3.66            | 14.0           | 1144           | 574            | (353, −46)    | 4.405          | V             |

**Note.** \(a, e,\) and \(i\) represent the semimajor axis, eccentricity, and inclination, respectively. \(P_{\text{orb}}\) is the orbital period, and \(Abs_{\text{mag}}\) is the absolute magnitude. \(N_{\text{facets}}\) and \(N_{\text{vertices}}\) describe the number of shape facets and vertices in the shape models, respectively. \(P_{\text{rot}}\) is the rotation period.

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5 According to the orbital database at AstDyS node (http://hamilton.dm.unipi.it/astdys/), we take (7001) Neother as a Vesta family asteroid, because the proper orbital elements of (7001) Neother are within the range of those of the Vesta family (Zappalà et al. 1995). The other nine Vesta family asteroids here are simply adopted from the Vesta family list (Nesvorný et al. 2015).

6 https://astro.troja.mff.cuni.cz/projects/asteroids3D/web.php
Each asteroid.

Figure 1. 3D convex shape models of the Vesta family asteroids (from DAMIT) in this work, where the red arrows illustrate the direction of the spin orientation for each asteroid.

2.2. Observations

In this work, thermal-infrared data are obtained from three space-based telescopes: WISE/NEOWISE, IRAS, and AKARI. For example, WISE surveyed the sky in four wave bands (3.4, 4.6, 12.0, and 22.0 μm noted as W1, W2, W3, and W4, respectively) until the solid hydrogen cryostat (which was utilized to cool down the W3 and W4 bands) was depleted on 2010 September 30. Thereafter, the satellite continued to work at the W1 and W2 bands, known as NEOWISE. In this situation, we can download the data from two source tables of the WISE archive (http://irsa.ipac.caltech.edu/applications/wise/), WISE All-Sky Single Exposure (L1b) and NEOWISE-R Single Exposure (L1b). Here, we should emphasize that the surface temperatures of the MBAs are relatively lower than those of the NEAs, and as a result, the data obtained in shorter wavelengths (e.g., W1) can include a large percentage of reflected sunlight. As will be discussed in the following section, the W1 band contains roughly 90% reflected sunlight in the observations, indicating that the thermal portion is merely comparable to the uncertainty of the entire observed flux. For this reason, we do not adopt the W1 band data of the Vesta family asteroids in our fitting. In the target searching, we employ the Moving Object Catalog Search with a search cone radius of 1″. Similar to that of Masiero et al. (2011) and Grav et al. (2012), all artifact identification CCG_FLAG, other than 0 and p, is rejected, where 0 indicates no evidence of known artifacts found whereas p means that an artifact may be present. Additionally, the modified Julian date needs to be within 4 s of the epochs given in MPC.

Subsequently, we follow the method described by Wright et al. (2010) to convert the magnitudes into fluxes and the color correction factors of 1.3448, 1.0006, and 0.9833 for the W2–W4 bands. Since the observed flux is proportional to the cross-sectional area of the asteroid in the direction of the observer, the thermal light curve of an asteroid should not have an amplitude that may exceed a certain value (Jiang et al. 2019). According to this point, we further screen the data set for each asteroid, and the thermal light curves will be discussed later in this work. Table 2 reports the number of observations for the W2–W4 wavelengths of WISE, the range of the phase angle, heliocentric distance, and distance from the asteroid in reference to the observer. Detailed WISE/NEOWISE observations for each asteroid are summarized in the Appendix. The observational uncertainties here are set to be 10% for all Vesta family asteroids. Here, the observations from AKARI and IRAS are only applied to the fitting for (63) Ausonia and (556) Phyllis, which are not given in the table.

2.3. Advanced Thermophysical Model with Reflected Sunlight

Here, ATPM accepts global shape models in the triangular facet formalism and adopts a hemispherical crater to represent the roughness surface. In order to constrain the thermal properties such as thermal inertia, roughness fraction, and geometric albedo, we need to compute the temperature distribution over the asteroid’s surface. For each shape facet, the temperature T can be determined by solving the 1D heat-conduction function

\[ \frac{\partial T}{\partial t} = \frac{k}{\rho C} \frac{\partial^2 T}{\partial x^2}, \]

with a specific boundary condition in which the shadowing effect, multiple-sunlight scattering, and re-absorption of thermal radiation are taken into consideration (Rozitis & Green 2011). Here, k, \( \rho \), and C represent the thermal conductivity, surface density, and heat capacity, respectively. The methods for simplifying and solving the heat-conduction equation are described in Spencer et al. (1989) and Lagerros (1996). Once the temperature distribution is ascertained, we can use the Planck function to evaluate the theoretical thermal emission of each facet; thus, the total theoretical thermal emission of an asteroid can be written as

\[ F_{\text{thermal}} = (1 - f_i) \sum_{i}^{N} \pi \epsilon B(\lambda, T_i) A_i v_i \]

\[ + f_i \sum_{j}^{M} \sum_{i}^{N} \pi \epsilon B(\lambda, T_j) A_{ij} v_{ij}, \]

where \( f_i \) is the roughness fraction, and \( \epsilon \) is the monochromatic emissivity at wavelength \( \lambda \), which is assumed to be 0.9. For facet \( i \) and sub-facet \( ij \), \( A \) and \( v \) denote the area and the view factor, respectively. \( B \) is the Planck function, described by

\[ B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}. \]
and the view factor \( v \) is defined as

\[
v_i = \frac{s_i \cdot n_{i,\text{obs}}}{\pi d_{ao}^2},
\]

where \( s_i \) indicates whether facet \( i \) can be seen by the observer, \( n_i \) and \( n_{obs} \) represent the facet normal and the vector pointing to the observer, respectively, and \( d_{ao} \) is the distance between the asteroid and the observer.

