THE ASTEROID DISTRIBUTION IN THE ECLIPTIC

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ABSTRACT

We present analysis of the asteroid surface density distribution of main-belt asteroids (mean perihelion $\Delta \approx 2.404$ AU) in five ecliptic latitude fields, $-17 \lesssim \beta (^\circ) \lesssim +15$, derived from deep Large Binocular Telescope V-band (85\% completeness limit $V = 21.3$ mag) and Spitzer Space Telescope IRAC $8 \mu m$ (80\% completeness limit $\sim 103$ $\mu$Jy) fields enabling us to probe the $0.5$–$1.0$ km diameter asteroid population. We discovered 58 new asteroids in the optical survey as well as 41 new bodies in the Spitzer fields. The derived power-law slopes of the number of asteroids per square degree are similar within each $\sim 5^\circ$ ecliptic latitude bin with a mean value of $-0.111 \pm 0.077$. For the 23 known asteroids detected in all four IRAC channels mean albedos range from $0.24 \pm 0.07$ to $0.10 \pm 0.05$. No low-albedo asteroids ($p_V \lesssim 0.1$) were detected in the Spitzer FLS fields, whereas in the SWIRE fields they are frequent. The SWIRE data clearly samples asteroids in the middle and outer belts providing the first estimates of these km-sized asteroids’ albedos. Our observed asteroid number densities at optical wavelengths are generally consistent with those derived from the Standard Asteroid Model within the ecliptic plane. However, we find an overdensity at $\beta \gtrsim 5^\circ$ in our optical fields, while the infrared number densities are underdense by factors of 2 to 3 at all ecliptic latitudes.

Key words: infrared: solar system – minor planets, asteroids – surveys

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1. INTRODUCTION

The present main-belt asteroid size distribution provides important constraints on models of the original size distribution of planetesimals and their collisional evolution. The size–frequency distribution, main-belt asteroid scale height, and albedo variations extant in a large, well sampled population are also essential to model the size distribution of the Near-Earth Asteroid (NEA) population and to determine the evolution of main-belt objects as compared with those bodies injected into Earth crossing orbits (e.g., Trilling et al. 2008).

Most main-belt asteroids are found between 2.2 and 3.4 AU from the Sun and at ecliptic latitudes nominally less than 20\°. The size–frequency distribution of main-belt asteroids with diameters less than 1 km is essentially unknown due to observational flux limits. For asteroids with diameters greater than 1 km, the derived size–frequency distribution estimates range from $7 \times 10^3$ km-sized objects (optical Sloan Digital Sky Survey, SDSS; Abazajian et al. 2004; Ivezic et al. 2001) to $(1.2 \pm 0.5) \times 10^6$ km-sized objects (derived from surveys with the Infrared Space Observatory, ISO; Tedesco & Desert 2002) within the main belt. Recently, Stapelfeldt et al. (2006) have derived an size–frequency estimate for the $>1$ km-sized bodies for two fields at 0\° and 10\° ecliptic latitude from 24 $\mu$m photometry obtained with the NASA Spitzer Space Telescope (Spitzer; Gehrz et al. 2007; Werner et al. 2004) that concurs with values derived from analysis of the Sloan fields. While the infrared (IR) and optical methodologies yield comparable size estimates, these surveys are potentially biased as they are unable to detect (either through intrinsic sensitivity limits or survey design) fainter objects within the main belt. Thus, the size–frequency distribution may not be complete due to the preferential selection of a cross section of the asteroid population with high-albedo values or large sizes.

Bottke et al. (2005) have modeled the collisional evolution of the size distribution of the main belt using the current size–frequency distributions within the main belt as well as the size–frequency distribution of NEAs to constrain the primordial asteroid distribution. Their best-fit models, based on the current size–frequency distribution, predict $\sim 10^6$ asteroids within the 0.3 to 1 km size range. Collisional models by O’Brien & Greenberg (2005) predict $\sim 10^5$ bodies in a similar size range within the main belt. However, the validity of the population extrapolation is based on an accurate understanding of the current size–frequency distribution necessitating deep observations to provide accurate number counts at all optical wavelengths (higher-albedo objects) and IR (larger dark asteroids) wavelengths. The collisional evolution model by Bottke et al. (2005) suggests that the primordial main belt contained $\sim 150$ to $250$ times the current population of objects with diameters, $D \lesssim 1000$ km. The Bottke et al. (2005) model produces a parent population of similar magnitude to that required by interpretation of the meteoritic record. For instance Wetherill (1989) argues that the surface density within the main belt must be at least 100 times higher than that currently observed to be consistent with the meteoritic record. The total mass of known asteroids in the main belt is $5 \times 10^{-4} \, M_{\oplus}$. However, both the meteoritic record and collisional models require a primordial main-belt mass of $7.5 \times 10^{-2} \, M_{\oplus}$ to 1.25 $\times 10^{-1} \, M_{\oplus}$. The significant discrepancy between the mass of the primordial main belt and the current mass, primarily derived from large ($D \geq 10$ km) sized asteroids, may be resolved by extending the
asteroid number census to properly encompass smaller sizes while including populations found at higher ecliptic latitudes.

Here we present new observational results to constrain the size–frequency distribution of main-belt asteroids and their ecliptic scale height derived from a deep optical survey of select ecliptic fields obtained with the Large Binocular Telescope (LBT) as well as near- and mid-IR fields observed with Spitzer drawn from the data archive. Section 2 describes our observations and reduction techniques, Section 3 discusses the newly discovered asteroids and our derivation albedo, size–frequency distribution, and scale height, and Section 4 summarizes our conclusions.

