The Origin of Near Earth Asteroids

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Priors, Quaternions and Residuals, Oh My!
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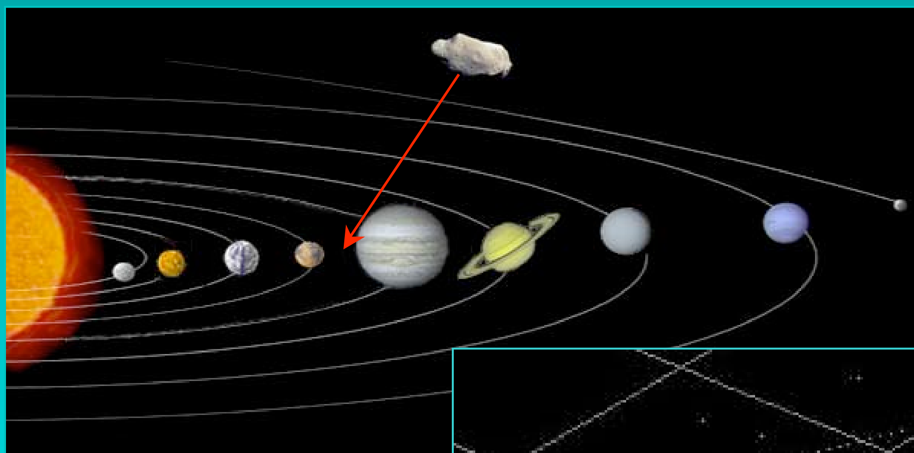
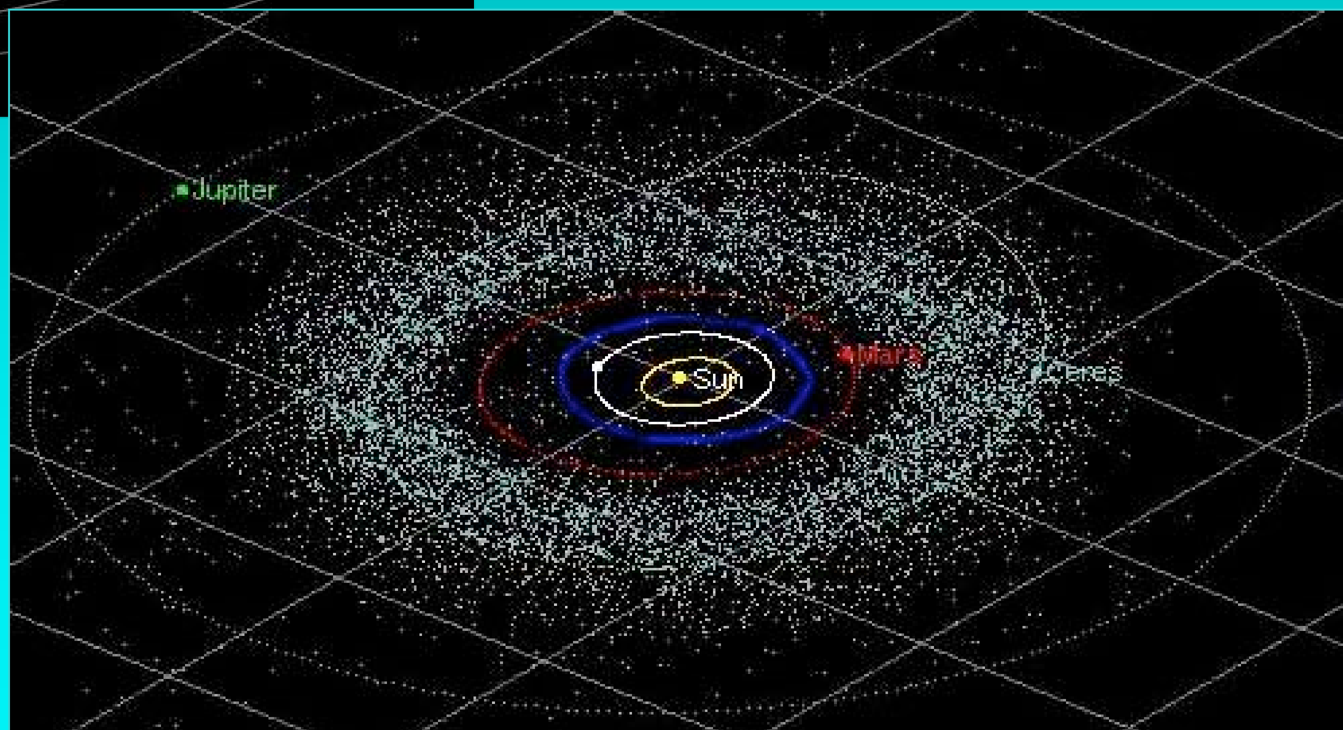
Outline

