NEA discovery, orbit calculation and impact probability assessment

Asteroid Grand Challenge
Seminar Series

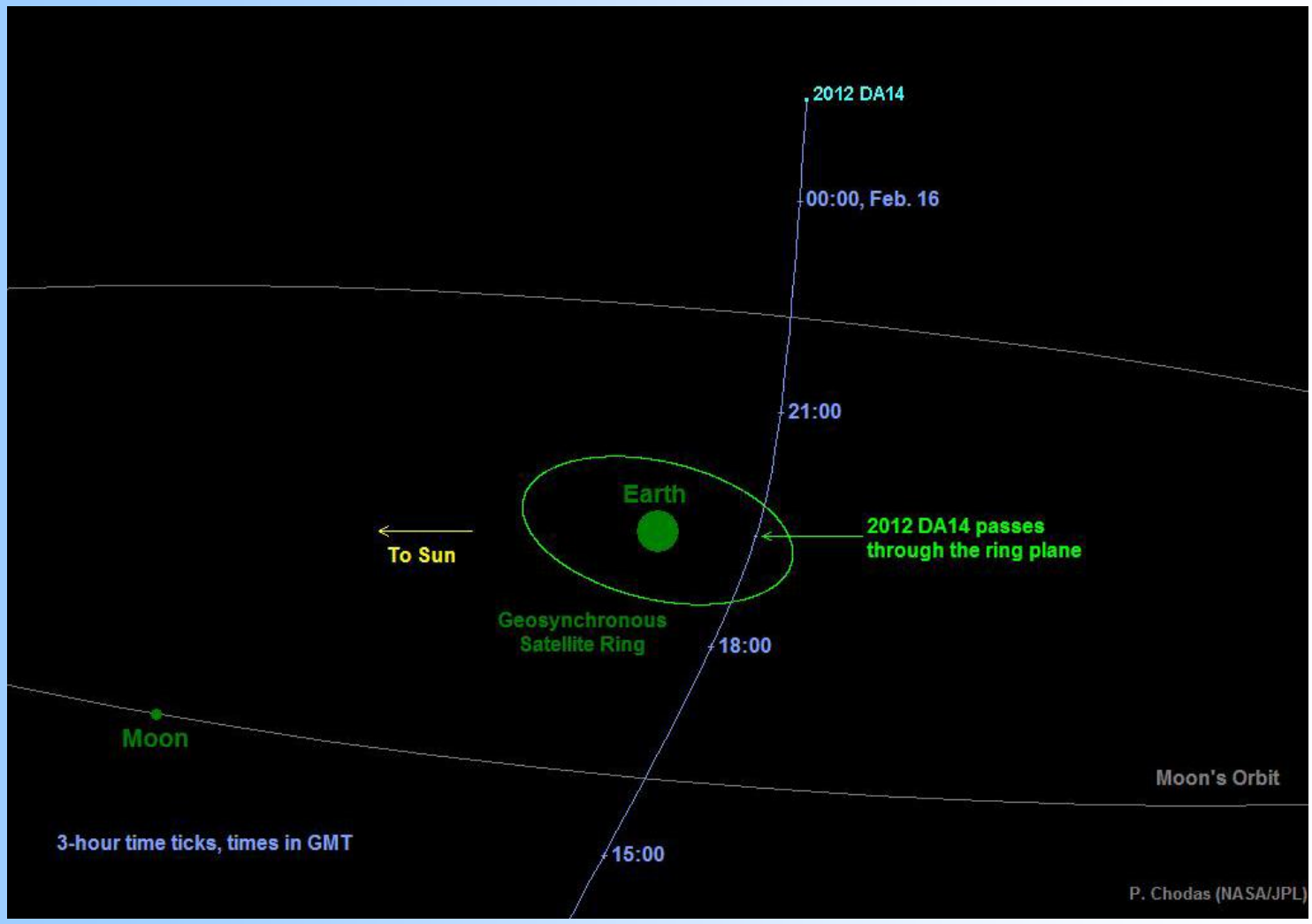
Paul Chodas

NASA NEO Program Office

JPL/Caltech

March 14, 2014

Asteroid 2012 DA14, Feb. 15, 2013



Chelyabinsk, Russia, Feb. 15, 2013

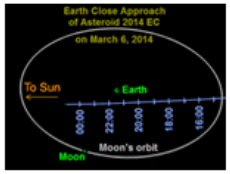
~20-meter asteroid, 500 kt of energy released at ~30 km altitude

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

http://neo.jpl.nasa.gov

NEO BASICS | SEARCH PROGRAMS | DISCOVERY STATISTICS | ACCESSIBLE NEAs | NEWS | FAQ

ORBIT DIAGRAMS | ORBIT ELEMENTS | CLOSE APPROACHES | IMPACT RISK | IMAGES | RELATED LINKS

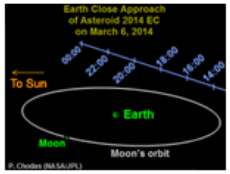


Small Asteroid 2014 EC Will Pass Earth Safely on March 6

March 6, 2014

An asteroid about 25 feet (8 meters) across will safely pass Earth at about 1:21 p.m. PST (4:21 p.m. EST) today, March 6, approaching us six times closer than the moon.

Full Story



Asteroid 2014 DX110 Will Safely Pass Closer Than Moon on March 5

March 4, 2014

As happens about 20 times a year with current detection capabilities, a known asteroid will safely pass Earth Wednesday closer than the distance from Earth to the moon.

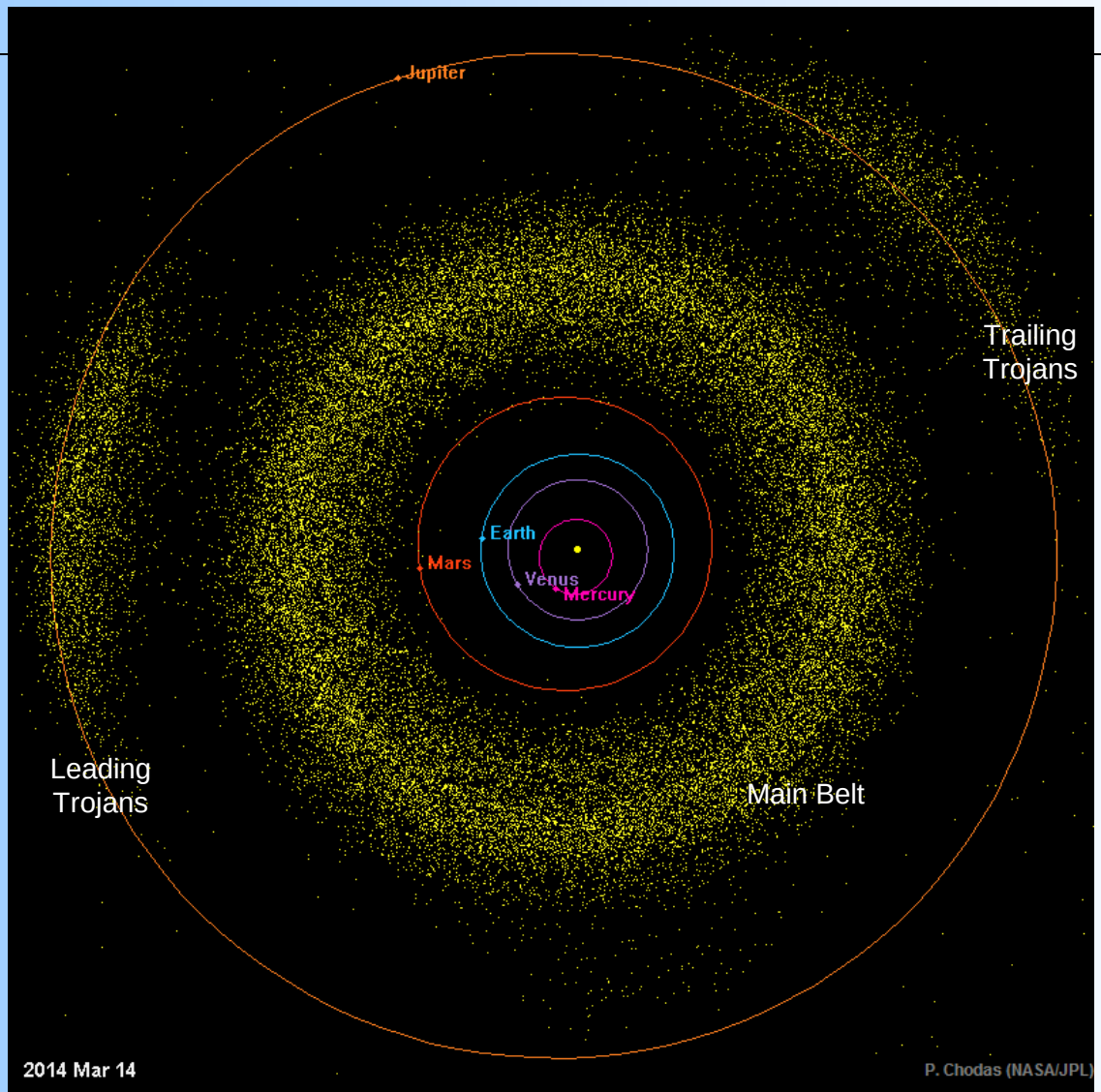
Full Story

Asteroid Grand Challenge: Virtual Seminar Series

NASA is sponsoring a series of virtual seminars on the properties of Near Earth Asteroids (NEAs) and what is being done to learn more about the hazards and the opportunities they may pose for us here on Earth.

- ~~Feb 14 - David Morrison (NASA Ames & SSERVI)~~
  ~~History of impacts research and planetary defense~~
- ~~Feb 28 - Lindley Johnson (NASA Headquarters)~~
  ~~NASA's NEA programs~~
- Mar 14 - Paul Chodas (NEO Program Office at JPL)
  NEA discovery, orbit calculation and impact probability assessment
- Mar 28 - Alan Harris (JPL retired)
  NEA populations and impact frequency
- Apr 11 - Dan Britt (University of Central Florida)

