Revisiting the Advanced Thermal Physical Model: New Perspectives on Thermophysical Characteristics of (341843) 2008 EV5 from Four-band WISE Data with the Sunlight-reflection Model

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Abstract

In this paper, we investigate thermophysical characteristics of near-Earth asteroid (341843) 2008 EV5, based on our improved advanced thermal physical model by considering the contribution of sunlight reflection for rough surfaces, along with four bandwave observations from the Wide-field Infrared Survey Explorer and the radar-derived shape model. Here we derive that 2008 EV5 has a relatively low thermal inertia of $\Gamma = 110^{+40}_{-32} \, \text{J} \, \text{m}^{-2} \, \text{s}^{-1/2} \, \text{K}^{-1}$ but a high roughness fraction. The geometric albedo and effective diameter are then constrained to be $p_g = 0.095^{+0.016}_{-0.003}$ and $D_{\text{eff}} = 431^{+39}_{-33} \, \text{m}$, respectively. The low thermal inertia indicates that 2008 EV5 may have undergone sufficient space weathering over secular evolution. The high roughness may have resemblance to the appearances of Bennu and Ryugu recently observed by spacecraft, where a great number of boulders are widely distributed on the asteroid’s surface. Moreover, we numerically perform 1000 backward simulations of 2008 EV5’s cloned orbits within 1 Myr to explore its origin, and present a probability of $\sim 6.1\%$ that the asteroid originates from the main belt. Finally, we estimate that the mean grain size of the surface ranges from 0.58 to 1.3 mm, and infer that it is unlikely to find water ice on most of the area of 2008 EV5, but there may exist water ice on high latitudes near the polar region.

Unified Astronomy Thesaurus concepts: Near-Earth objects (1092)

1. Introduction

Over past decades, space missions to solar system small bodies, such as near-Earth asteroids and comets, have captured the interest of scientists. For these missions, multiple factors should be taken into account when selecting the target small bodies, such as whether a delta-v parameter is low enough to make it more accessible for a rendezvous mission, what composition the asteroid’s surface may be made up of, and what types of asteroids may contain important clues to understand the origin and evolution of the early solar system (Perna et al. 2018). Asteroid (341843) 2008 EV5 (hereafter EV5) is taxonomically classified as a C-type asteroid (Reddy et al. 2012a), and is recognized as a potentially hazardous object, which was discovered by the Mount Lemmon Survey (which was a part of the Catalina Sky Survey) in 2008. Because of a small orbital eccentricity of 0.0835 and a low inclination of $7.37^\circ$, as well as a low delta-v for rendezvous (Benner 2010), EV5 was ever proposed to be a potential target for the ESA’s asteroid mission MarcoPolo-R and the baseline target for NASA’s Asteroid Redirect Mission. In addition, this asteroid is considered to be the backup target for the future asteroid sample return mission of the China National Space Administration. Therefore, the size, shape, and surface characteristics of EV5 should be extensively investigated prior to the mission.

Arecibo Goldstone planetary radars and the Very Long Base Line Array observed EV5 in 2008 during its close approach to Earth at a distance of 8.4 lunar distance (approximately 0.022 au; Busch et al. 2011). Using the radar measurements, a high-resolution shape model of EV5 was derived and the diameter for this top-shaped asteroid was given to be $400 \pm 50 \, \text{m}$ (Busch et al. 2011). From the delay Doppler images, two possible pole orientations were solved, giving J2000 ecliptic longitudes and latitudes of $(0^\circ, 84^\circ)$ and $(180^\circ, -84^\circ) \pm 10^\circ$. Moreover, two geological features can be clearly seen from the radar images—the equatorial ridge which may be induced by Yarkovsky–O’Keefe–Radzievskii–Paddack (YORP) acceleration (Busch et al. 2011; Vokrouhlický et al. 2015) and a big concavity with a size roughly one-third of the diameter of EV5, which may be caused by an impact event (Busch et al. 2011). Reddy et al. (2012a) observed EV5 in the visible (0.30 $\sim$ 0.92 $\mu$m) and near-infrared (0.75 $\sim$ 2.5 $\mu$m) wavebands with the Palomar Mountain 200 inch telescope and SpeX instrument on the NASA Infrared Telescope Facility, respectively, and determined its surface composition. They showed that the spectrum of EV5 shows a weak 0.48 $\mu$m spin forbidden of Fe$^{2+}$. This sort of spectral feature is well consistent with CI carbonaceous chondrites similar to Orgueil. Furthermore, Reddy et al. (2012a) presented the albedo of 0.05 $\sim$ 0.2 for EV5 based on a modified Standard Thermal Model (Spencer et al. 1989; Reddy et al. 2012b), whereas Busch et al. (2011) calculated the albedo of 0.12 $\pm$ 0.04 for the asteroid. These physical parameters provide a good understanding of the evolution for EV5. However, the surface characteristics should be made clear, which play a vital role in a small-body sample return mission.

The surface characteristics of an asteroid, such as the thermal inertia, geometric albedo, and roughness, can be revealed using thermophysical models (TPMs) to fit the mid-infrared observations of the asteroid (Rozitis & Green 2011; Delbo et al. 2015). Among these parameters, thermal inertia, defined by $\Gamma = \sqrt{\kappa/\rho c}$ (where $\kappa$ is the thermal conductivity, $\rho$ represents...
the density, and \( c \) is the thermal capacity), dominates the surface temperature environment of small bodies. This parameter represents the resistance of temperature variations in the surface and subsurface of an asteroid. Moreover, thermal inertia also plays a significant role in Yarkovsky and YORP effects (Rozitis & Green 2012). In the previous study, Alfi-Lagoa et al. (2014) showed that EV5 appears to be smooth on its surface with an averaged thermal inertia to be \( \sim 450 \pm 60 \text{ J m}^{-2} \text{s}^{-1/2} \text{K}^{-1} \) based on the classical TPM (Lagerros 1996) with W2 \( \sim \) W4 band Wide-field Infrared Survey Explorer (WISE) data.