In addition, as pointed out by Myrhrvold (2018), thermal-infrared observations of shorter wavelengths (e.g., W1 and W2) are dominated by reflected sunlight. It is necessary to remove the effects of the reflected part when we use these observations in shorter wavelengths. Hence, we further deal with the reflected sunlight contained in the observed flux by using the method described in Jiang et al. (2019). We treat each facet \( i \) and sub-facet \( ij \) as a Lambertian surface, and the reflected part can be expressed as

\[
F_{\text{ref}-i}(\lambda) = B(\lambda, 5778) \frac{R_{\text{sun}}^2}{r_{\text{helio}}^2} \cdot A_B \cdot \psi_i \cdot A_i \cdot v_i,
\]

\[
F_{\text{ref}-ij}(\lambda) = B(\lambda, 5778) \frac{R_{\text{sun}}^2}{r_{\text{helio}}^2} \cdot A_B \cdot \psi_{ij} \cdot A_{ij} \cdot v_{ij},
\]

where \( B(\lambda, T) \) is the Planck equation for the temperature of the Sun, \( R_{\text{sun}} \) is the radius of the Sun, \( r_{\text{helio}} \) is the heliocentric distance of the asteroid, \( A_B \) is the bond albedo, and \( \psi \) is the sine value of the solar incidence angle. \( S \) and \( v \) are the area and view factor, respectively. The entire reflected sunlight portion is be given by

\[
F_{\text{ref}} = (1 - f_j) \sum_{i}^N F_{\text{ref}-i} + f_j \sum_{i}^N \sum_{j}^M F_{\text{ref}-ij}.
\]

According to our sunlight reflection model, we assess the reflected sunlight contained in the W1–W4 observations, which covers \( \sim90\% \) at W1, \( 30\%–50\% \) at W2, and can be negligible at W3 and W4. Therefore, as described above, the W1 band is not adopted in this work. The reflected sunlight contributes to a significant part of the W2 observation, but the proportion is no more than \( 50\% \). As will be discussed in the following section, we account for the overall contribution of the thermal emission and reflected sunlight to fit the observations. In addition, WISE only surveyed the sky for roughly 9 months in 2010, which is suggestive of the observations of the MBAs in W3 and W4 simply covering a very narrow range of the solar phase angle. In comparison, utilization of the W2 data can provide diverse observational solar phases, wavelengths, as well as observational numbers, which make the fitting process more reliable. Thus, we utilize the observations from the W2 band, but we also take reflected sunlight into consideration in our fitting.

### 2.4. Thermal-infrared Fitting

Heat conduction both in and out of the asteroids’ subsurface material can lead to a certain thermal memory, named the thermal inertia. In particular, thermal inertia is defined as \( \Gamma = \sqrt{\kappa \rho c} \), where \( \kappa, \rho, \) and \( c \) have the same meaning as in Equation (1). In fact, the thermal inertia plays the very important role of governing the heat-conduction process and inducing the nonzero nightside temperature of an asteroid. Moreover, this thermal parameter can result in the surface temperature peaking on the afternoon side of an asteroid, thereby causing the diurnal Yarkovsky effect (Delbo et al. 2015). In order to derive the best-fitting thermal emission with the observed fluxes, we set the initial thermal inertia in the range \( \Gamma = 0 \sim 300 \) J m\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\) at equally spaced steps of \( 10 \) J m\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\). Other parameters, such as pole orientation, absolute magnitude, and rotation period are listed in Table 1. A bolometric and spectral emissivity of 0.9 is assumed for all wavelengths in the fitting procedure. On the other hand, as shown in Table 2, for each Vesta family asteroid, the solar phase angle only covers a very small range; therefore, it brings about the difficulty in placing constraints on the thermal inertia.
and roughness fraction at the same time. In general, the roughness fraction of the MBAs is usually small; thus, we assume a priori roughness for these Vesta family asteroids to be 0.1–0.5. Hence, for each wavelength, we obtain three free parameters, i.e., thermal inertia $\Gamma$, geometric albedo $p_v$, and the rotation phase $\phi$. In fact, the effective diameter $D_{\text{eff}}$ is connected with the geometric albedo via

$$D_{\text{eff}} = 1329 \times \frac{10^{-0.2H_v}}{\sqrt{p_v}},$$

where $H_v$ is the absolute magnitude. For each asteroid, the entire theoretical flux $F_m$ can be written as

$$F_m = F_{\text{thermal}} + F_{\text{ref}},$$

where $F_{\text{thermal}}$ is the total theoretical thermal emission, and $F_{\text{ref}}$ represents the reflected sunlight. Then, we compare $F_m$ with the observations, and we adopt the minimum $\chi^2$ fitting defined by Press et al. (2002) as

$$\chi^2 = \frac{1}{n - 3} \sum_{i=1}^{n} \left[ \frac{F_m(p_v, \Gamma, f_i, \lambda, \phi) - F_{\text{obs}}(\lambda)}{\sigma_{\lambda}} \right]^2,$$

where $n$ is the observation number, and $\sigma_{\lambda}$ is the observation uncertainty. In the following section, we report the details of our results for the 10 Vesta family asteroids.

3. Results

3.1. (63) Ausonia

Asteroid (63) Ausonia is the largest Vesta family member with a diameter of roughly 100 km. In the Tholen classification, (63) Ausonia is a stony S-type asteroid (Tholen 1984), and in the SMASSII classification, it is classified as an Sa-type asteroid (Bus & Binzel 2002), while in the Bus-Demeo taxonomy, it is an Sw subtype (DeMeo et al. 2009). Tanga et al. (2003) estimated the overall shape, spin orientation, and angular size of (63) Ausonia using the observations from the Fine Guidance Sensors of HST. They derived an effective diameter of 87 km for this asteroid, which was smaller than the IRAS diameter (103 km; Tedesco et al. 2004) and that of Masiero et al. (2012; 116 km). In this work, we adopt 97 observations from IRAS (3 $\times$ 12 $\mu$m, 3 $\times$ 25 $\mu$m, 3 $\times$ 60 $\mu$m, and 1 $\times$ 100 $\mu$m), AKARI (4 $\times$ 9 $\mu$m, 2 $\times$ 18 $\mu$m; Usui et al. 2011; Alí-Lagoa et al. 2018), and WISE/NEOWISE (47 $\times$ 4.6 $\mu$m, 17 $\times$ 12.0 $\mu$m, and 17 $\times$ 22.0 $\mu$m) to explore the thermal parameters for (63) Ausonia. Figure 2 illustrates the $\Gamma - \chi^2$ profile of (63) Ausonia, where the minimum value $\chi^2$ is related to the thermal inertia 50$^{+5}_{-12}$ J m$^{-2}$ s$^{1/2}$ K$^{-1}$ and the roughness fraction 0.5$^{+0.0}_{-0.3}$. The horizontal line represents the 3$\sigma$ range of $\Gamma$. Furthermore, we derive the effective diameter 94.595$^{+2.348}_{-2.483}$ km, and the geometric albedo is then evaluated to be 0.189$^{+0.009}_{-0.010}$ for this asteroid.