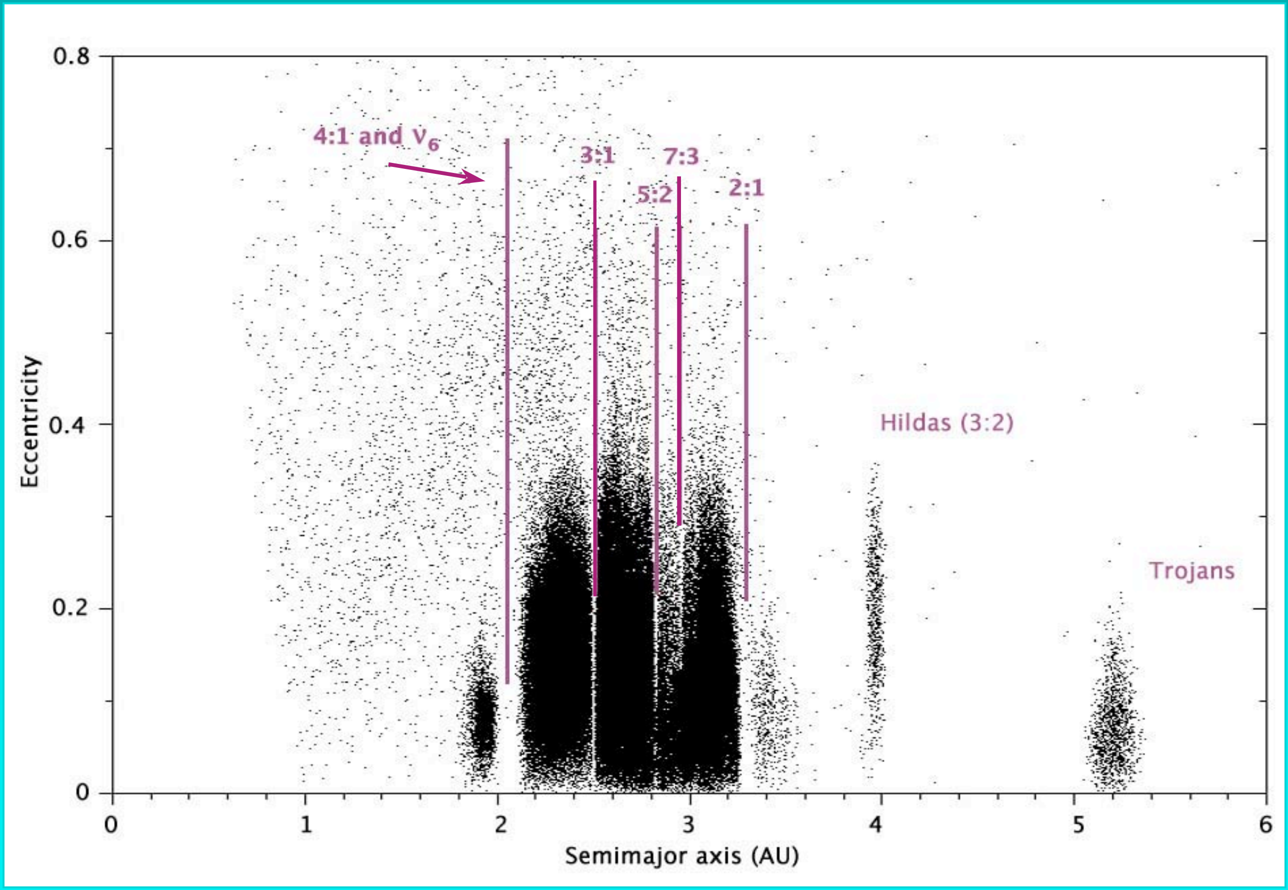
- Why are we interested in Near Earth Asteroids?
- How does an asteroid become an NEA?
  - The structure of the Asteroid Belt
    - Collisions
    - Mean motion and secular resonances
    - Non-gravitational effects
  - Transport from the Main Belt
- McDonald Observatory and NEA research
    - Time permitting

Asteroids and the Asteroid Belt





Structure of the Asteroid Belt



Kirkwood (1867)

Orbital elements reveal structure at mean motions, where

$$i\, n_A \approx j\, n_J$$

$$n = (GM/a^3)^{1/2}$$

i and j are small integers

No satisfactory explanation till the mid 1980es and even then…

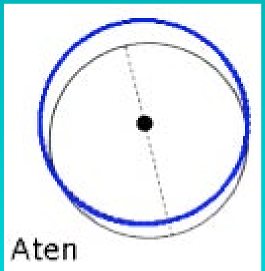
Near Earth Objects: NEOs

NEOs: Asteroids and comets with $q < 1.3$ AU

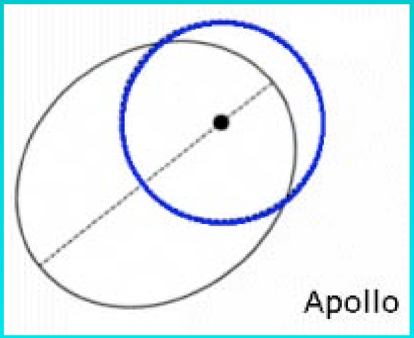
NECs: $q < 1.3$ AU, $P < 200$ years

q = perihelion distance
Q = aphelion distance
a = semi-major axis

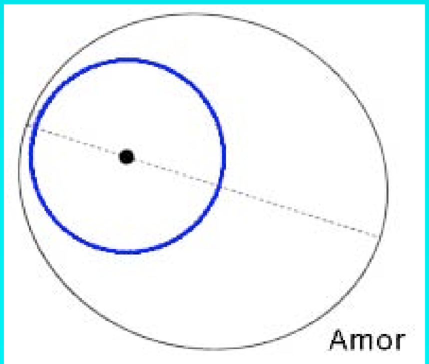
NEA groups:



- Aten: $a < 1.0$ AU, $Q > 0.983$ AU
  (Earth crossers from inside)



- Apollo: $a > 1.0$ AU, $q < 1.017$ AU
  (Earth crossers from outside)



- Amor: $a > 1.0$ AU, $1.017 < q < 1.3$ AU
  (Exterior to Earth's orbit but interior to Mars')

More Definitions…

PHAs - Potentially Hazardous Asteroids

- Minimum orbit intersection distance with the Earth ≤ 0.05 AU

  Chance to get closer to Earth than 20 lunar distances

- Absolute magnitude is H= 22.0 or brighter.
  - H is defined as the mean brightness at zero phase angle 1 AU from the Earth and the Sun
  - Estimated size D

$$\log(D) = 3.129 - 0.5\log(p) - 0.2H \quad 0.05 \le p \le 0.025$$

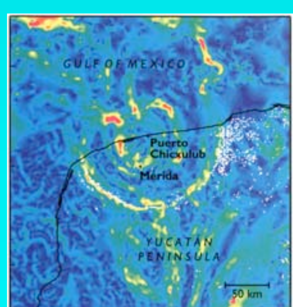
H	**D**
14	4000 - 9000 m
18	670 - 1500 m
22	110 - 240 m

1 magnitude uncertainty in H introduces a factor of 2 error in D, corresponding to a factor of 8 in impact energy

Terrestrial Impact Structures

Geological evidence for old collisions:

- Impact structures
- Iridium abundance



Observed Events

1908 Tunguska Valley

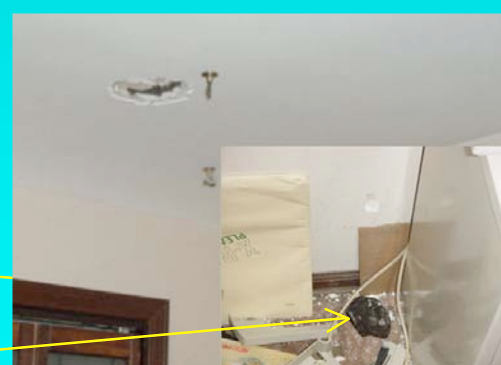
- 2000 km^2 flattened, seismic vibrations recorded as far away as 600 miles
- At 300 miles loud bangs heard, a fiery cloud on the horizon
- At 110 miles brilliant fireball seen with 500 mile tail, thunderous noises reported
- At 40 miles people were thrown to the ground, knocked unconscious; windows broken
- Magnetic storm after the event, unusually bright night all over the world

