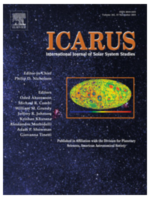
Icarus 314 (2018) 64–97

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



An empirical examination of WISE/NEOWISE asteroid analysis and results

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ARTICLE INFO

Article history:
Received 21 November 2016
Revised 2 May 2018
Accepted 8 May 2018
Available online 22 May 2018

Keywords:
Asteroids
Near-Earth objects
NEATM
WISE
NEOWISE

ABSTRACT

Asteroid observations by the *WISE* space telescope and the analysis of those observations by the NEOWISE project have provided more information about the diameter, albedo, and other properties of approximately 164,000 asteroids, more than all other sources combined. The raw data set from this mission will likely be the largest and most important such data on asteroids available for many years. To put this trove of data to productive use, we must understand its strengths and weaknesses, and we need clear and reproducible methods for analyzing the data set. This study critically examines the *WISE* observational data and the NEOWISE results published in both the original papers and the NASA Planetary Data System (PDS). There seem to be multiple areas where the analysis might benefit from improvement or independent verification. The NEOWISE results were obtained by the application of 10 different modeling methods, many of which are not adequately explained or even defined, to 12 different combinations of *WISE* band data. More than half of NEOWISE results are based on a single band of data. The majority of curve fits to the data in the NEOWISE results are of poor quality, frequently missing most or all of the data points on which they are based. Complete misses occur for about 30% of single-band results, and among the results derived from the most common multiple-band combinations, about 43% miss all data points in at least one band. The NEOWISE data analysis relies on assumptions that are in many cases inconsistent with each other. A substantial fraction of *WISE* data was systematically excluded from the NEOWISE analysis. Building on methods developed by Hanuš et al. (2015), I show that error estimates for the *WISE* observational data were not well characterized, and all observations have true uncertainty at least a factor of 1.3–2.5 times larger than previously described, depending on the band. I also show that the error distribution is not well fit by a normal distribution. These findings are important because the Monte Carlo error-analysis method used by the NEOWISE project depends on both the observational errors and the normal distribution. An empirical comparison of published NEOWISE diameters to those in the literature that were estimated by using radar, occultation, or spacecraft (ROS) measurements shows that, for 129 results involving 105 asteroids, the NEOWISE diameters presented in tables of thermal-modeling results exactly match prior ROS results from the literature. While these are only a tiny fraction (0.06%) of the asteroids analyzed, they are important because they represent the only independent check on NEOWISE diameter accuracy. After removing the exact matches and adding additional ROS results, I find that the accuracy of diameter estimates for NEOWISE results depends strongly on the choice of data bands and on which of the 10 models was used. I show that systematic errors in the diameter estimates are much larger than previously described and range from − 5% to + 23%. In addition, random errors range from − 15% to + 19% when all four *WISE* bands were used, and from − 39% to + 57% in cases employing only the W2 band. The empirical results presented here show that much work remains to be done in analyzing data from the *WISE*/NEOWISE mission and interpreting it for asteroid science.

1. Introduction

Infrared (IR) observations by space telescopes have generated information about asteroids that is unique or hard to obtain via other means, including estimates of their diameters and, when

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https://doi.org/10.1016/j.icarus.2018.05.004

Table 1
Summary of published NEOWISE papers and numbers of asteroids analyzed in each. FC: primary papers that analyze *WISE* observations from the full-cryo (FC) mission phase. 3B + PC: primary papers analyzing observations from the three-band (3B) and post-cryo (PC) phases, Re: primary papers from the reactivation mission. Other: non-NEOWISE papers that estimate diameters by thermal modeling. For the FC papers, the NEOWISE group reported model fits that estimate the parameters D, H, p_V, p_{IR}, η; where noted, the studies may determine separate W1 and W2 albedos p_{IR1}, p_{IR2}. Note that many asteroids appear in multiple NEOWISE studies or other source studies. The count column contains the number of asteroids for which thermal modeling results were presented in the paper.

	Source Studies			
	Reference	Abbreviation here (abbreviation in PDS)	Topic	Count
FC	(Mainzer et al., 2014b)	Mainzer/NEO:Tiny (Mai14)	Tiny near-Earth objects (NEO)	106
	(Grav et al., 2011a)	Grav/JT:Pre (Gr11)	Jovian Trojans	1742
	(Grav et al., 2011b)	Grav/Hilda (Gr12a)	Hildas	1023
	(Grav et al., 2012)	Grav/JT:Tax (Gr12b)	Jovian Trojans p_{IR1}, p_{IR2}	478
	(Mainzer et al., 2011c)	Mainzer/TMC	Thermal-model parameters	0
	(Mainzer et al., 2011b)	Mainzer/NEO:Pre (Mai11)	NEO	428
	(Masiero et al., 2011)	Masiero/MB:Pre (Mas11)	Main-belt asteroids (MBA)	129,478
	(Masiero et al., 2014)	Masiero/MB:NIR (Mas14)	MBA p_{IR1}, p_{IR2}	2835
3B + PC	(Mainzer et al., 2012a)	Mainzer/PP:3	MBA, NEO	116
	(Masiero et al., 2012)	Masiero/MB:3 (Mas12)	MBA	13,669
Re	(Nugent et al. 2015)	Nugent/Re1 (Nug15)	1st year	7956
	(Nugent et al., 2016)	Nugent/Re2	2nd year	9092
Other	(Tedesco et al., 2002)	IRAS	IRAS	2228
	(Ryan and Woodward, 2010)	RW	STM, NEATM	118
	(Usui et al., 2014, 2012, 2011a, 2011b)	AKARI	AKARI	4844