2. OBSERVATIONS & ARCHIVAL ANALYSIS

2.1. LBT Observations

Optical observations were obtained at the Large Binocular Telescope (LBT; Hill et al. 2006) facility of the Mt. Graham International Observatory with the blue channel of the Large Binocular Camera (LBC; Ragazzoni et al. 2006; Giallongo et al. 2008) and a single 8.4 m mirror on various nights during 2007 January 16 through 24 UT as part of Science Demonstration Time (SDT) activities. The LBC is a wide-field imager incorporating four 2048 × 4608 pixel CCD detectors with a 23′ × 23′ field of view (FOV) and a 0′′.23 per pixel plate scale. Four fields at ecliptic latitudes of 0°, 5°, 10°, and 15° were observed using a series of 4 minute exposures in the V band (λ0 = 0.55 μm; Δλ = 0.094 μm) under nonphotometric conditions with seeing between ≃1′/3 and 3′/0. Fields were selected to be at solar elongations near 160°, such that sufficient asteroid motion on the plane of the sky could be detected within the ~3 hr observational baseline. Observations of each field consisted of two pointings, with one pointing offset by ~7′.85, resulting in a total areal coverage per field of 0.2835 deg2.

Table 1 provides complete observational details.

The data were reduced using standard IRAF7 routines in the mscred package. Images were trimmed, bias-subtracted, and flat-fielded using median sky flats created with twilight flats and additional data obtained during 2007 January SDT time. Astrometric solutions for each data frame were generated using IRAF routines, in conjunction with the stellar positions obtained from the USNO A2.0 astrometric catalog (Zacharias et al. 2004). The solutions had a positional accuracy of 0′′.04.

Asteroid detection was performed using a three-color method. Images with astrometric solutions were displayed in image display tool D9 (Joye & Mandel 2003), with each individual epoch (Table 1) loaded into a different color table. Asteroids were identified by pairs or triplets of individually colored

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7 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
sources. From these identifications, absolute pixel coordinates for each target were obtained, which were subsequently used for photometric measurements. Due to the conditions under which the data were obtained, a high signal to noise of 10 is required for any asteroid detection. Secondary confirmation of this asteroid detection technique was performed by registering individual epoch frames by the world coordinate system (WCS) and then subtracting, leaving positive and negative asteroid pairs. While this latter technique would be preferred over the three-color detecting technique was performed by registering individual source. From these identifications, absolute pixel coordinates for each target were obtained, which were subsequently used for photometric measurements. Due to the conditions under which the data were obtained, a high signal to noise of 10 is required for any asteroid detection. Secondary confirmation of this asteroid detection technique was performed by registering individual epoch frames by the world coordinate system (WCS) and then subtracting, leaving positive and negative asteroid pairs. While this latter technique would be preferred over the three-color technique, the seeing varied by 1\(^\circ\) to 3\(^\circ\) over each night causing the WCS subtraction technique to be less reliable.

Photometry was performed using a circular aperture with a radius of 10 pixels for each asteroid coordinate. The photometry was calibrated from stellar sources in the fields using published \(V\)-band magnitudes taken from the Tycho and USNO A2.0/YB6 catalogs (mean photometric errors of the order \(\leq 0.1\) mag). Forty stars (10 stars per chip) were identified by their astrometric positions and were used to find a photometric offset between the measured and reported absolute values from Tycho/USNO A2.0. This zero-point photometric offset, which includes the mean photometric error, was then used to calibrate the asteroid photometry in each pointing as described in Table 1, Column [7].

We detected 62 asteroids in the LBC \(V\)-band images, of which only four are previously known objects with orbital determinations. The 58 newly discovered asteroids detected in this survey were observed in either two or three epochs. Due to the field overlap between pointings, some asteroids were detected six times, allowing for both precise astrometry and photometry. Table 2 summarizes the number of asteroids found in each field as well as the extrapolated number counts per square degree at each latitude and the limiting magnitudes for each field. The extrapolated optical number counts were obtained by multiplying the asteroid number counts in a field by the number 0.2835 \(\text{deg}^2\) fields necessary to tile a 1 \(\text{deg}^2\) field assuming a uniform asteroid density at each latitude.

### 2.2. Spitzer Archival Fields

Asteroid photometry and number counts in select ecliptic fields discussed in Section 3 were derived from new ground-based optical observations and point-source extractions obtained from fields observed with the Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Infrared Photometer on Spitzer (MIPS; Rieke et al. 2004) as part of various IR survey programs retrieved in the Spitzer public archive.

Post-pipeline (pipeline version 15) basic calibrated data (BCDs) of selected Spitzer IRAC fields were downloaded from the public archive and utilized for asteroid detection. Fields were selected from the ecliptic plane component of the Spitzer First Look Survey (FLS, program identification (PID) 98; Meadows et al. 2004), and SWIRE XMM-LSS fields (PID 181; Lonsdale et al. 2003). IRAC 8.0 \(\mu\text{m}\) data are preferable for asteroid detection due to the detector plate scale (\(\sim 1\text{''}\)) and detector sensitivity. The 5\(\sigma\) detection limit for a 500 s IRAC 8.0 \(\mu\text{m}\) observation is 27 \(\mu\text{Jy}\), enabling detection of small main-belt asteroids with high signal-to-noise ratios (S/Ns) in short integration times. For example, the 8.0 \(\mu\text{m}\) flux from a 1 km diameter main-belt asteroid radiating as a blackbody with an orbital semimajor axis of 2.5 AU (3.2 AU) viewed at opposition is \(\approx 1096 \mu\text{Jy}\) (\(\approx 20.1 \mu\text{Jy}\)). Once an asteroid candidate is identified at 8.0 \(\mu\text{m}\) its sky coordinate can then be used to examine pixels at the same location in the IRAC 3.6, 4.5, and 5.8 \(\mu\text{m}\) images. Although the flux densities for small-sized asteroids near the outer belt edge are not easily detectable with IRAC in single frames at shorter wavelengths, their motion will separate them from the confusion caused by faint extragalactic sources or point-spread function (PSF) smearing of the telescope.