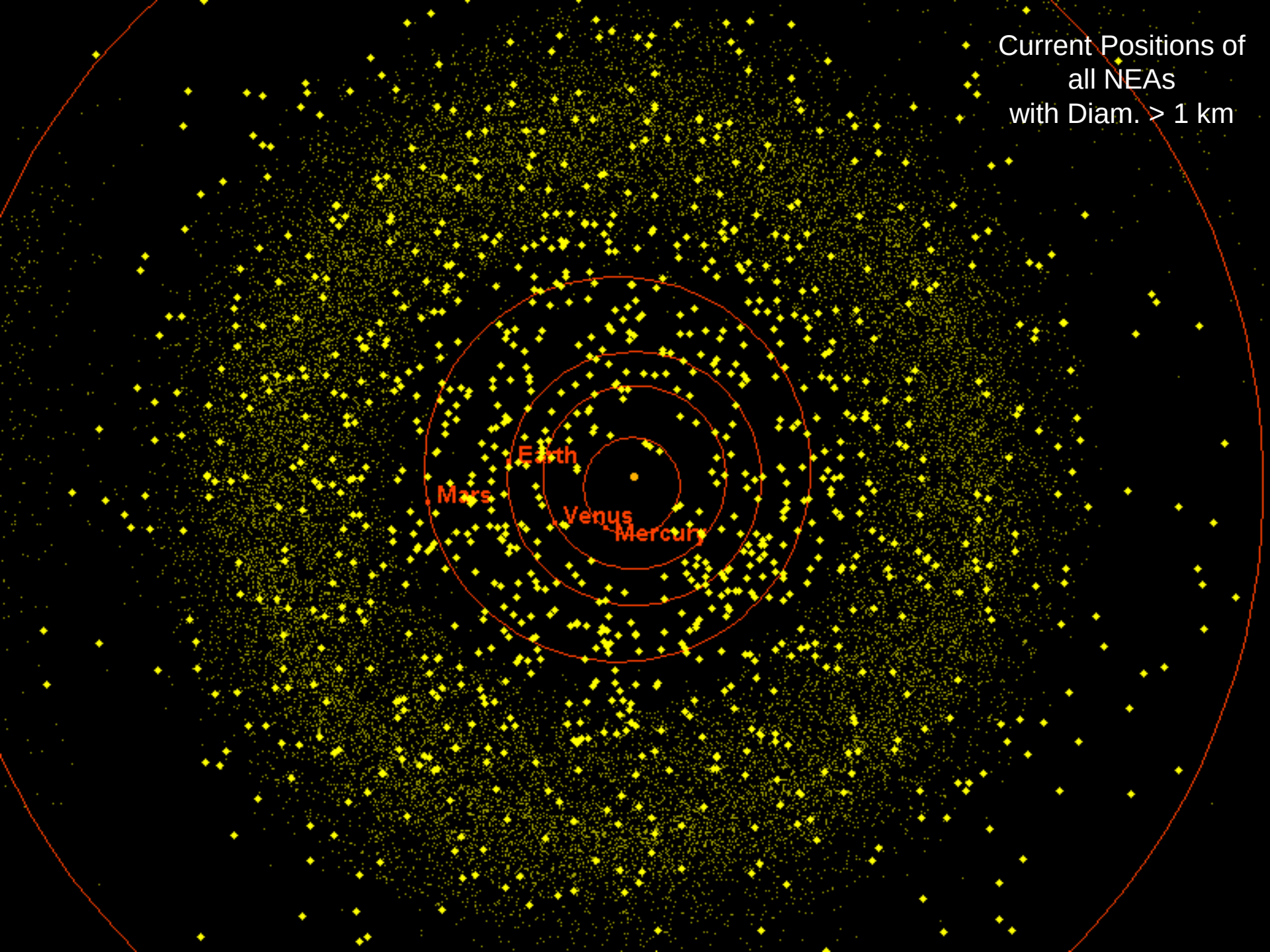
Current locations of large asteroids

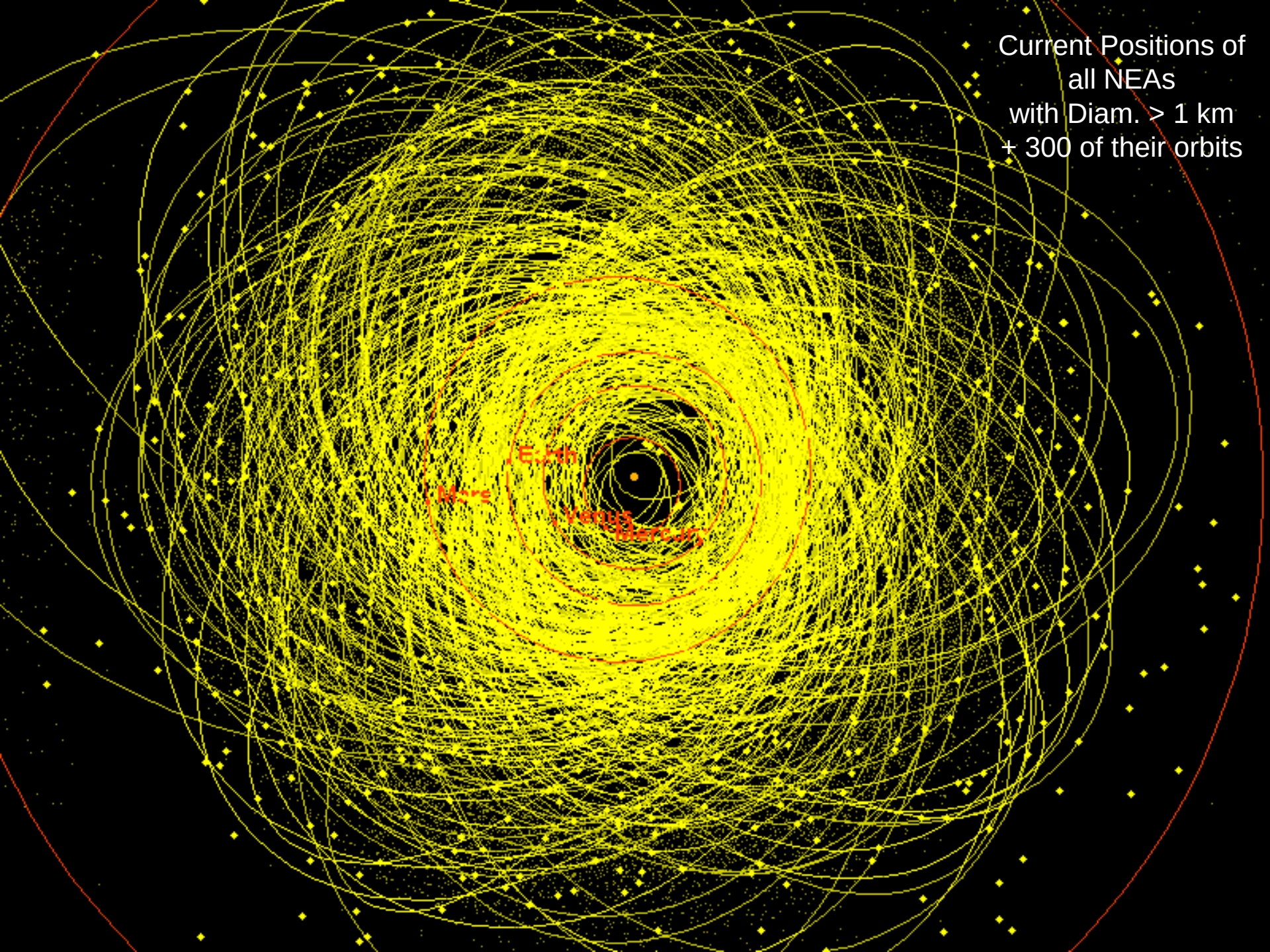


About 43,000 asteroids larger than 5 km (3 miles) are currently known.

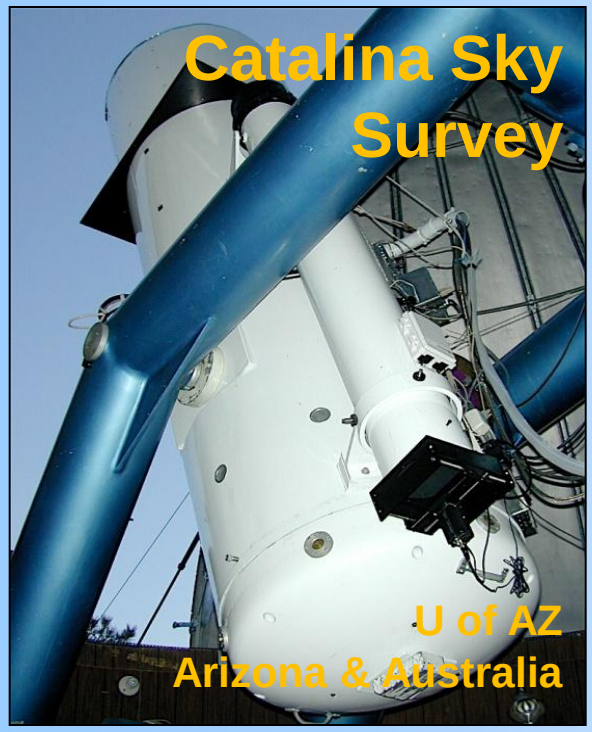
These are their positions as of today.

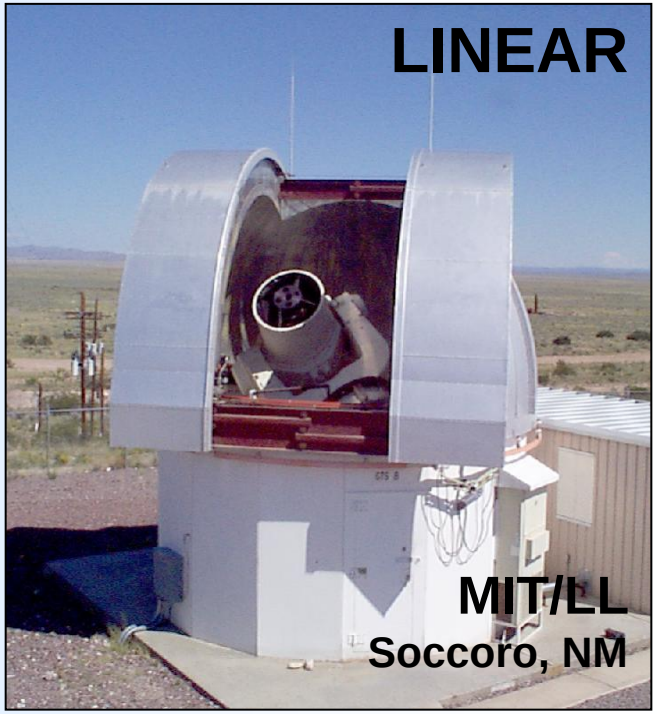
Only 20 of these are NEAs, and only 2 are PHAs.


Current Positions of
all NEAs
with Diam. > 1 km
Earth
Mars
Venus
Mercury


Current Positions of
all NEAs
with Diam. > 1 km
+ 300 of their orbits
Earth
Mars
Venus
Mercury

NASA's NEO Search Programs



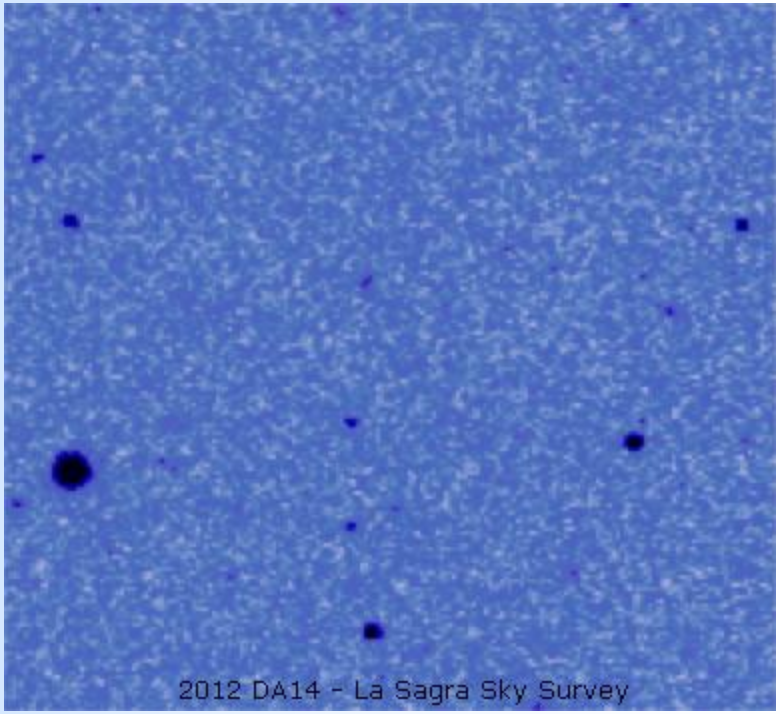


- Currently, most Near-Earth Asteroid discoveries are made by: Catalina Sky Survey (60%) and Pan-STARRS-1 (35%).
- LINEAR is now retired, but was very productive at finding large NEAs.