To examine the best-fitting parameters for (63) Ausonia, here, we follow the method described in Yu et al. (2017) and Jiang et al. (2019) to plot the theoretical thermal light curves of (63) Ausonia compared with the mid-infrared observations. As shown in Figure 3, the thermal flux from ATPM offers a good match with the data at the W2 band for each of the four separate epochs. In addition, Figure 4 exhibits a similar behavior of the thermal light curves to the observations at the W3 and W4 bands, respectively. In order to examine the reliability of our derived results, we again calculate the ratio of the theoretical flux obtained by ATPM and the observational flux at diverse wavelengths. Figure 5 displays the observation/ATPM ratios as a function of wavelength for (63) Ausonia at each wavelength, distinguished by color, and the values of the ratio fluctuate about 1 for each wavelength, which is indicative of a reliable outcome for (63) Ausonia.

3.2. (556) Phyllis

(556) Phyllis is also taxonomically classified as an S-type (Tholen 1984; Bus & Binzel 2002) asteroid with a diameter of 36.28 km and a geometric albedo of 0.201 (Masiero et al. 2014). The first photometric observations and optical light curves of (556) Phyllis were performed by Zappalà et al. (1983), and they derived a rotation period 4.28 ± 0.002 hr. Marciniak (2007) observed this asteroid for five distinct observational epochs in 1998, 2000, 2002, 2004, and 2005–2006, respectively. They updated the rotation period to
that the theoretical model the outcomes of W3 and W4. Figures 7 and 8 both demonstrate curves for four different epochs at W2, while Figure 8 reveals the number of data points is too small to fully reflect the asteroid’s varied flux with rotational phases. Moreover, Figure 7 gives the results of thermal light curves for four different fluxes at W2, while Figure 8 reveals the asteroid (5 × 12 μm, 5 × 25 μm, and 5 × 60 μm), AKARI (5 × 9 μm, 4 × 18 μm) and WISE/NEOWISE (75 × 4.6 μm, 30 × 12.0 μm, and 29 × 22.0 μm), where the number of entire observations is 130. We derive an effective diameter of 35.606 ± 0.090 km with a geometric albedo 0.209 ± 0.011 by considering the absolute magnitude 9.56. As shown in Figure 6, the thermal inertia and roughness fraction are constrained to be $30^{+12}_{-11} \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$ and $0.40^{+0.10}_{-0.20}$, respectively, with respect to a minimum $\chi^2$ value of 2.715. WISE/NEOWISE observed this asteroid during eight different epochs. However, for several epochs, the number of data points is too small to fully reflect the asteroid’s varied flux with rotational phases. Moreover, Figure 7 gives the results of thermal light curves for four different fluxes at W2, while Figure 8 reveals the outcomes of W3 and W4. Figures 7 and 8 both demonstrate that the theoretical model fits the observations well. Further evidence is provided by Figure 9, which shows the Observation/ATPM ratio of (556) Phyllis for each wavelength.

3.3. (1906) Neaf

Asteroid (1906) Neaf, provisional designation 1972 RC, is a V-type asteroid (Xu et al. 1995) in the inner main-belt region. It orbits the Sun at a heliocentric distance 2.1–2.7 au every 3.66 yr. Masiero et al. (2014) derived its diameter of 7.923 ± 0.09 km and geometric albedo 0.234 ± 0.052 based on observations from WISE/NEOWISE. Similarly, we utilize the observations from WISE/NEOWISE, which are combined with ATPM, to derive its thermal properties. Here, we use all 57 WISE observations at three separate epochs (30 in W2, 16 in W3, and 16 in W4). We obtain an effective diameter of this asteroid of 7.561 ± 0.44 km and a geometric albedo of 0.257 ± 0.03, and these results agree with the findings of Masiero et al. (2014). According to the $\Gamma - \chi^2$ profile in Figure 10, the thermal inertia and roughness fraction are confined to be $70^{+19}_{-16} \mu \text{m}^2 \text{s}^{-1/2} \text{K}^{-1}$ and $0.5^{+0.0}_{-0.2}$, respectively. From the results of $\Gamma$ and $f_r$, we plot the three-band thermal light curves in Figures 11 and 12. Our computed thermal fluxes reasonably fit the WISE observation with $\chi^2_{\text{min}} = 7.095$. This may be the reason that the W4 theoretical flux does not agree well with the observations according to Figure 12, but the fluctuation trends of the thermal light curves are consistent with the observations. In the lower panel of Figure 12, we again provide an additional thermal curve at W4 with a high roughness $f_r = 0.5$ (marked by the black dashed line) in comparison with the case of low roughness, which leads to a better-fitting solution at the W4 band. When using all of the data, the best-fitting thermal inertia is evaluated to be approximately $70 \mu \text{m}^2 \text{s}^{-1/2} \text{K}^{-1}$ with respect to a low roughness fraction. The ratio of the observed flux and theoretical flux is plotted in Figure 13.