1935 British Guyana?

- Native legends

1947 Sikhote-Alin

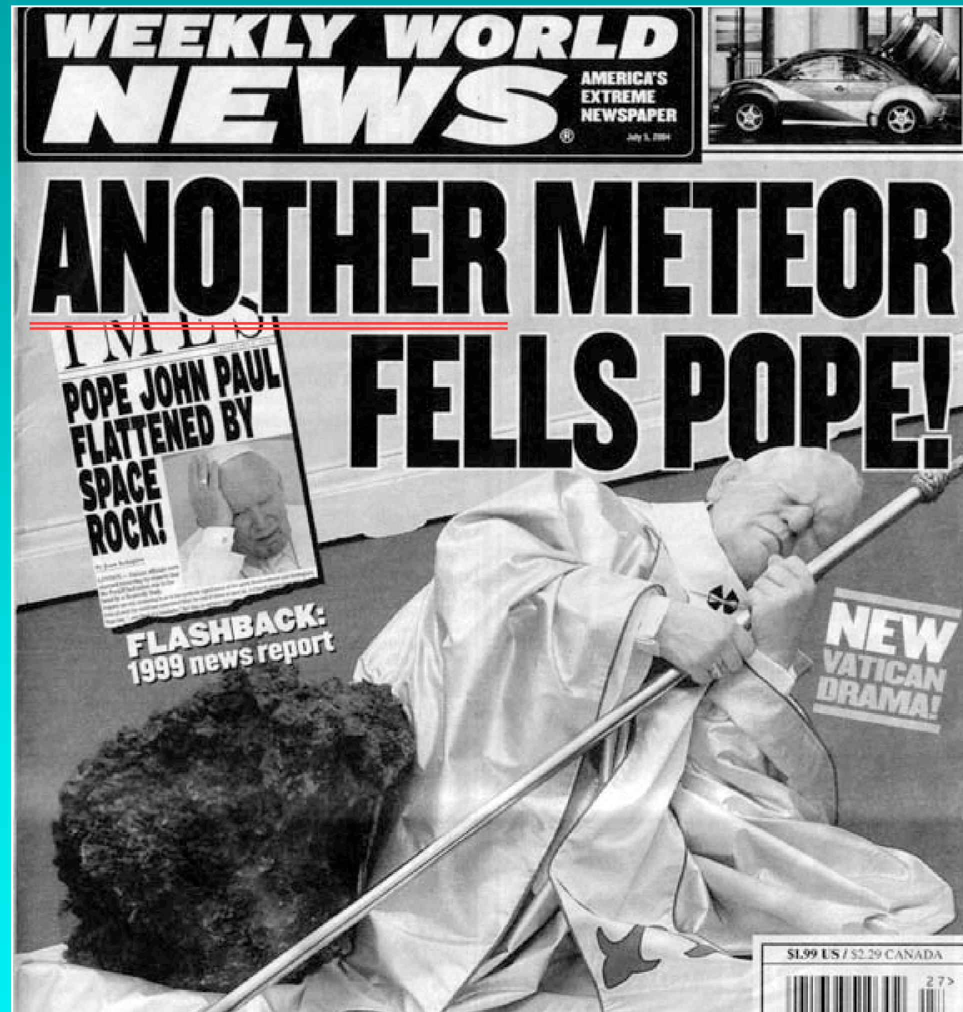
1992 Peekskill, New York



2003 Chicago, Illinois

But the real reason to monitor NEAs

is because…



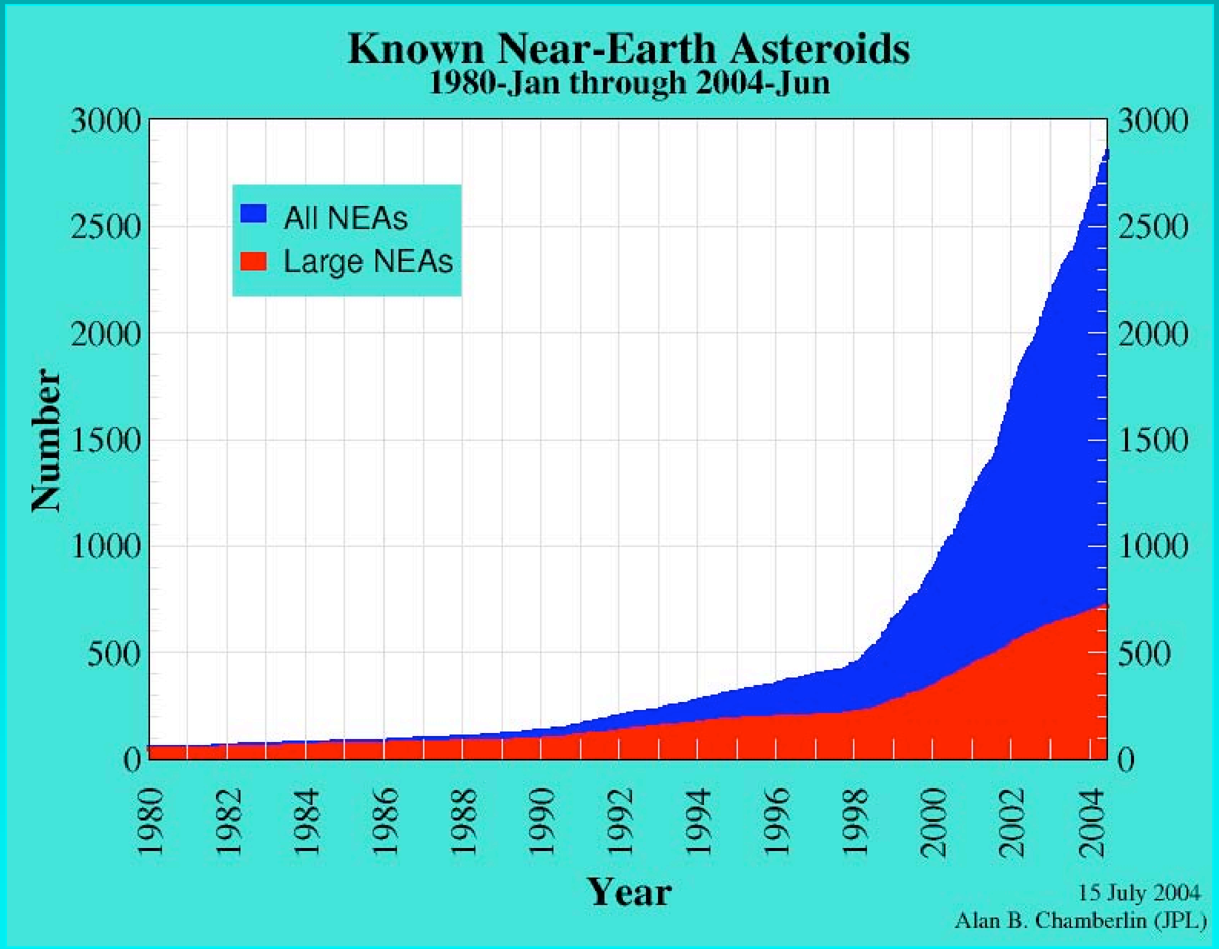
….no one is completely safe

Number of Known NEAs

Largest NEA is 25 km in diameter, majority is less than 1 km in size

At present, we do not know of any NEA which is actually destined to hit the Earth

- Of the 55 objects having the highest collision probability, the three largest are ~ 700m
- One object requires careful monitoring
  - two potential impacts in 2101
  - size ~230m



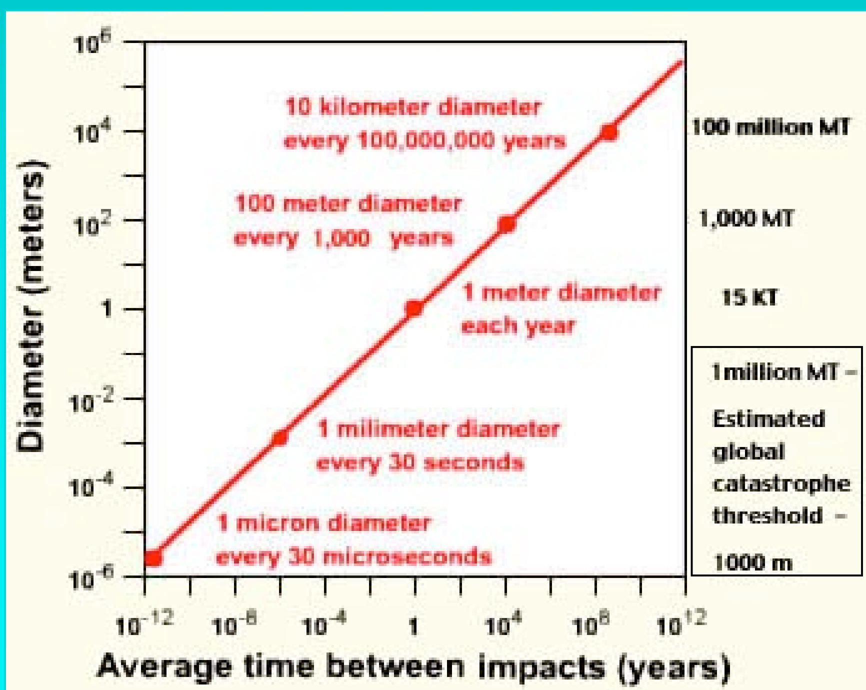
So, is IT coming, and when?

