The Red Baron Scenario In An Interplanetary Context

Even young readers without aeronautical interests will recall the dog fighting exploits of a certain heroic beagle in his self-imagined World War I flying ace persona, as portrayed by Charles Schultz in the comic strip *Peanuts*. More often than not, aerial combat would commence with Snoopy's archrival, The Red Baron, diving at him from out of the Sun's glare. Bullet holes would immediately riddle our hero's Sopwith Camel biplane, faithfully depicted by Schultz as a doghouse with Snoopy astride the ridgepole.

A similar scenario plays out all too often as humanity struggles to detect populations of small-sized near-Earth objects (NEOs). Although we've found nearly 90% of NEOs having diameters 1 km or more, the population with diameters less than 100 m is far more prolific and more than 95% of this population has yet to be detected. These diminutive NEOs are significant for two reasons. First, they encompass the minimum size thresholds capable of inflicting local to regional damage should a member impact Earth. For example, the Tunguska impact, in which 2000 km^2 of Siberian forest were decimated in June 1908, is thought to be associated with a NEO 30 to 50 m in diameter. Second, a NEO destination 50 to 100 m in diameter is considered the minimum size justifying cost/risk of a human space flight (HSF) mission sent to explore it.

Due to their small size, these NEOs *must* approach Earth closely or they'll escape detection because all our instrumentation is currently confined to Earth's surface. Such discoveries are typically made in a clear dark sky at near-zenith elevation. If a NEO approaches Earth from the Sun's general direction, as roughly half do, it'll go undetected by Earthbound instrumentation until its apparent angular separation from the Sun, or *solar elongation*, approaches 180°. If the NEO's aphelion falls inside Earth's heliocentric orbit, *this geometry never occurs*.

In the case of an impacting NEO 30 to 50 m diameter or larger, approach from Earth's dayside is a Red Baron scenario with potential consequences far greater than those Snoopy ever suffered. Even in the context of HSF, a NEO approaching from Earth's day side greatly hampers mission planning because the prospective destination remains undetected until it's already receding from Earth. Current human factors limitations from microgravity and radiation exposure impose HSF mission durations well under a year on travel to a NEO and back to Earth. Consequently, a viable NEO destination must be no more than about 0.1 AU (15 million km) from Earth when humans arrive to explore it. If a NEO is near that threshold and *receding* from Earth at arrival, this visit will likely be disappointingly brief.

Red Baron scenarios during close NEO Earth encounters develop with surprising frequency. Let's look at two relevant examples observed so far in 2011 using data from the Jet Propulsion Laboratory (JPL) Solar System Dynamics Division's (SSD's) *Horizons* online ephemeris computation service, accessible at URL http://ssd.jpl.nasa.gov/?horizons. Our first example, a NEO with provisional designation* 2011 CQ_1, was benign with respect to the Red Baron

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* In our solar system, small body provisional designations consist of the discovery year, followed by a space, two letters, and zero or more subscripted numeric digits. The first letter is alphabetically incremented such that {A, C, E,..., X} cover the first 15 days of each possible discovery month and {B, D, F,...,Y} cover remaining days of each possible discovery month. Neither "I" nor "Z" is used as a first letter. The second letter indicates the chronological order of discovery during a particular half-month, and "I" is again excluded. No numeric subscript is appended for the first 25 discoveries in a half-month, but it is incremented from 0 and appended each time the second letter recycles from "Z" to "A". Thus, beginning on March 16 and extending through March 31 in a particular year, letters and subscripts would progress through the sequence {FA, FB,...FZ, FA_1, FB_1,...FZ_1, FA_2, FB_2,...}.

scenario during its discovery timeframe. According to *Horizons*, it came to perigee on 2011 Feb 04.8 UT at a geocentric distance of 0.000079 AU (12,000 km). But 2011 CQ_1 came to *perihelion* 111.6 days later on 2011 May 27.4 UT at a heliocentric distance of 0.665 AU. With Earth always orbiting the Sun at a distance near 1 AU, 2011 CQ_1 therefore approached Earth in February from its night side.