Discovery of 2012 DA14

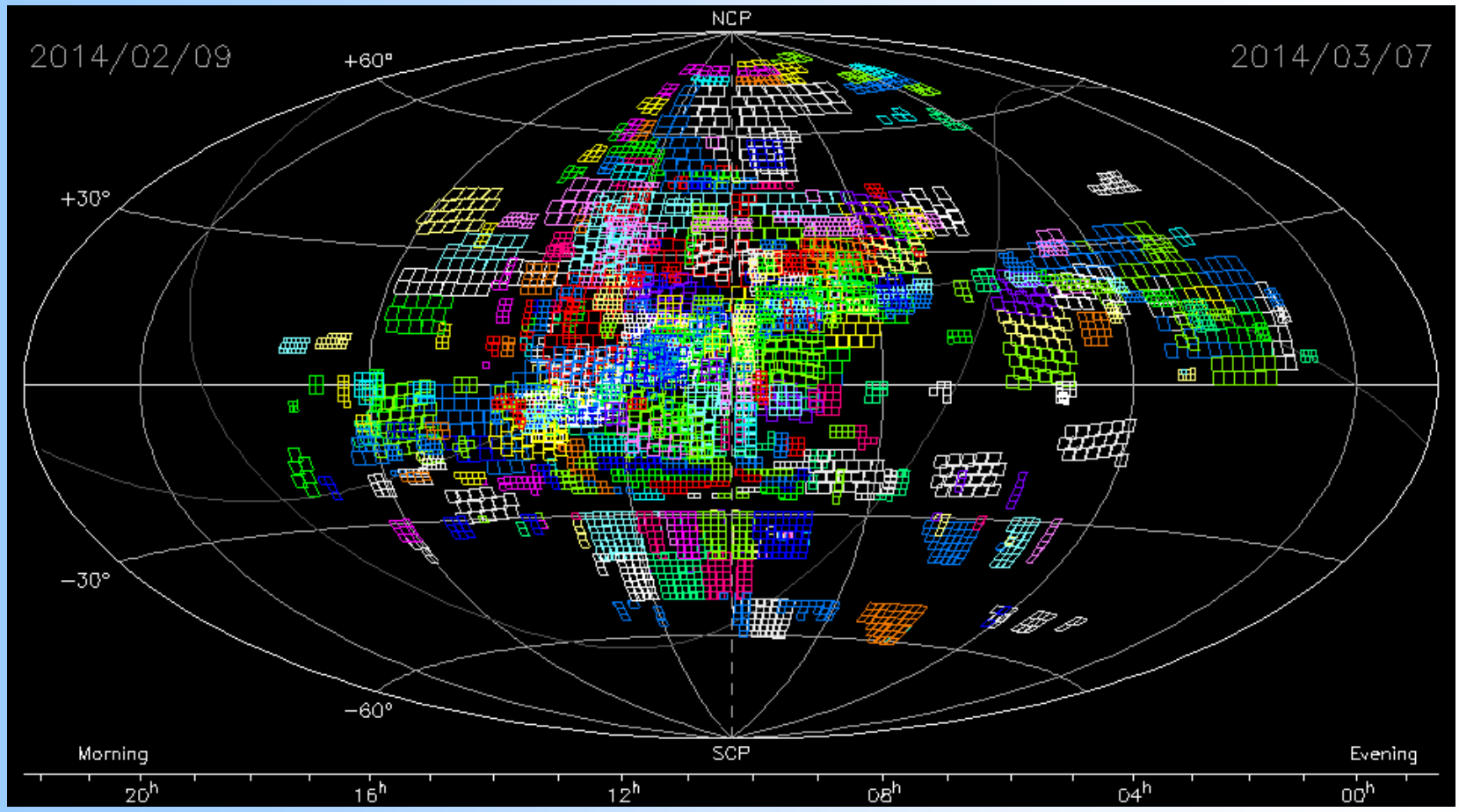
- Discovered by an amateur astronomer in La Sagra, Spain using a state-of-the-art fast readout camera and detection software that looked for trails produced by fast-moving asteroids.
- The asteroid was found in a less searched region of the sky.
- Moderately faint: magnitude 18.8, and moving quite fast: 11 arc-sec per minute.

Discovery Images, Feb. 22, 2012



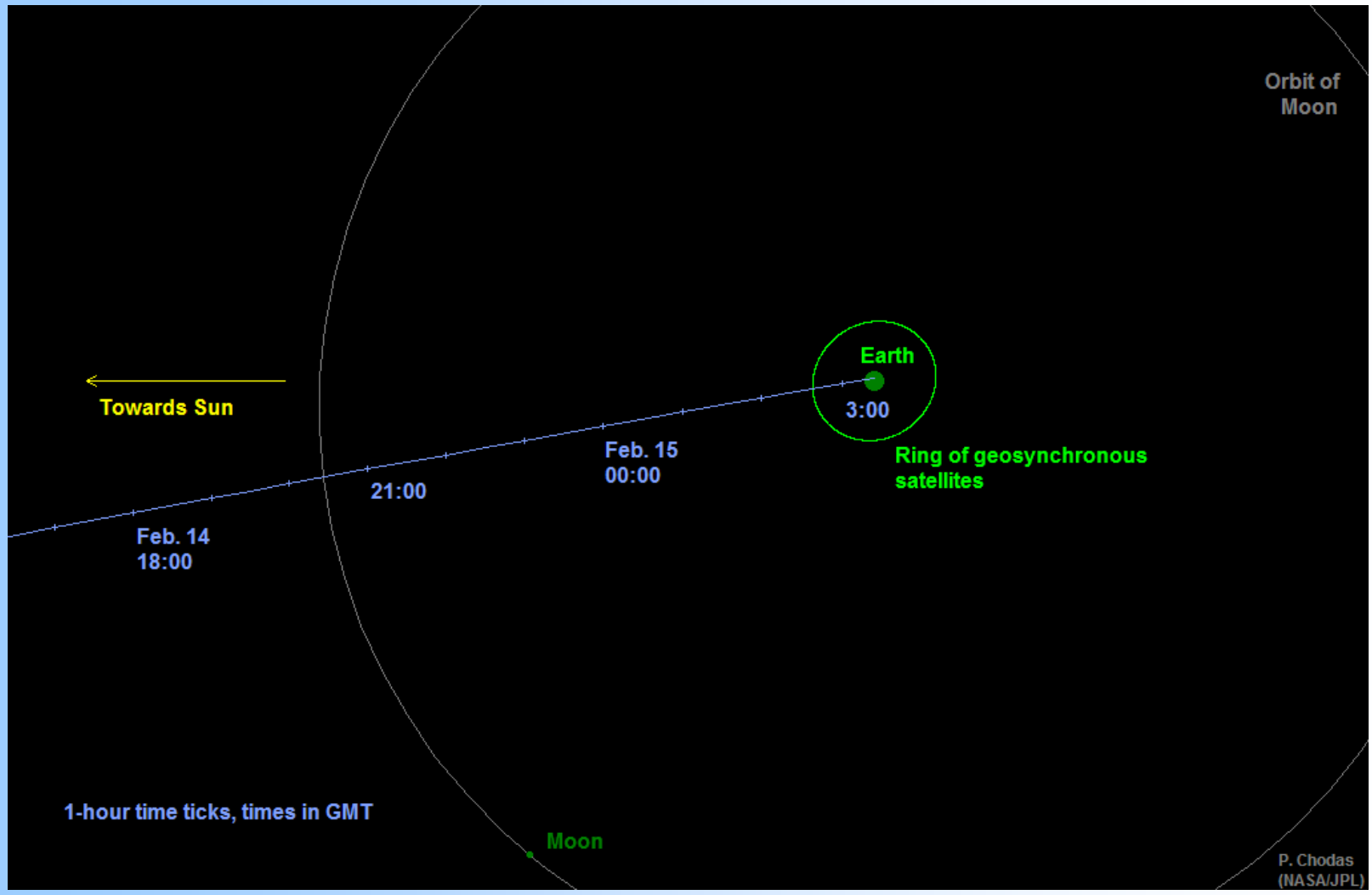
Courtesy Jaime Nomen, La Sagra Observatory

Sky Coverage, Feb.-Mar. 2014



Courtesy of Tim Spahr, Minor Planet Center

Trajectory of Chelyabinsk Impactor

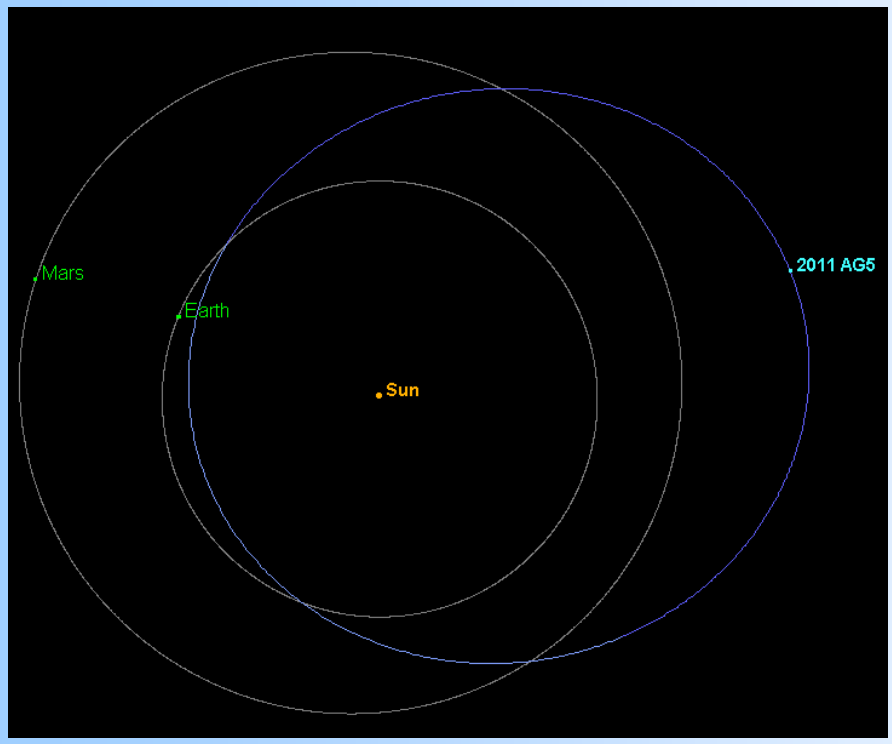


Kepler's Laws

1. The orbit of each planet (or asteroid) is an ellipse, with the Sun at one focus.
   - Each orbit lies in a plane; the plane of the Earth's orbit is called the ecliptic.
2. The line joining the planet (or asteroid) to the Sun sweeps out equal areas in equal times.
   - A body moves slower when far from the Sun, faster near the Sun.
3. The square of the orbital period of a planet (or asteroid) is proportional to the cube of the mean distance from the Sun.
   - Two neighboring bodies at slightly different mean distances from the Sun will steadily separate along their orbit tracks, an effect known as "Keplerian sheer".

Orbital Elements

- Six parameters which describe the orbit of an asteroid and the asteroid's position at a fixed time called the "epoch".