None that we know of at the moment

- The last big one (~10-15 km) came 65 million years ago

The population of hazardous objects is unknown

- Estimated 40 - 50 % of large asteroids is still undiscovered)
- Amount of damage by a given impactor is uncertain



Chances of Dying from Selected Causes in the USA

Motor Vehicle Accident	1 in 100
Murder	1 in 300
Fire	1 in 800
Firearms Accident	1 in 2,500
Electrocution	1 in 5,000
Passenger Aircraft Accident	1 in 20,000
ASTEROID IMPACT	**1 in 25,000**
Flood	1 in 30,000
Tornado	1 in 60,000
Venomous Bite or Sting	1 in 100,000
Fireworks Accident	1 in 1 million
Food poisoning	1 in 3 million

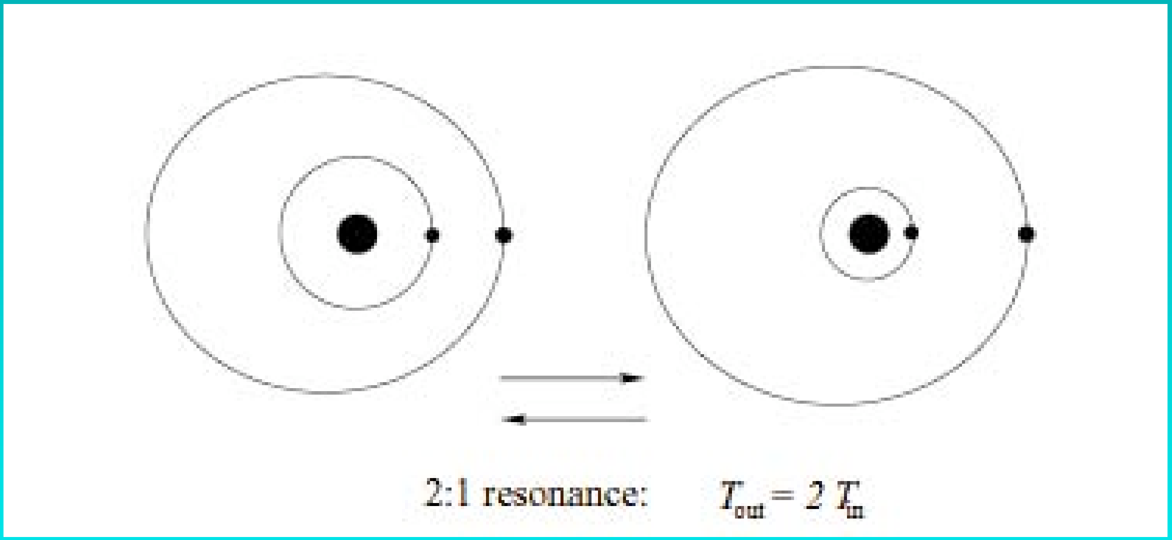
How do Asteroids Become NEAs?