A NEO's motion relative to the Earth/Sun line can be illustrated using *heliocentric UV plots*. In this application, the "UV" signifies plots are projections onto Earth's heliocentric orbit plane, the *ecliptic*. From such plots, a NEO's geocentric apparent solar elongation is readily perceivable, typically over many years. As defined below, Earth's heliocentric orbit motion at any specified instant in time or *epoch* defines the basis for a Cartesian UVW coordinate system from which UV plots are generated.

U: unit vector directed from the Sun toward Earth's position at epoch.

V: unit vector of Earth's velocity component orthogonal to ***U*** at epoch.

W: unit vector orthogonal to the ecliptic plane at epoch such that $\boldsymbol{U} \times \boldsymbol{V} = \boldsymbol{W}$ in the right-handed convention.

Figure 1 is a heliocentric UV plot for 2011 CQ_1 spanning calendar years 2006 through 2015. The start of each year during this interval is annotated adjacent to the UV locus, and "+" time ticks appear on this locus at 30-day intervals. Prior to its year 2011 discovery, 2011 CQ_1 was a member of the *Apollo* orbit group as denoted by the UV locus colored green. An Apollo orbit crosses Earth's but has a mean heliocentric distance or semi-major axis *a* exceeding 1 AU. A NEO in an Apollo orbit tends to approach Earth from the +***V*** direction because Earth's orbit period is shorter. After February 2011, 2011 CQ_1 became a member of the *Aten* orbit group due to Earth gravity perturbations on its heliocentric orbit, and its UV locus is colored russet. An Aten orbit also crosses Earth's, but its *a* is less than 1 AU. Consequently, a NEO in an Aten orbit tends to approach Earth from the -***V*** direction.

To attain a geocentric apparent solar elongation greater than 90° in Figure 1, 2011 CQ_1 must have a ***U*** position component exceeding +1 AU. Elongation can approach 180°, satisfying geometry necessary for Earthbound discovery, only when 2011 CQ_1 lies very nearly in the +***U*** direction from Earth. Figure 1 indicates this geometry prevailed for about 30 days prior to perigee, but another factor undoubtedly delayed 2011 CQ_1 discovery: its absolute magnitude[†] H = +32.037. Assuming 2011 CQ_1 is about as dark as conceivable, with a reflectivity of 5%, the following formula estimates its near-maximum possible diameter d_X = 2.3 m. It's therefore no surprise that all 35 usable observations of 2011 CQ_1 were confined to 2011 Feb 04.

$$d_X = 5{,}944{,}000 * 10^{-0.2\,H}$$

[†] Absolute magnitude is a measure of an astronomical object's *intrinsic* visual brightness at a distance of 1 AU from the observer. Note that, because visible wavelengths are used, an ambiguity arises in relating absolute magnitude to the object's size: it could be relatively large and dark, or it could be relatively small and bright. A magnitude decrease of 5 units is equivalent to a brightness increase by a factor of 100. To the Earthbound human eye, the dimmest stars have an *apparent* magnitude of +6, and the brightest star Sirius has an apparent magnitude of -1.4.