However, recent close-up observations of small-size asteroids, like (101955) Bennu by NASA’s asteroid sample return mission Origins, Spectral Interpretation, Resource Identification and Security-Regolith Explorer (OSIRIS-REx; Dellagiustina et al. 2019; Lauretta et al. 2019) and (162173) Ryugu by Hayabusa2 mission (Michikami et al. 2019; Sugita et al. 2019; Watanabe et al. 2019), unveil that the surface of these two asteroids bears a high roughness but low thermal inertia, due to the existence of highly space weathered boulders that are widely distributed on the asteroids. In comparison, the shape of EV5 is very similar to the appearances of Bennu or Ryugu. Thus, this raises a key question whether EV5 had experienced similar evolution like Bennu or Ryugu, thereby producing the surface of a high roughness with low thermal inertia. The investigations indicate that low thermal inertia and high roughness have similar influence on the radiometry procedure, suggesting that the degeneracy of thermal inertia and roughness fraction may not be well removed by the classical TPMs on some occasions. Further analysis is required to shed light on this issue, which would enable us to have a better understanding of the thermophysical procedure for small bodies.

The primary objective of this work is to investigate EV5’s thermal characteristics and dynamical history from several perspectives. First, we adopt an alternative technique to screen the data set from the WISE archive and all four wavebands (W1 \( \sim \) W4) of the WISE data. Second, we employ our improved Advanced Thermophysical Model (Rozitis & Green 2011; Yu et al. 2014) to derive a new set of thermal parameters for EV5, in which the multiple scattering, self-heating, and thermal-infrared beaming effects are taken into account. Besides, in order to remove the effect of reflected sunlight on the results, we propose a new method to evaluate the percentage of the reflected parts contained in different wavebands, although the reflected parts only have marginal effects for the W2 \( \sim \) W4 bands. Based on our results, we show that EV5 bears a high roughness surface with a relatively low thermal inertia of \( I = 110_{-48}^{+40} \text{ J m}^{-2} \text{s}^{-1/2} \text{K}^{-1} \). The high roughness fraction of EV5 is consistent with the rough surfaces of Bennu and Ryugu (Dellagiustina et al. 2019; Lauretta et al. 2019; Sugita et al. 2019; Watanabe et al. 2019). Usually the values of thermal inertia for near-Earth asteroids (NEAs) are relatively large compared to main-belt asteroids (Dello et al. 2015), and such low thermal inertia of EV5 indicates that it may have undergone secular evolution from the main-belt region. Therefore, we further study the dynamical evolution of EV5 by performing 1000 backward simulations of its cloned orbits over a timescale of 1 Myr, and the numerical results show a probability of 6.1% that EV5 may originate from the main-belt region, which provides substantial evidence for our radiometric results for this asteroid. Finally, we estimate the mean grain size and explore the possibility of the existence of water ice on the surface of EV5.

### 2. Observation

In this work we adopt thermal data of EV5 observed by the WISE space telescope, which mapped the entire sky in infrared wavelengths centered at 3.4, 4.6, 12.0, and 22.0 \( \mu m \) noted as W1, W2, W3, and W4, respectively (Wright et al. 2010; Masiero et al. 2011; Mainzer et al. 2011). Currently, WISE data are available from the WISE archive,\(^5\) which allows us to explore the study. In the procedure, we first achieve the data from the WISE All-Sky Known Solar System Object Possible Association List with a search cone radius of 10\(^\circ\) to ensure that the observation target matches our explored asteroid well. Next, we remove the epochs that cannot provide magnitudes and uncertainties for all four wavebands to ensure our selected data is precise enough for further study. Subsequently, we then convert the magnitudes into fluxes for EV5, following the method described by Wright et al. (2010), where we use the color correction factors of 1.3917, 1.1124, 0.8791, and 0.9865 for the W1 \( \sim \) W4 bands, respectively, for this asteroid.

Since the observed fluxes are proportional to the cross-section area of the asteroid in the observational direction, and EV5 is nearly spherical with rotational variations of the cross-section area no more than 8%, it should thus be expected that the light curves of this asteroid should not have an amplitude larger than 30%, if considering maximum observation uncertainties of \( \sim 20\% \). Therefore we further carry out selections of the observation by considering the amplitude of the WISE thermal light curves. The thermal light curves are derived for each band by correcting the observed flux at various epochs into one rotation period at a reference epoch via (Yu et al. 2017)

\[
F_{\text{corr}} = F_i \cdot \left( \frac{r_{\text{helio},i}}{r_{\text{helio},0}} \right)^2 \cdot \left( \frac{r_{\text{obs},i}}{r_{\text{obs},0}} \right)^2,
\]

where \( F_{\text{corr}} \) is the corrected flux, \( F_i \) is the observed flux at epoch \( i \), \( r_{\text{helio},i} \) and \( r_{\text{helio},0} \) are the heliocentric distance of epoch \( i \) and the reference epoch, respectively, and \( r_{\text{obs}} \) represents the distance between the asteroid and the space telescope. Here we use the first epoch in our data set as the reference epoch. Then we remove those data that exceeded \( \pm 30\% \) of the corrected fluxes’ error-weighted mean value.