3.4. (2511) Patterson

Asteroid (2511) Patterson is a V-type asteroid (Bus & Binzel 2002) that was discovered by the Palomar Observatory in 1980. It has a semimajor axis of 2.298 au, an eccentricity of 0.104, and an orbital inclination of 8°046. Dürrech et al. (2018b) derived the shape model of (2511) Patterson by using the sparse-in-time photometry from the Lowell Observatory photometry database and WISE observations, which can be obtained from DAMIT. They further presented the pole orientation (194°, 51°). Using the Near Earth Asteroid Thermal Model (NEATM), Masiero et al. (2011) derived the geometric

**Figure 4.** Thermal light curves of (63) Ausonia at the W3 and W4 bands.

**Figure 5.** The observation/ATPM ratios as a function of wavelength for (63) Ausonia.

**Figure 6.** $\Gamma - \chi^2$ profile fit to the observation of (556) Phyllis.
albedo and effective diameter to be $0.287 \pm 0.039$ and $7.849 \pm 0.174$ km, respectively. In this work, we use the ATPM combined with 24 WISE/NEOWISE observations ($11 \times 12.0 \mu m$ and $13 \times 22.0 \mu m$) to determine the thermal characteristics of $(2511)$ Patterson. As shown in Figure 14, the minimum $\chi^2$ corresponds to a thermal inertia of $90^{+58}_{-43}$ J m$^{-2}$ s$^{1/2}$ K$^{-1}$, and the roughness fraction can be constrained to be $0.0^{+0.50}_{-0.035}$. In addition, the geometric albedo is estimated to be $0.180^{+0.055}_{-0.034}$, which is smaller than that of Masiero et al. (2011), and thus, the effective diameter is $9.034^{+0.997}_{-1.128}$ km. To examine our results, we plot the observation/ATPM ratio and thermal light curves for each wave band in Figures 15 and 16. The solid curves in Figure 15 are modeled with $\Gamma = 90$ J m$^{-2}$ s$^{1/2}$ K$^{-1}$ and $f_r = 0.0$. The model seems to slightly overestimate the W4 data, but the fit to the WISE light curve seems to be reliable for all wavelengths.

3.5. $(3281)$ Maupertuis

Asteroid (3281) Maupertuis is a Vesta family member that orbits the Sun at a distance $2.121 \sim 2.579$ au every 3.6 yr and has an absolute magnitude 12.9. The spectral type of this
asteroid is not determined yet. Using the Lowell photometric data and light-curve inversion method, Durech et al. (2016) derived the shape model of this asteroid and a sidereal period of $6.72894 \pm 0.00001$ hr. Two pole orientations of $(231^\circ, -74^\circ)$ and $(62^\circ, -66^\circ)$ were given in their work. Masiero et al. (2014) showed that (3281) Maupertuis has a geometric albedo of $0.489 \pm 0.02$ and an effective diameter of $5.482 \pm 0.043$ km. This result was close to that of Mainzer et al. (2011). For this asteroid, we employ 45 thermal observations from WISE/NEOWISE at two separate epochs ($18 \times 4.6 \mu m$, $13 \times 12.0 \mu m$, and $14 \times 22.0 \mu m$) in the fitting. For (3281) Maupertuis, we find that its diameter is constrained to be $5.509_{-0.447}^{+0.447} \pm 0.270$ km with a geometric albedo $0.484_{-0.074}^{+0.051}$. The value of the geometric albedo is a bit high for an MBA, but as a fragment of asteroid (4) Vesta, it is consistent with the wide range of $p_v$ on (4) Vesta’s surface. Figure 17 exhibits the
best-fitting values of the thermal inertia $60_{-15}^{+58} \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$ and roughness $0.50_{-0.30}^{+0.00}$. As can be seen in Figure 18, the model seems to overestimate the W4 data. Figure 19 shows the ratio of Observation/ATPM for (3281) Maupertuis with respect to $\Gamma = 60 \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$ and $f_r = 0.5$. However, the values of $\Gamma$ and $f_r$ correspond to the minimum value of $\chi^2$.

### 3.6. (5111) Jacliff

Asteroid (5111) Jacliff, known as provisional designation 1987 SE24, orbits the Sun once every 3.61 yr. In the SMASS II classification, (5111) Jacliff is an R-type asteroid (Bus & Binzel 2002), while in the Bus-Demeo taxonomy, the asteroid is classified as a V-type asteroid (DeMeo et al. 2009). Moreover, Moskovitz et al. (2010) compared the near-infrared (0.7–2.5 $\mu$m) spectra of this asteroid with the laboratory spectra of HED meteorites and showed that they suggest a V-type asteroid. By using all available disk-integrated optical data as an input for the convex input method, Hanuš et al. (2016) derived the 3D shape model for (5111) Jacliff, and the pole orientation and rotation period were derived to be (259$^\circ$, –45$^\circ$) and 2.840 h. In our study, we employ 47 WISE/NEOWISE observations ($28 \times 4.6 \mu$m, $11 \times 12.0 \mu$m, and $8 \times 22.0 \mu$m) to derive the thermal parameters of (5111) Jacliff. In the fitting process, when we set the step width of thermal inertia to be $10 \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$, we can finally obtain a best-fitting value for $\Gamma$ of $0 \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$. Thus, to derive a more accurate value of $\Gamma$, we again set the step width of the thermal inertia to be $0.1 \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$ to perform additional fittings with observations. However, as shown in Figure 20, the derived thermal inertia still remains $0_{-2}^{+5} \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$ with a corresponding $\chi^2_{\min}$ 3.583 and a roughness fraction $0.00_{-0.00}^{+0.40}$. Here, it should be emphasized that the derived thermal inertia is given at the 3$\sigma$ confidence level. Although $\chi^2_{\min}$ is related to thermal inertia of $0 \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$, this does not mean the value of $\Gamma$ should be zero but suggests that the probability of the thermal inertia between $0$–$15 \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$ is about 99.7%. We derive an effective diameter of $5.302_{-0.237}^{+0.237}$ km, which produces a geometric albedo of $0.523_{-0.044}^{+0.088}$. The results of $p_v$ and $D_{\text{eff}}$ are slightly different from those of Masiero et al. (2014) from NEATM. Figures 21 and 22 show the thermal light curves at W2, W3, and W4, respectively, and Figure 23 displays the ratio of observed flux and theoretical flux.

### 3.7. (7001) Neother

Asteroid (7001) Neother orbits the Sun with an orbital period of 3.67 yr. It has a perihelion distance of 2.023 au and an aphelion distance 2.739 au. Until now, the spectral type of this asteroid has been unknown. Warner et al. (2009) determined a rotation period 9.581 hr. Using 40 WISE observations ($18 \times 4.6 \mu$m, $11 \times 12.0 \mu$m, and $11 \times 22.0 \mu$m) and ATPM, we derive the thermal properties of (7001) Neother, i.e., a thermal inertia of $\Gamma = 20_{-30}^{+21} \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$, roughness fraction of $f_r = 0.00_{-0.00}^{+0.40}$, geometric albedo of $p_v = 0.241_{-0.013}^{+0.034}$, and effective diameter of $D_{\text{eff}} = 5.923_{-0.378}^{+0.167}$ km. The outcomes of $p_v$ and $D_{\text{eff}}$ are close to those of Masiero et al. (2011), where...
$p_\nu = 0.216 \pm 0.022$ and $D_{\text{eff}} = 6.122 \pm 0.073$, respectively.

