THE TRAJECTORY DYNAMICS OF NEAR-EARTH ASTEROID 101955 (1999 RQ_{36}).
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Introduction: 101955 (1999 RQ_{36}), a ~500-m diameter Potentially Hazardous Asteroid, is the target of the OSIRIS-REx sample return mission. A prime objective of the mission is to measure the Yarkovsky effect on this asteroid and constrain the properties that contribute to this effect. This objective is satisfied both by direct measurement of the acceleration imparted by anisotropic emission of thermal radiation, the first results of which are reported here, and by constructing a global thermophysical model of the asteroid to confirm the underlying principles that give rise to this effect.

September 2011 radar astrometry from the Arecibo Observatory unambiguously reveals the action of the Yarkovsky effect. This, when combined with observational constraints on the thermal inertia of the body, allows us to estimate the bulk density. The new orbit is extraordinarily precise, allowing determination of past and future deterministic planetary encounters and a more careful assessment of the impact hazard.

Observational Data: Arecibo and Goldstone obtained radar astrometry and an extensive sequence of delay-Doppler images during close Earth approaches in 1999 and 2005. Inversion of the radar images by Nolan et al. [1] yielded a detailed 3D model with an effective diameter of 493±20 m and an estimate of the pole direction, which is within 15° of ecliptic latitude −90°. In Sept. 2011, Arecibo successfully measured the radar delay with a precision of 2 μs at a range of 0.20 AU. The 22 radar range and 7 Doppler measurements are augmented by 462 optical astrometric measurements from 1999-2012.

Orbit Estimation: The new orbit for 1999 RQ_{36} is the most precise in the asteroid catalog, as measured by the 6 m formal uncertainty in the osculating semimajor axis. Such precision requires an unprecedented level of fidelity in the force model used when computing the asteroid trajectory. As an example, the relativistic effects of the Earth's gravity potential are seen in the orbit at the 3-sigma level. We include the gravitation of the Sun, planets, Moon, and 17 minor planets, and relativity for the Sun, planets and Moon, although only the Earth and Sun appear relevant. We also consider direct solar radiation pressure, but the Yarkovsky effect is the most significant nongravitational acceleration. We model the thermal acceleration as a constant times r^{-2} in the transverse direction, and average in time to obtain the mean rate of change of semimajor axis, $da/dt = -18.99 \pm 0.10 \times 10^{-4}$ AU/My.

Close Approaches. Eleven approaches to Earth closer than 0.05 AU over a span of 481 years can be confidently predicted. The closest approach is a sub-lunar distance encounter in 2135, the last that can be predicted without statistical arguments.

Year	Sept. Date	Nom. Dist. (AU)	Enc. Time Uncert. (s)
1654	18.12	0.0203	43226
1788	20.55	0.0098	2218
1848	21.92	0.0079	104
1911	22.89	0.0142	2
1970	27.11	0.0214	2
1999	22.76	0.0147	<<1
2005	20.45	0.0331	<<1
2054	30.04	0.0393	2
2060	23.03	0.0050	1
2080	22.03	0.0155	399
2135	25.44	0.0023	5719

Earth Impact Hazard. Milani et al. [2] found a cumulative probability of impact of ~10^{-3} in the few decades after 2160, with most of the risk associated with a potential Earth encounter in 2182. The new radar astrometry allows us to eliminate the 2182 impact hazard, but we find that the increased orbital precision increases the impact probabilities of those potential impacts that persist, as well as revealing new potential impacts in the same timeframe that were previously too remote to resolve. Thus, the tabulation of potential impacts is qualitatively similar, with the cumulative impact probability still of order 10^{-3}.

Thermal modeling: The drift in semimajor axis due to the Yarkovsky Effect is primarily dependent on the body's thermal inertia Γ, bulk density ρ, diameter, and obliquity. From radar we have an excellent estimate of the last two of these, while modeling of Spitzer and Herschel space telescope observations indicates $\Gamma = 600 \pm 150$ $Jm^{-2}s^{-0.5}K^{-1}$ from [3,4]. Using these data and applying the Yarkovsky model described in [5] leads to an estimate of the bulk density of $\rho = 0.97 \pm 0.15$ g/cm^3. This suggests a macroporosity of ~50-60%, assuming a material density of 2-2.5 g/cm^3.

References: [1] Nolan et al. (2012) ACM 2012 Abstract. [2] Milani et al. (2009) *Icarus, 203,* 460-471. [3] Emery et al. (2010) *LPS XLI*, Abstract #1533. [4] Mueller et al. (2012), *A&A*, in prep. [5] Vokrouhlický, Milani, Chesley (2000), *Icarus, 148,* 118-138.