Due to limits on observation durations (driven by on-board data storage issues and downlink frequency), the Spitzer deep large area surveys must consist of multiple epochs of data with multiple pointings. For asteroid detections this is advantageous as the observation duration limit for all IRAC observations is 6 hr which allows observations to be repeated with a cadence of a few hours. Assuming circular Keplerian orbits within the asteroid belt, the angular velocity \(\omega\) (rad s\(^{-1}\)), or rate of motion on the sky of an object near opposition is

\[
\omega = \sqrt{\frac{GM_\odot}{R^3}},
\]

where \(G = 6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}\), \(M_\odot\) is the mass of the Sun, and \(R\) is the orbital distance in meters. For inner main-belt...
asteroids with a semimajor axis of 2.2 AU, the expected rate of motion is 45″ per hour, while the expected rate of motion for outer main-belt asteroids is 24″ per hour. However, the actual rates and direction of motion on the sky may significantly differ from these values (e.g., near quadrature, when the FLS fields were observed at solar elongation ≥115°). Nevertheless, movement on the sky of many tens of arcsec per hour enables one to detect asteroids in the field on timescales of hours.

The FLS consisted of IRAC observations of two 0.13 square degree fields (10′ × 48′) centered on a solar elongation of 115° as seen from Spitzer, at ecliptic longitudes β = 0° and +5° on 2004 January 21 UT. In J2000 coordinates, this corresponds to field centers of R.A. = 12h03m22.03, decl. = −00°21′53.8″ for the β = 0° field, and R.A. = 12h11m20.10, decl. = +04°13′18.7″ for the β = +5° field as viewed by Spitzer. To detect asteroid motion, each IRAC field was observed at three epochs separated by 70 minutes.

For each of the latitude fields, we colored each epoch and coadded the IRAC 8.0 μm mosaics of the three epochs using a fixed stellar WCS to create a composite red-blue (RB) image. The IRAC image, fixed sources appear white, and moving targets were seen as RB quasi-linear sequences of sources. The typical S/N for fixed sources appear white, and moving targets were seen as RGB quasi-linear sequences of sources. We identify a total of 46 asteroids in the FLS and SWIRE data sets. Pixel coordinates for each asteroid were recorded at the time of detection and associated uncertainty, while [14] is the filter used for the observations.

The corresponding column format is used: [1] the asteroid name, [2] a true/false = 1/0 flag indicating if asteroid is a new discovery, [3]–[5] are respectively the year, month, and UT date of observation, [6]–[11] are the right ascension and declination (J2000.0) of the detected target, [12] and [13] are the observed asteroid magnitude and associated uncertainty, while [14] is the filter used for the observations.

Asteroid detection in the SWIRE data sets was also performed by coloring and coadding IRAC 8.0 μm mosaics of each epoch to create a composite red-blue (RB) image. In this RB image, fixed sources appear purple, and moving targets were seen as RB quasi-linear sequences of sources. We identify a total of 46 sources in the field. The faintest sources have 8.0 μm fluxes of ≳300 μJy and were detected with a S/N ∼ 20 in both fields. Of the 46 sources detected, only 14 asteroids have ground-based detections and orbital elements.

Fluxes in all four IRAC channels were obtained for all asteroids in the FLS and SWIRE data sets. Pixel coordinates for each asteroid were recorded at the time of detection and associated uncertainty, while [14] is the filter used for the observations.
3. DISCUSSION

The distribution of asteroids within the main belt provides a means to ascertain the mass distribution of material within the main belt and provides constraints for theoretical models developed to describe planet formation from protoplanetary disks encompassing our own proto-Sun, as well as those extant around other young stellar systems. By probing the asteroid distribution in reflected optical light and in the thermal IR in coordinated observational programs, a more complete picture of the number of asteroids and sizes and albedos can be obtained. Current models of solar system dynamics (e.g., Bottke et al. 2005) use the distribution of absolute magnitudes of asteroids combined with a single geometric albedo to estimate the size–frequency distribution of asteroids as observationally determined diameters and albedos of main-belt asteroids only exist for ~2400 objects. However, new survey data now available from fields observed with the Spitzer can be used to determine asteroid albedos and diameters for sizes under 1 km, enabling a more robust determination of albedo trends and size as a function of latitude for a more representative population of objects (e.g., a broader sampling of the total distribution). Our study describes the first results for main-belt asteroids with diameters of 0.5 km.

3.1. Completeness Limits

To test completeness of our optical and Spitzer data sets, we used the IRAF task *mkobjects* to create synthetic point sources in data frames. To assess completeness in the optical data, synthetic point sources were added with the same seeing values measured in each frame and with coordinates that varied to mimic asteroid motion. To model the Spitzer images, synthetic objects were randomly placed into an image with motions equivalent to the median rates of a body in Keplerian orbit at the corresponding ecliptic latitude. Synthetic asteroids were then recovered using the same RGB technique originally used to detected asteroids in the observational images. Our completeness values are not only sensitive to source fluxes, but also to motion. For valid completeness detection, an asteroid must be detected in at least 2 of the 3 epochs of data.

In our optical data, the 85% moving target completeness limit in all fields is $V = 21.3$. Because the moving target completeness samples the completeness due to (1) a limiting flux and (2) motion, a point-source completeness test was also performed. This exercise shows that the point-source completeness at $V = 21.3$ is 90%. For all asteroids counts at magnitudes greater than 21.3, the difference in the two completeness values of 5%, is applied by assuming that the number of asteroids not detected due to motion is the same at all magnitudes. These completeness values have been used to obtain corrected asteroid number counts which are reported in Column [3] in Table 2. Figure 1 shows the number counts per square degree as a function of magnitude in each optical field.