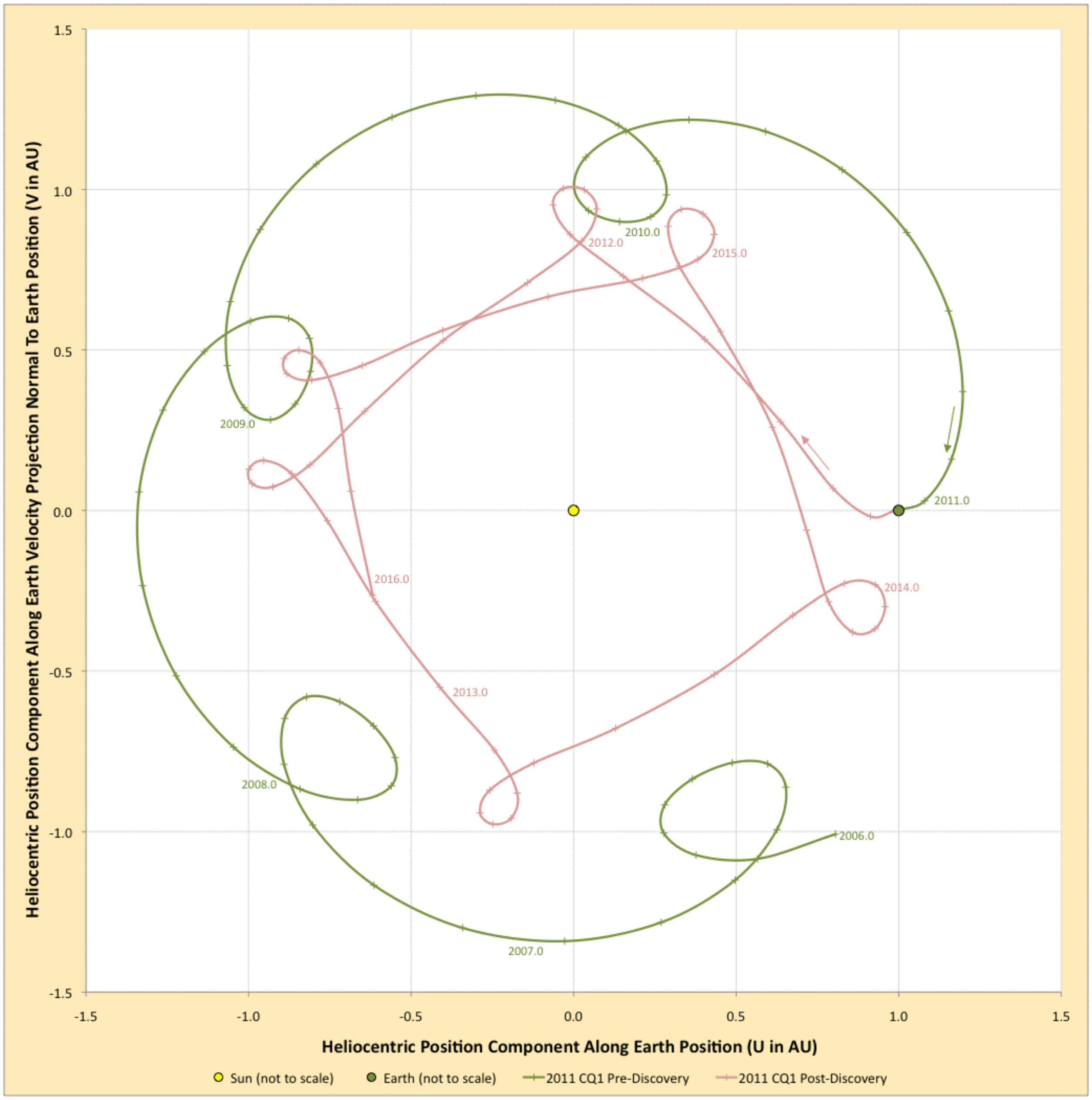

Figure 1. Heliocentric UV Plot of 2011 CQ_1 Relative To The Earth/Sun Line

With observations confined to an interval less than one day, our ability to model 2011 CQ_1 heliocentric motion years into the future or past is problematic at best. For the Figure 1 scale and time interval, UV coordinates are reasonably correct, but a 2011 CQ_1 approach to Earth sufficiently close to obtain additional ground-based observations and a refined orbit is likely decades in the future. Consequently, 2011 CQ_1 has been assigned an orbit condition code (OCC) of 5[‡]. It's indeed fortunate that 2011 CQ_1 is of a size not posing an impact threat to Earth. From

[‡] A NEO with an OCC in the range of 3 to 5 may or may not be acquired when it's next observable. With an OCC from 6 to 9, a NEO is effectively lost after discovery observations cease. Only at OCC values of 0, 1, or 2 is a NEO likely to be observed during the next opportunity to do so.

post-discovery motion in Figure 1, it's evident 2011 CQ_1 will likely pose a Red Baron scenario during its next close Earth approach.

Our second example Red Baron scenario received provisional designation 2011 JV_{10} after discovery on 2011 May 08. According to *Horizons*, it came to perigee on 2011 May 05.7 UT at a geocentric distance of 0.0023 AU (340,000 km). In this case, 2011 JV_{10} came to perihelion 65.1 days *earlier* on 2011 March 04.6 UT at a heliocentric distance of 0.895 AU. Because 2011 JV_{10} approached Earth from its day side in 2011, a Red Baron scenario was in effect, delaying discovery until after perigee. This geometry is illustrated in Figure 2's UV plot.

