THE YARKOVSKY DRIFT’S INFLUENCE ON NEAS: TRENDS AND PREDICTIONS WITH NEOWISE MEASUREMENTS

C. R. Nugent1, A. Mainzer2, J. Masiero3, T. Grav1, and J. Bauer2

1 Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095, USA
2 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
3 Planetary Science Institute, Tucson, AZ, USA

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ABSTRACT

We used WISE-derived geometric albedos ($p_V$) and diameters, as well as geometric albedos and diameters from the literature, to produce more accurate diurnal Yarkovsky drift predictions for 540 near-Earth asteroids (NEAs) out of the current sample of ~8800 known objects. As 10 of the 12 objects with the fastest predicted rates have observed arcs of less than a decade, we list upcoming apparitions of these NEAs to facilitate observations.

Key words: astrometry – minor planets, asteroids: general – minor planets, asteroids: individual (2010 JG87, 2006 HY51, (137924) 2000 BD19, 2010 HX107, 2002 LT24, (153201) 2000 WO107, 2010 EX11, 2008 EY5, 2006 NL, 2006 MD12, 2010 GQ75) – radiation mechanisms: thermal

Online-only material: machine-readable and VO table

1. INTRODUCTION

The Yarkovsky effect is a non-gravitational force that perturbs the orbits of small bodies, including near-Earth asteroids (NEAs). Despite its small magnitude, it must be included in the calculation of precise asteroid trajectory predictions (Giorigini et al. 2002; Milani et al. 2009), and it is believed to be a key mechanism in the process that delivers asteroids from the main belt to near-Earth space (Bottke et al. 2006).

The diurnal Yarkovsky effect (or drift) is caused by anisotropic re-radiation of absorbed sunlight. It is driven by the thermal properties of an asteroid as well as the amount of absorbed incident radiation. A given surface point on an asteroid observes maximum incident radiation at local noon, but thermal inertia causes the time of maximum emitted radiation (usually at infrared wavelengths) to occur later. Each arriving and departing photon has an associated momentum $p = E/c$, where $E$ is the photon’s energy and $c$ is the speed of light. Since the body is rotating, the incident radiation is in a different direction than the later emitted radiation, and the body experiences a very small net acceleration. If the body has a prograde spin, the net acceleration has a component aligned with the motion of the body’s orbit, nudging the body away from the Sun. Similarly, a body with a retrograde spin will feel an acceleration with a component anti-aligned with its velocity, shifting it toward the Sun (Bottke et al. 2006).

There is also a seasonal component to the Yarkovsky effect. The seasonal Yarkovsky effect is largest when an asteroid’s obliquity is 90$^\circ$, and goes to zero as obliquity approaches 0$^\circ$ or 180$^\circ$ (Bottke et al. 2006). Vokrouhlický et al. (2000) calculated the diurnal and seasonal components of the Yarkovsky effect for several objects, and in all cases the seasonal component was significantly smaller. Even in the case of (1566) Icarus, which has an obliquity equal to 103$^\circ$, the diurnal component for this object was more than twice the magnitude of the seasonal component over a range of likely thermal conductivities.

There have been few direct measurements of the Yarkovsky drift. Chesley et al. (2003) used radar ranging to make the first direct detection of the Yarkovsky drift. They measured the rate of change of (6489) Golevka’s semimajor axis ($da/dt$) to be of the order of $10^{-4}$ AU Myr$^{-1}$. A magnitude $da/dt$ of $10^{-3}$ AU Myr$^{-1}$ Yarkovsky drift was associated with asteroid 1992 BF by linking modern astrometry with observations from 1952 (Vokrouhlický et al. 2008). Nugent et al. (2012) used an orbit-fitting method to measure Yarkovsky drifts for 54 NEAs, and found an average rate magnitude of $(10.4 \pm 11.4) \times 10^{-4}$ AU Myr$^{-1}$.

The Yarkovsky effect has been modeled by several researchers (Vokrouhlický et al. 2000; Spilve & Greenberg 2001, for example). Mathematical formulations, such as those by Vokrouhlický et al. (2000), indicate that Yarkovsky drift is inversely proportional to diameter. Although the amount of absorbed radiation increases with the square of the diameter, mass increases with the cube of the diameter ($D$), so drift rate is expected to show a $1/D$ dependence.