- Mean motion resonances with Jupiter
  - Eccentricity of the asteroid grows large, leading to collisions with neighbors and ejecting fragments
  - Eccentricity of the asteroid grows large, no collisions with neighbors, becomes terrestrial planet crosser (most end up in the Sun)
  - Ejection from the inner solar system
- Secular resonance with major planets
  - In the case of secular resonance, what matters are not the orbital periods, but rather the periods of time (on the order of tens of thousands of years) over which the orbits change their mutual orientation
  - The ν_6 resonance affects orbits whose direction of perihelion precesses around the Sun at the same rate as Saturn
    - Combined with the 4:1 mean motion resonance, it provides the inner and high-inclination boundary to the observed distribution of asteroids
    - Steady provider of chaotic Earth crossing orbits

Example of a mean motion resonance

$$\phi_{221} = (\nu_i - 2\nu_o)t + 2(\varpi_i - \varpi_o)$$

$$\dot{\phi}_{221} \simeq \nu_i - 2\nu_o \simeq 0$$



Energy exchange tends to be in same direction at conjunction

ϕ_{221} is slowly varying - terms depending on this angle no longer time-average to zero

THEY ARE CAPABLE OF EXCHANGING ENERGY

How do Asteroids Become NEAs?

Median lifetime for a resonant asteroid before it becomes Earth crosser

3:1 resonance, few million years

cannot be the only source, we know meteorite ages up to 20 million years

2:1, hard to remove bodies, most of them ejected on hyperbolic orbits

5:2, lifetime a few 100,000 years, but most of them ejected

ν_6, 2 million (6 million as NEA) shorter than the age of the Solar System

Needs replenishing, cratering rates indicate steady NEO flux over the last 3 billion years

We can look at overlapping resonances, diffusion, resonance with terrestrial planets, close encounters with Mars

Helps but still does not explain steady flux or old meteorites

What about non-gravitational forces ?

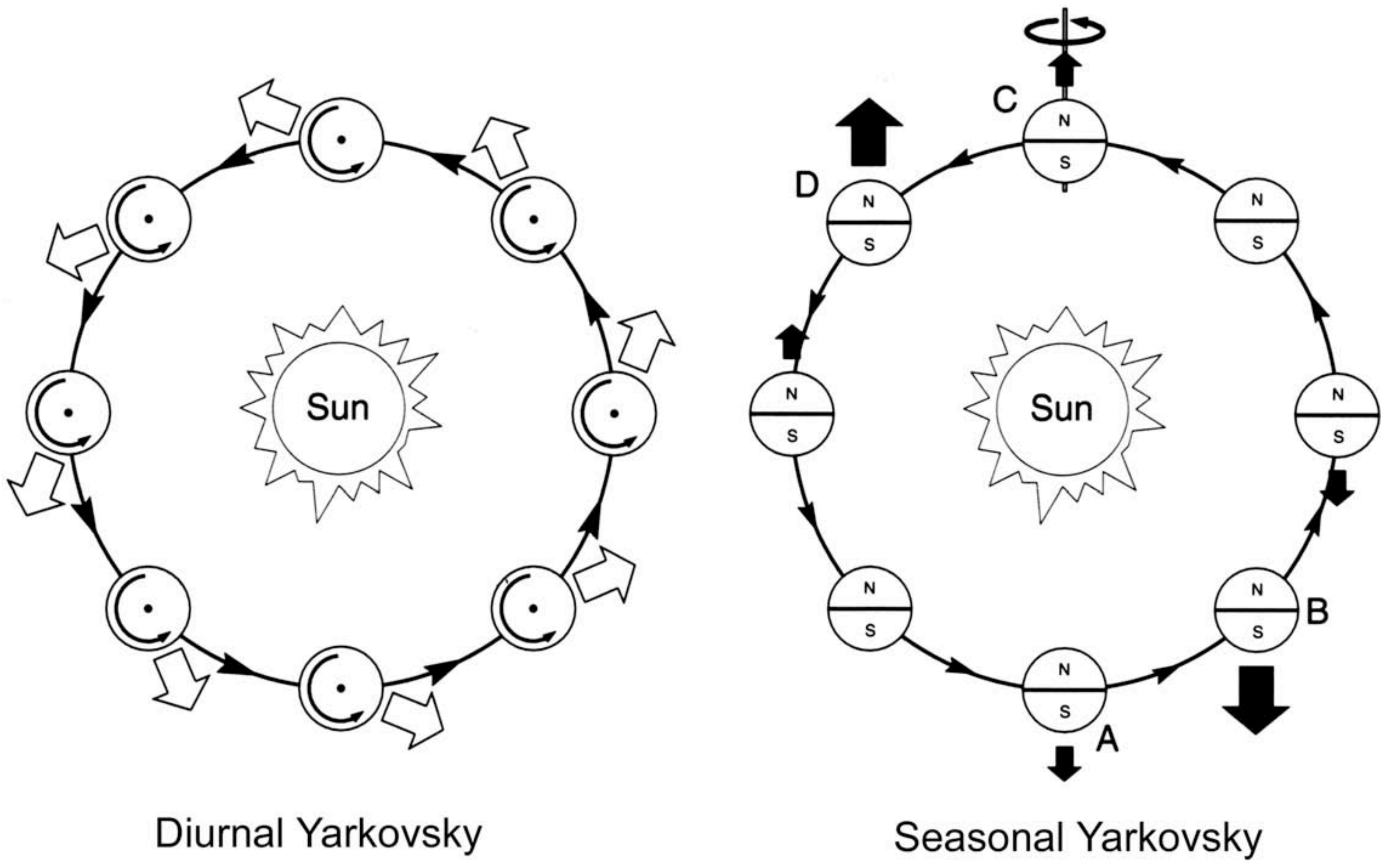
Solar Radiation Effects

- Radiation pressure - no secular effect
- Poynting-Robertson drag - more applicable to dust
- Yarkovsky effect - delayed re-radiation of absorbed Solar radiation