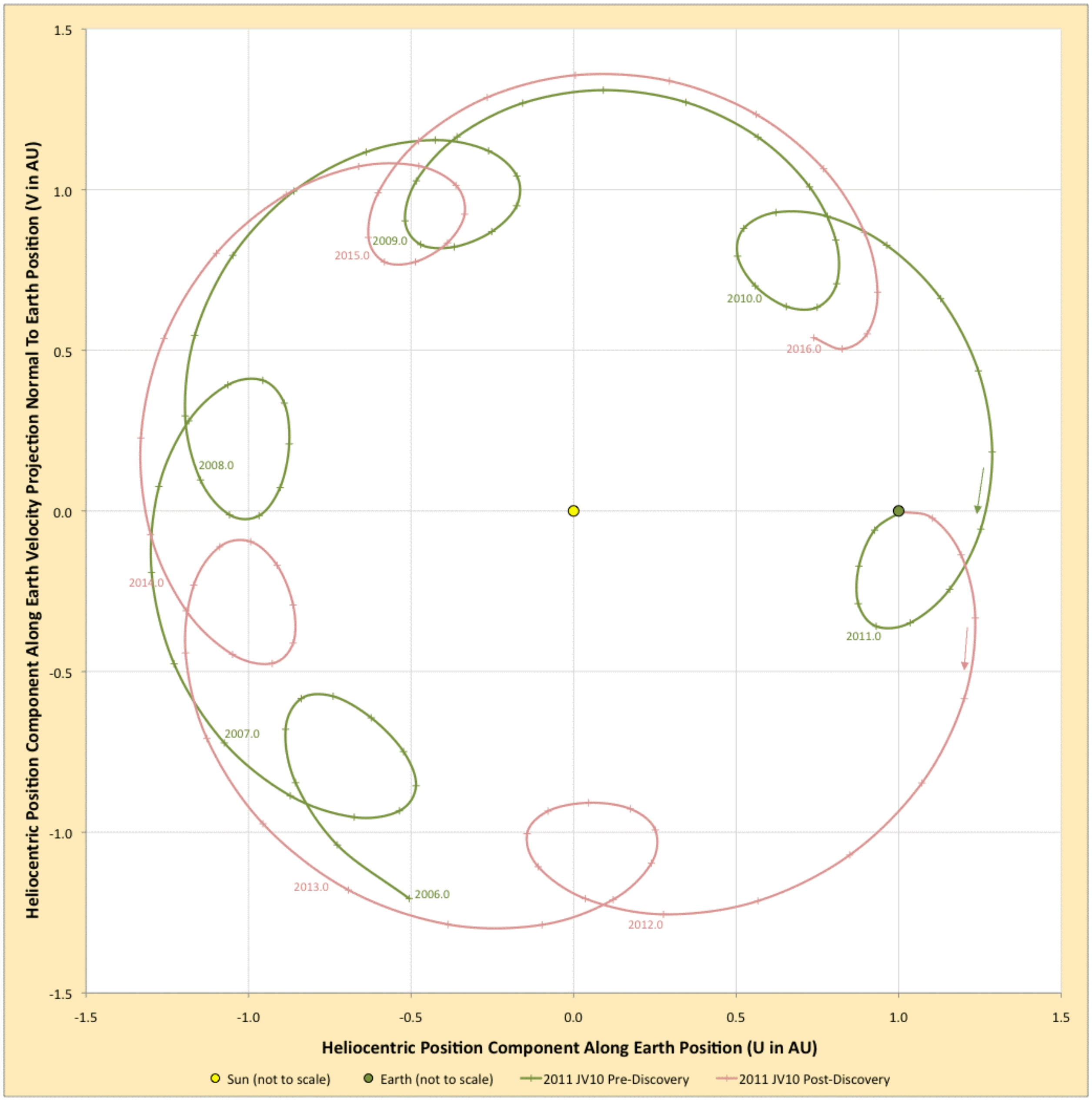

Figure 2. Heliocentric UV Plot of 2011 JV_{10} Relative To The Earth/Sun Line

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Unlike the 2011 CQ_1 example in Figure 1, 2011 JV_{10} remains in an Apollo orbit after its 2011 Earth encounter. As is evident from the UV arcs at the top of Figure 2, 2011 JV_{10}'s Earth encounter at discovery does little more than slightly increase aphelion.