Finally, we obtained 204 data points that contain all four wavebands with respect to the 51 observational epochs, thus producing four thermal light curves at four wavebands. EV5 was monitored by WISE from 2010 January 25 until March 7. However, in our screened data set, the observation epochs spread from 2010 January 25 19:27 to February 23 17:22. The solar phase angle ranges from 71\(^\circ\)48 to 73\(^\circ\)2.

It is noteworthy that the WISE data in the W1 band contains a significant fraction of reflected sunlight, approximately 20% \( \sim \) 30% of the entire flux. As a comparison, the reflected sunlight contributes about 2% \( \sim \) 3% in the W2 band whereas it can be negligible in the W3 and W4 bands, as shown in Figure 1, where a sunlight-reflection model is applied to calculate the reflected sunlight. The reflection model will be described in detail in the next section.

\(^5\) http://irsa.ipac.caltech.edu/applications/wise/
represents the normal vector of the facet, that most of the observations of the \( W1 \) band contain reflected sunlight in a ratio of about 20% but no more than 4% for the \( W2 \) band, as for the \( W3 \) and \( W4 \) bands, the reflected sunlight simply contributes to a very small portion of the entire flux. The blue fitted curve was obtained by polynomial fitting to express the descending trend of the ratio of reflected sunlight.

### 3. Radiometric Model

#### 3.1. Advanced Thermal Physical Model

To determine EV5’s thermophysical characteristics, we utilize our independently developed codes of the advanced thermal physical model (ATPM), which has been successfully applied in our previous investigations (Yu et al. 2017). ATPM treats an asteroid as a polyhedron made up by \( N \) triangular facets, and can be used to calculate the surface temperature of each triangular facet at each observation epoch by solving a 1D heat conduction equation under consideration of a rough surface boundary. The surface roughness is modeled by a fractional coverage of hemispherical craters to represent the surface boundary. The surface roughness is modeled by a certain number \( M \) of smaller triangular subfacets. The roughness fraction is symbolized by \( f_r \), and thus \( 1 - f_r \) represents the flat smooth surface on the asteroid. Both the \( 1 - f_r \) fraction of the shape facet and subfacets in the crater can be treated as smooth Lambertian surfaces. Then the nonlinear surface boundary condition can be written as

\[
(1 - A_B) \left( v \psi F_{\text{Sun}} + F_{\text{scat}} \right) + (1 - A_{\text{th}}) F_{\text{rad}} + k \left( \frac{dT}{dx} \right)_{x=0} - c \sigma T_{\text{fac}}^4 = 0,
\]

where \( \kappa \) is the thermal conductivity, \( \sigma \) is the Stefan–Boltzmann constant, \( \varepsilon \) is the emissivity, which was assumed to be 0.9, \( A_B \) is the Bond albedo, \( \psi \) is the cosine of the solar altitude, \( x \) is the depth below the surface, and \( v \) represents whether the facet can be seen from the direction of the Sun, which mainly depends on the rotation pole orientation and asteroid’s rotation phase. \( F_{\text{Sun}} = 1367/r_{\text{helio}}^2 \) W m\(^{-2} \) is the incident solar flux to the asteroid at a heliocentric distance of \( r_{\text{helio}} \), while \( F_{\text{scat}} \) and \( F_{\text{rad}} \) are the total scattered and thermal re-emitted flux from other facets, respectively, here \( r_{\text{helio}} \) is in unit of astronomical units.

With the temperature distribution, the theoretical thermal emission of each facet can be computed using the Planck function

\[
B(\lambda, T) = \frac{2hc^2}{\lambda^5} \exp \left( \frac{hc}{\lambda kT} \right) - 1,
\]

where \( T \) represents the temperature of the facet, and then the observable thermal emission of the entire body will be

\[
F_{\text{th}}(\lambda) = (1 - f_r) \sum_{i=1}^{N} \epsilon_i B(\lambda, T_i) S_i f_i + f_r \sum_{i=1}^{N} \sum_{j=1}^{M} \epsilon_{ij} B(\lambda, T_j) S_{ij} f_{ij},
\]

where \( \epsilon \) is the monochromatic emissivity at wavelength \( \lambda \), \( i \) represents the facet \( i \) of the shape model, while \( ij \) means the subfacet \( j \) in the crater on facet \( i \), and hence \( S_i \) and \( S_{ij} \) stand for their areas respectively; \( f_i \) and \( f_{ij} \) are the view factors to the telescope. The so-called view factor is defined as

\[
f_i = \frac{n_i \cdot n_{\text{obs}}}{\Delta},
\]

where \( n_i \) represents the normal vector of the facet, \( n_{\text{obs}} \) is the unit vector pointing to the observer, \( \Delta \) is the observation distance, and \( v_i \) indicates the visible fraction of facet \( i \) to the observer.

#### 3.2. Sunlight-reflection Model of Rough Surface

The observed flux is composed by the thermal flux component \( F_{\text{th}} \) and the reflected sunlight component \( F_{\text{ref}} \). As mentioned above, for EV5, the observed \( W1 \) band flux contains a significant part of reflected sunlight of ~20%. Compared with former studies, in this work we utilize the \( W1 \) data and the reflected sunlight should be corrected. Alí-Lagoa et al. (2013) introduced one technique for calculating the reflected sunlight, which was applied to the near-Earth asteroid thermal model (Harris 1998). Based on the method developed by Alí-Lagoa et al. (2013), Rozitis et al. (2018) re-evaluated the reflected sunlight contained in the WISE \( W2 \) band while using ATPM to determine the thermal properties of several near-Earth asteroids. In addition, Myhrvold (2018) presented a new derivation of a simple asteroid thermal model using the NEOWISE data, and the Kirchhoff’s law was taken into account when infrared observations contained substantial reflected sunlight. Here we proposed a new method to determine the ratio of reflected sunlight contained in four full wavebands, although it simply covers a tiny percentage in the \( W2 \sim W4 \) bands.