The Spitzer IRAC 8.0 μm analysis, under the constraints that the synthetic asteroid rate of motion was comparable to the median rates of motion in a field at a given ecliptic latitude combined with the requirement of a minimum of two detections per synthetic asteroid yields an 80% completeness limit for the FLS and SWIRE data for $F_{8\mu m} = 103$ μJy. Our derived completeness value differs somewhat from that reported for the FLS by Meadows et al. (2004) who cite 90% completeness at 100 μJy based on fixed target detections. With the completeness limit at 103 μJy, we calculate that the number of asteroids in the FLS 0° and 5° fields is 148 ± 12 and 133 ± 12 per square degree, respectively, and 5 ± 2 per square degree for the −17° SWIRE field. In Figure 2 are histogram plots of the surface density of asteroids as a function of 8.0 μm flux in the Spitzer FLS and SWIRE fields.

3.2. Bulk Size-Frequency Distribution

Comparison of these two major data sets in different wavelength is complicated in part by the potential for a disparate probe of asteroid sizes. Using the completeness limits in the V band and at IRAC 8.0 μm we can estimate the minimum radii of asteroids detectable in our survey from

$$F_{\text{reflected}} = \frac{2h \nu^3}{c^2} \frac{1}{e^{\frac{\nu k T}{c}} - 1} \frac{R_\odot R_p \pi D^2 \cos(\tilde{\alpha})}{16 \pi \Delta^2}$$

and

$$F_{\text{thermal}} = \frac{2\epsilon D^2 \nu^3}{d_{\text{Spitzer}}^2 c^2} \left( \int_0^\phi \int_\alpha^\pi \sin^2(\phi) \cos(\theta - \alpha) d\theta d\phi \right)$$

where

$$T_{\text{ast}} = \left( \frac{1 - A}{r_h \eta \epsilon \sigma_{SB}} \right)^{\frac{1}{4}} (\cos \phi)^{\frac{1}{4}} (\cos \theta)^{\frac{1}{4}}.$$
The terms $F_{\text{reflected}}$ and $F_{\text{thermal}}$ are the observed $V$-band and IRAC 8.0 $\mu$m band fluxes (W m$^{-2}$ Hz), respectively. Variables in the equation for reflected flux are: $\nu$ is the frequency of observation, in this case $V$-band, $R_{\odot}$ and $T_{\odot}$ are the radius (m) and temperature (K) of the Sun, $r$ is the asteroid heliocentric distance in meters, $D$ is the asteroid diameter in meters, and $\Delta$ is the asteroid geocentric distance, $p_v$ is the geometric albedo of the asteroid in $V$-band, $R$ is the relative reflectance of the asteroid as measured with respect to the $V$-band reflectance and $\tilde{\alpha}$ is the observed phase angle in radians. Other variables in the equation for thermal flux are: $d_{\text{Spitzer}}$ is the asteroid–Spitzer separation (AU), $\epsilon$ is the asteroid emissivity which is assumed to be 0.9, $A$ is the Bond Albedo, $S_{\odot}$ is the solar constant, $r_h$ is the asteroid heliocentric distance in AU, $\eta$ is the beaming parameter, and $\sigma_{\text{SB}}$ is the Stefan-Boltzmann Constant with the value $5.6704 \times 10^{-8}$ Wm$^{-2}$ K$^{-4}$. Adopting mean values for the known asteroids in our data sets $r_h = 2.82$ AU, $\delta = 1.89$ AU (optical) and $r_h = 2.68$ AU, $d_{\text{Spitzer}} = 2.28$ AU, (Spitzer asteroids; Table 6), assuming $\eta = 1$ with $p_v = 0.15$ and $\cos(\tilde{\alpha}) = 0.99$, the minimum asteroid radii detected in our data are $\gtrsim 1020$ m in the optical and $\gtrsim 450$ m in the IRAC 8.0 $\mu$m channel. Although Spitzer is far more efficient than optical imaging surveys at detecting smaller asteroids, asteroids identified from these two data sets comprise a set of bodies with similar size ranges within the main belt.

The IR and optical data can be used to obtain the power-law size–frequency distribution at three similar latitudes. In both the optical and the mid-IR, flux can be used as a proxy for size in obtaining the size–frequency distribution assuming that the Bond albedo is well behaved as a function of wavelength. By adopting a power-law distribution for the surface density distribution $\propto f^{-\alpha}$, we use the completeness corrected counts.
to measure the power-law slopes summarized in Table 7. The derived optical and IR slopes are similar at all latitudes within the uncertainties, with a mean value of $\alpha = -0.111 \pm 0.077$ for the surface density distribution of asteroids. However, the formal errors suggest that the optical data provide a better constraint on $\alpha$. Our derived $\alpha$-values (Table 7) for the Spitzer fields differ somewhat from those cited by Meadows et al. (2004). The differences can be attributed to how the asteroid photometry was conducted; Meadows et al. (2004) employed PSF-fitting (using, at that time, a poorly determined IRAC PSF), whereas we resort to aperture photometry to measure the flux density. In addition, differences in completeness also lead to variances in our results as opposed to those presented in Meadows et al. (2004). We cite 80% completeness at 100 $\mu$Jy for moving-objects, while Meadows et al. (2004) quote 90% completeness at the same flux level for point sources.

As the derived slopes of the surface density distributions are similar at optical wavelengths, we employed a Kolmogorov–Smirnov (KS) test using the mean rates of motion of the asteroids at 0° and 15° ecliptic latitude to discriminate whether these bodies detected in the optical fields are drawn from the same size and magnitude population distributions. Unlike a $\chi^2$ test, data are not binned in the KS test and the KS test can be used on data sets of different lengths. Due to the low number of asteroids detected in the 10° and 15°, binning of the data was rejected due to the associated loss of information and arbitrariness of defining bin sizes. The derived probability is 96.88%, strongly suggesting that the two fields represent the same distance (rate) population. Similarly, a KS test to determine the likelihood that the asteroids represent the same size distribution yields only a 41.32% probability that the objects at 15° represent the same size distribution as those detected.