  affects sizes few meters to 20 km

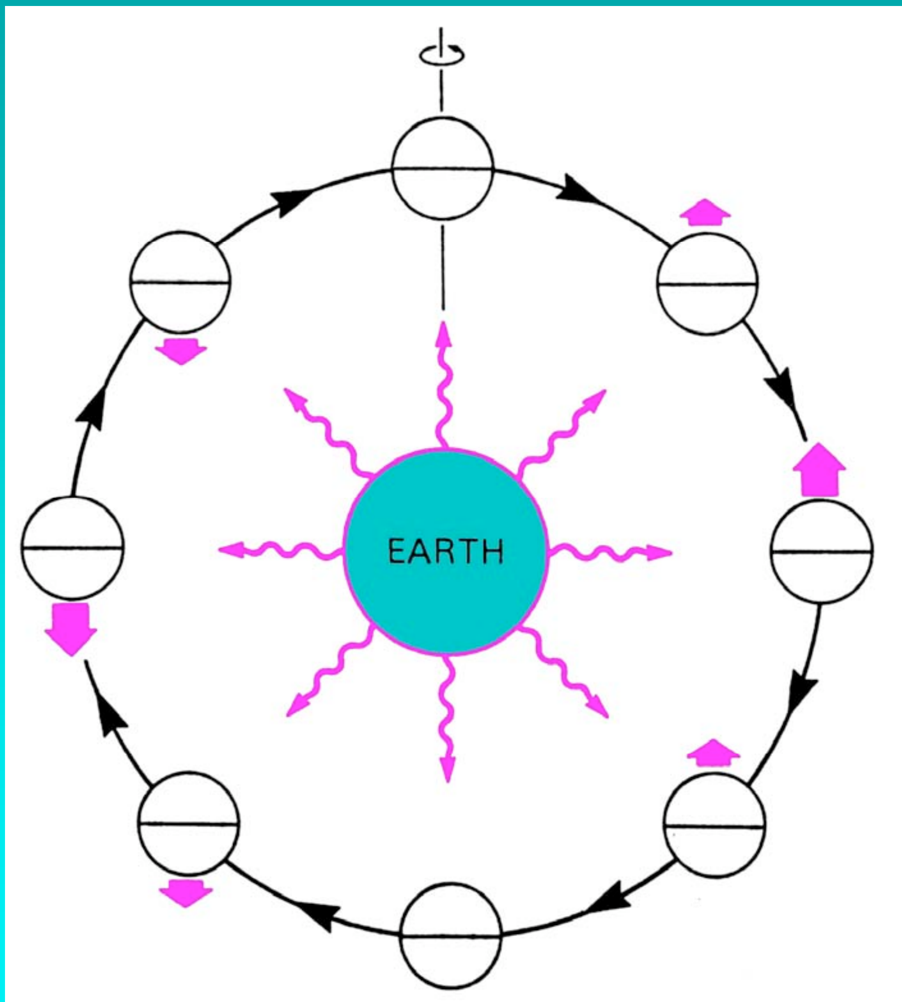
  - Diurnal and seasonal Yarkovsky effect
  - Additional perturbation due to surface inhomogeneities and irregular shapes (YORP effect)

Yarkovsky Effect
(Delayed reradiation of heat)



From Asteroids III, Bottke et al., 2002

LAGEOS - EARTH THERMAL HEATING



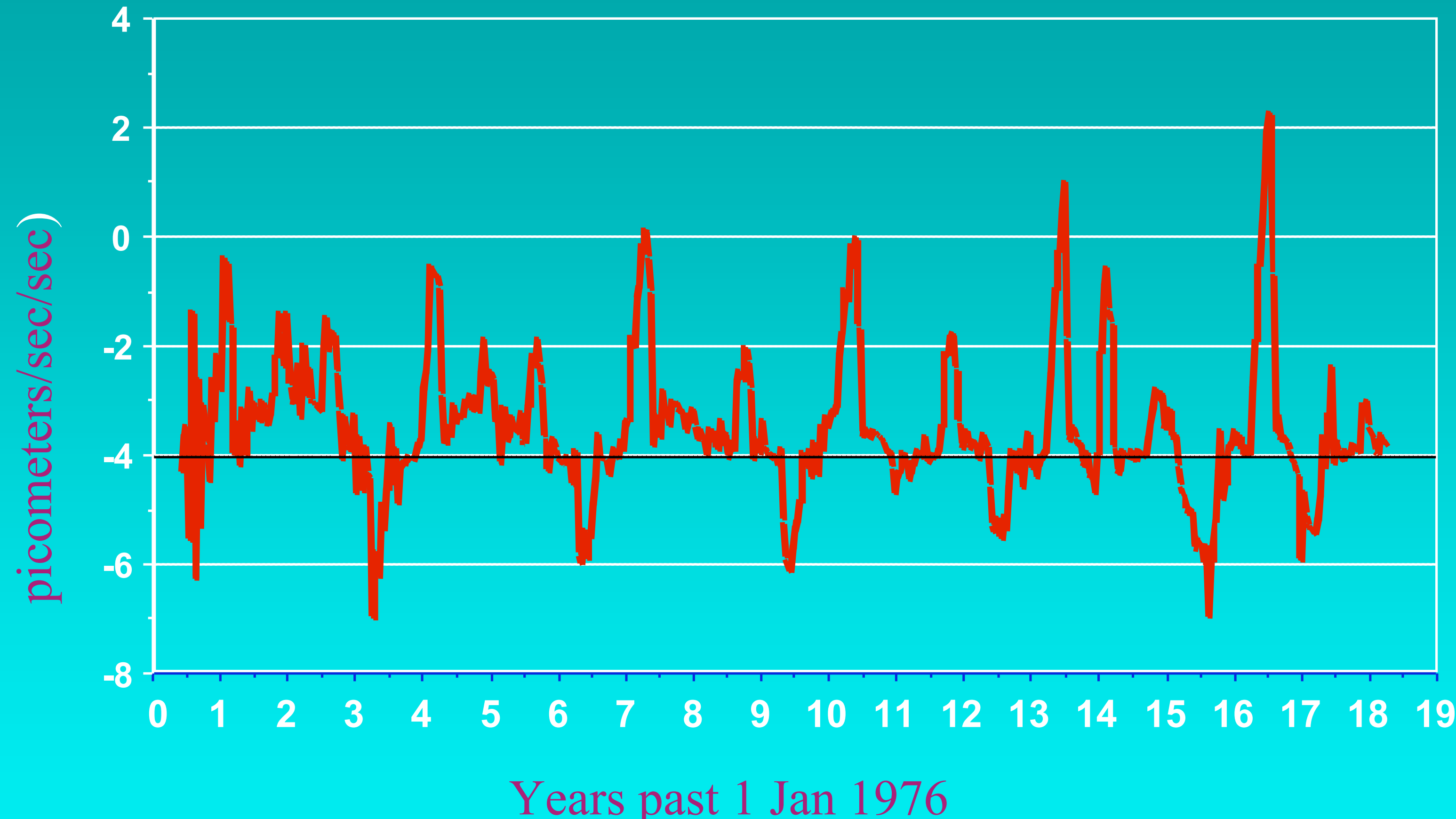
Delayed reradiation
of heat absorbed from the Earth
results in a non-zero net
transverse acceleration that
decreases the semimajor axis

Effect is maximum when the
spin axis is in the orbital plane
(leads to periodic variations as
orbit plane precesses)

10 meters in 28 years

from Rubincam, 1987

Yarkovsky-type Accelerations for LAGEOS



Drag-like forces observed on LAGEOS soon after launch that was several times larger than expected from drag, reducing semi-major axis by ~37 cm/yr.

