

A bolide explosion above the Russian city of Chelyabinsk on 15 February 2013 at 3:20:26 UT is the most powerful event of its kind since 1908 (reference JPL's report at this [link](#)). According to a

report filed 16 February and posted at this [link](#), the resulting shock wave injured over 1100 people. Coincidentally, the near-Earth object (NEO) 2012 DA<sub>14</sub> reached perigee about 16 hours later at

19:25:49 UT<sup>1</sup>.

With preliminary bolide position data now available from video imagery of the event, reasonably accurate reconstructions of the bolide's ter-

restrial trajectory can be made. Such a reconstruction has been performed using the earliest two positions from IAU Telegram #3423 as reproduced in Table 1.

**Table 1. Phase Elapsed Time (PET) associated with the following two positions reported in IAU Telegram #3423 is assumed to be zero on 15 February 2013 at 3:20:14.800 UT. This assumption places bolide explosion near the 3:20:26 UT epoch reported by JPL at +11.20 s PET. "Height" in the telegram is assumed to be geodetic altitude.**

PET (s)	Latitude (°N)	Longitude (°E)	Height (km)
0.00	54.508	64.266	91.83
+9.18	54.788	61.913	41.02

The two Table 1 positions serve as boundary values defining a perturbed Lambert problem solution accounting for Earth gravity, including its  $J_{20}$  "oblateness" harmonic, together with gravity from the Sun and Moon. Ballistic atmospheric drag is also modeled using

bolide mass = 10 million kg and a spherical radius of 8.5 m per the referenced JPL report. These physical data are equivalent to a bolide mean density of 3.9 g/cm<sup>3</sup>.

The Lambert solution, expressed as a geocentric iner-

tial position and velocity at zero PET, has a speed of 17.673 km/s, a heading of 282.666° E of N, and a flight path angle of -18.823° relative to the local horizontal plane. Standard Small Bodies Database (SBDB) elements for this solution coasted back-

ward to a geocentric range of 1.365 million km appear in Table 2.

**Table 2. Heliocentric ecliptic elements in standard SBDB format at UT epoch 14.0 February 2013 are documented for the bolide reconstruction based on Table 1 data.**

SBDB Element	Value
JED EPOCH	2456337.500777605255
EC	0.525941229805981
AU QR	0.760370788517564
JED TP	2456292.279850039662
° OM	326.461152943781
° W	109.362847047727
° IN	4.06570147976527

A bolide trajectory reconstruction by Zuluaga and Ferrin (reference the paper downloadable at <http://arxiv.org/abs/1302.5377>) was published on 22 February 2013. It contains mean heliocentric ecliptic elements at an undisclosed epoch, together with standard deviation uncertainties ( $1\sigma$ ) in

these elements from a Monte Carlo simulation of 50 reconstruction cases. These data are compared in Table 3 with corresponding values arising from Table 2 elements at UT epoch 00:01:07.1851 on 14 February 2013 (14.0 February 2013 CT).

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**Table 3. Bolide heliocentric ecliptic elements from a Monte Carlo analysis by Zuluaga and Ferrin are compared to those arising from the Table 2 reconstruction. Elements related to Table 2 falling more than  $\pm 1\sigma$  from the corresponding mean value are underlined.**

<sup>1</sup> This epoch and other trajectory information relating to 2012 DA<sub>14</sub> appearing in this paper are obtained from JPL's *Horizons* on-line solar system data and ephemeris computation service accessible at <http://ssd.jpl.nasa.gov/?horizons>.

Element	Zuluaga and Ferrin (mean $\pm 1\sigma$ )	Adamo (best estimate)
Semi-major axis $a$ (AU)	1.73 $\pm$ 0.23	1.60
Eccentricity $e$	0.51 $\pm$ 0.08	0.53
Inclination $i$ (deg)	3.45 $\pm$ 2.02	4.07
Arg. of perihelion $\omega$ (deg)	120.62 $\pm$ 2.77	<u>109.36</u>
Lon. of asc. node $\Omega$ (deg)	326.70 $\pm$ 0.79	326.46
Perihelion dist. $q$ (AU)	0.82 $\pm$ 0.03	<u>0.76</u>
Aphelion dist. $Q$ (AU)	2.64 $\pm$ 0.49	2.45

