Periodic mass extinctions and the Planet X model reconsidered

Daniel P. Whitmire

Department of Mathematics, The University of Arkansas, Fayetteville, AR

October 22, 2015

Abstract

The 27 Myr periodicity in the fossil extinction record has been confirmed in modern data bases dating back 500 Myr, which is twice the time interval of the original analysis from thirty years ago. The surprising regularity of this period has been used to reject the Nemesis model. A second model based on the sun’s vertical galactic oscillations has been challenged on the basis of an inconsistency in period and phasing. The third astronomical model originally proposed to explain the periodicity is the Planet X model in which the period is associated with the perihelion precession of the inclined orbit of a trans-Neptunian planet. Recently, and unrelated to mass extinctions, a trans-Neptunian super-Earth planet has been proposed to explain the observation that the inner Oort cloud objects Sedna and 2012VP113 have perihelia that lie near the ecliptic plane. In this Letter we reconsider the Planet X model in light of the confluence of the modern palaeontological and outer solar system dynamical evidence.

Key Words: astrobiology - planets and satellites - Kuiper belt: general - comets: general

Background

The discovery of an apparent 26 Myr period in mass extinctions by Raup & Sepkoski (1984) invited the proposal of three astronomical models. The Nemesis model postulated that the extinction period was associated with comet showers that were triggered when a solar companion object in an eccentric orbit scattered comets when passing through it’s perihelion point located in the inner Oort cloud. One version of the Nemesis model (Davis et al., 1984) assumed that the companion was a common M-dwarf star. This version was ruled out by full sky surveys, the latest of which is the NASA WISE mid-IR survey (Luhman, 2014). However, the other version of Nemesis (Whitmire and Jackson, 1984)
assumed the companion was a sub-stellar object with a mass between $0.07 \, M_\odot$ and $2 \times 10^{-4} \, M_\odot$. The lower end of this mass range is not ruled out by WISE or any other full sky survey given that the object would likely be closer to aphelion today.

Using the revised 2012 geological timescale, Melott & Bambach (2014, 2013, 2010) have given a period analysis based on two independent sets of data with increased taxonomic resolution. Their analysis confirmed a 27 Myr period over the entire Phanerozoic (500 Myr), which is twice the time interval of the original Raup and Sepkoski analysis. Using two different statistical tests they give period p-values of 0.004 and 0.02, which is more significant than the original 0.05 given by Raup and Sepkoski. As they note, there is not a local maxima in extinction at each 27 Myr interval and there are some peaks that lie between intervals. This is expected if comet showers are the proximate cause of the peaks. We note that large KT-size comet impacts are not necessarily the only or even the primary mechanism for mass extinctions. Dust and numerous smaller impacts from the breakup of giant comets is a more likely scenario (Napier, 2015).

Using the new geological timescale the spectrum of interval lengths does not show a 27 Myr period, eliminating this as a possible artifact producing the original periodicity (Melott and Bambach, 2014). The period appears to be not only real but also highly regular with a variation of no more that 2 - 10\% over 500 Myr. If correct, as they point out, this rules out both versions of the Nemesis model (Melott & Bambach, 2010, 2013) since the orbital period of Nemesis is expected to increase by 20\% over only 250 Myr due to stellar and galactic tidal perturbations (Hut, 1984). The variation in period may be further complicated due to the galactic radial migration of the sun by several kpc over the last few Gyr (Kaib, et al., 2011).

The second astronomical model associates the extinction period with the vertical galactic oscillations of the solar system. However, this model has been challenged on the basis of an inconsistency in phasing and period. The period of galactic plane crossings ($\sim 33$ Myr) in this model appears to be inconsistent with the 27 Myr period, unless a significant thin disk of weakly interacting dark matter is postulated to lie in the galactic plane (Rampino, 2015). The most recent plane crossing was $\sim 1$ Myr ago (Gies & Helse, 2005) while the most recent predicted periodic extinction event was $\sim 11$ Myr ago (Melott & Bamback, 2010).