Eventually, it became clear that Yarkovsky-type forces were the cause.

Origin of NEOs - Summary

Long term numerical simulation (based on the debiased NEO population, distribution of main belt rotation rates, assuming thermal properties)

- 23% form 3:1 resonance
- 25% from Mars crossers
- 37% from ν_6 secular resonance
- 8% Diffusive resonances in the outer belt
- 6% trans - Neptunian

While these regions deplete on the order of 10 million years the Yarkovsky effect can move collisional fragments to these region to provide a steady source.

NEO Astrometry @ McDonald Observatory

Why bother with follow-up observation?

Orbits for confirmation objects and provisional designations are based on a limited number of observations:

- Short arc
- Limited time coverage
- Only gravitational effects inc.

Orbital prediction are limited, some NEAs are lost due to insufficient follow-up

2004/09 17 - 9 out of the 151 “new” objects posted were not confirmed, 3 were not real, and 51 were not interesting.

0.7m telescope with prime focus camera

(22^{nd} magnitude in R in 15 minute exposure)

NEO Astrometry @ McDonald Observatory

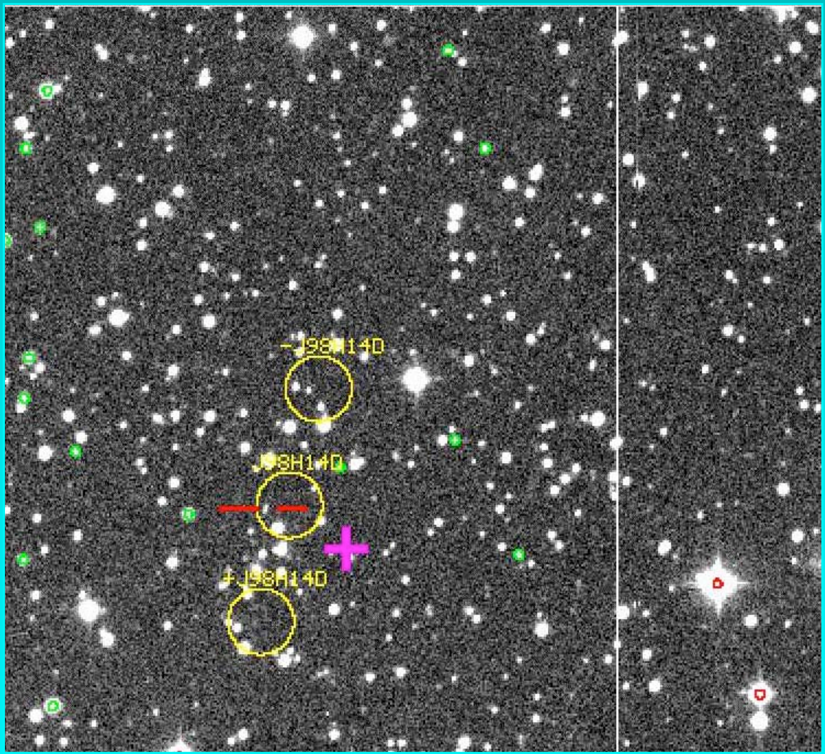
We take a set of three CCD images with the R filter, on each plate:

- Match stellar images with positions calculated from coordinates given in USNO-A2.0
- Determine plate solution

  x $= a_1x + a_2y + a_3 + a_4xy + a_5(x^2 + y^2) + a_6x(x^2 + y^2)$

  h $= b_1y + b_2x + b_3 + b_4xy + b_5(x^2 + y^2) + b_6y(x^2 + y^2)$

- Measure and calculate target position



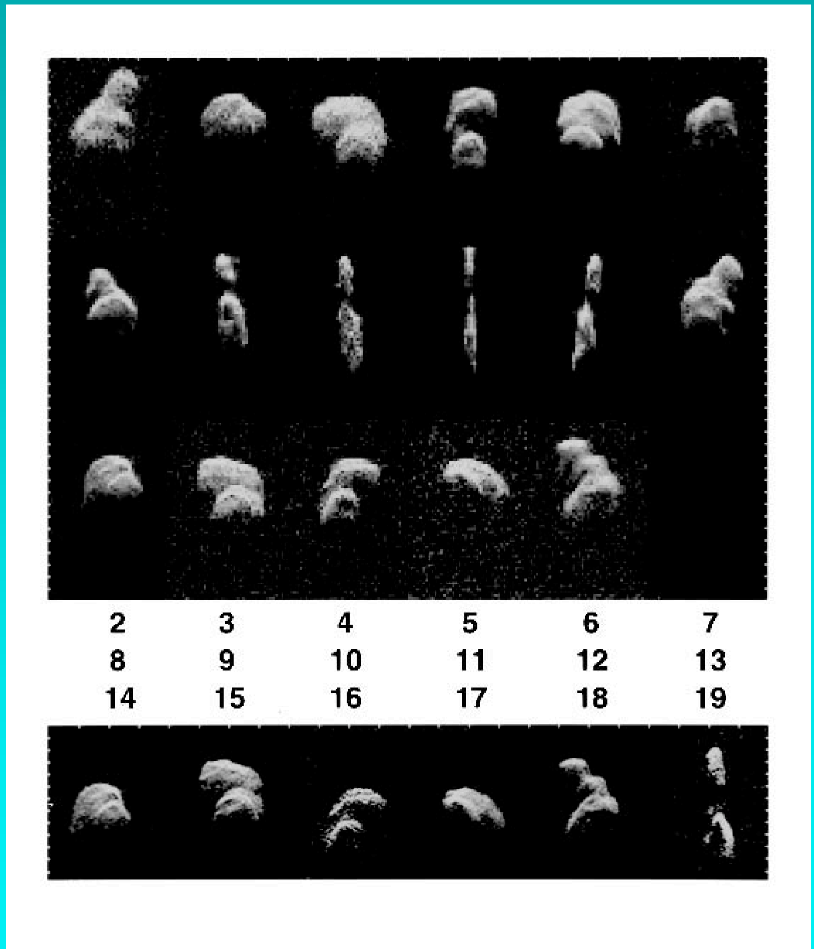
Accuracy from residuals provided by MPC is about 0.3-0.6 arcsec