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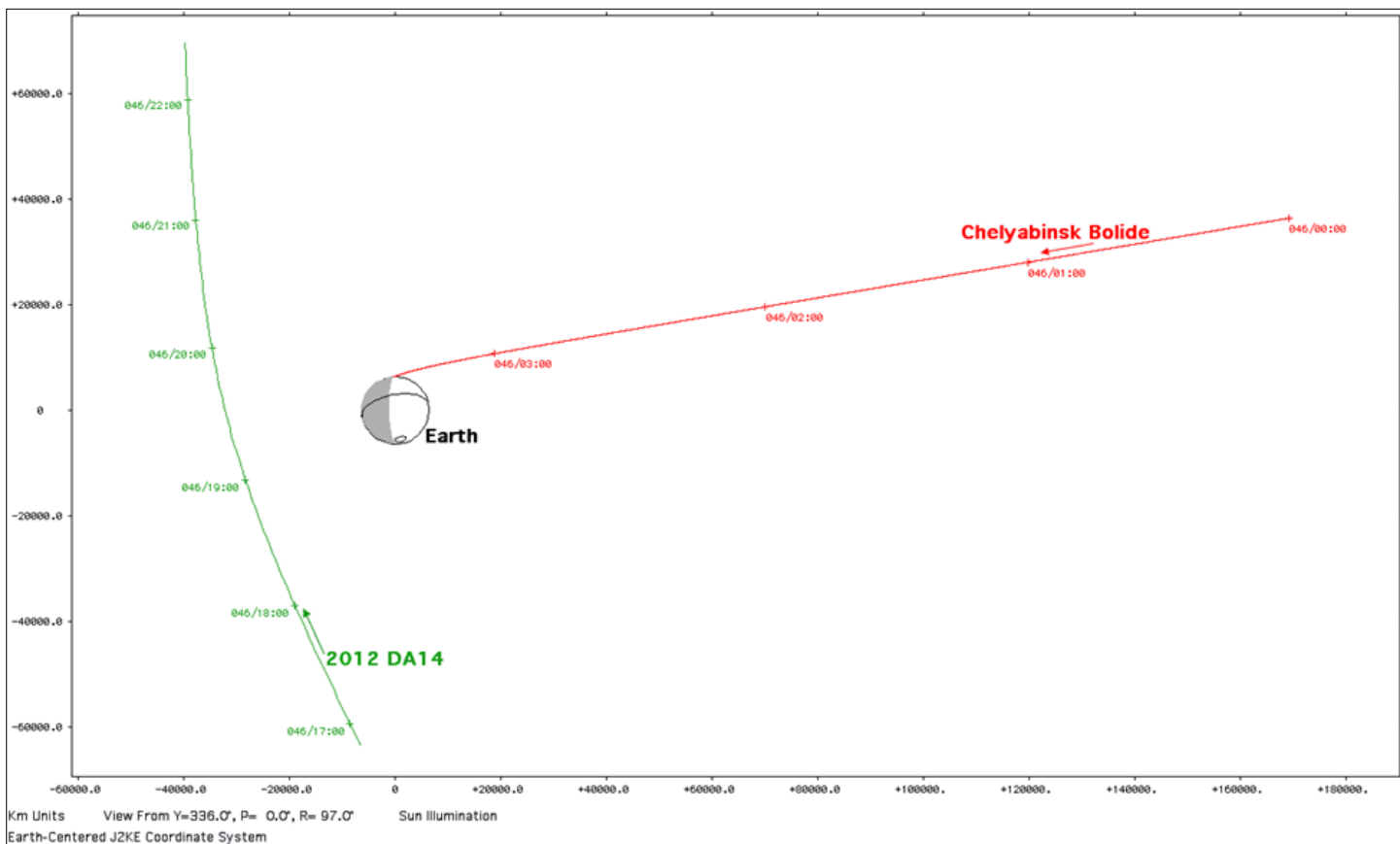
A geocentric plot of the bolide reconstruction arising from Table 1 data, along with a geocentric plot from 2012 DA<sub>14</sub>'s JPL#65 ephemeris, appear in Figure 1. Although both Earth encounters fall on the same day, their geocentric approach velocities are distinctly different.

Radar measurements of 2012 DA<sub>14</sub> on 15/16 February 2013 indicate its major (long) axis is 40 m (reference JPL's report at this [link](#)), more than

twice the bolide's estimated size. Along with its larger size and intrinsic brightness, 2012 DA<sub>14</sub> spends much of its time in Earth's night sky when close enough to detect with ground-based telescopes. These factors enabled 2012 DA<sub>14</sub>'s discovery nearly a year before its 15 February 2013 Earth encounter.

As is evident from Figure 1, the Chelyabinsk bolide approached from Earth's Sun-facing hemisphere and could not be observed by ground-based telescopes. This ap-

proach geometry has been termed a "Red Baron scenario" after Snoopy's dog-fighting escapades in the comic strip *Peanuts*. Such approaches can only be observed with a telescope placed a sufficient distance from Earth in the Sun's direction.



**Figure 1.** This geocentric inertial plot of the Chelyabinsk bolide's terminal approach to Earth (red) is viewed from a direction very nearly perpendicular to its plane of motion. Earth's nightside is shaded gray, and the subsequent flyby of NEO 2012 DA<sub>14</sub> is co-plotted (green) to illustrate its distinctly differing speed and direction. Time ticks accompanying both trajectories are at one-hour intervals and annotated with 15 February 2013 UT in day-of-year/hour:minute format.