Figure 1. (Continued)
at $0^\circ$ ecliptic latitude. This statistical inference suggests that the size distribution of asteroids at $0^\circ$ and $15^\circ$ are dissimilar; however, the veracity of this conclusion is limited by small number detection statistics of our data. Table 8 summarizes our probability analysis of the magnitude distribution (e.g., asteroid diameters) as a function of ecliptic latitude compared to the $0^\circ$ field. Lastly, although the KS test indicates that the $0^\circ$ and $15^\circ$ optical fields are likely not the same population, they do appear to follow a distribution in which large, thus bright, objects are rare, whereas small and thus faint, objects are more numerous.

3.3. Comparison to Models

Our observed asteroid frequency distribution can be juxtaposed with current models describing the evolution of the asteroid populations in the solar system, such as the Statistical Asteroid Model (SAM) developed by Tedesco et al. (2005). The SAM uses a set of 8603 asteroids with absolute magnitudes less than 15.75 (asteroids with diameters of $\gtrsim 2.5$ km) to determine a size–frequency distribution of asteroids which is assumed to be smooth to diameters of 1 km. This model also incorporates an albedo distribution derived from 15 dynamical families and three “background” populations based on 1980 asteroids which have diameter and albedo determinations from MSX (Tedesco et al. 2002) and IRAS (Veeder & Tedesco 1992; Tedesco et al. 2002). A number of asteroids are excluded from this model, including those with inclinations greater than $25^\circ$, and those with eccentricities $>0.3$.

The asteroid number counts observed with both Spitzer and the LBT are less than those predicted by the SAM. For a limiting flux of 0.06 mJy at 8 $\mu$m the SAM predicts 430 $\pm$ 40 asteroids at $0^\circ$ latitude and 250 $\pm$ 20 asteroids at $5^\circ$ latitude. One reason the SAM may overestimate the number of asteroids is the assumed faint flux limit of Tedesco et al. (2005) which corresponds to an effective diameter of 0.6 km. This flux limit is fainter than the completeness for both fields, thus the SAM overpredicts the number of small asteroids which would be observed by Spitzer. The overestimate of the number of asteroids may also be due to a fundamental assumption of the SAM—the power-law slope of the size–frequency distribution is continuous to diameters less than 1 km. This is not observed in the optical. The size–frequency distribution appears to fall off around 3 km (Jedicke & Metcalfe 1998); however, the reasons for this falloff are not well understood. Two possible reasons for the falloff in observed data are: (1) the bright limiting magnitude of most asteroid surveys excludes detections of asteroids smaller than 1 km in diameter, or (2) the asteroids smaller than 1 km may not be solid, but may instead be easily disruptible piles of rubble. If the predicted number of asteroids is scaled from the SAM with a model that yields the number of asteroids with diameters greater than 0.6 km being 2.4 times the number of asteroids with diameters greater than 1.0 km, the SAM still predicts 179 $\pm$ 17 asteroids in the $0^\circ$ latitude field and 104 $\pm$ 8 asteroids in the $5^\circ$ latitude field. The estimate at the high latitude is nearly in agreement with our FLS results; however, the SAM still overestimates the number of asteroids in the $0^\circ$ field. The latter discrepancy may due to asteroids with high albedos ($>0.25$) which are not detected in the IRAC channels because they are too cool and thus their thermal fluxes are below the detection thresholds in this data.

For the LBT data which have limiting diameters of $\sim 2$ km, the number counts are within the uncertainty of the SAM prediction. For the SDSS survey that has a point-source completeness limit of $V = 22.2$, the SAM predicts 115 $\pm$ 10 asteroids at $0^\circ$ latitude and 75 $\pm$ 5 asteroids at $5^\circ$ latitude. This completeness limit is fainter than ours by 0.9 mag; however, the model values are nearly in agreement with the asteroid number counts at these two latitudes. Unfortunately, the SAM does not predict asteroid counts at higher latitudes ($\beta > 5^\circ$) and the current version of the SAM only uses asteroids with inclinations less than 20$^\circ$ to make estimates on number counts. A subset of our newly detected asteroids has large inclinations. In fact, this limitation of the SAM complicates derivation of the size–frequency distribution.
distribution and physical characteristics of well-known and well characterized targets such as Pallas and asteroid dynamical groups such as Hungarias and Phocaeas (Carvano et al. 2001).

3.4. Asteroid Diameters, Albedos, and Colors

Direct comparison of mean and median IRAC 8.0 μm fluxes (Section 2.2) of asteroids in the two FLS fields and the SWIRE field, reveals that the SWIRE asteroids are, on average across the population, brighter than those asteroids at 0° and 5° latitude detected in the FLS fields, by a factor of two. This variance in brightness could be explained as a difference in asteroid diameter assuming that the populations have comparable albedos. We explored this possibility by estimating the diameters and deriving albedos for all asteroids which were detected in all four IRAC bands using the Near-Earth Asteroid Thermal Model (NEATM; Harris 1998). In this model, the thermal flux is dependent upon the subsolar temperature and the temperature distribution of the surface of the asteroid. The latter is solely dependent on the albedo and η as model variables. Thus, our implementation of NEATM follows the Delbo & Harris (2002) and Delbo (2004) prescription whereby the model fits the IR fluxes and the optical absolute magnitude of asteroids (H) by varying the geometric albedo (through a χ²-minimization) until a best fit is found. The Spitzer fluxes were first color-corrected according to the prescription described in the IRAC Data Hand- book (Spitzer Science Center 2006), resulting in the measured fluxes being divided by 1.1717 and 1.1215 at 5.8 μm and 8.0 μm, respectively. The asteroid diameter is then calculated by the relation of Fowler & Chillemi (1992) which uses only the geometric albedo and the absolute magnitude as input values. Because IRAC asteroid spectral energy distributions are composites of both thermal emission and reflected solar light (e.g., Mueller et al. 2007), we derived albedo and diameter estimates of the asteroids using only data from IRAC channels 3 and 4. From the channel 3 and 4 fits, we find that the percentage of reflected solar light in our channel 1 photometry to be ≥56% and ≤14% in the channel 2 photometry. Our modeling results for known asteroids detected in our IRAC fields are summarized in Table 6. The mean diameter of asteroids in SWIRE is 5.91 km while the mean asteroid diameter in the FLS is 2.28 km.