On the basis of the aforementioned roughness model, the reflected sunlight can be calculated in a similar way as the thermal emission. So when treating the facet \( i \) of the shape model and the subfacet \( j \) in the crater on facet \( i \) both to be smooth Lambertian surfaces, the reflected sunlight from them can be expressed via Lambertian reflection as

\[
F_{\text{ref,}}(\lambda) = B(\lambda, 5778) \frac{R^2_{\text{Sun}}}{r_{\text{helio}}} \cdot \pi \cdot A_B \cdot \psi_i \cdot S_i \cdot f_i,
\]

\[
F_{\text{ref,ij}}(\lambda) = B(\lambda, 5778) \frac{R^2_{\text{Sun}}}{r_{\text{helio}}} \cdot \pi \cdot A_B \cdot \psi_{ij} \cdot S_{ij} \cdot f_{ij},
\]

where \( \psi_i \) and \( \psi_{ij} \) are the cosine values of the solar altitudes, \( f_i \) and \( f_{ij} \) are the view factors defined as Equation (5), \( R_{\text{Sun}} \) is the
radius of the Sun, \( r_{\text{helio}} \) nearly equals to the heliocentric distance of the asteroid, and \( B(\lambda, 5778) \) is the Planck function under the average temperature (5778 K) of the Sun. Then the total reflected sunlight that can be observed by the telescope is

\[
F_{\text{ref}}(\lambda) = (1 - f_i) \sum_i N F_{\text{ref}_i}(\lambda) + f_i \sum_j M F_{\text{ref}_j}(\lambda). \tag{8}
\]

Figure 1 shows the ratio of reflected sunlight contained in each point of observational data. As we can see, the reflected sunlight contained in the W3 and W4 bands appears to be very small, of only \( \sim 10^{-4} \) and \( 10^{-5} \), whereas it covers a few percent of the W2 band. As mentioned previously, the WISE data for the W1 band contributes \( \sim 20\% \) to the total observed flux, which should be considered in the model.

### 3.3. Fitting Procedure

The radar-derived shape model of EV5 released by Busch et al. (2011) contains 3996 facets and 2000 vertexes. Considering the size of the asteroid and the computational efficiency, we further simplified the shape model, which is composed of 1996 facets and 1000 vertexes. The rotation period for EV5 is adopted to be 3.725 ± 0.001 hr (Galad et al. 2009) and the retrograde pole orientation of \((180^\circ, -84^\circ)\) ± 10\(^\circ\) is also applied. In fact, using the delay Doppler images, Busch et al. (2011) presented a prograde pole orientation of \((180^\circ, -84^\circ)\) ± 10\(^\circ\). By tracking EV5’s radar speckle pattern, Busch et al. (2010) determined that EV5 rotates in a retrograde mode. Therefore we here do not consider the prograde pole orientation, but use the same pole orientation as Alí-Lagoa et al. (2014) adopted.

Thermal inertia, which dominates the surface temperature of the asteroid, and roughness fraction, which causes the thermal-infrared beaming effect, are two free parameters of this model to fit observation data. In order to find the best-fitting thermal inertia, the search range of thermal inertia values were set to be \( \Gamma = 0 \sim 700 \text{ J m}^{-2} \text{s}^{-1/2} \text{ K}^{-1} \), and the step size of \( \Gamma \) was set to be 50 J m\(^{-2} \) s\(^{-1/2} \) K\(^{-1} \). For each thermal inertia value, the temperature distribution can be obtained, and thus the theoretical thermal emission can be calculated via Equation (4). As is known, the diameter of an asteroid \( D_{\text{eff}} \) is correlated with its geometric albedo via (Fowler & Chillemi 1992)

\[
D_{\text{eff}} = \frac{1329 \times 10^{-1.5}}{\sqrt{\beta_v} \lambda}. \tag{9}
\]

On the other hand, an asteroid’s effective Bond albedo \( A_{\text{EB}} \) is correlated to the Bond albedo \( A_B \) and roughness fraction \( f_r \) via (Wolters et al. 2011)

\[
A_{\text{EB}} = f_r \frac{A_B}{2 - A_B} + (1 - f_r)A_B. \tag{10}
\]

Furthermore, the geometric albedo \( p_v \) can be expressed by

\[
p_v = \frac{A_{\text{EB}}}{q_{\text{ph}}}, \tag{11}
\]

in which \( q_{\text{ph}} \) represents the phase integral that was defined by

\[
q_{\text{ph}} = 0.290 + 0.684 G, \tag{12}
\]

where \( G \) is the slope parameter in the \( H, G \) magnitude system of Bowell et al. (1989). We adopted the value of \( H = 20.0 \) and \( G = 0.15 \), respectively, from the Minor Planet Center (MPC). Hence, for an input \( f_r \) and \( p_v \), we can obtain a unique Bond albedo \( A_B \) and effective diameter \( D_{\text{eff}} \).