The $f_r - \Gamma$ is plotted in Figure 24 with a minimum $\chi^2_{\text{min}}$ value of 3.851. With the aid of the outcomes of $\Gamma$ and $f_r$, we offer the thermal light curves for (7001) Neother at the W2, W3, and W4 wavelengths (see Figure 25) with respect to two epochs, 2010.05.03 and 2016.08.31, respectively, indicating that the theoretical results from fitting agree with the observations. The Observation/ATPM ratio is shown in Figure 26.
Asteroid (9158) Plate was discovered in 1984 and has an orbital period of 3.49 yr. According to the SDSS-based taxonomic classification developed by Carvano et al. (2010), it is an SQp-type asteroid. Using the combined data from the Lowell Photometric Database and WISE, Durech et al. (2018a) constructed the 3D convex shape model of (9158) Plate. The rotation period and spin axis were found to be 5.165 hr and (119°, −52°), respectively (Durech et al. 2018a). The NEATM results of the diameter and geometric albedo from the WISE observation are 4.734 ± 0.125 km and 0.314 ± 0.075 (Masiero et al. 2011). In this study, we use 54 WISE/NEOWISE observations (16 × 4.6 μm, 16 × 12.0 μm, and 22 × 22.0 μm) to investigate the thermal parameters for this asteroid. As shown in Figure 27, a low thermal inertia of $10^{+18}_{-10}$ J m$^{-2}$ s$^{-1/2}$ K$^{-1}$ as well as a low roughness fraction of $0.30^{+0.20}_{-0.30}$ are obtained, with respect to a $\chi^2_{\text{min}} = 4.902$. The geometric albedo is given as 0.379 ± 0.02, and the diameter is 4.113$^{+0.137}_{-0.134}$ km. Our result for the effective diameter is close to that of Masiero et al. (2011). The thermal light curves for (9158) Plate are displayed in Figure 28. As can be seen, our results provide a formally acceptable fit; although, the modeled fluxes seem to match the observations at the W2 and W4 wave bands rather than those of the W3 band. Similarly, Figure 29 shows that the value of the Observation/ATPM ratios of various wavelengths moves around 1.
3.9. (12088) Macalintal

(12088) Macalintal was discovered by the Lincoln Observatory in 1998. In the SDSS-based taxonomic classification, it is a V-type asteroid (Carvano et al. 2010). Durech et al. (2018a) presented the rotation period of this asteroid to be 3.342 hr. Additionally, using the WISE observations and NEATM, the geometric albedo and diameter of this asteroid are, respectively, 0.385 ± 0.097 and 3.724 ± 0.250 km. In this work, we first collect the observations for our fitting procedure but find that fewer WISE data are available for this asteroid (10 × 12.0 μm and 5 × 22.0 μm). By performing the fitting, we derive a geometric albedo of -0.349 ± 0.025 and an effective diameter of 3.591 ± 0.202 km. From Figure 30, we can constrain the thermal inertia and roughness fraction to be 70 ± 57 J m² s⁻¹/² K⁻¹ and 0.00 ± 0.00, respectively. The uncertainties for Γ and f_r are quite large because we simply adopt 15 observations during the fitting process. Using the derived Γ and f_r, the thermal light curves and observation/ATPM ratio for the W3 and W4 wave bands are shown in Figures 31 and 32. We note that the observed fluxes are generally larger than the theoretical results.

3.10. (15032) Alexlevin

Asteroid (15032) Alexlevin was discovered in 1998. In the Moving Objects VISTA catalog and SDSS-based taxonomic classification, it is recognized as a V-type asteroid (Carvano et al. 2010; Licandro et al. 2017). This asteroid has an orbital period of 3.66 yr. Masiero et al. (2011) derived a diameter and albedo for (15032) Alexlevin of 3.579 ± 0.059 km and 0.288 ± 0.048, respectively. In this work, we adopt an absolute magnitude of 14.5 from MPC and a rotation period of 4.406 hr from Durech et al. (2018a) in our ATPM model, and 42 WISE/NEOWISE observations (16 × 4.6 μm, 12 × 12.0 μm, and 14 × 22.0 μm) are utilized in the fitting. By comparing the theoretical flux and the observations, we further obtain a geometric albedo of 0.349 ± 0.025 and an effective diameter of 2.832 ± 0.093 km. The derived diameter is smaller than that of Masiero et al. (2011). As shown in Figure 33, we can constrain the thermal inertia of asteroid (15032) Alexlevin to be 20 ± 16 J m² s⁻¹/² K⁻¹ and the roughness fraction to be 0.50 ± 0.00. In addition, the three-band thermal light curves of (15032) Alexlevin are exhibited in Figure 34. As can be seen, our theoretical flux fits the observations well. The ratios between the observed and theoretical fluxes for the three wave bands are plotted in Figure 35.