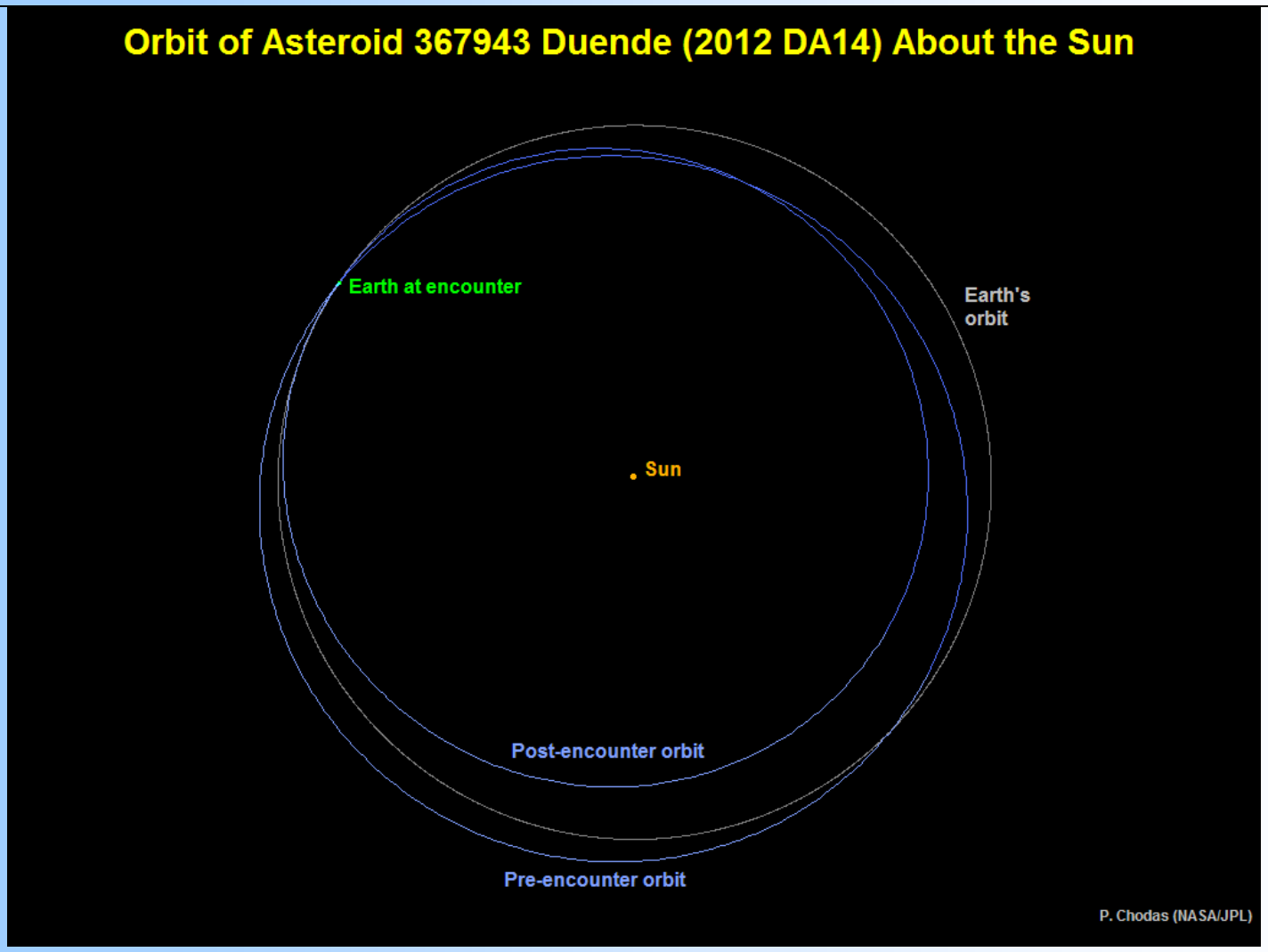


- Closest point to the Sun is called the perihelion.
- Farthest point is called the aphelion.
- Distances are typically measured in astronomical units (au), which is essentially the mean distance between the Earth and Sun.

Orbit Propagation Models

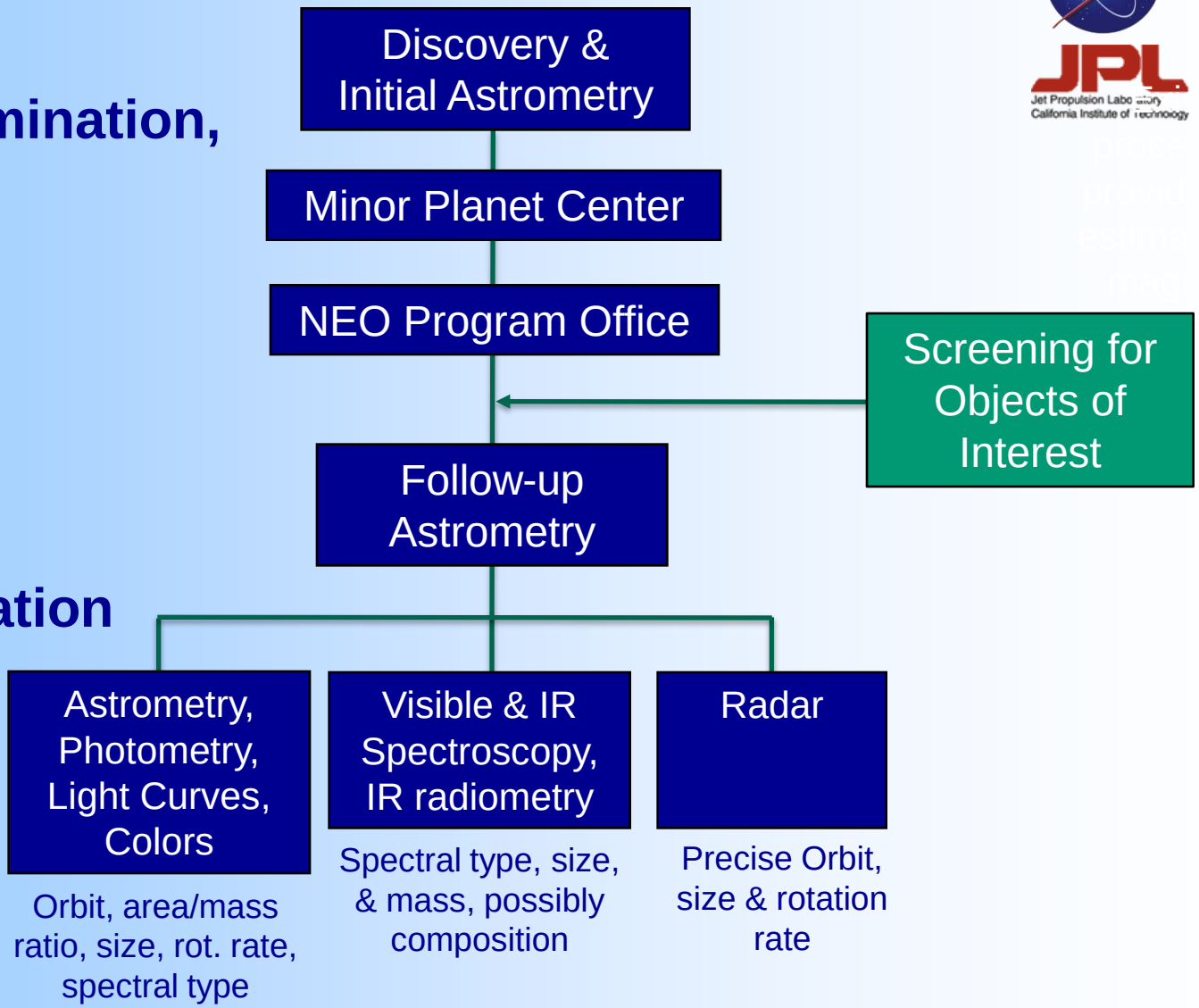
- Kepler's Laws do not hold exactly because of *perturbations*.
- Perturbations cause asteroid orbits to change with time, especially for those asteroids which are planet-crossers.
- The following perturbations are accounted for:
  - Gravitational attraction of the planets, the Moon, and 16 of the largest asteroids
  - Relativity
  - In some cases, non-gravitational forces such as Solar Radiation Pressure and the Yarkovsky Effect (recoil from thermal emission)
- The precise trajectory of the asteroid is computed by a process called numerical integration.
- The sensitivity matrix is also numerically integrated, relating variations in initial orbital elements to variations in position and velocity at any other time.

Planetary Encounters Can Change an Asteroid's Orbit



NEO Discovery & Characterization Processes

Discovery, Orbit Determination, Rough Size Estimation



Physical Characterization

Optical Observations

- Asteroid tracking observations are mostly from optical telescopes.
- An image is taken of the region of the sky around the asteroid, wide enough to include catalog stars.
- Celestial coordinates (Right Ascension and Declination) of the asteroid are determined using the known coordinates of the stars.
- Distance to asteroid is not known!
- Typical accuracy is about 0.5 arc-sec, or better.
- Over time, dozens or hundreds of observations are accumulated.

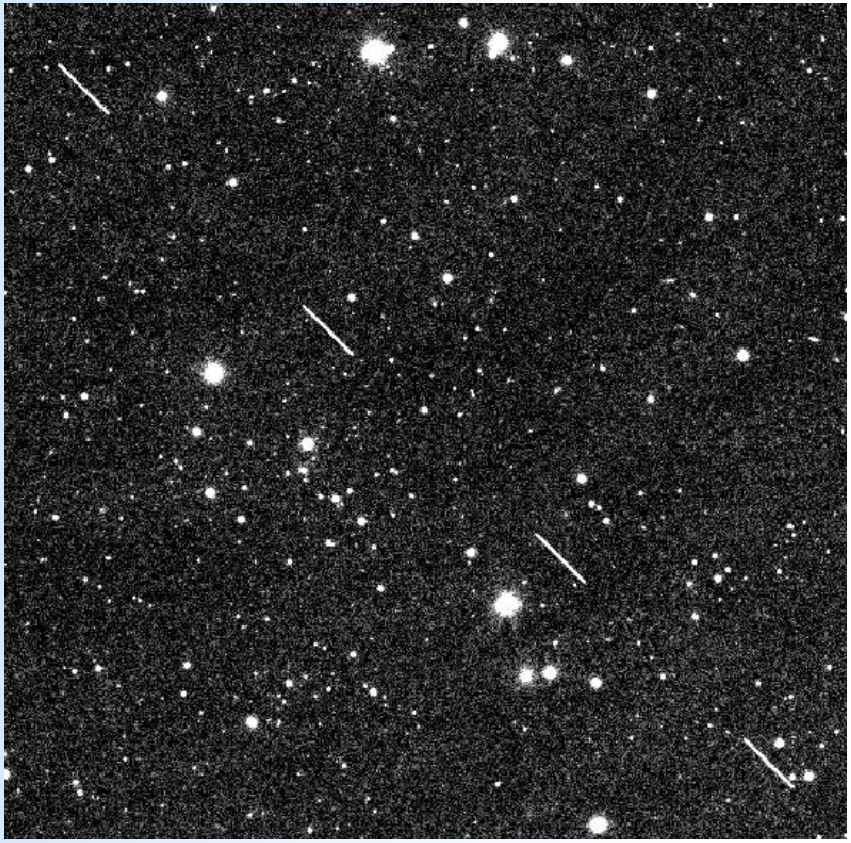


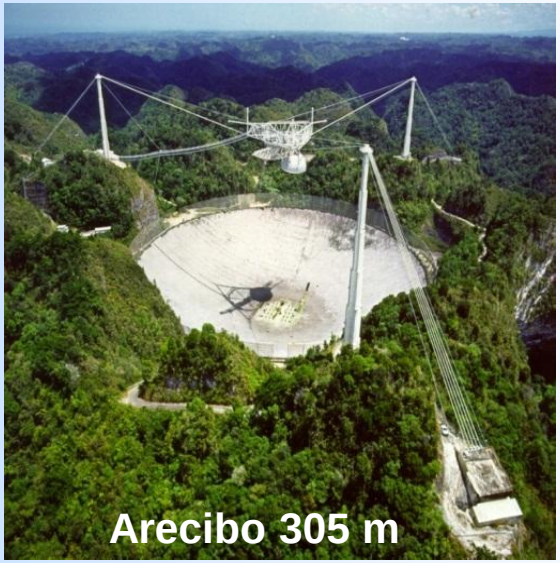
Image of 2008 FP from Catalina Sky Survey