Thus we actually have three parameters to be used in our fitting procedure: geometric albedo \( p_v \), thermal inertia \( \Gamma \), and roughness fraction \( f_r \). The other input parameters employed are listed in Table 1. Next, if taking the reflected sunlight of Equation (8) into consideration, the total flux measured by the observer can be written as \( F_{\text{model}} = F_{\text{ph}} + F_{\text{ref}} \), which can be compared with the observational mid-infrared fluxes from WISE. In order to reappraise the fitting degree of the modeled flux, the reduced \( \chi^2 \) defined by Press et al. (2007)

\[
\chi^2 = \frac{1}{n - 3} \sum_{i=1}^{n} \left( \frac{F_{\text{model}}(p_v, \Gamma, f_r, \lambda_i) - F_{\text{obs}}(\lambda_i)}{\sigma_{\lambda_i}} \right)^2 \tag{13}
\]

was adopted, where \( n \) is the number of observation data points and \( \sigma_{\lambda_i} \) is the observational flux uncertainty.

### 4. Radiometric Results

#### 4.1. Thermal Inertia and Roughness Fraction

In order to obtain the best-fitting value of thermal inertia, the \( \Gamma - \chi^2 \) profile is plotted in Figure 2. As we can see from Figure 2, the minimum \( \Gamma - \chi^2 \) is 1.13 is related to a thermal inertia of 110 J m\(^{-2} \) s\(^{-1/2} \) K\(^{-1} \) with a high roughness fraction. The 3\( \sigma \) and 4\( \sigma \) ranges are noted as red dashed lines. The lower dashed line labeled 3\( \sigma \) corresponds to the \( \chi^2 \) value of \( \chi^2_{\text{min}} + 14.2/(N - 3) = 1.206 \) where \( N = 204 \) is the number of observations, whereas the upper dashed line labeled 4\( \sigma \) is associated with the \( \chi^2_{\text{min}} + 21.0/(N - 3) = 1.2345 \) (Press

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**Table 1**

| Parameter                          | Value | Reference     |
|-----------------------------------|-------|---------------|
| Number of vertices                | 1000  | Busch et al. (2011) |
| Number of facets                  | 1996  | Busch et al. (2011) |
| Spin orientation                  | \((180^\circ, -84^\circ)\) | Busch et al. (2011) |
| Rotation period                   | 3.725 hr | Galad et al. (2009) |
| Absolute magnitude                | 20.0  | MPC           |
| Slope parameter                   | 0.15  | MPC           |
| Emissivity                        | 0.9   | Assumed       |

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**Figure 2.** \( \Gamma - \chi^2 \) profile fit to the observations for EV5. Each dashed curve represents a roughness fraction \( f_r \) in the range of 0.0–1.0, and the red solid lines indicate the 3\( \sigma \) and 4\( \sigma \) ranges for thermal inertia, respectively.
et al. 2007). Considering the 4σ confidence level, we can constrain thermal inertia to be $110^{+10}_{-8} \text{ J m}^{-2} \text{s}^{-1/2} \text{ K}^{-1}$, whereas the 3σ confidence level gives a value of $110_{-10}^{+30} \text{ J m}^{-2} \text{s}^{-1/2} \text{ K}^{-1}$. Because of a large number of observations, we use the 4σ principle to constrain the uncertainties of our results.

To further examine the fitting results of thermal inertia, Figure 3 shows the contour image of $\chi^2(\Gamma, f_r)$. The blue profile labeled 1σ indicates the deviation of the $\chi^2$ value of 3.52/(N – 3) from the minimum $\chi^2$ value. The yellow and red curves are directly concerned with the 3σ and 4σ confidence level, respectively. As can be noted, the minimum $\chi^2$ is located at a high roughness fraction and low thermal inertia value of $110 \text{ J m}^{-2} \text{s}^{-1/2} \text{ K}^{-1}$. Moreover, the $\chi^2$ fitting gives the best-fitting geometric albedo of $p_v = 0.095^{+0.016}_{-0.003}$ using Equation (9), where the correlated effective diameter is thus $D_{\text{eff}} = 431^{+6}_{-53} \text{ m}$. Furthermore, Figure 4 shows the $p_v$ profile for each roughness fraction and thermal inertia derived in the range of the 4σ level, and the albedo under the 4σ range are noted as red squares. Our results are summarized in Table 2.

To verify that our outcomes are reliable, we compute the ratio of theoretical flux obtained by ATPM and the observational flux, as shown in Figures 5 and 6. Note that the observation/ATPM of the $W1 \sim W4$ bands are represented by different colors and the x-axis represents the solar phase angle and wavelengths. As seen from Figure 6, the ratio of theoretical and observed flux fluctuates at 1 for various observational epochs.

### 4.2. Thermal Light Curve Fitting of EV5

Although the WISE data used in this work covers long consecutive observation epochs, the time interval between two adjacent observation epochs is larger than that of the rotation period of only 3.725 hr. In this case, these data cannot be used to directly produce thermal light curves of the asteroid. Hence we applied the method used in Yu et al. (2017) to generate the rotation phase and thermal light curves of EV5. In the study we adopted the extensive radar shape model of EV5 to define the local body fixed coordinate system. If the telescope viewed the asteroid in a direction of $(\Phi, \theta)$, where $\Phi$ and $\theta$ are local longitude and local latitude, respectively, then the rotation phase of one observational epoch can be written as

$$\text{phase} = 1 - \frac{\Phi}{2\pi}. \quad (14)$$

We assume EV5’s rotation phase at epoch 2010 January 25 19:27 to be zph and the rotational phase at other epochs can be deduced according to the observation time and geometry. Besides, the observed flux of other epochs were also converted using Equation (1). With the derived rotational phases and the converted data, we can compare with the modeled thermal light curve as shown in Figure 7. The red error bars are observational data of the $W1 \sim W4$ bands and the blue curves are the
modeled thermal light curves. In Figure 7 we can see that the modeled light curves change periodically as the asteroid rotates, and high roughness results can better fit the thermal light curves as well.