coupled with optical observations, of their visible albedos, as recently reviewed by Mainzer et al. (2015b).

WISE, a medium-class space telescope deployed by NASA, observed in four bands: W1, W2, W3, and W4, centered on the wavelengths 3.4, 4.6, 12, and 22 µm, respectively (Wright et al., 2010). NASA's NEOWISE project added to *WISE* the post-processing capability necessary to identify and observe asteroids and other small bodies in the solar system (Mainzer et al., 2011a). *WISE* and NEOWISE data are available for download from the Infrared Science Archive (IRSA)/*WISE* image archive (NASA/IPAC Infrared Science Archive, 2017).

The NEOWISE project used asteroid thermal modeling to estimate the diameters and albedos of about 164,000 asteroids, far more than all previous studies combined by more than a factor of 16. The enormous *WISE*/NEOWISE data (both raw observations and modeled results) is a treasure trove of data for planetary science and will be critically important for understanding asteroids for many years to come. No current or planned space mission will produce more four-band IR observations of asteroids.

This study was undertaken to independently examine the results and methodology published as part of the NEOWISE project in order to assess how best to use this incredible resource. It is vitally important that the astronomical community understands which aspects of the NEOWISE analysis represent the best or final word on extracting astronomical information from the data, as well as where more research work remains to be done.

Table 1 lists the publications by the NEOWISE group that include fits to thermal models, notably the Near-Earth Asteroid Thermal Model (NEATM), as well as resulting asteroid physical properties—including diameter D, visible-band albedo p_V, and near-infrared albedo covering the W1 and/or W2 bands (p_{IR}, p_{IR1}, p_{IR2}). These results are available from the electronic archives of the journals in which the papers were published. For convenience, I refer to the NEOWISE studies listed in Table 1 collectively as the "NEOWISE papers." Although the papers were published by collaborations that include members of the NEOWISE group, some collaborators and some aspects of the work may have been performed outside the official scope of the NASA/JPL NEOWISE project. Table 1 also includes other papers that report asteroid physical parameter estimates used in this study but that did not make use of *WISE*/NEOWISE data.

Together, the suite of NEOWISE papers asserts that their estimates of asteroid diameter, visible albedo, and infrared albedo are relatively precise in the majority of cases. Some of the NEOWISE papers include caveats that errors can be higher in certain cases and that the results must be interpreted with caution. But the assertion by Masiero et al., (2011) that "Using a NEATM thermal model fitting routine, we compute diameters for over 100,000 main belt asteroids from their IR thermal flux, with errors better than 10%" (Masiero et al., 2011) is a claim typical of the papers. The claim is repeated in the NASA Planetary Data System (PDS) archive of NEOWISE results (Mainzer et al., 2016) documentation and is explained in some detail in a 2015 review that stated:

> NEATM-derived diameters generally reproduce measurements from radar, stellar occultations, and *in situ* spacecraft visits to within ± 10%, given multiple thermally dominated IR measurements that adequately sample an asteroid's rotational light curve with good signal-to-noise ratio (SNR) and an accurate determination of distance from knowledge of its orbit (Mainzer et al., 2011c). It is worth noting that the accuracy of the diameters of objects used to confirm the performance of radiometric thermal models (such as radar or stellar occultations) is typically ∼10%. (Mainzer et al., 2015b)

These assertions imply that analysis of the *WISE*/NEOWISE data is complete, at least with respect to diameter, because it is already within or close to the tolerance of the best available comparison data (measurements from radar, occultation and spacecraft observations, denoted here as ROS).

Work outside the NEOWISE group to fully understand and exploit the data is still in its early stages, however. Seven years after the initial publication of the NEOWISE calculations, the results have yet to be replicated (i.e., physical properties obtained by model fits performed on the observational data) by any independent group. The question of replicability is important because numerous astronomers have relied on the NEOWISE results to draw conclusions about many salient topics in solar-system science (Bauer et al., 2013; Faherty et al., 2015; Mainzer et al., 2012b, 2012c, 2011e; Masiero et al., 2015a; 2015b, 2013; Nugent et al., 2012; Sonnett et al., 2015). The initial paper by Mainzer et al. (2011a) has been cited at least 270 times, and at