Sample Asteroid Observations

```
M.P.E.C. 2014-E22                                    Issued 2014 Mar. 2, 18:50 UT

     The Minor Planet Electronic Circulars contain information on unusual
         minor planets and routine data on comets.  They are published
   on behalf of Commission 20 of the International Astronomical Union by the
          Minor Planet Center, Smithsonian Astrophysical Observatory,
                          Cambridge, MA 02138, U.S.A.

            Prepared using the Tamkin Foundation Computer Network

                                MPC@CFA.HARVARD.EDU
          URL http://www.minorplanetcenter.net/    ISSN 1523-6714


                                 2014 DX110

Observations:
     K14DB0X* C2014 02 28.36199 09 34 13.259+02 12 58.11          19.9 wLEE022F51
     K14DB0X  C2014 02 28.37465 09 34 11.900+02 13 20.64          19.9 wLEE022F51
     K14DB0X  C2014 02 28.38633 09 34 10.633+02 13 41.46          20.0 wLEE022F51
     K14DB0X  C2014 02 28.39801 09 34 09.361+02 14 02.39          20.2 wLEE022F51
     K14DB0X  C2014 03 01.02239709 33 36.98 +02 38 13.5           20.1 VqEE022K93
     K14DB0X  C2014 03 01.02343209 33 36.90 +02 38 16.1           20.2 VqEE022K93
     K14DB0X  C2014 03 01.02446009 33 36.79 +02 38 18.1           20.4 VqEE022K93
     K14DB0X  C2014 03 01.02549109 33 36.70 +02 38 20.7           20.0 VqEE022K93
     K14DB0X  C2014 03 01.02651909 33 36.59 +02 38 22.9           19.9 VqEE022K93
     K14DB0X  C2014 03 01.02859009 33 36.41 +02 38 27.9           19.7 VqEE022K93
     K14DB0X  C2014 03 01.02963509 33 36.28 +02 38 30.2           19.6 VqEE022K93
     K14DB0X  C2014 03 01.03066209 33 36.18 +02 38 32.4           20.2 VqEE022K93
     K14DB0X  C2014 03 01.03169409 33 36.09 +02 38 34.8           19.9 VqEE022K93
     K14DB0X  C2014 03 01.03272309 33 35.98 +02 38 37.3           19.9 VqEE022K93
     K14DB0X KC2014 03 02.02430 09 32 48.82 +03 21 39.3           19.5 RqEE022J95
     K14DB0X KC2014 03 02.03580 09 32 47.32 +03 22 20.4           19.1 RqEE022J95
```

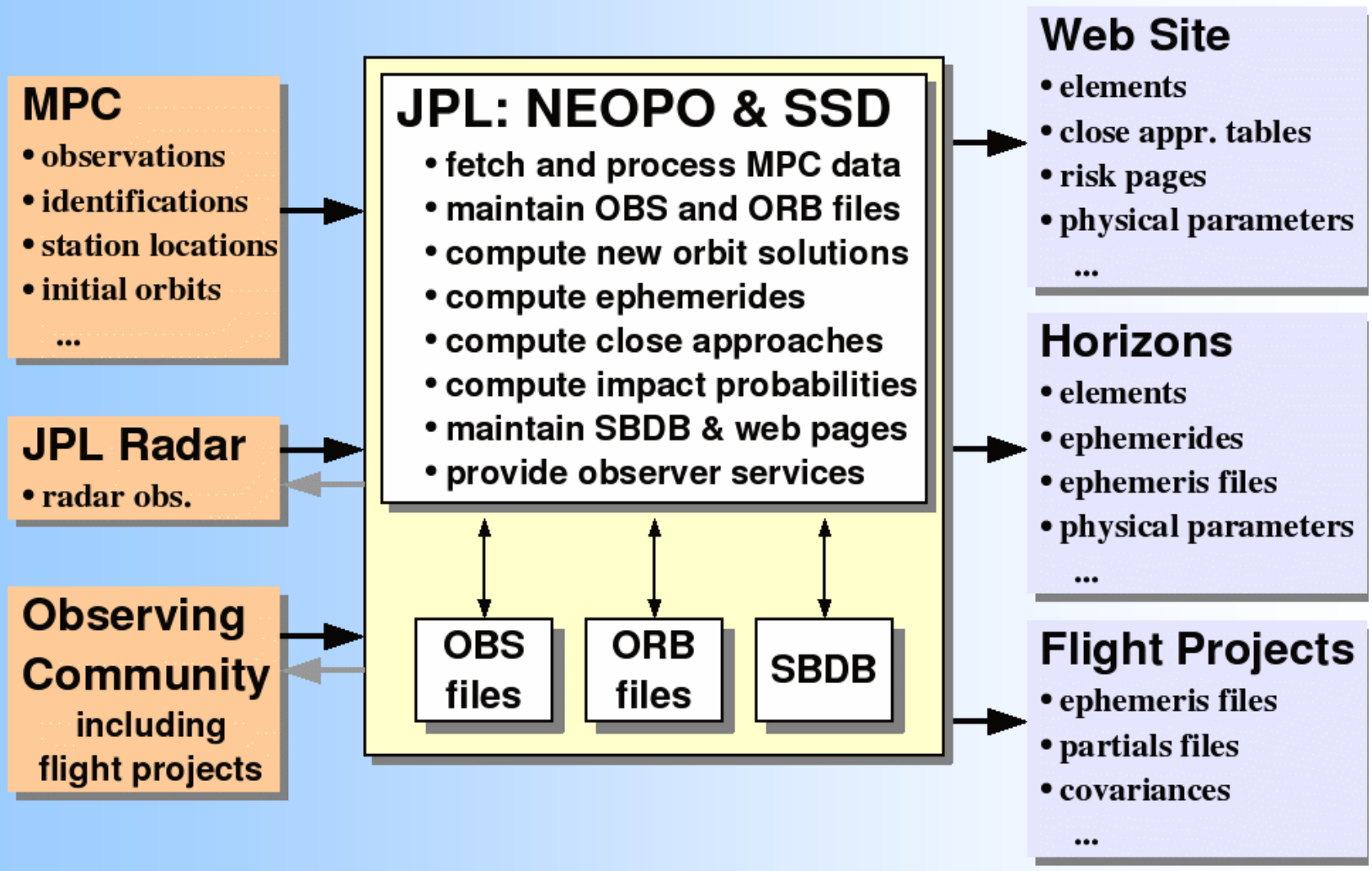
Top portion of a sample MPEC, courtesy of the Minor Planet Center

Radar Observations



- A powerful burst of radar pulses is transmitted to the asteroid, and the echoes are received within a listening window.
- The precise time delay from transmission to reception is determined to a fraction of a microsecond, and the Doppler shift of the signal is determined to a fraction of a Hertz. *Radar observations are extremely precise.*
- The asteroid must have a fairly well known orbit for accurate antenna pointing, and it must be within range.

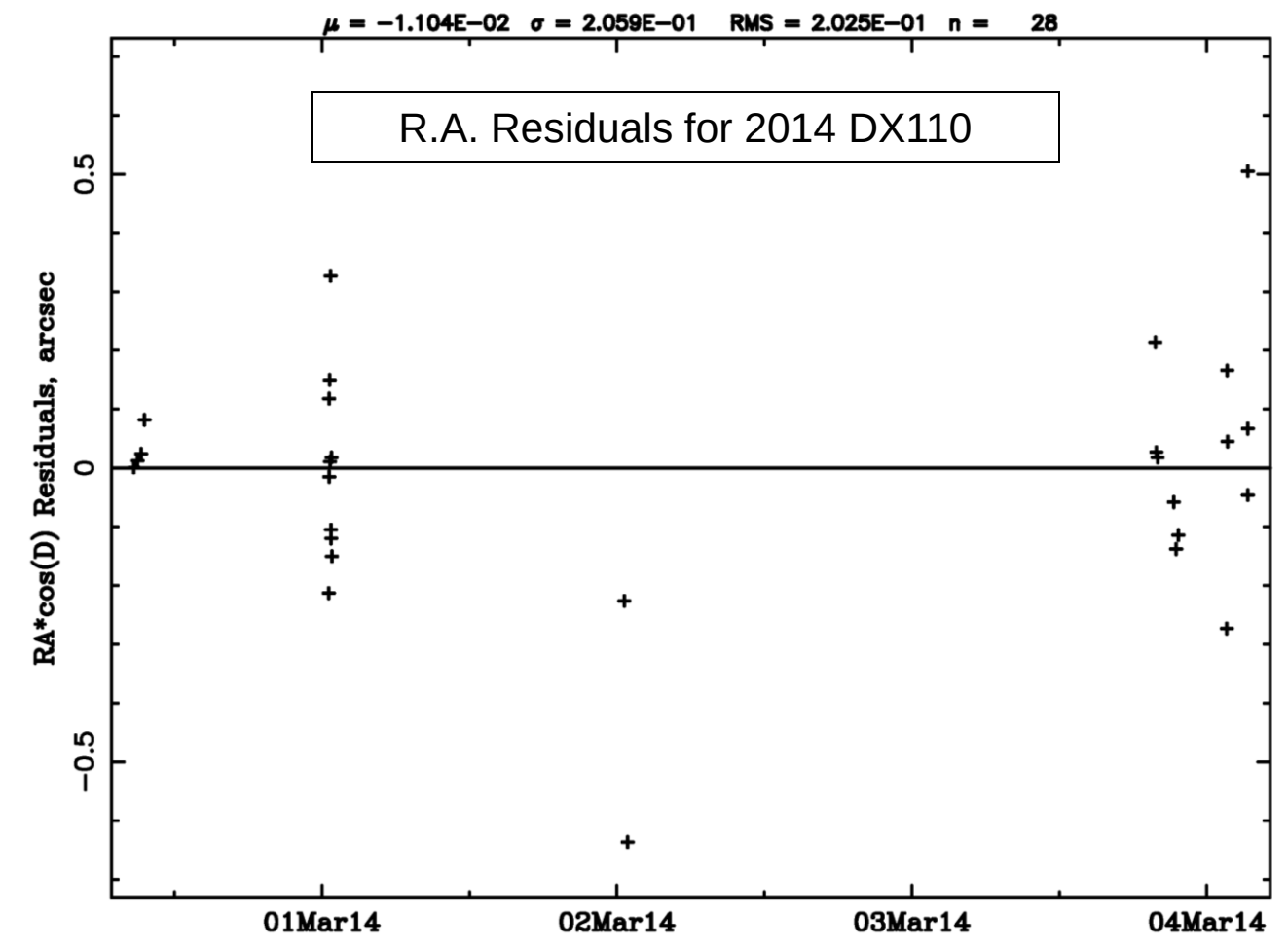
NEO Program Office Data Flow



Orbit Determination

- The process of estimating the asteroid's orbital parameters given a set of observations.
- The initial orbit estimate is made by the Minor Planet Center typically using just a handful of the initial optical observations.
- Thereafter, orbit determination is an iterative process of refining the orbit:
  - Given an orbit, each of the observations is computed at the observation time and differenced with the actual observation to form a "residual". The sensitivity of each observation to the orbital elements is also computed.
  - The residuals are weighted according to their accuracies, and then combined with their sensitivities in a process called weighted least squares estimation, yielding a correction to the orbit; the process repeats until the corrections are small.
- The process also computes uncertainties in the orbital elements, and these can be used to predict position uncertainties at other times.

Observation “Residuals”



- Each observ-ation is reduced to a “residual”: observed value minus computed value
- Observations with large residuals are deleted.
- A good orbit fit is indicated by zero mean and no systematic trend.

Jet Propulsion Laboratory
California Institute of Technology

http://ssd.jpl.nasa.gov

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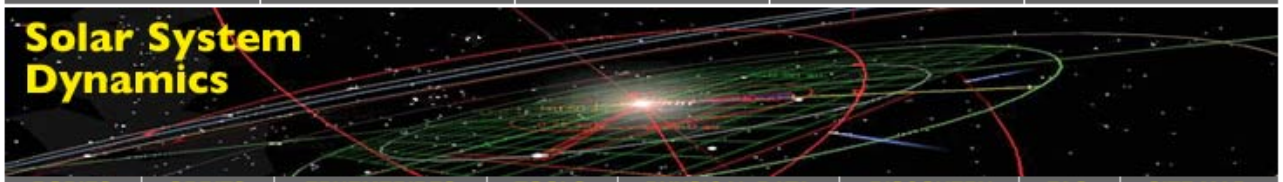

BODIES | ORBITS | EPHEMERIDES | TOOLS | PHYSICAL DATA | DISCOVERY | FAQ | SITE MAP

Quick Links
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- HORIZONS
- Small-Body Search
- Small-Body Browser
- Small-Body Missions
- Astrodynamic Constants
- Date/Time Converter
- Related Links
- Kids!