Here we compare our results with those of Ali-Lagoa et al. (2014). The major difference may be interpreted as follows. First, we use an alternative method to screen the WISE data set, where the W1 ~ W4 bands data are here adopted for fitting. Second, in this work we adopt the modified ATPM, where the modeling of roughness differs from that of the classical TPM, thus it is very different for the response of theoretical thermal flux to vary with the input roughness and thermal inertia for ATPM and TPM. Hence, both aspects can lead to alternative results from the optimization fitting process between the two models. As is well known, roughness and thermal inertia show similar influence in the radiometry procedure, and only if the degeneracy of thermal inertia and roughness fraction is well removed, the derived radiometric results are reliable. According to our fitting results, either high roughness with low thermal inertia or low roughness with high thermal inertia (close to the result of Ali-Lagoa et al. 2014) can be well fitted to the observations. But in our model, the case of high roughness can produce a minimum reduced $\chi^2$, and we believe that high roughness with low thermal inertia for EV5 can better explain the observations. Furthermore, as shown in Figure 7, the thermal light curves of the W1, W2, and W3 bands with high roughness show the best-fitting outcomes with respect to the observational data, whereas for the low roughness fraction, the thermal light curves have a poor fitting degree with the observations. While in 22 $\mu$m of W4, the theoretical flux of both high roughness and low roughness cross the observational data. Hence, we conclude that the W1 ~ W3 data may mostly contribute to the result of $f_r = 1.0$. In addition, as Figure 1 shown, in the W1 band, the reflected sunlight $F_{\text{ref}}$ contributes to $\sim20\%$ of the observational flux, whereas in the W2 ~ W4 bands, the reflected sunlight $F_{\text{ref}}$ can be negligible. If we remove $F_{\text{ref}}$ from $F_{\text{model}}$, we find that the thermal inertia is approximately $100 \ J \ m^{-2} \ s^{-1/2} \ K^{-1}$ with a geometric albedo of $0.095^{+0.012}_{-0.003}$, which is slightly different from those considering the reflected sunlight. However, in such case the value of $\chi^2_{\text{min}}$ is larger than that of Figure 2.

The weak influence of reflected sunlight here may be further explained. According to Wein’s displacement law ($\lambda_{\text{max}} = b/T$, where $b = 2898 \ \mu$m K is the Wein’s displacement constant and $T$ the temperature), if we consider $T = 300 K$, the spectral radiance of EV5 peaks at about $10 \ \mu$m, which means the signal-to-noise ratio of W1 and W4 will be smaller than that of W2 and W3. Under such circumstances, the uncertainties of W1 and W4 will be larger than those of W2 and W3, thereby resulting in the low weight of the W1 data in the fitting process which, in turn, reduces the contribution from reflected sunlight. However, for other asteroids with different temperatures from EV5, the uncertainties in W1 may be smaller than that of EV5, thus the reflected sunlight could have a significant effect on the fitting result. Moreover, the reflected part here plays an essential role in improving the fitting degree.

5. Simulations of Dynamical History

As the thermal inertia we obtained is quite small for an NEA, we infer that this asteroid may be a rubble pile asteroid, which has already been formed for a long time, thus the rocks or boulders on its surface have experienced a long time of space weathering and thermal fatigue (Delbo et al. 2014, 2015), thereby even showing low thermal inertia but still remaining high roughness. In order to examine the possibility of our inference, we will investigate the dynamical history of EV5 to see whether the asteroid originates from the outer region of the solar system. Here, we simply concentrate on orbital information within a specific time interval before the current epoch, and the evolution time span was chosen to be 1 Myr. In our extended simulations, we use the widely adopted package MERCURY (Chambers 1999) to numerically integrate the orbits of EV5.

Here we adopt the initial orbital elements of the nominal orbit and their uncertainties for EV5 from the Minor Planet Center (MPC; see Table 3). Similar to Hanuš et al. (2016), we generated 1000 orbital clones except for the nominal orbit. All of the orbital elements in each clone were yielded within the uncertainties given in Table 3. The initial epoch was set to be MJD = 58482.03712, in which the asteroid was near the perihelion. We adopt the time step to be 7 days in the integrations. In addition, the perturbations from eight major planets and Pluto in the solar system were considered in the model (without including the non-gravitational forces, influences from large asteroids such as Ceres, Pallas, and Vesta) when we integrate backward 1000 cloned orbits. The ephemerides of these major planets are from JPL DE405 with an initial epoch of MJD = 51000.

Figure 8 shows the backward integration results of EV5’s clone orbits within 1 Myr, where panels (a), (b), (c), and (d) each refer to the trace-back evolution of the semimajor axis, eccentricity, inclination, and aphelion distances for test particles, respectively. As a comparison, the blue curves are relevant to the orbital evolution of the nominal orbit for EV5. As shown in Figure 8, we observe that even a tiny difference in initial orbital parameters can eventually give rise to diverse evolution outcomes for these orbits. To obtain the evidence that EV5 originates from the main belt or outer region, we need to find out whether a solution exists where the orbital aphelion can reach the main-belt region (i.e., $a \cdot (1 + e) \geq 2.0 \ au$, where $a$ is the semimajor axis and $e$ is the eccentricity). Because of the small eccentricity of EV5, the semimajor axis and aphelion distances show some similarities in their evolution profiles.