Analysis of the mean geometric albedos and derived sizes for these objects suggest they divide between the two populations. The mean geometric albedo for asteroids in the FLS fields is 0.24 ± 0.07 as opposed to 0.10 ± 0.05 for asteroids in the SWIRE fields. No low-albedo asteroids (pV ≤ 0.1) were detected in the Spitzer FLS fields, whereas in the SWIRE fields they are frequent. Evidently the surface composition of the asteroids in the SWIRE fields contains more carbonaceous material than the asteroids in the FLS, as carbonaceous chondrites have significantly lower albedos in the 0.03 to 0.11 range (Gaffey 1976; Johnson & Fanale 1973).

### Table 5

| Provisional Designation | F₁₆ (μJy) | F₅₅ (μJy) | F₃₆ (μJy) | F₅₆ (μJy) |
|-------------------------|----------|----------|----------|----------|

#### SWIRE Asteroids

| 2004TH222 | 18.5 ± 14.1 | 53.6 ± 30.6 | 241.0 ± 80.3 | 1682.6 ± 246.3 |
| 2005Y181 | 6.0 ± 5.6 | 16.25 ± 12.8 | 128.4 ± 55.2 | 933.8 ± 179.0 |
| 2005Y50 | 16.7 ± 14.2 | 12.7 ± 12.4 | 64.5 ± 36.0 | 570.6 ± 136.2 |
| 1999WA1 | 45.1 ± 27.1 | 113.4 ± 50.0 | 938.5 ± 172.8 | 7314.0 ± 532.0 |
| 2004TO8 | 109.2 ± 48.7 | 259.0 ± 82.6 | 1684.4 ± 237.5 | 10301.9 ± 634.3 |
| 2006AP1 | 5.8 ± 5.4 | 32.8 ± 21.7 | 263.8 ± 84.7 | 1677.9 ± 245.7 |
| 2005WX162 | 10.4 ± 8.9 | 38.0 ± 24.1 | 311.5 ± 93.5 | 2287.0 ± 290.30 |
| 1999YYYY | 75.7 ± 38.5 | 383.9 ± 103.8 | 2867.7 ± 314.2 | 18500.0 ± 856.9 |
| 1999Z7 | 4.0 ± 4.9 | 25.5 ± 18.1 | 196.8 ± 71.2 | 1512.8 ± 232.3 |
| 2000VP1 | 15.9 ± 12.7 | 25.0 ± 17.8 | 113.9 ± 51.2 | 775.1 ± 161.3 |
| 2005YH117 | 6.7 ± 6.2 | 48.0 ± 28.4 | 470.0 ± 118.0 | 3570.0 ± 366.2 |
| 2002FE15 | 12.0 ± 10.1 | 47.9 ± 28.4 | 355.7 ± 100.8 | 4308.9 ± 403.4 |
| 2005XX74 | 83.1 ± 42.7 | 118.5 ± 52.0 | 538.9 ± 127.5 | 4465.2 ± 411.6 |
| 2002CN96 | 15.5 ± 12.3 | 65.0 ± 35.3 | 584.1 ± 133.3 | 3106.3 ± 343.6 |

#### FLS Asteroids

| 2001YY16b | 8.9 ± 7.8 | 31.8 ± 22.6 | 101.3 ± 47.5 | 905.4 ± 175.8 |
| 2000AX136b | 114.8 ± 50.4 | 217.6 ± 74.2 | 1228.2 ± 200.3 | 8993.1 ± 593.3 |
| 2004BH160 | 9.1 ± 9.3 | 11.4 ± 10.9 | 11.5 ± 11.7 | 73.6 ± 39.6 |
| 2001QD49b | 7.1 ± 7.4 | 11.2 ± 12.2 | 16.1 ± 16.0 | 109.9 ± 51.3 |
| 2002WL7b | 18.2 ± 13.9 | 50.0 ± 29.1 | 497.6 ± 121.4 | 3239.4 ± 347.8 |
| 1999Z24b | 41.7 ± 25.9 | 45.2 ± 27.3 | 211.0 ± 74.1 | 2116.3 ± 277.6 |
| 2001RP137b | 8.3 ± 7.6 | 14.3 ± 14.2 | 34.9 ± 24.1 | 273.5 ± 89.2 |
| 2004EU91 | 9.3 ± 9.2 | 7.2 ± 6.8 | 35.7 ± 26.5 | 1165.3 ± 53.3 |
| 2004CA105 | 61.7 ± 35.8 | 54.6 ± 33.7 | 59.9 ± 34.8 | 487.4 ± 124.5 |
| 2002RG106 | 12.2 ± 10.4 | 5.3 ± 5.3 | 22.9 ± 17.6 | 228.3 ± 80.5 |
| 2004BU09 | 6.3 ± 5.8 | 7.9 ± 7.4 | 40.3 ± 25.9 | 398.9 ± 110.9 |
| 2004BS160 | 8.1 ± 8.6 | 3.1 ± 3.1 | 21.4 ± 30.7 | 101.9 ± 49.0 |
| 2001SB182 | 14.1 ± 11.9 | 11.8 ± 11.0 | 32.6 ± 22.6 | 164.0 ± 70.1 |
| 2004FG8 | 6.1 ± 7.2 | 7.7 ± 7.0 | 25.5 ± 19.2 | 185.5 ± 70.7 |

Notes.