However, because thermal inertia could also depend on size, the size dependence of Yarkovsky drift could be more complicated than presently assumed. Theory predicts that the more massive a body is, the more regolith it should retain (Scheeres et al. 2002), and regolith may act as an insulating blanket (though for bodies smaller than 10 km in diameter, spin state may be more indicative of regolith presence). Low porosity and high thermal inertia should create a longer time lag between absorbed radiation and thermal re-radiation, perhaps resulting in a stronger Yarkovsky effect (depending on the rotation state).

Additionally, these models incorporate physical properties of asteroids that are often poorly measured. Although obliquity, heat capacity, thermal conductivity, and bulk density are generally difficult to quantify, more basic properties such as geometric albedo ($p_V$) and diameter can be ill-constrained. This dearth of information has hindered the accuracy of Yarkovsky predictions.

The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) has observed over 150,000 minor planets (including ~600 NEAs) at infrared wavelengths (Mainzer et al. 2011a). It is these infrared measurements, combined with optical observations, that can separate the contributions of size and $p_V$ to the observed flux. The dependence of flux on $p_V$ is weaker in the thermal wavelengths, since the majority of the light emitted from the asteroid is from thermal emission, not reflected infrared sunlight. With a thermal model that incorporates both infrared and optical observations, size and $p_V$ can be determined. With thermally dominated WISE wavelengths, it has been shown...
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Table 1
Physical and Thermal Properties Used for Generating Predictions of $\frac{da}{dt}$ Drifts

| Composition       | $C$  | $K$  | $\rho_c/\rho_b$ |
|-------------------|------|------|-----------------|
|                   | (J kg$^{-1}$ K$^{-1}$) | (W m$^{-1}$ K$^{-1}$) | (kg m$^{-3}$) |
| Rubble Pile       | 500  | 0.01 | 1000            |
| Rock Chunk        | 500  | 0.50 | 3000            |

Notes. Thermal properties are based on the work of Opeil et al. (2010), who measured three meteorites at 200 K. Listed are heat capacity $C$, thermal conductivity $K$, bulk density of the surface $\rho_c$, and mean bulk density $\rho_b$. The surface and bulk densities are assumed to have a similar range of values; however, $\rho_c$ was not necessarily equal to $\rho_b$ for a given object and realization.

that for asteroids observed with good signal-to-noise ratios and relatively low-amplitude light-curve variations, diameter can be determined to within ±10%, and $p_V$ can be determined to within ±25% of the amount of the albedo (Mainzer et al. 2011c, 2011d). Combining WISE measurements with published reliable diameters determined from in situ spacecraft visits, stellar occultations, and radar produces a list of NEAs with well-determined diameters and geometric albedos.

2. METHODS

We employed the mathematical formulation of the diurnal Yarkovsky effect developed by Vokrouhlický et al. (2000) to numerically estimate Yarkovsky drifts. Although our methods are not identical, this work follows that of Vokrouhlický et al. (2005), who predicted drifts for 28 NEAs. We expand from this foundation, incorporating newly available physical properties.

For a time step along an NEA's orbit, the Yarkovsky acceleration was computed following Equation (1) of Vokrouhlický et al. (2000). This equation assumes a spherical body and that temperatures throughout the body do not greatly deviate from an average temperature. Obliquity was assumed to be $0^\circ$ to produce maximum drift. Therefore, the reported drifts in this paper are upper limits. Additionally, a $0^\circ$ obliquity assumes that all drift is due to the diurnal Yarkovsky effect, as the seasonal Yarkovsky effect has zero magnitude for this case (Bottke et al. 2006). This acceleration was resolved along orthogonal directions, and Gauss's form of Lagrange's planetary equations (Danby 1992) was employed to calculate average $\frac{da}{dt}$.

The magnitude of the diurnal Yarkovsky drift depends on physical parameters, which can be ill-defined. The drift magnitude is not linearly related to these unknown parameters, and so the resultant drift magnitude was statistically modeled to more accurately determine the effect of these uncertainties. For each NEA, we used $p_V$, and diameter measurements derived by WISE (Mainzer et al. 2011b) or other sources of reliable diameter and $p_V$ measurements in the literature, primarily radar detections and stellar occultations. We employed a Monte Carlo method to explore how variations in physical parameters contribute to errors in the prediction of $\frac{da}{dt}$. For 1000 realizations per NEA, we added Gaussian-distributed noise to the diameter and $p_V$ measurements, so that standard distribution of the noise corresponded to the 1σ error bars on those measurements.