For convenience, we define three types of test orbits noted as type A, type B, and type C, respectively. Type A represents the orbits that can reach the main-belt region at the end of 1 Myr in
the backward integration, type B stands for the orbits with aphelion distances temporarily larger than 2 au at a certain time, while type C denotes the orbits that cannot reach the main-belt region in the simulations. In the following, we will characterize the results of the clone orbits according to three types.

At the backward integration of 1 Myr, the aphelion distances of some orbital clones are even larger than 4 au, which were completely different from the nominal orbit. For some orbital clones, their eccentricities can be stirred up to several times of the current value (i.e., about 0.083). By analyzing the simulations results, we have counted the number of type-A orbits to be 61, type-B orbits 105, and type-C orbits 834. The simulations indicate that this asteroid has a probability of 6.1% of some orbital clones are even larger than 4 au, which were completely different from the nominal orbit. For some orbital clones, their eccentricities can be stirred up to several times of the current value (i.e., about 0.083). By analyzing the simulations results, we have counted the number of type-A orbits to be 61, type-B orbits 105, and type-C orbits 834. The simulations indicate that this asteroid has a probability of 6.1% of the cumulative number of type-A orbits varies with time, giving an increasing trend in the probability.

It is usually postulated that the main-belt asteroids with larger diameters tend to have smaller thermal inertia (Delbo & Tanga 2009). For example, Yu et al. (2017) presented the thermal inertia and effective diameter of (349) Dembowska to be 20.1±2 J m⁻² s⁻¹/₂ K⁻¹ and 155.8±7.5 km using ATPM and thermal data from WISE, Subaru, Akari, and IRAS. Horner et al. (2012) derived the thermal inertia and effective diameter of the Trojan asteroid (1173) Anchises to be 25–100 J m⁻² s⁻¹/₂ K⁻¹ and 136–111 km. Most of these asteroids have thermal inertia no more than 200 J m⁻² s⁻¹/₂ K⁻¹. Our result of thermal inertia for EV5 is consistent with those of Horner et al. (2012). Hence, we infer that EV5 may originate from the main-belt region and was one of the fragments of a larger asteroid. Thus the dynamic history of this asteroid could be long enough to produce a fine regolith layer with a low thermal inertia.

6. Predictions

6.1. Mean Grain Size—Does Dust Exist?

Since EV5 is the potential target for the future sample return mission, we are also interested in the surface features of the asteroid, such as whether dust layers on its surface exist and how the dust grain sizes behave. In this work, based on the thermal inertia we derived and the method of Gundlach & Blum (2013), we can further estimate the dust grain size of EV5.

First, the relation between thermal conductivity and thermal inertia can be written as

\[ \kappa = \frac{\Gamma^2}{(1 - \phi) \rho c^3}. \] (15)
where \( f \) is porosity, \( \rho \) is the material density, and \( c \) is the specific heat capacity. The thermal conductivity could also be derived by a theoretical model developed for granular materials in a vacuum (Gundlach & Blum 2012), which can be given as

\[
\kappa = \kappa_{\text{solid}} \left[ \frac{9\pi}{4} \frac{1 - \mu^2}{E} \right]^{1/3} \left[ f_1 e^{f_2(1 - \phi)} \right] \cdot \chi + \frac{8\sigma \varepsilon T^3}{1 - \phi} - b.
\]

The quantities we used in Equations (15) and (16) are listed in Table 4. \( b \) represents the mean grain radius of interest. Figure 10 shows the \( b \sim \kappa \) curve based on the two equations above with the parameters in Table 4. The results of different values of volume filling factors are noted as blue asterisks.

\[
\Gamma = 110 \text{ J m}^{-2} \text{s}^{-1/2} \text{ K}^{-1}.\]

Our results of the grain sizes differ from those of Alí-Lagoa et al. (2014) in that we use the different assumption of thermal inertia. This value of grain radius suggests at least the existence of dust aggregates on the surface of EV5. Considering the high roughness, these dust aggregates may be produced from boulders by space weathering or thermal fatigue (Delbo et al. 2014), but they are cohered there and thus do not fall down to form a smooth regolith layer across the surface. As a result, thermal inertia of the boulders becomes much lower but the roughness still remains high.

### 6.2. Can EV5 Retain Water Ice?

If the asteroid comes from the main belt, EV5 may be initially formed as an icy small body due to a C-type object from spectral analysis. The C-type asteroids are mostly believed to be primitive, volatile-rich residuals from the early solar system (Rivkin et al. 2002). Therefore, we are curious of...
whether it is likely for EV5 to retain water ice at its present near-Earth orbit. To answer this issue, we assume EV5 to be an icy small body that bears a homogeneous ice–dust mixture interior with a dust mantle covered on top, then we apply the dust–ice two-layer model of icy small bodies built by Yu et al. (2019). On the basis of the previous results, the assumed physical parameters for the dust mantle for EV5 are listed in Table 5.

The rotation axis of EV5 is nearly perpendicular to its orbital plane, which leads to the polar regions that can receive less solar insolation than the equatorial regions (the left panel in Figure 11), and thus show lower temperature. In the right panel of Figure 11, the red curve shows the equilibrium subsurface temperature $\tilde{T}_0$ on each local latitude of EV5, whereas the blue profile represents the relevant temperature $T_i$ of the ice front (the interface between the dust mantle and the icy interior). The equatorial subsurface temperature is approximately $\tilde{T}_0 = 308\text{ K}$, much higher than the corresponding ice front temperature of $T_i = 208\text{ K}$, while on the polar regions $T_i$ is nearly equal to $\tilde{T}_0$ with a very low value of $\sim 124\text{ K}$. Thus the larger temperature gradient in the dust mantle at the equator would make the water ice there sublimate and escape more quickly, nevertheless the low temperature environment of the polar regions would be good reservoirs for retaining water.