- a Observed fluxes, no IRAC color-correction applied.
- b Asteroids also reported in Meadows et al. (2004).
Table 6
Standard Thermal (NEATM) Model Derived Asteroid Diameters and Albedos

| Provisional Designation | Heliocentric a Distance (AU) | Spitzer a Distance (AU) | Phase Angle (°) | Absolute b Magnitude | NEATM Geometric Diameter (km) | Geometric Albedo | Beaming parameter | Model χ² |
|-------------------------|-----------------------------|-------------------------|----------------|---------------------|-------------------------------|-----------------|------------------|---------|
| SWIRE Asteroids         |                             |                         |                |                     |                               |                 |                  |         |
| 2004 TH222              | 2.08                        | 1.79                    | 29.4           | 15.4                | 2.83                          | 0.14            | 1.69             | 0.0002  |
| 2005 YV181              | 3.27                        | 3.09                    | 18.20          | 15.5                | 3.91                          | 0.07            | 0.79             | 0.0157  |
| 2005 YV50               | 2.38                        | 2.14                    | 25.36          | 16.0                | 2.45                          | 0.12            | 1.66             | 0.0087  |
| 1999 WA1                | 2.82                        | 2.60                    | 21.25          | 12.7                | 9.16                          | 0.18            | 1.01             | 0.0225  |
| 2004 TO8                | 2.66                        | 2.44                    | 22.57          | 14.5                | 9.02                          | 0.03            | 1.04             | 0.5826  |
| 2006 AP1                | 2.91                        | 2.71                    | 20.53          | 15.5                | 3.59                          | 0.09            | 0.77             | 0.0035  |
| 2005 WX162              | 2.83                        | 2.61                    | 21.20          | 15.3                | 5.10                          | 0.05            | 0.10             | 0.0141  |
| 1999 YV171              | 2.56                        | 2.34                    | 23.48          | 14.0                | 10.92                         | 0.04            | 1.04             | 0.6644  |
| 1999 JZ7                | 2.33                        | 2.08                    | 26.02          | 14.0                | 3.39                          | 0.39            | 1.35             | 0.0308  |
| 2000 VP1                | 2.43                        | 2.21                    | 24.83          | 15.7                | 1.99                          | 0.23            | 1.03             | 0.0143  |
| 2005 YX74               | 2.85                        | 2.64                    | 20.99          | 14.8                | 5.35                          | 0.08            | 1.05             | 0.0859  |
| 2002 CN96               | 2.95                        | 2.74                    | 20.29          | 14.8                | 5.88                          | 0.06            | 0.87             | 0.9232  |
| FLS Asteroids           |                             |                         |                |                     |                               |                 |                  |         |
| 2001 QY160              | 2.96                        | 2.39                    | 17.74          | 15.0                | 3.26                          | 0.17            | 1.02             | 0.0241  |
| 2000 AX136              | 2.40                        | 1.80                    | 22.02          | 13.1                | 6.89                          | 0.21            | 1.33             | 0.0002  |
| 2004 BH160              | 2.42                        | 1.82                    | 21.86          | 18.4                | 0.51                          | 0.30            | 1.03             | 0.0001  |
| 2001 QD49               | 2.77                        | 2.19                    | 18.98          | 17.5                | 0.94                          | 0.20            | 1.00             | 0.0048  |
| 2002 WL7                | 2.69                        | 2.11                    | 19.55          | 15.3                | 4.48                          | 0.07            | 1.05             | 0.1406  |
| 1999 FZ24               | 3.10                        | 2.53                    | 16.93          | 13.8                | 5.81                          | 0.16            | 1.03             | 0.1115  |
| 2001 RP137              | 2.93                        | 2.36                    | 17.90          | 16.7                | 1.72                          | 0.13            | 1.02             | 0.0012  |
| 2004 EU91               | 2.40                        | 1.80                    | 22.04          | 18.1                | 0.51                          | 0.39            | 0.76             | 0.1778  |
| 2004 CA105              | 2.80                        | 2.22                    | 18.77          | 14.7                | 2.27                          | 0.44            | 1.03             | 0.0062  |
| 2002 RG106              | 2.69                        | 2.10                    | 19.58          | 16.1                | 1.30                          | 0.38            | 1.045            | 0.108   |
| 2004 Bu99               | 2.17                        | 1.54                    | 24.53          | 17.4                | 1.84                          | 0.06            | 2.50             | 0.0008  |
| 2004BS160               | 2.41                        | 1.81                    | 21.99          | 18.6                | 0.57                          | 0.20            | 1.01             | 0.0178  |
| 2001SB182               | 3.02                        | 2.46                    | 17.36          | 15.6                | 1.39                          | 0.53            | 0.75             | 0.0636  |
| 2004FG8                 | 2.01                        | 1.37                    | 26.61          | 18.5                | 0.74                          | 0.13            | 1.90             | 0.0001  |

Notes.
a Heliocentric, n, and Spitzer-asteroid distances at epoch of observation.
b Absolute Magnitudes are values given in the JPL Horizons database, http://ssd.jpl.nasa.gov/?horizons.

Table 7
Power-Law Slopes of the Surface Density Distributions

| Field Ecliptic Latitude (°) | Probability a (%) | Median (mag) | Mean (mag) |
|-----------------------------|-------------------|--------------|------------|
| 0                           | 100               | 20.6         | 20.45      |
| 5                           | 66.24             | 20.5         | 20.41      |
| 10                          | 38.89             | 19.8         | 20.00      |
| 15                          | 41.32             | 20.8         | 20.65      |