With $H = +29.705$ and an inferred $d_X = 6.8$ m, 2011 JV_{10} wasn't an easy object to observe from Earth even after it moved into the night sky post-perigee. A total of 18 usable observations were obtained during 2011 May 08 - 10. Although this dataset extends over a longer period than the few hours 2011 CQ_1 was observed, 2011 JV_{10}'s perigee distance was 0.88 of the Moon's mean distance from Earth or 28 times that of 2011 CQ_1's perigee. The relative lack of 2011 JV_{10} observational data in close proximity to Earth is likely responsible for its current OCC = 6.

Projected onto the ecliptic plane, the Figure 2 UV plot's russet segment indicates future close Earth approaches by 2011 JV_{10} could occur before or after perihelion, making it difficult to determine whether or not such an approach will be a Red Baron scenario. But only post-perihelion Earth orbit crossings occur near an ecliptic plane crossing or *node*, so any pre-perihelion approaches from Earth's night side will also be millions of km "below" the ecliptic plane and unobservable with current instrumentation.

Public notifications associated with our two Red Baron scenario examples present a noteworthy contrast. Because 2011 CQ_1 had a geocentric perigee distance well under half the Moon's mean geocentric distance (equivalent to 0.001285 AU or 192,200 km) following its discovery, SSD's policy is to inform news media channels of the event. The associated news release can be viewed at URL http://neo.jpl.nasa.gov/news/news170.html.

On the other hand, notifying the public of events like 2011 JV_{10}'s close Earth approach would quickly overwhelm channels with relatively insignificant news items issued at roughly weekly intervals. The only known public notification of the 2011 JV_{10} Red Baron scenario in 2011 was posted to JPL's Space Calendar homepage at URL http://www2.jpl.nasa.gov/calendar/. Because of this scenario, however, the approach was history by the time it was posted.

The only public notifications of Earth approaches *farther* than about 0.001285 AU are associated with objects of special interest, such as 2005 YU_{55}. This NEO's next perigee, at a geocentric distance of 0.00217 AU (325,000 km), falls on 2011 Nov 09.0 UT. With an OCC = 0, confidence is high in this prediction. Special interest in 2005 YU_{55} undoubtedly lies with its $H = +21.929$, inferring a $d_X = 244$ m. According to the JPL news release at http://neo.jpl.nasa.gov/news/news171.html, 2005 YU_{55} was observed with radar in 2010 "and shown to be a very dark, nearly spherical object 400 meters in diameter". If an object this large impacts Earth, devastation on a continental scale is estimated to result.

As SSD notes in the 2011 CQ_1 news release, "small objects of this size create visually impressive fireball events [should they enter Earth's atmosphere] but only rarely do even a few small fragments reach the ground". In citing Red Baron scenario examples involving harmless NEOs evading Earth so far, the long-term message is that dire consequences could easily prevail from very similar approaches in which larger objects impact Earth.

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Ongoing research indicates the most cost-effective means of greatly reducing or eliminating Red Baron scenarios is with NEO survey instrumentation operating at least a million km from Earth. In addition to improving prospects for defending our planet from devastating impacts, such instrumentation will vastly extend our knowledge of arguably the most extensive and poorly understood territory in the inner solar system. This knowledge will certainly contribute to planetary science's advancement. It will also greatly inform our selection of the most rewarding and appropriate NEO destinations for HSF. With this instrumentation, close Earth approaches by at least some of the myriad NEOs 50 m or more in diameter can be accurately predicted many years in advance. In some cases, this advance knowledge will be sufficient to plan and launch HSF missions taking advantage of NEO approaches with adequate accessibility from Earth.

A NEO survey conducted from a deep space vantage point therefore offers a triple payoff, with beneficiaries in planetary defense, planetary science, and HSF exploration. This payoff can be achieved with mature technology, much of it already having flown in space. It's hard to imagine instrumentation with a greater return on investment to offer taxpayers.

Nearly all the general NEO information conveyed in this article is more formally and thoroughly documented by two recent publications available for free download as follows.

1) National Research Council Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies, *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies: Final Report*, The National Academies Press, Washington, D.C., 2010, downloadable from URL http://www.nap.edu/catalog.php?record_id=12842.

2) Barbee, B. W. (ed.), *Target NEO: Open Global Community NEO Workshop Report*, 2011, downloadable from URL http://www.targetneo.org/.