JPL Solar System Dynamics

Welcome to the JPL solar system dynamics web site. This site provides information related to the orbits, physical characteristics, and discovery circumstances for most known natural bodies in orbit around our sun.

Features

Ephemerides
High-precision ephemerides with custom selected observing parameters are available using our HORIZONS system.

Orbits
Orbit diagrams for most solar system bodies as well as tables of orbital elements for the planets, planetary satellites, asteroids and comets are available.

Physical Characteristics
Selected physical characteristics of the planets, planetary satellites, and some small-bodies are available.

Discovery Circumstances
For many solar system bodies, discovery circumstances such as date, location, and discoverers are available.

On-Line Tools
We provide a number of on-line tools in addition to our HORIZONS system, including a date/time converter and small-body identification from astrometry.

JPL Small-Body Database Browser

BODIES | ORBITS | EPHEMERIDES | TOOLS | PHYSICAL DATA | DISCOVERY | FAQ | SITE MAP

JPL Small-Body Database Browser

Search: [help]

2014dx110

Introduction/Overview

Enter the IAU number, name, or designation for the object of interest in the **Search** form above. For example, to display information about asteroid 433 Eros, you can enter either "**433**" or "**eros**" (names are not case-sensitive). Detailed instructions are available via the help link.

The **JPL Small-Body Database Browser** provides data for all known asteroids and many comets. Available data include:

- orbital elements
- orbit diagrams
- physical parameters
- discovery circumstances

Newly discovered objects and their orbits are added on a daily basis. Discovery circumstances are updated on a roughly monthly interval. Physical parameters, other than magnitude parameters, are updated on a less frequent basis.

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FIRSTGOV Your First Click to the U.S. Government

2014-Mar-09 19:26 UT (server date/time)

Site Manager: Donald K. Yeomans
Webmaster: Alan B. Chamberlin

Orbital Elements Page for 2014 DX110

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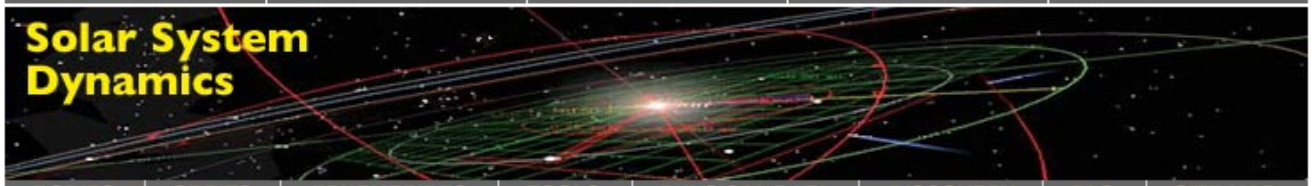


BODIES | ORBITS | EPHEMERIDES | TOOLS | PHYSICAL DATA | DISCOVERY | FAQ | SITE MAP

JPL Small-Body Database Browser

Search: [help]

(2014 DX110)

Classification: Apollo [NEO] **SPK-ID:** 3662876

[Ephemeris | Orbit Diagram | Orbital Elements | Physical Parameters | Close-Approach Data]

[show orbit diagram]

Orbital Elements at Epoch 2456800.5 (2014-May-23.0) TDB
Reference: JPL 2 (heliocentric ecliptic J2000)

Element	Value	Uncertainty (1-sigma)	Units
e	.6239860567632933	0.00057152	
a	2.199801389846979	0.0030538	AU
q	.8271559949339504	0.00010897	AU
i	5.730942016045152	0.0045759	deg
node	163.8249552946962	7.7034e-05	deg
peri	56.53484467966418	0.0029277	deg
M	12.21986765612447	0.022861	deg
t_p	2456760.048219995537 (2014-Apr-12.54822000)	0.0085598	JED
period	1191.718373014288	2.4815	d
	3.26	0.006794	yr
n	.3020847946561648	0.00062903	deg/d
Q	3.572446784760008	0.0049593	AU

Orbit Determination Parameters

# obs. used (total)	28
data-arc span	4 days
first obs. used	2014-02-28
last obs. used	2014-03-04
planetary ephem.	DE431
SB-pert. ephem.	SB431-BIG16
condition code	7
fit RMS	.33273
data source	ORB
producer	Otto Matic
solution date	2014-Mar-04 06:44:19

Additional Information

Earth MOID = .00194791 AU
T_jup = 3.376

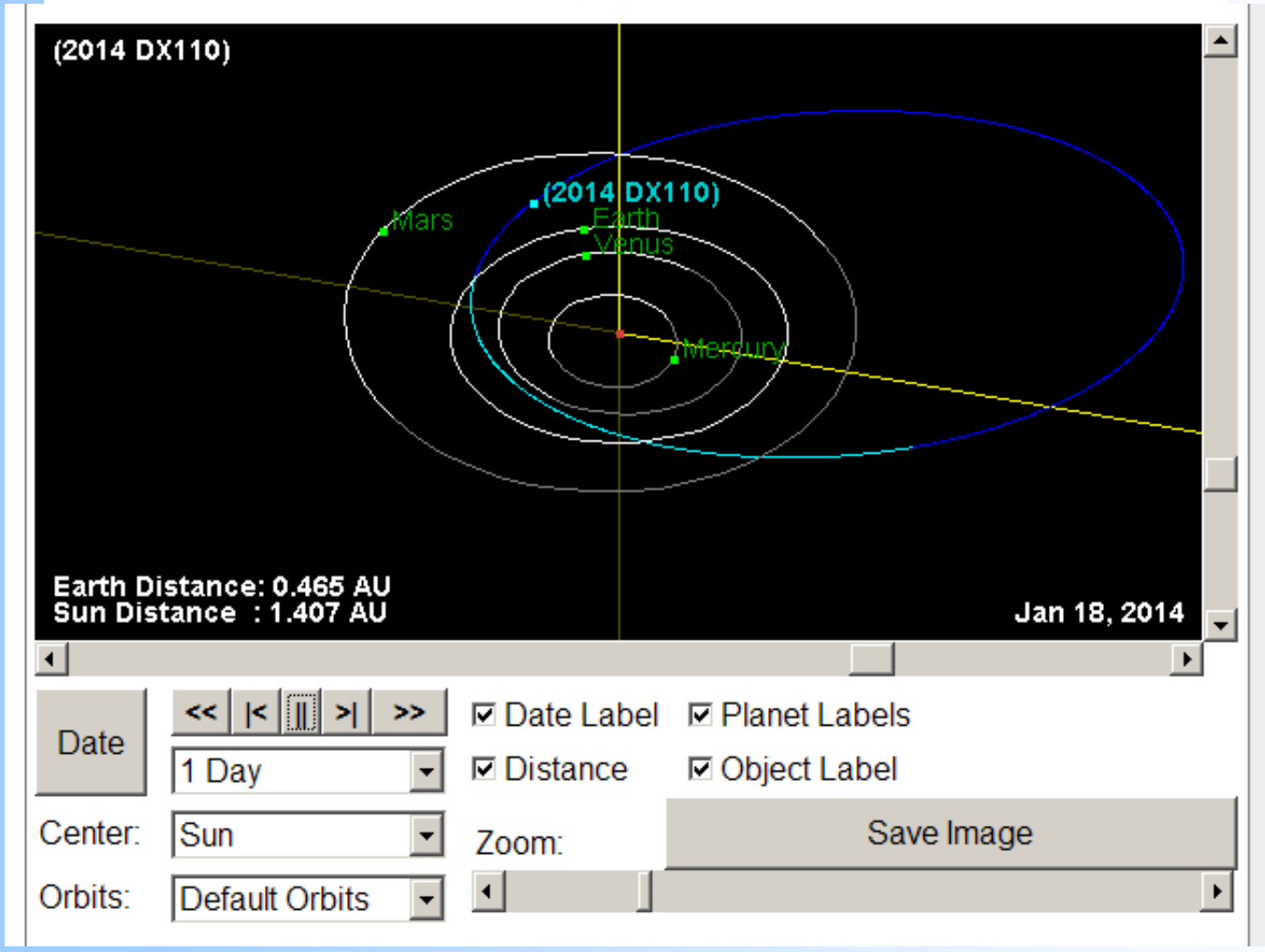
[show covariance matrix]

[Ephemeris | Orbit Diagram | Orbital Elements | Physical Parameters | Close-Approach Data]

Physical Parameter Table

Parameter	Symbol	Value	Units	Sigma	Reference	Notes
absolute magnitude	H	25.7	mag	n/a	E2014E24	

Orbit Viewer App for 2014 DX110

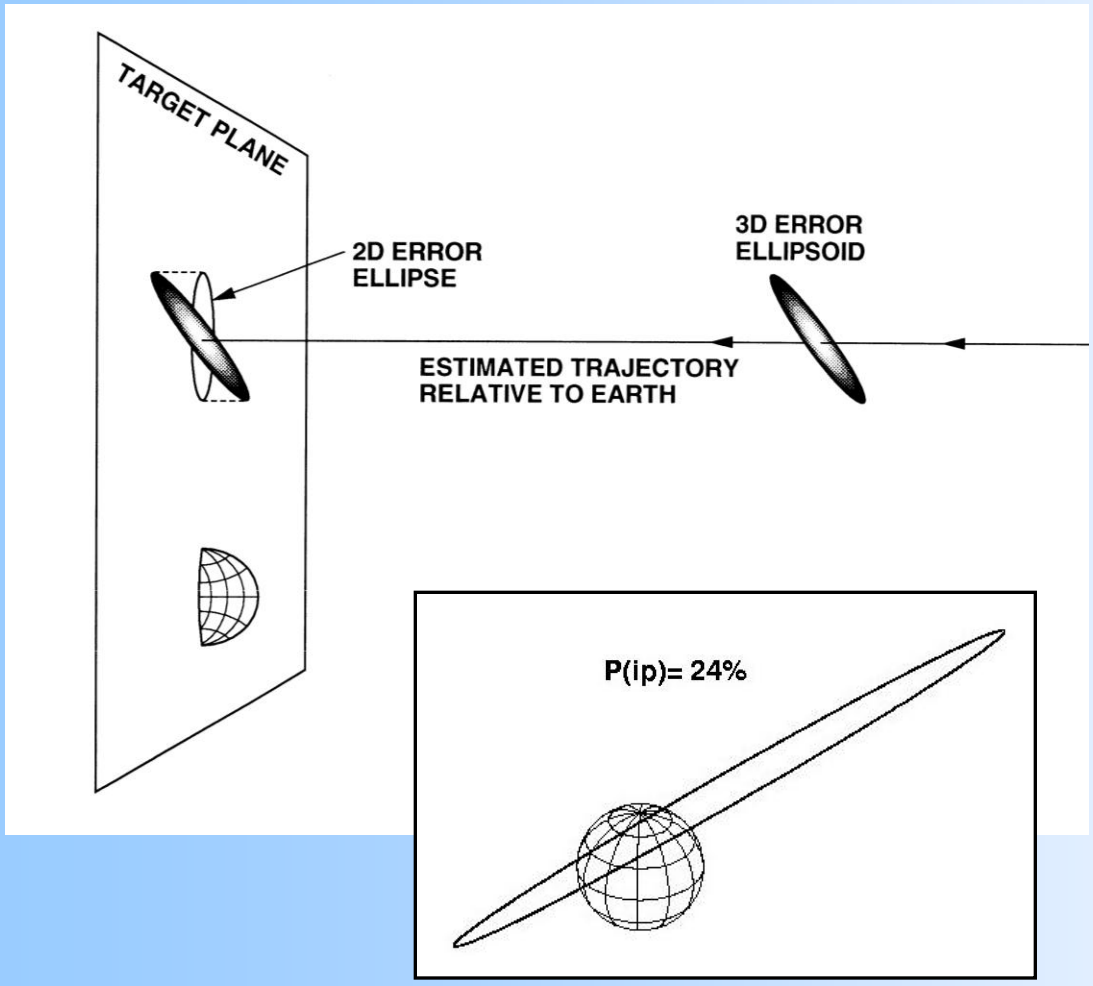


Orbit Viewer applet originally written and kindly provided by Osamu Ajiki (AstroArts), and further modified by Ron Baalke (JPL).