As the formulation of Vokrouhlický et al. (2000) relies on Bond albedo $A$, we approximated $A$ using $A \approx (0.290 \pm 0.684G)p_V$, where $G$ is the slope parameter (Bowell et al. 1989). In seven cases, $G$ was available in the JPL Small-Body database (Chamberlin 2008). In the remaining cases, $G$ was taken to equal 0.15, as this was the value used to compute physical properties of NEAs in Mainzer et al. (2011a), based on the standard value assumed by the Minor Planet Center for computing $H$.

Additionally, we varied the thermal conductivity, bulk density, and density of the surface layer within the ranges shown in Table 1. The physical parameters in Table 1 were chosen to represent a range of asteroid compositions, so that our Yarkovsky estimates would represent reasonable estimates of the range of physical properties of rocky asteroids. At one end of the spectrum are physical properties mimicking a low-density rubble pile, and at the other, a regolith-free rock chunk.

Emissivity was always assumed to be 0.9. If rotation rate was not available in the JPL Database (Chamberlin 2008), the rotation rate was assumed to be five revolutions per day, based on the average spin rate values for asteroids 1 to 10 km in diameter shown in Figure 1 of Pravec & Harris (2000). Rotation rates were unavailable for 81% of the NEAs.

The $\frac{da}{dt}$ values quoted in this paper are the mean of these 1000 realizations. Error bars on $\frac{da}{dt}$ were determined by computing the standard deviation from the mean.

3. RESULTS

We estimated diurnal Yarkovsky drifts for 540 NEAs with measured diameters and geometric albedos. The dozen objects with the highest drifts are listed in Table 2, upcoming apparitions

Table 2
The 12 NEAs with Largest Predicted Yarkovsky Drift Rates

| NEA         | $a$  | $e$  | $i$  | $D$  | $p_V$ | Arc  | $\frac{da}{dt}$ | $\Delta \rho$ |
|-------------|------|------|------|------|-------|------|-----------------|--------------|
|             | (AU) | (deg) | (km) | (km) | (AU Myr$^{-1}$) | (km) |
| 2010 JG87   | 2.76 | 0.95 | 16.91 | 0.41 | 0.02 | 54 days | 72.11 ± 25.12 | 110.0        |
| 2006 HY51   | 2.60 | 0.97 | 30.58 | 1.22 | 0.16 | 2006–2011 | 54.35 ± 23.85 | 90.8         |
| 2007 EP88   | 0.84 | 0.89 | 20.78 | 0.64 | 0.17 | 2007–2010 | 48.57 ± 16.22 | 443.8        |
| (137924) 2000 BD19 | 0.88 | 0.89 | 25.69 | 0.97 | 0.25 | 1997–2010 | 34.30 ± 12.02 | 292.6        |
| 2010 HX107  | 0.80 | 0.30 | 33.7 | 0.06 | 0.19 | 60 days | 33.11 ± 23.05 | 323.6        |
| 2002 LT24   | 0.72 | 0.50 | 0.76 | 0.14 | 0.14 | 2002–2010 | 29.06 ± 16.58 | 333.1        |
| (153201) 2000 WO107 | 0.91 | 0.78 | 7.78 | 0.51 | 0.13 | 2000–2010 | 23.45 ± 10.14 | 188.7        |
| 2010 EX11   | 0.96 | 0.11 | 9.75 | 0.04 | 0.23 | 37 days | 23.09 ± 18.64 | 173.0        |
| 2008 EY5    | 0.63 | 0.63 | 5.07 | 0.36 | 0.12 | 2008–2011 | 23.00 ± 9.75 | 324.6        |
| 2006 NL     | 0.85 | 0.58 | 20.08 | 0.22 | 0.46 | 2006–2009 | 20.05 ± 12.66 | 179.8        |
| 2006 MD12   | 0.84 | 0.61 | 27.27 | 0.27 | 0.43 | 2006–2009 | 19.60 ± 12.15 | 178.6        |
| 2010 GQ75   | 2.43 | 0.87 | 43.23 | 0.37 | 0.11 | 34 days | 19.48 ± 9.83 | 36.0         |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
of those objects are in Table 3, and predicted drifts for all objects are available in the online-only portion of Table 2. Table 2 and the online-only material include an order-of-magnitude estimate of along-track displacement (Δρ) that would result from the da/dt drift over 10 years. For this we use the following formulation from Vokrouhlický et al. (2000):