4. Discussion of the Radiometric Results

In this work, we present the first attempt to determine the thermal parameters of 10 Vesta family asteroids by using
ATPM and combined with the thermal-infrared observations from IRAS, AKARI, and WISE/NEOWISE. Our results are summarized in Table 3. All of the Vesta family asteroids have a thermal inertia less than 100 J m$^{-2}$ s$^{-1/2}$ K$^{-1}$ as well as relatively low roughness fractions, which may suggest that they have undergone a long-term surface evolution process. We note that, among the 10 Vesta family members, (1906) Neaf, (2511) Patterson, (5111) Jacliff, (12088) Macalintal, and (15032) Alexlevin are V-type asteroids (they are also called “Vestoids”), and the other five members are non-Vestoids. We obtain a mean value of $p_c$ for the five Vestoids of 0.328, which is very close to the median value (0.362 $\pm$ 0.100) of V-type (Bus-Demeo taxonomy) asteroids in Mainzer et al. (2011). For non-Vestoids, the mean value is 0.300. As mentioned above, the derived values of $p_c$ for (63) Ausonia (Sa/Sw) and (556) Phyllis (S) are 0.180$^{+0.010}_{-0.009}$ and 0.209$^{+0.016}_{-0.010}$, respectively, which are similar to the median values of $p_c$ for these two spectral types obtained by Mainzer et al. (2011). As for the SQp-type asteroid (9158) Plate, we derived the value of $p_c$ to be 0.379$^{+0.026}_{-0.024}$, which is within the geometric albedo range (0.062–0.617) of the SQp-type asteroid obtained by Mainzer et al. (2012). Additionally, (3281) Maupertuis has a geometric albedo of 0.484$^{+0.051}_{-0.074}$, which is within the range of the value of $p_c$ for the V-type asteroids in Mainzer et al. (2011) but is larger than their median value. For (7001) Neother, the derived $p_c$ is 0.241$^{+0.034}_{-0.013}$, which is comparable with the geometric albedo of S-type asteroids obtained by Mainzer et al. (2011, 2012). Except for asteroids (63) Ausonia and (556) Phyllis, the Vesta family asteroids we studied have effective diameters smaller than 10 km. In the following section, we provide a brief discussion on the thermal nature of the Vesta family asteroids based on our derived results.

4.1. Thermal Inertia, Effective Diameter, and Geometric Albedo

Delbo et al. (2007) investigated the relationship between thermal inertia and effective diameter and provided the power-law formula $\Gamma = d_0 D^{-\xi}$, where a linear regression finds the best-fitting parameters of $d_0$ and $\xi$ to be $300 \pm 47$ and $0.48 \pm 0.04$, respectively. Furthermore, Delbo & Tanga (2009) showed the thermal inertia of MBAs by using IRAS data, and they obtained values for $\xi$ of $1.4 \pm 0.2$ for MBAs and $0.32 \pm 0.09$ for NEAs, respectively. In addition, Hanuš et al. (2018) presented the thermal parameters of $\sim 300$ MBAs. Here, we combine our results of $\Gamma$ and $D_{\text{eff}}$ with those of Delbo et al. (2015) and Hanuš et al. (2018) to further explore the relationship between thermal inertia and effective diameter. In Figure 36, we present our results given by the red (Vestoids) and cyan (non-Vestoids) dots with error bars, where the values of thermal inertia and effective diameter from Delbo et al. (2015) and Hanuš et al. (2018) are shown with gray (for MBAs) and green (for NEAs) dots, respectively (in order to make the diagram clearer, we do not plot the error bars for each value of $\Gamma$ and $D_{\text{eff}}$). The green dashed line is fitted by using the value of $\xi = 0.32$ for NEAs from Delbo & Tanga (2009). However, according to our results, it should be noted that the small-sized MBAs can have low thermal inertia; thus, the gap in kilometer-sized MBAs and low thermal inertia is filled. By fitting the results of $\Gamma$ and $D_{\text{eff}}$ for the MBAs from Delbo & Tanga (2009) and Hanuš et al. (2018) as well as the Vesta family asteroids we have investigated in this work, we then obtain values for $d_0$ and $\xi$ of $51.68$ and $0.023$, respectively. Moreover, we further explore the relationship of $\Gamma$–$D_{\text{eff}}$ by
Table 3
Derived Thermal Characteristics of the 10 Vesta Family Asteroids in This Work

| Asteroid        | $\Gamma$ (J m$^{-2}$s$^{-1/2}$ K$^{-1}$) | $f_r$   | $D_{\text{eff}}$ (km) | $p_v$ | $\chi_{\text{min}}$ | $p_v^*$ | $D_{\text{eff}}^*$ (km) |
|-----------------|------------------------------------------|---------|------------------------|-------|----------------------|---------|------------------------|
| (63) Ausonia    | 50$^{+7.1}_{-1.1}$                      | 0.5$^{+0.03}_{-0.03}$ | 94.595$^{+2.343}_{-2.483}$ | 0.189$^{+0.010}_{-0.009}$ | 3.102 | 0.168$ \pm 0.008$ | 102.975$ \pm 2.754$ |
| (556) Phyllis   | 30$^{+12}_{-11}$                        | 0.4$^{+0.03}_{-0.03}$ | 35.600$^{+0.883}_{-0.801}$ | 0.209$^{+0.010}_{-0.009}$ | 2.715 | 0.185$ \pm 0.011$ | 37.810$ \pm 1.100$ |
| (1906) Neaf     | 70$^{+19}_{-16}$                        | 0.5$^{+0.04}_{-0.04}$ | 7.728$^{+0.407}_{-0.411}$  | 0.246$^{+0.014}_{-0.014}$ | 8.748 | 0.228$ \pm 0.047$ | 8.057$ \pm 0.083$ |
| (2511) Patterson| 90$^{+28}_{-31}$                        | 0.5$^{+0.05}_{-0.05}$ | 9.034$^{+0.997}_{-1.128}$  | 0.180$^{+0.034}_{-0.034}$ | 3.853 | 0.287$ \pm 0.039$ | 7.849$ \pm 0.174$ |
| (3281) Maupertuis| 60$^{+31}_{-38}$                      | 0.5$^{+0.03}_{-0.03}$ | 5.059$^{+0.447}_{-0.470}$  | 0.484$^{+0.074}_{-0.074}$ | 3.698 | 0.489$ \pm 0.020$ | 5.482$ \pm 0.043$ |
| (5111) Jaciliff | 0$^{+15}_{-0}$                          | 0.5$^{+0.04}_{-0.04}$ | 5.302$^{+0.237}_{-0.267}$  | 0.522$^{+0.044}_{-0.044}$ | 3.583 | 0.425$ \pm 0.039$ | 6.447$ \pm 0.129$ |
| (7001) Neother  | 20$^{+21}_{-20}$                        | 0.5$^{+0.05}_{-0.05}$ | 5.923$^{+0.167}_{-0.178}$  | 0.241$^{+0.034}_{-0.034}$ | 3.851 | 0.216$ \pm 0.022$ | 6.122$ \pm 0.073$ |
| (9158) Plate    | 10$^{+10}_{-9}$                         | 0.3$^{+0.03}_{-0.03}$ | 4.113$^{+0.137}_{-0.147}$  | 0.379$^{+0.024}_{-0.024}$ | 4.902 | 0.314$ \pm 0.075$ | 4.734$ \pm 0.125$ |
| (12088) Macalintal| 70$^{+88}_{-73}$                     | 0.5$^{+0.05}_{-0.05}$ | 3.591$^{+0.203}_{-0.209}$  | 0.340$^{+0.052}_{-0.052}$ | 3.253 | 0.385$ \pm 0.097$ | 3.724$ \pm 0.250$ |
| (15032) Alexlevin| 20$^{+15}_{-10}$                      | 0.5$^{+0.04}_{-0.04}$ | 2.832$^{+0.184}_{-0.203}$  | 0.349$^{+0.035}_{-0.035}$ | 7.054 | 0.288$ \pm 0.048$ | 3.579$ \pm 0.059$ |