Given the ice sublimation front temperature, we can trace the secular evolution of the ice front in EV5, as shown in Figure 12. We find that the ice at the equatorial region cannot be retained for a timescale of $\sim 10^5\text{ yr}$ for its present orbit and for most low-latitude regions ($\leq 60^\circ$), the ice cannot be maintained longer than $1\text{ Myr}$. Therefore, if EV5 is transferred from the main-belt region to the present orbit within $\sim 1\text{ Myr}$, it is unlikely to discover water ice on most regions of EV5 except in high latitudes near the polar region ($> 60^\circ$).

### 7. Conclusion and Discussion

In this work, we explore the thermal characteristics of EV5 using our newly improved ATPM by considering the contribution of reflected sunlight, in combination with the 3D radar-derived shape model (Busch et al. 2011) and the four-band observations from WISE. We show that EV5 has a thermal inertia of $110^{+40}_{-12}\text{ J m}^{-2}\text{s}^{-1/2}\text{ K}^{-1}$, a geometric albedo

![Figure 10](image1.png)

**Figure 10.** Heat conductivity derived from the thermal inertia (red lines) and by heat conductivity model (black curves) where the blue asterisks represent the result particle sizes.

![Figure 11](image2.png)

**Figure 11.** Left panel: annual mean solar insolation as a function of the local latitude on EV5. Right panel: equilibrium subsurface temperature $\tilde{T}_0$ and ice front (if there ever was) temperature $T_i$, assuming a geometric albedo of $p_v = 0.09$.}

| Table 5 | Assumed Physical Parameters of EV5’s Dust Mantle |
|---------|--------------------------------------------------|
| Property | Value                                            |
| Grain density $\rho_d$ | $3110\text{ kg m}^{-3}$ |
| Mean grain radius $b$ | 1 mm |
| Tortuosity $\varsigma$ | 2 |
| Porosity $f$ | 0.4 |
| Ice/dust ratio $\chi_0$ | $0.1 \sim 0.2$ |
of $p_v = 0.095^{+0.016}_{-0.003}$, an effective diameter of $D_{eff} = 431^{+66}_{-33}$ m, and a high roughness fraction through the computations. As a comparison, the effective diameter is consistent with that of Busch et al. (2011), but the values of thermal inertia and geometric albedo given in this work are smaller than those of Alí-Lagoa et al. (2014). The derived thermal inertia indicates the mean grain size of the surface materials ranging from 0.58 to 1.3 mm.

For a small-size NEA, it is generally believed to be a rubble pile object, where the surface of which should be made up by of boulders of a wide variety of size, thereby having an averaged high thermal inertia and high roughness initially. Our findings suggest that EV5 may have a low thermal inertia with a high roughness. The likely interpretation for such low thermal inertia may be induced by the scenario that the surface had suffered an ever-lasting history of space weathering and thermal fatigue (Delbo et al. 2014, 2015), after it had been formed for a certain amount of time. Under such circumstances, dust aggregates or smaller fragments can be produced from the boulders, thereby making the surface have a lower thermal inertia. From the extensive backward simulations of 1000 clone orbits for EV5 for 1 Myr, we show that there is a likelihood of 6.1% that this asteroid can originate from the main belt or the outer region in our solar system, which is supportive of the low thermal inertia in this work. However, during the secular evolution history, the surface can still have a high roughness (see Figure 7), being indicative of that most of the produced dust aggregates should be coherent on the parent boulders and thus did not fall down to form a smooth regolith layer across the surface. Sánchez & Scheeres (2014) showed that rubble pile asteroids have nonzero cohesive strength due to small van der Waals forces between constituent grains, and this strength allows some aggregates or smaller fragments to remain where they were produced, therefore it would not alter the high roughness of the surface. Moreover, such low thermal inertia but high rough surface texture recently happens on Bennu (Dellagiustina et al. 2019; Lauretta et al. 2019) and Ryugu (Sugita et al. 2019; Watanabe et al. 2019) as observed by OSIRIS-REx and Hayabusa2, respectively, which provides strong support for our inference and results.

The prediction of possibility of finding water ice on high latitudes near the polar region of EV5 is based on the current small axial tilt of $\sim 10^\circ$ between its rotational axis and orbital axis, but largely depends on the historical axial tilt. So the solution may be diverse if EV5 had a totally different axial tilt in the past. Nevertheless, for the current EV5, the polar regions are good reservoirs for retaining water ice due to low temperature. If the rotation axis changes in the future, the water ice can sublimate to release gas and then produce activity. As a matter of fact, recent observations provide direct evidence that several B-type asteroids, e.g., (3200) Phaethon (Devogele et al. 2018; Yu et al. 2019) and Bennu (Cellino et al. 2018), may be active asteroids or dormant comets. Recently, OSIRIS-REx did discover ejection events of dust particles from Bennu’s surface, thereby raising an interesting issue: whether Bennu would be a comet, although the mechanism of the ejection events is not clear yet.

In conclusion, we speculate that EV5 may have a low thermal inertia but high rough surface, being indicative of a long-lasting evolution timescale in the main belt. There may exist dust aggregates on the surface and water ice on the polar regions. Hence, EV5 appears to be a suitable target for a sample return mission to retrieve high rewards for science in the future.

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