\[ Δρ \simeq 7a_4(a_{10}t)^2a_{AU}^{-3/2}, \]

where Δρ is in units of km, \( a_4 \) is \( da/dt \) in units of \( 10^{-4} \text{ AU Myr}^{-1} \), \( a_{10}t \) is the time difference between observations in tens of years, and \( a_{AU} \) is the semimajor axis of the object in AU. We note that the four of the twelve objects with the largest predicted drifts were discovered by the NEOWISE portion of the WISE mission (2010 JG87, 2010 HX107, 2010 EX11, and 2010 GQ75).

Individual realizations for the NEA with the fastest predicted drift, 2010 JG87, are examined in Figures 1 and 2. In each of these figures, all 1000 realizations of physical parameter combinations are shown, so their individual influences are apparent for this object.

2010 JG87’s diameter was determined to within ±10% (Mainzer et al. 2011b) based on the WISE observations (Figure 1), and as diameter and bulk density are used to

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
NEA & da/dt (10^{-4} \text{ AU Myr}^{-1}) & Apparition & V (mag) Range & Decl. Range (deg) \\
\hline
2010 JG87 & 64.99 ± 23.26 & 2014 May 29–2014 Sep 20 & 20.3, 24.4 & 07, 19 \\
2006 HYS1 & 34.32 ± 14.86 & 2014 Feb 8–2014 Jul 6 & 21.5, 23.6 & −12, −03 \\
2006 EY5 & 23.26 ± 10.60 & 2015 Feb 4–2015 Jun 17 & 20.4, 22.9 & 06, 22 \\
2006 MD12 & 19.60 ± 12.15 & 2016 May 25–2016 Aug 15 & 18.3, 21.5 & −15, 55 \\
2010 GQ75 & 36.30 ± 12.49 & 2017 Apr 30–2017 Jul 25 & 21.5, 24.5 & −70, 36 \\
\hline
\end{tabular}
\caption{Observing Opportunities for NEAs with Highest Predicted Yarkovsky Drift Rates}
\end{table}
Figure 1. One thousand realizations of diameter vs. \( \frac{da}{dt} \) for NEA 2010 JG87. Each point represents the drift produced by a different combination of physical parameters. This object has the fastest predicted diurnal drift of all the NEAs in this paper, with \( \frac{da}{dt} = (72.11 \pm 25.12) \times 10^{-4} \text{ AU Myr}^{-1} \). Although Yarkovsky drift has a \( \frac{1}{D} \) dependence, the relatively small error bars on this object’s diameter (and therefore the small range of diameters shown in this plot), combined with the variations in the other parameters (surface density, bulk density, thermal conductivity \( K \), \( p_v \), and \( G \)) prevent this dependence from being immediately apparent in this figure. For a clearer illustration of the relationship between \( \frac{da}{dt} \) and diameter, see Figure 3. For the relationship between \( \frac{da}{dt} \) and the other physical properties that were varied during each realization, see Figure 2.

Figure 2. One thousand realizations of predicted diurnal \( \frac{da}{dt} \) drift for 2010 JG87, the NEA with the fastest predicted diurnal drift in this paper. For each realization, diameter, thermal conductivity, geometric albedo, slope parameter \( G \), density of the surface layer, and bulk density were varied as described in the text. Gray lines are running averages. For this object, it is the uncertainty in bulk density that is mainly responsible for the span of calculated \( \frac{da}{dt} \) drifts, as the diameter of this object is well-constrained (see Figure 1). Also visible are the relationships between thermal conductivity and surface density and drift. These two properties govern the thermal lag angle.

We now examine the values that govern Yarkovsky strength for all objects in our sample. As we are comparing the mean \( \frac{da}{dt} \) values of each object, the following compares drifts effectively computed with the same bulk density and density of the surface layer. The predicted diurnal \( \frac{da}{dt} \) has a \( \frac{1}{D} \) dependence, and also depends on the amount of average incident radiation the NEA receives per orbit and \( \frac{da}{dt} \).

The \( \frac{1}{D} \) dependence can be seen in Figure 3. As all objects in these plots are assumed to have the same bulk density (2000 kg m\(^{-3}\)), it is only the difference in diameters that produces different mass estimates.

