Chelyabinsk Bolide Trajectory Reconstruction

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 http://www.jpl.nasa.gov/news/news.php?release=2013-061). According to a report filed 16 February and posted at http://www.huffingtonpost.co.uk/patrick-reevell/chelyabinsk-meteor-found-in-lake_b_2698548.html?utm_hp_ref=world&ir=World, the resulting shock wave injured over 1100 people. Coincidentally, the near-Earth object (NEO) 2012 DA_{14} reached perigee about 16 hours later at 19:25:49 UT*.

With preliminary bolide position data now available from video imagery of the event, reasonably accurate reconstructions of the bolide's terminal 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^3.

The Lambert solution, expressed as a geocentric inertial 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 backward 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

* This epoch and other trajectory information relating to 2012 DA_{14} 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.

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 (1σ) 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).

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 ±1σ from the corresponding mean value are underlined.

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

A geocentric plot of the bolide reconstruction arising form Table 1 data, along with a geocentric plot from 2012 DA_{14}'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_{14} on 15/16 February 2013 indicate its major (long) axis is 40 m (reference JPL's report at http://www.jpl.nasa.gov/news/news.php?release=2013-063), more than twice the bolide's estimated size. Along with its larger size and intrinsic brightness, 2012 DA_{14} spends much of its time in Earth's night sky when close enough to detect with ground-based telescopes. These factors enabled 2012 DA_{14}'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 approach 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.

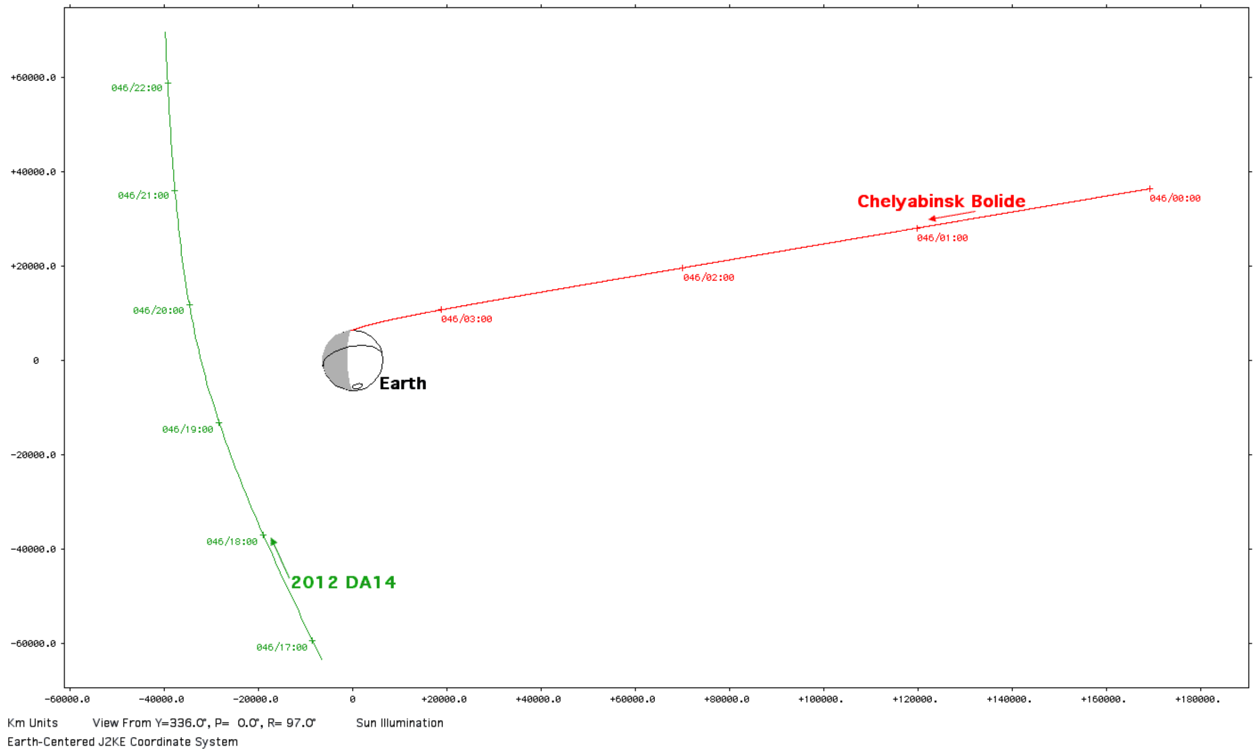

Figure 1. This geocentric inertial plot of the Chelyabinsk bolide's terminal approach to Earth (red) is viewed from a direction very nearly perpendicular to its plane of motion. Earth's nightside is shaded gray, and the subsequent flyby of NEO 2012 DA_{14} is co-plotted (green) to illustrate its distinctly 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.