However, the marked dichotomy in derived albedos is most likely a result of the two Spitzer surveys sampling different asteroid taxonomy classes within the general asteroid belt. An extensive analysis of ∼ 800,000 objects in the Sloan Digital Sky Survey Moving Object Catalog (SDSS MOC) 4 by Parker et al. (2008) demonstrates that there is a strong correlation between SDSS color, asteroid taxonomy (C-, S-, V-type), and orbital elements. In Figure 3, we plot the proper orbital elements a (orbital semimajor axis) versus i (orbital inclination) of our SWIRE (green squares) and FLS (red triangles) detected asteroids overlaid on 207,942 numbered asteroids (black dots) with orbital elements in the ASTORB files (Bowell2001). The location of the major Kirkwood gaps as defined by Parker et al. (2008) are indicated, and the colored symbols used to identify the Spitzer-detected asteroids are coded by derived albedo. Open symbols are for Spitzer asteroids with derived albedos, pV ≲ 0.1, while filled symbols identify asteroids with pV > 0.1. The majority (≃80%) of the low-albedo asteroids detected in the Spitzer data reside at high inclination in the outer belt. Primitive asteroids, with C-type colors and generally low albedos (pV < 0.1), are seen to dominate the asteroid population in the outer belt, while S-type asteroids with pV ranging from ∼ 0.15 to 0.2 tend to be more dominant in the middle and inner asteroid belt (Parker et al. 2008). Our SWIRE data clearly sample asteroids in the middle and outer belts, and in fact, for the first time, we are able to estimate the albedos of km-sized asteroids in the outer belt (Table 6).
Figure 3. Proper orbital elements $a$ (orbital semimajor axis) vs. $i$ (orbital inclination) of asteroids. The Spitzer SWIRE and FLS asteroids are denoted respectively by green squares and red triangles, while 207,942 numbered asteroids with orbital elements in the ASTORB files are plotted with black dots. Open colored symbols indicate asteroids with derived albedos, $p_V \leq 0.1$, while filled symbols denote asteroids with $p_V > 0.1$. The location of the major Kirkwood gaps as defined by Parker et al. (2008) are indicated by the labels and vertical arrows.

Figure 4. IRAC colors of astronomical objects and asteroids. The plus signs correspond to asteroids in the FLS 5° field, asterisks correspond to asteroids in the FLS 0° field, and boxes correspond to asteroids in the SWIRE field. This plot is an adaptation of Lacy et al. (2004) as modified by Ryan & Woodward (2006).

The low albedos ($p_V \lesssim 0.1$) of the $\simeq 6$ km-sized outer belt SWIRE asteroids are similar to the albedos derived for Jupiter-family comets, $0.02 \lesssim p_V \lesssim 0.06$ (Fernández et al. 2008; Lamy et al. 2004). Recent modeling by Levison et al. (2008) investigating the capture likelihood of cometary planetesimals into the asteroid belt (leading the establishment of a D-type population) suggests that the inner edge of the D-type population is near $a \sim 2.6$ AU. Whether the population of low-albedo asteroids discovered in our SWIRE fields discussed here are organic-rich, primitive objects can only be verified with follow-up spectroscopy.

From flux measurements in all four IRAC channels, we can also begin to constrain the colors of asteroids. This is beneficial for both the understanding of bulk asteroid albedo variations as a function of size and other orbital parameters such as orbital semimajor axis or inclination and for the future exclusion of asteroids from galactic or extragalactic catalogs. Figure 4 is an adaptation of the work by Lacy et al. (2004) which shows the IRAC colors of fixed astronomical objects where we have now included asteroid color data derived from the our FLS and SWIRE field photometry. Asteroids mainly reside in one isolated locus in color space. The size of this locus is dependent
upon both temperature and albedo. The shortest wavelength observations with IRAC at 3.6 μm trace the fraction of reflected incident solar flux, thus the albedo, while the 8.0 μm to 4.5 μm ratio traces the thermal emission and thus the albedo and distance of an asteroid.

4. CONCLUSION

Our combined optical survey of ≃ 0.96 deg² and Spitzer IRAC 8.0 μm fields encompassing from 0.26 to ≃ 9.1 deg² of sky at five latitudes perpendicular to the ecliptic plane resulted in detection of 118 main-belt asteroids, of which 91 are newly identified objects either at optical or IR wavelengths. The optical and mid-IR asteroid counts and fluxes demonstrate that the slope of the size–frequency distribution is consistent with that of a similar size population at 0° and 15° ecliptic latitude. The derived power-law slopes of the asteroid surface density distribution are similar at each ∼5° ecliptic latitude bin with a mean slope of −0.111 ± 0.077. The observed asteroid number densities at optical wavelengths are generally consistent with those derived from the Standard Asteroid Model within the ecliptic plane. However, we find an overdensity at β > 5° in our optical fields, while the IR number densities are underdense by factors of 2 to 3 at all ecliptic latitudes.

For the 28 known asteroids detected in all four IRAC channels, mean albedos range from 0.24 ± 0.07 to 0.10 ± 0.05, statistically suggesting that these are two different populations. Our SWIRE data clearly samples low-albedo asteroids in the middle and outer belts, and in fact, for the first time, we are able to estimate the albedos of km-sized asteroids in the outer belt.

The errors in the slope of the size–frequency distribution cannot be decreased by greater number statistics alone. The use of fluxes as proxies for asteroid sizes does not account for variations in albedo; therefore, additional mid-IR data is required to obtain albedos and sizes for a large number of asteroids. We are in the process of completing the data-mining of additional, extant multiphase survey Spitzer IRAC and MIPS data sets while undertaking complimentary ground-based optical observations with the LBT and the 2.3 m Bok Telescope at Kitt Peak in order to increase our number statistics and lower the completeness statistics uncertainties. These data will provide an ecliptic survey area more than 3 times larger than that described in this manuscript and will also expand analysis of asteroid number counts to ecliptic latitudes of 20°. These data will extend the number of asteroids with accurate sizes to diameters much smaller than the 10 km IRAS detection limit enabling reliable number counts for asteroids with diameters ≤1 km and assessment of whether the falloff in the size–frequency distribution of main-belt asteroids distribution with diameters ≤1 km is a real signature, or an artifact introduced by the limiting magnitudes of current asteroid surveys.

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