Orbit Uncertainties

- Since the observations contain measurement errors, the resulting orbit will be uncertain.
- Ways to reduce orbit uncertainty:
  - Obtaining more observations helps somewhat
  - Obtaining observations over a longer time span (“data arc”) helps a lot
  - Obtaining radar observations helps a lot
- **As more and more observations are made of an asteroid, its orbit is updated and the orbit uncertainties get smaller and smaller.**
- Orbit uncertainties can be mapped forward or backward in time, and used to compute the position uncertainty of the asteroid.
- Position uncertainty is represented by an *uncertainty ellipsoid* centered on the nominal position.
- The position uncertainty of an asteroid generally grows with time along the orbit path.

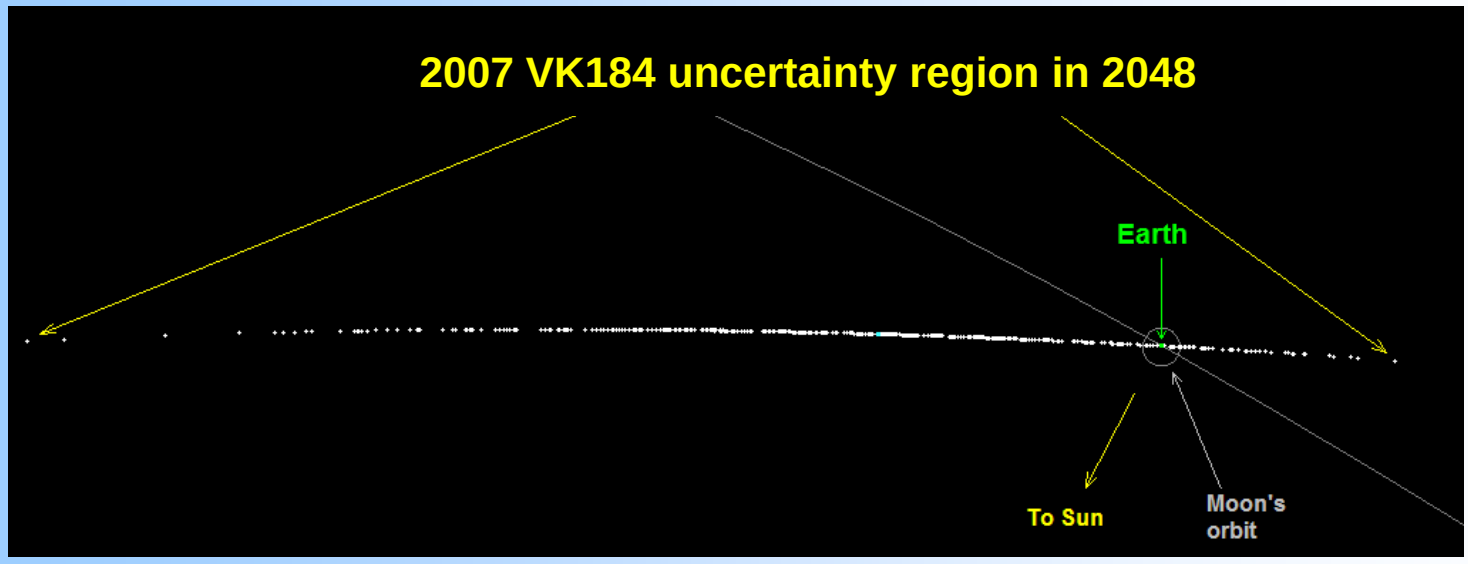
Basic Impact Probability Computation



- Propagate uncertainty region to time of close approach.
- Define target plane ("*b-plane*") and project the uncertainty region into the plane.
- If any portion intersects the Earth disc, impact is possible during that encounter.
- Numerically integrate uncertainty ellipse probability density over Earth disc to get impact probability.

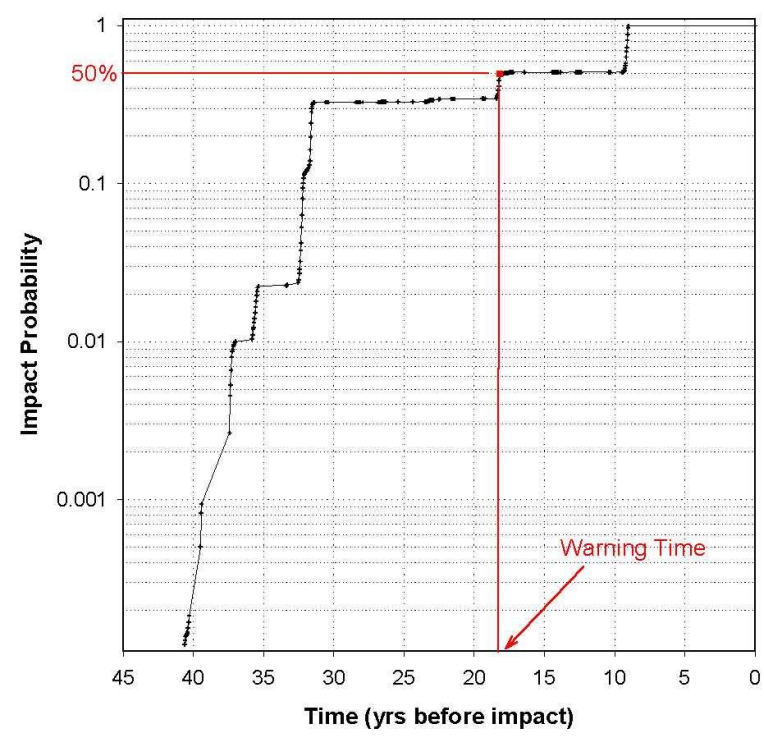
Tracing Uncertainties with Monte Carlo Points

- Position uncertainties grow as we map farther into the future.
- When the uncertainties get large, they start curving around the orbit, so we call it an *uncertainty region*.
- Monte Carlo tracer points are useful for a detailed mapping of what happens to the uncertainty region, including seeing which parts of it might impact.



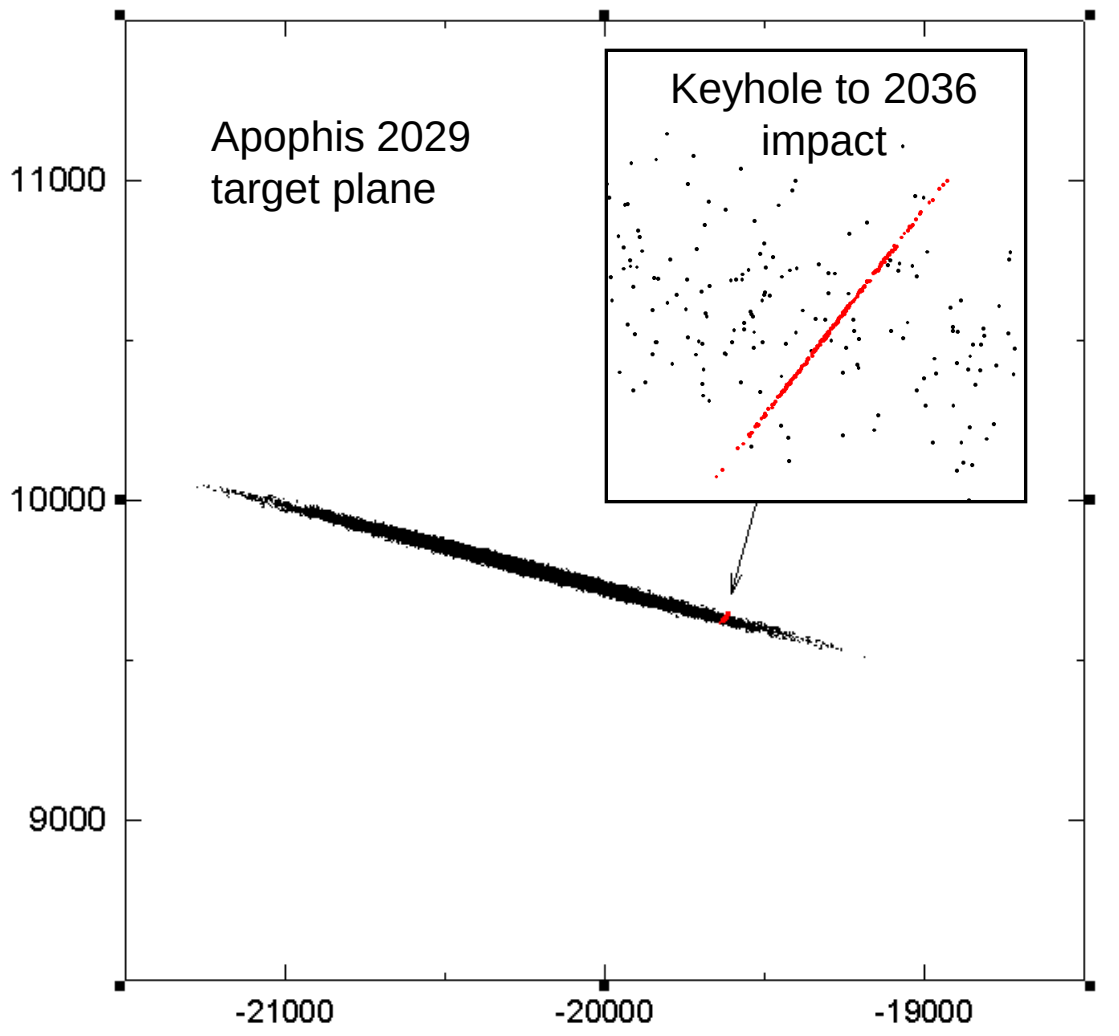
Impact Probability Changes with Time

- Warning time is the time before impact when the probability reaches a level that causes concern.
- It could take months or years after discovery before impact probability reaches this level.
- Until impact probability reaches 50%, the most likely scenario is that the impact probability will drop to zero.



Impact probability for a hypothetical impacting asteroid discovered 40 years before impact.

Keyholes



- **Keyhole**: narrow slice through the uncertainty region leading to impact in a later year.
- There may be many keyholes for impacts in many different years.
- Typically 10–100 km wide, but the Apophis 2036 keyhole was only 600m wide.
- Positions and widths of keyholes are essentially fixed by the encounter geometry.