Using USNO-A2.0 to provide stellar magnitudes in R, we can achieve an accuracy of about 0.1 - 0.15 mag

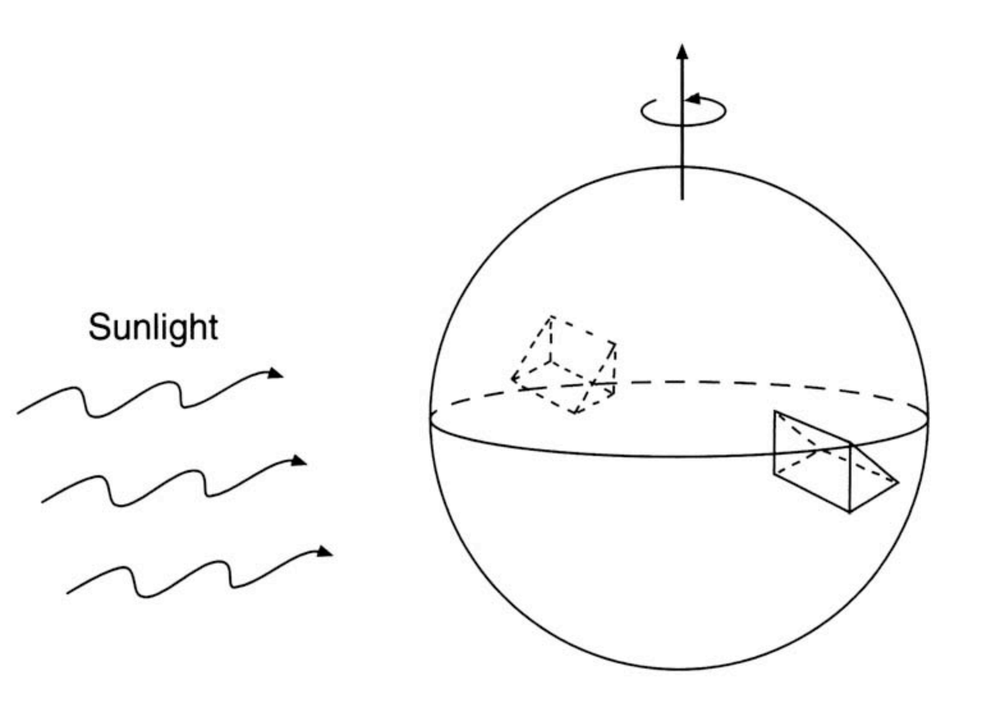
Rotation period determination

Measuring asteroid brightness in R

- Brightness changes
  - Distance of asteroid from Sun and Earth changes
  - Amount of surface reflecting light changes
  - Surface reflectivity changes
- We can determine
  - Rotation rate
  - Shape
  - Pole orientation
  - Surface reflectivity



Yarkovsky-O'keefe-Radzievskii-Paddack (YORP) Effect



From Asteroids III, Bottke et al., 2002

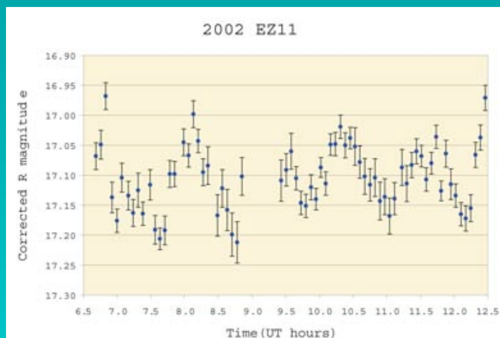
Simple model of an asymmetric asteroid:

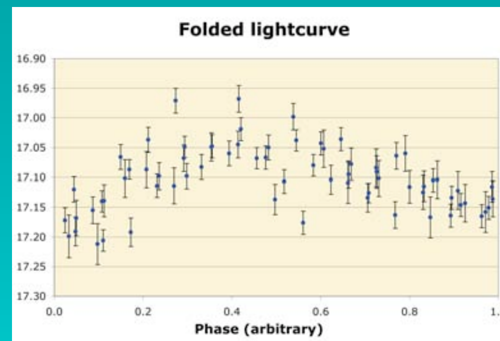
Rotating BB sphere with wedges at the equator emit radiation in opposite directions providing a torque

Asteroids spins up or really slows downs

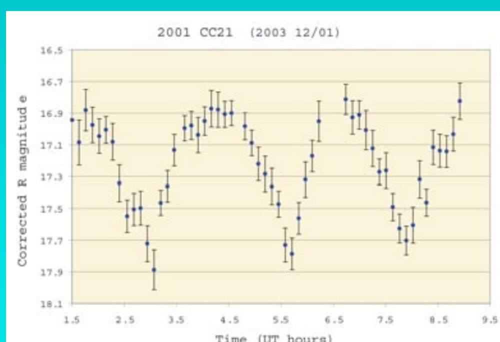
We can measure asteroid rotation periods

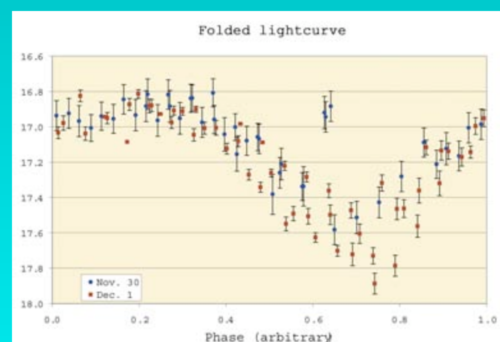
Lightcurves obtained @ McDonald Observatory



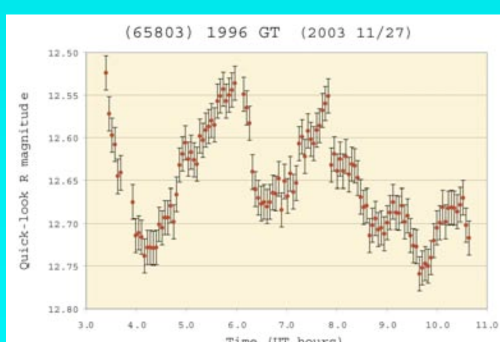


P= 1.16 h
Peak to peak variation 0.15 mag





P= 2.49 h
Peak to peak variation 0.95 mag



P= 2.22* h
Peak to peak variation 0.2 mag
Arecibo radar target, binary asteroid