Note. All of the results of thermal properties are in SI units, where $\Gamma$ is the thermal inertial, $f_r$ is the roughness fraction, $D_{\text{eff}}$ is the effective diameter, and $p_v$ is the geometric albedo. $p_v^*$ and $D_{\text{eff}}^*$ represent the geometric albedo and effective diameter outcomes of Mainzer et al. (2011) and Masiero et al. (2012, 2014).

means of the data from NEAs (green dots) and binned MBAs (blue squares), which is denoted by the black dashed line, with respect to values of $d_0$ and $\xi$ of 344 and 0.441, respectively. To obtain the binned data, we divide the MBAs into 12 intervals according to the diameter size, and then, the average effective diameter and thermal inertia in each interval are calculated. As shown in Figure 36, the gray dashed line is almost horizontal because of the very low value of $\xi$ for MBAs when compared with that of Delbo & Tanga (2009) for NEAs. Note that the slope of the black dashed line is a bit higher than that of the green dashed line by fitting the NEA results.

As shown in Equation (8), the effective diameter $D_{\text{eff}}$ and geometric albedo $p_v$ are correlated with each other. Thus, Figure 37 shows thermal inertia as a function of geometric albedo for MBAs, NEAs, and Vesta family asteroids (including Vestoids and non-Vestoids), represented by blue, green, red, and cyan dots, respectively. In Figure 37, we further show the mean value of the thermal inertia and geometric albedo for MBAs, NEAs, Vestoids, and non-Vestoids by the dashed lines in the relevant colors. From Figure 37, we can see that the $p_v$ of the Vesta family members is relatively larger than that of other MBAs. Again, the average $\Gamma$ of the Vesta family asteroids here
is very close to the average thermal inertia of all of the MBAs in Figure 37. The average $p_v$ of the five Vestoids bears resemblance to that of (4) Vesta (see Figure 37), which may indicate a close relationship between Vesta family asteroids and (4) Vesta.

Figure 38 shows the profile of $D_{\text{eff}}$ and $p_v$ for 10 Vesta family asteroids (the left panel), where the red and cyan circles with error bars represent our results whereas the blue dots with error bars indicate those of the literature (Mainzer et al. 2011; Masiero et al. 2011, 2014). To compare our results with the previous work, we again plot the mean value of effective diameter and geometric albedo, shown by the dashed lines in different colors. As can be seen from the left panel of Figure 38, we observe that the $p_v$ and $D_{\text{eff}}$ of most Vesta family asteroids agree well with the earlier results (Mainzer et al. 2011; Masiero et al. 2011, 2014) from the NEATM model. Moreover, we show the $D_{\text{eff}}$–$p_v$ profile for over 1000 MBAs using the data from Masiero et al. (2011; the right panel of Figure 38). From Figure 38, we infer that the geometric albedo may show a downward trend with the increasing effective diameter.

4.2. Thermal Inertia and Rotation Period

Harris & Drube (2016) developed an NEATM-based thermal inertia estimator and calculated the thermal inertia for roughly 50 asteroids provided by Delbo et al. (2015). Based on their results, Harris & Drube (2016) investigated the dependence of thermal inertia on asteroid rotation period and showed that for both MBAs and NEOs, $\Gamma$ has an increasing trend with decreasing spin rate. This is probably because for slowly rotating asteroids, thermal waves penetrate much deeper into the subsurface than for fast rotators. However, Marciniak et al. (2019) investigated 16 slow rotators with sizes ranging from 30–150 km and found that for slowly rotating asteroids, there exists no obvious correlation between thermal inertia and rotation period. In this work, we obtain the thermal inertia for 10 Vesta family members, which may have suffered similar dynamical and thermal histories since their formation. Therefore, it is more reliable to investigate the relationship between spin rate and thermal inertia in the asteroid family. For the 10 Vesta family asteroids, the rotation period ranges from 2.839–11.010 hr, while the thermal inertia varies from 0–90 J m$^{-2}$ s$^{-1/2}$ K$^{-1}$. However, as shown in Figure 39, we do not find any obvious correlation between thermal inertia and rotation period, probably because of the limited population of asteroids. Thus, it does not mean there is no growing relationship between $\Gamma$ and $P_{\text{rot}}$; future study using an abundance of Vesta family asteroids may reveal a clear correlation between $\Gamma$ and rotation period.

4.3. Regolith Grain Size

According to the method described by Gundlach & Bulm (2013), the thermal conductivity can be expressed by thermal inertia $\kappa = \Gamma^2/(\phi \rho c)$, where $\phi$ is the volume filling factor, $\rho$ is the bulk density, and $c$ is the specific heat capacity. Additionally, $\kappa$ can be regarded as a function of regolith grain size, according to the theoretical model developed for granular materials in vacuum (Gundlach & Bulm 2012). Based on our thermal inertia, we derive a regolith grain size for the 10 Vesta family asteroids, the results of which are shown in Figure 40. We use various colors to denote the volume filling factors, which range from 0.1–0.6, and the temperature is set to be 200 K. As can be seen, we obtain eight
values of thermal inertia for the Vesta family asteroids. Here, when an asteroid has a thermal inertia $\Gamma < 50 \text{ J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$, there is no good agreement between the model and the derived thermal conductivities from the thermal inertia measurements for some volume filling factors. Taking (9158) Plate (with a thermal inertia of $10 \text{ J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$) as an example, we simply have a regolith grain size of 0.006 mm with a volume filling factor $\phi = 0.1$. While, for the asteroids with $\Gamma < 10 \text{ J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$, the regolith grain sizes cannot be well constrained but may be smaller than 0.006 mm. Table 4 summarizes the major outcomes for the Vesta family asteroids. We also evaluate the lower and upper limits of the regolith grain sizes for these Vesta family members according to the errors of the thermal inertia we obtained. As can be seen in the table, the lower limits of grain radius of (7001) Neother, (9158) Plate, and (15032) Alexlevin are not constrained, because the lower limits of $\Gamma$ for these three asteroids are smaller than $10 \text{ J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$.