After diameter, the second parameter that strongly influences drift magnitude is the average incident radiation per orbit, as estimate mass, it is the uncertainty in bulk density that mainly determines the predicted drift for this object (Figure 2). Surface density and thermal conductivity both contribute to the thermal lag, and for this object, low values of \( K \) and \( \rho_s \) lead to a thermal lag that produces the strongest drifts (given the object’s assumed rotation period of 5 revolutions day\(^{-1}\)). As geometric albedo has been determined to be 0.20 \( \pm \) 0.04 for this object, the range of geometric albedo values explored do not strongly influence the resulting drift.
Figure 3. Relationship between the average incident radiation each NEA receives per orbit and predicted diurnal da/dt drift. Circle sizes are proportional to the diameter of the object. The more sunlight an object receives during its orbit, the more power is available to the Yarkovsky drift. However, this link is tempered by the diameter—larger objects experience a smaller drift than smaller objects, given the same average incident radiation.

seen in Figure 3. The more light received by the NEA over its orbit, the more light is available for re-emission and the loss of momentum that powers the drift.

Many values of $da/dt$ reported in the online-only material of Table 2 have large error bars due to uncertainties in physical properties. Observations that further constrain the obliquity, density, rotation rate, thermal conductivity, and heat capacity would also constrain predicted drift rates. Measurements of thermal properties of these objects would be valuable, as would the measurement of rotation rates and obliquities (either from light curves or radar observations). It is expected that one out of six objects larger than 200 m are binary systems (Margot et al. 2002; Pravec et al. 2006), a property which could enable density measurements.

Historically, Yarkovsky detections require either radar observations over three apparitions (Chesley et al. 2003) or optical observations that meet a set of criteria. Nugent et al. (2012) required an object to (1) have an observed arc of at least $\sim$15 years, (2) have observations distributed throughout that arc in time (defined as at least eight observations per orbit for at least five orbits), and (3) have a fraction of these observations at favorable geometries and distances (defined by the Yarkovsky sensitivity $s_Y > 2.0$).

None of the objects in Table 2 have enough optical or radar observations to meet the above criteria for detection. Therefore, when possible we encourage the community to observe these objects and contribute astrometry to the Minor Planet Center. More astrometry is needed for all these objects to enable a future Yarkovsky detection via a fit to optical-only data.

To facilitate these observations, Table 3 provides apparitions and associated apparent magnitude ranges for these objects between 2012 April 1 and 2022 April 1. These apparitions are defined as the times when the object’s elongation is greater than 90°, and were generated using the JPL’s Horizons ephemeris computation service.

The worldwide community of amateur and professional follow-up observers is encouraged to consult this table when planning their observations. Several of the brighter objects may also be automatically picked up by sky surveys such as (in order of decreasing number of observations) PanSTARRS, the Catalina Sky Survey, Spacewatch, and the Lincoln Near Earth Asteroid Research Program (Larson 2007; McMillan 2007; Stokes et al. 2000). However, some of these objects only have brief windows where their elongation is greater than 90° and $V < 20.5$ mag (which is roughly the sensitivity limit of most surveys) and may be missed without special attention. The two brightest objects are likely to be automatically observed by surveys; however, additional observations that expanded coverage over the orbit in mean anomaly would be useful.

Unfortunately, not all objects are easily observable. 2010 EX11 does not have an elongation greater than 90° during that time span, though on two apparitions (in 2012 and 2013) it does exceed 60°. Several of the remaining objects are extremely faint, with $V$ (mag) rarely brighter than 23.5. Although these observations may be challenging, they are vital for well-defined orbits and future Yarkovsky detections.

4. CONCLUSION

In this paper, we use WISE-derived geometric albedos and diameters, as well as values for geometric albedos and diameters published in the literature, to produce more accurate diurnal Yarkovsky drift predictions for 540 NEAs. Table 2 lists the 12 objects in our sample with the fastest rates, and Table 3 gives their apparitions over the next decade. Three of these objects have observed arcs of less than a year, and we encourage observers to obtain more astrometry of these objects when possible. Predicting which NEAs are most likely to be subject to strong Yarkovsky drifts relies upon robust determinations of asteroid physical properties, underscoring the need to continue to obtain such characterization data.

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