Sentry Risk Table: http://neo.jpl.nasa.gov/risk

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Sentry Risk Table

461 NEAs: Last Updated Mar 05, 2014

Sort by Palermo Scale (cum.) or by Object Designation

Recently Observed Objects
(within past 60 days)

Object Designation	Year Range	Potential Impacts	Impact Prob. (cum.)	$V_{infinity}$ (km/s)	H (mag)	Est. Diam. (km)	Palermo Scale (cum.)	Palermo Scale (max.)	Torino Scale (max.)
2014 DN112	2018-2113	257	1.3e-05	9.30	19.9	0.357	-2.30	-2.82	0
2009 FD	2190-2190	1	4.3e-04	15.88	22.1	0.130	-2.39	-2.39	n/a
2014 AF16	2026-2072	7	9.6e-04	8.87	25.2	0.031	-2.56	-2.56	0
2014 DA	2027-2027	1	4.6e-06	12.66	22.6	0.100	-3.60	-3.60	0
2013 YD48	2094-2105	4	2.4e-05	14.98	22.6	0.100	-3.62	-3.66	0
2014 DM22	2093-2093	1	1.3e-10	26.30	18.7	0.610	-6.69	-6.69	0
2014 CE	2112-2112	2	4.8e-07	13.03	27.1	0.013	-7.57	-7.57	0
2014 EC	2025-2105	25	3.7e-07	15.75	28.2	0.008	-7.66	-8.39	0
2014 DK10	2060-2078	2	2.6e-07	11.83	27.8	0.009	-7.93	-8.07	0

Earth Impact Risk Table for 2014 EC, March 5, 2014

Torino Scale (maximum)	0
Palermo Scale (maximum)	-8.39
Palermo Scale (cumulative)	-7.66
Impact Probability (cumulative)	3.7e-07
Number of Potential Impacts	25

V_{impact}	19.30 km/s
$V_{infinity}$	15.75 km/s
H	28.2
Diameter	0.008 km
Mass	6.7e+05 kg
Energy	3.0e-02 MT

Analysis based on
14 observations spanning .19592 days
(2014-Mar-05.29096 to 2014-Mar-05.48688)

all above are mean values
weighted by impact probability

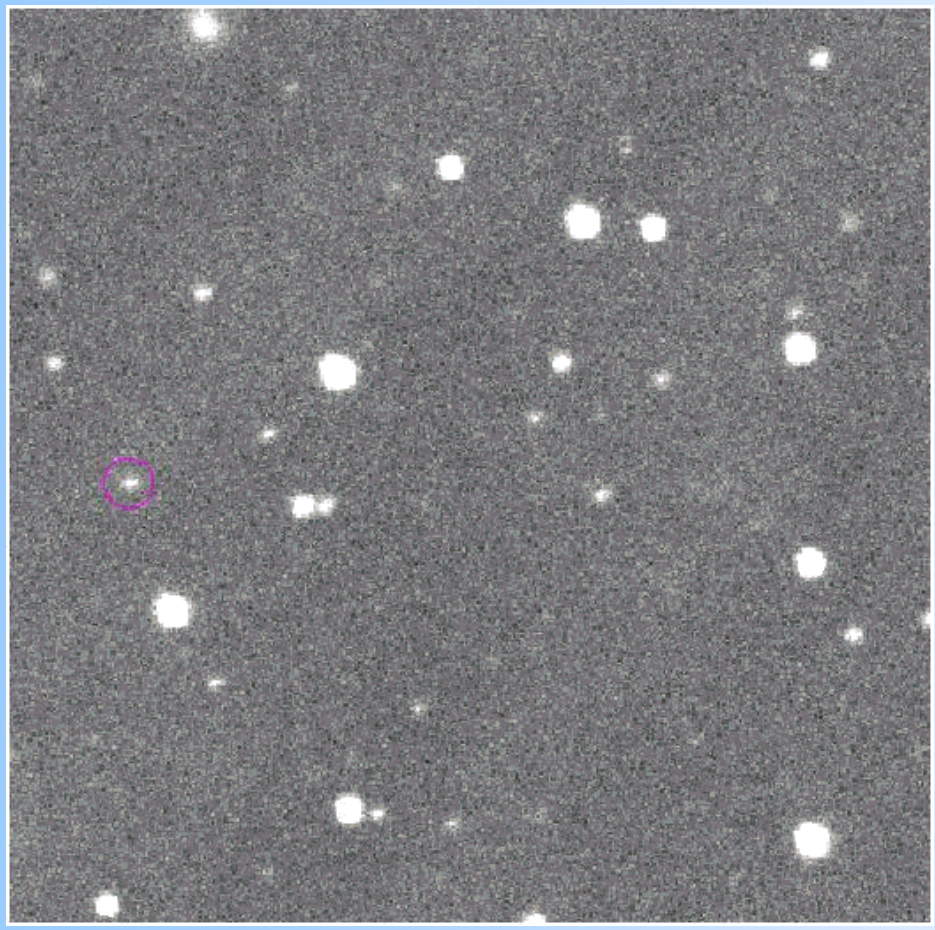
Orbit diagram and elements available here.

These results were computed on Mar 05, 2014

2014 EC
Earth Impact Table

Date	Distance	Width	Sigma Impact	Sigma LOV	Stretch LOV	Impact Probability	Impact Energy	Palermo Scale	Torino Scale
YYYY-MM-DD.DD	(r_{Earth})	(r_{Earth})			(r_{Earth})		(MT)		
2025-03-06.32	0.84	1.88e+00	0.000	-3.19981	2.02e+05	6.9e-09	3.05e-02	-8.89	0
2025-03-06.70	0.38	1.50e+00	0.000	-2.95392	3.82e+05	1.0e-08	3.05e-02	-8.72	0
2028-03-08.45	24.15	1.14e+01	2.037	0.69538	5.25e+06	6.9e-10	2.96e-02	-10.00	0
2039-03-08.00	1.56	1.54e+00	0.364	-1.18871	1.91e+06	5.0e-08	3.00e-02	-8.39	0
2042-03-05.58	4.49	7.89e+00	0.442	-0.06573	2.76e+06	1.9e-08	2.92e-02	-8.86	0
2042-03-05.60	0.30	7.30e+00	0.000	-0.00124	3.86e+06	1.8e-08	2.92e-02	-8.91	0
2042-03-08.45	10.23	5.94e+00	1.552	0.51380	6.25e+06	2.7e-09	2.96e-02	-9.72	0
2044-03-07.62	20.26	7.38e+00	2.611	-0.39234	5.43e+06	2.7e-10	2.98e-02	-10.70	0
2045-03-06.21	15.37	1.49e+01	0.964	-3.25791	4.83e+05	2.0e-10	3.05e-02	-10.90	0
2045-03-06.24	7.34	1.15e+01	0.550	-3.25577	3.59e+05	4.9e-10	3.05e-02	-10.50	0
2045-03-07.37	0.18	1.63e+00	0.000	-2.18097	5.19e+05	5.2e-08	3.03e-02	-8.47	0
2050-03-07.49	17.42	2.60e+01	0.631	-1.62262	1.05e+07	3.9e-10	3.02e-02	-10.70	0
2056-03-07.31	4.35	3.16e+00	1.061	-2.17419	2.73e+05	2.1e-08	3.04e-02	-8.99	0

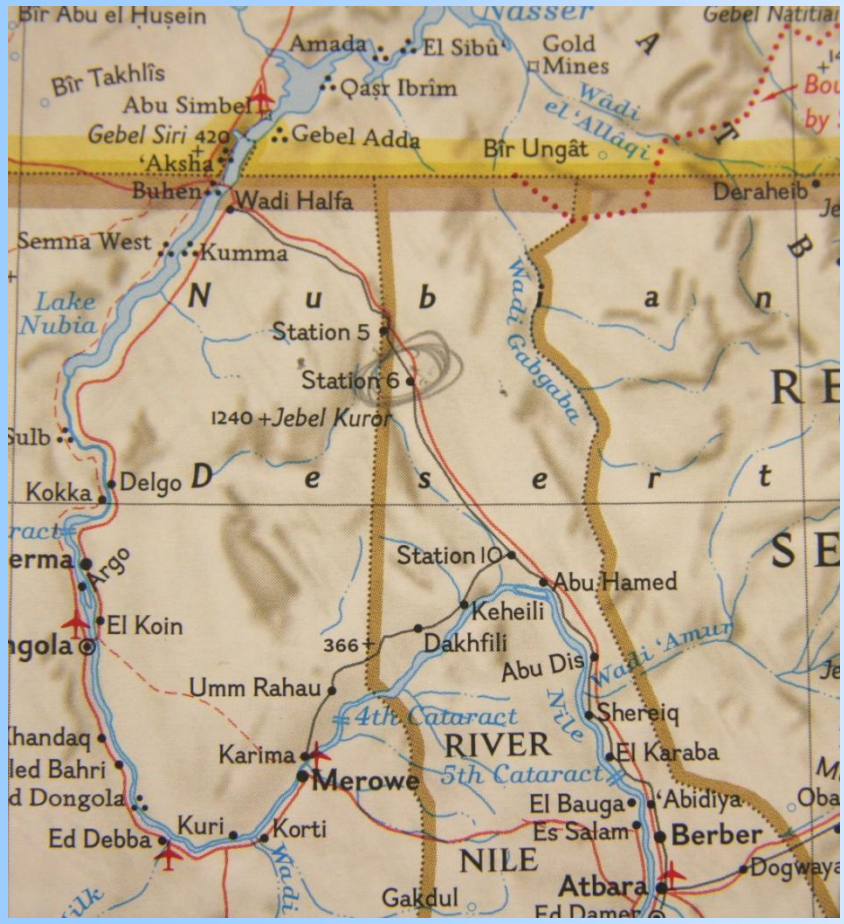
2008 TC3: A Real Impact



Discovery images of 2008 TC3 from Catalina Sky Survey

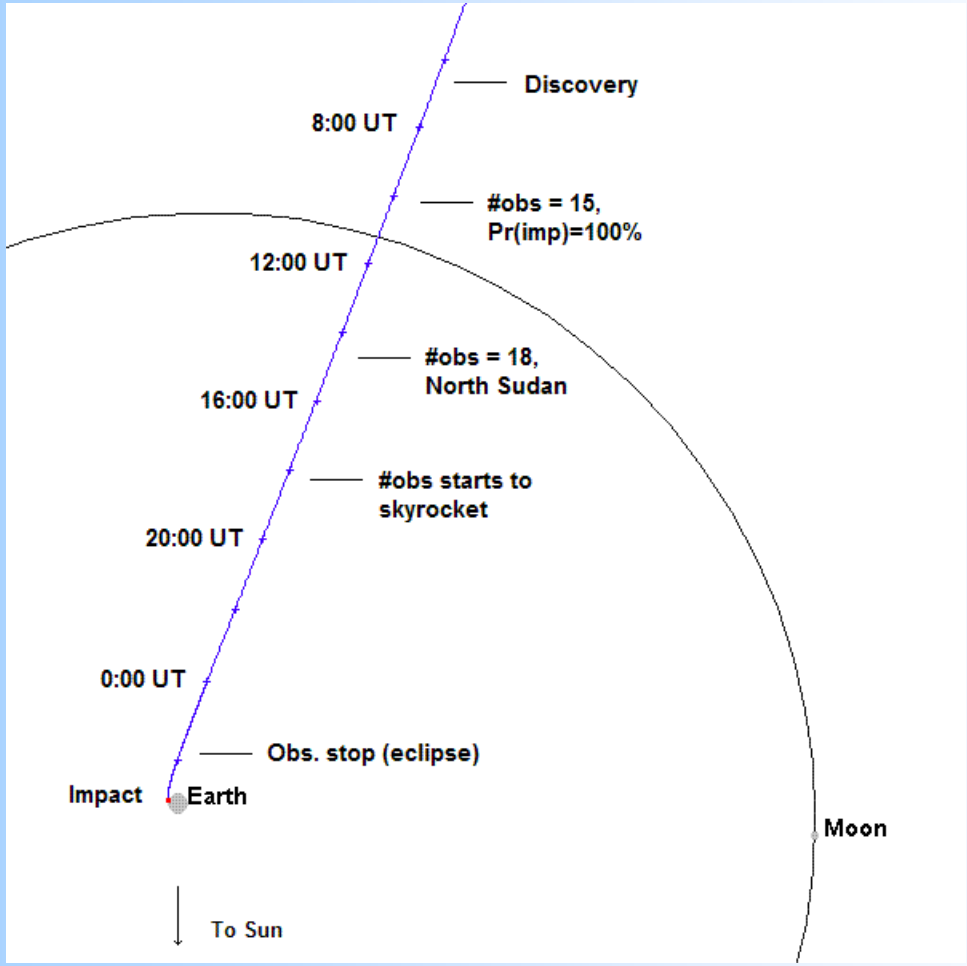
- On October 7, 2008 we had the first predicted impact of an asteroid: 2008 TC3.
- Discovered by Catalina Sky Survey at 1.3 lunar distances, 19 hr before impact.
- Impact location was 11 hours before impact.
- The object was clearly very small and would likely break up on entry.

Predicted Impact Location: N. Sudan



- Impact predicted to occur near a tiny town named Station 6, “Almahata Sitta”.
- Local time of impact was shortly before dawn.
- The impact event was actually observed and the impact time was within a few seconds of the predicted time.

2008 TC3 Trajectory & Timeline



Impact Site in Nubian Desert

(from Jenniskens et al. *Nature*, 26 March 2009)