### 5. Conclusions

In conclusion, we investigate the thermal properties of 10 Vesta family asteroids, including their thermal inertia, geometric albedo, effective diameter, and roughness fraction. The average thermal inertia of these Vesta family asteroids is $42 \text{ J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$. For the V-type family members (Vestoids), we derive an average geometric albedo of 0.328, while for the non-Vestoid family members, the average geometric albedo of 0.13, respectively. Panel blue dots with error bars represent those of the literature. The horizontal and vertical dash lines stand for the mean values of geometric albedo and effective diameter, respectively. Panel blue dots with error bars represent our results, while the red circles with error bars.

### Table 4

| Asteroid      | $r_{\text{Grain}}$ (mm) | $\phi$ |
|---------------|-------------------------|--------|
| (63) Ausonia  | 0.433 $^{+0.340}_{-0.341}$ | 0.1 $\sim$ 0.6 |
| (556) Phyllis | 0.082 $^{+0.156}_{-0.067}$ | 0.1 $\sim$ 0.3 |
| (1906) Neaf   | 0.976 $^{+0.974}_{-0.444}$ | 0.1 $\sim$ 0.6 |
| (2511) Patterson | 1.673 $^{+2.970}_{-1.314}$ | 0.1 $\sim$ 0.6 |
| (3281) Maupertuis | 0.687 $^{+1.749}_{-0.577}$ | 0.1 $\sim$ 0.6 |
| (5111) Jacliff | N.A.                     | ...    |
| (7001) Neother | 0.052 $^{+0.216}_{-0.137}$ | 0.1 $\sim$ 0.2 |
| (9158) Plate  | 0.006 $^{+0.194}_{-0.152}$ | 0.1     |
| (12088) Macalintal | 0.976 $^{+3.053}_{-0.953}$ | 0.1 $\sim$ 0.6 |
| (15032) Alexlevin | 0.052 $^{+0.134}_{-0.100}$ | 0.1 $\sim$ 0.2 |

Note. The uncertainties of the grain sizes are determined by the errors of thermal inertia. “N.A.” appears in the lower limits of the grain sizes because, for some asteroids, the thermal inertias are too small to constrain the corresponding regolith grain sizes.

### Figure 38

Panel (a): the geometric albedo $p_v$ with effective diameter $D_{\text{eff}}$ for the Vesta family asteroids. The red circles with error bars represent our results, while the blue dots with error bars represent those of the literature. The horizontal and vertical dash lines stand for the mean values of geometric albedo and effective diameter, respectively. Panel (b): the updated $p_v$ and $D_{\text{eff}}$ profile from Masiero et al. (2011) for nearly 1000 asteroids (blue dots with error bars). Our results are given by the red circles with error bars.

### Figure 39

Thermal inertia as a function of rotation period. There is no expected increasing trend for 10 Vesta family members.

### Figure 40

Regolith grain size of the 10 Vesta family asteroids as a function of thermal inertia, where different colors represent the different volume filling factors (Gundlach & Bulm 2013). The values of grain size give an obvious increasing trend with the increasing thermal inertia.
albedo is 0.300. The mean value of $\Gamma$ is a bit larger than that of (4) Vesta (Delbo et al. 2015), and the average values of $p_r$ for both Vestoids and non-Vestoids are smaller than that of Vesta, but they are similar to the mean values obtained by Masiero et al. (2013) and Mainzer et al. (2011, 2012). Moreover, we study the relationship between thermal inertia and effective diameter, as well as the relationship between thermal inertia and rotation period. Considering both NEAs and MBAs, we place constraints on a new set of coefficients in the $\Gamma$–$D$ equation, which is slightly different from the result of Delbo et al. (2015). In addition, taking the published physical data for known Vesta family asteroids into consideration, we do not find the expected increasing trend between thermal inertia and rotation period. Moreover, since Vesta family asteroids are deemed to be the fragments of a severe impact event, the wide range of geometric albedos for the 10 Vesta family asteroids is in line with that of the surface of (4) Vesta. In future work, we will address the thermophysical characteristics of more Vesta family asteroids and other families, which will help us to better comprehend the formation, evolution, and classification of diverse types of asteroid populations in the main-belt region.

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**Appendix**

**WISE Observation Flux**

We list the color-corrected WISE observational fluxes and uncertainties for the 10 Vesta family members in this work. Table A1 shows part of the observational flux for (63) Ausonia.

| Asteroid  | Epoch MID | $W_{2,\text{obs}}$ (mJy) | $W_{2,\text{err}}$ (mJy) | $W_{3,\text{obs}}$ (mJy) | $W_{3,\text{err}}$ (mJy) | $W_{4,\text{obs}}$ (mJy) | $W_{4,\text{err}}$ (mJy) |
|-----------|-----------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| (63) Ausonia | 55276.20263 | 100.43000 | 10.04300 | 12870.87000 | 1287.08700 | 19210.95000 | 1921.09500 |
|           | 55276.20275 | 108.61000 | 10.86100 | 15660.58000 | 1566.05800 | 20584.90000 | 2058.49000 |
|           | 55276.33506 | 98.15000 | 9.81500 | 10844.46000 | 1084.44600 | 17312.06000 | 1731.20600 |
|           | 55276.59967 | 117.46000 | 11.74600 | 13766.00000 | 1376.60000 | 20509.20000 | 2050.92000 |
|           | 55276.79819 | 124.93000 | 12.49300 | 14997.12000 | 1499.71200 | 20603.87000 | 2060.38700 |
|           | 55276.86427 | 96.62000 | 9.66200 | 11890.71000 | 1189.07100 | 17813.48000 | 1781.34800 |

(This table is available in its entirety in machine-readable form.)
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