The third proposed astronomical model is Planet X (Whitmire & Matese, 1985; Matese & Whitmire, 1986a, 1986b). In this model the extinction period is associated with the perihelion/aphelion precession period of a trans-Neptunian planet of mass $\sim 5 \, M_\oplus$. The planet’s perihelion and aphelion points pass through the ecliptic plane twice during each circulation period, triggering comet showers. The original model required the existence of the Kuiper belt (yet to be discovered) and a gap or edge in the belt like the now well-known Kuiper Cliff at $\approx 50$ AU. The model also necessarily produces a flux of short period comets. Though in the original model we focused on the idea that Planet X itself created the required gap, implying a mass range of 3 - 8 $M_\oplus$, we noted that the gap/edge might also be primordial (Matese & Whitmire, 1986a), as has
now been observed around some young stars. In this case the mass of Planet X could be lower, \( \sim 1 \, M_\oplus \), since it need not have cleared the gap itself. This lower limit is based solely on the comet scattering dynamics. Other hybrid scenarios (Lykawka and Mukai, 2008) are also possible whereby Planet X created the gap prior to major planet migration and subsequent evolution to its present orbit.

Recently it has been noted that the arguments of perihelia (\( \omega \)) of the two known inner Oort cloud objects with \( q \geq 75 \) AU, Sedna and 2012VP\(_{113}\), (as well as ten other trans-Neptunian objects (TNO’s) with \( q \geq 30 \) AU and \( a \geq 150 \) AU) cluster in the ecliptic around \( \omega = 0 \) (Trujillo & Sheppard, 2014). The absence of any clustering around \( \omega = 180^\circ \) implied that the effect was not due to observational bias. These authors showed that the clustering of the two inner Oort cloud objects could be explained/maintained by a super-Earth planet of mass 2 - 15 \( M_\oplus \) in a near circular, small inclination orbit between 200 and 300 AU but noted that those orbits were not unique. The orbit used for illustration was that of a 5 \( M_\oplus \) planet at 210 AU. The planet is needed to maintain the clustering (by causing the \( \omega \)’s to librate around \( \omega = 0 \)) over the age of the solar system since the known planets would precess and thus essentially randomize the \( \omega \)’s on timescales short compared to the age of the solar system (Trujillo & Sheppard, 2014). The reason for the original asymmetry in \( \omega = 0 \) versus \( 180^\circ \) is left unexplained, however see de la Fuente Marcos, de la Fuente Marcos & Aarseth (2015). In the simulations the smaller perihelia objects did not cluster in the same way but it was noted that simulations with planets in higher inclination orbits should be investigated (Trujillo and Sheppard, 2014). de la Fuente Marcos & de la Fuente Marcos (2014) confirmed that the clustering of \( \omega \)’s is not due to observational bias. They also noted a tendency for inclinations to cluster around \( 20^\circ \) and conjectured that there may be two such trans-Neptunian planets. The eccentricities of these TNO’s cluster around \( \sim 0.8 \). However, unlike the \( \omega \)’s, the clustering of \( e \)’s is likely to be at least partly a selection effect. Thus far there have not been any other complete explanations put forward as an alternative to the \( \omega = 0 \) clustering other than a trans-Neptunian super-Earth planet (C. Trujillo, personal communication).

**Analysis**

We wish to determine under what conditions, if any, the perihelion/aphelion precession of the orbit of Planet X is sufficiently regular to be consistent with the regularity found in the updated extinction period. This means that the precession period should not vary *systematically* by more than 2-10% over 500 Myr (Melott and Bambach, 2010, 2014), which as noted above is inconsistent with the Nemesis model. It is not obvious that this will naturally occur since the precession period depends on the orbit’s eccentricity and inclination, which might vary significantly over 500 Myr. On the other hand the timing of the peak maxima can fluctuate non-systematically about the 27 Myr timeline. This could occur because of small amplitude oscillations in eccentricity or inclination or just the statistics of shower event timings.
We use the truncated secular Lagrange equations as given by Gallardo et al. (2012) as an approximation to describe the motion of a massless Planet X, i.e. we neglect any back reaction on the giant planets. This approximation will thus be more accurate for the lower end of the Planet X mass range. These equations are based on an integral truncation of the secular Hamiltonian and as such will not exhibit the full complexity of the dynamics. Mean motion resonances with Neptune are also neglected in the present analysis. With these caveats, the secular truncated orbital equations are then:

\[
\frac{da}{dt} = 0 \quad (1)
\]

\[
\frac{de}{dt} = \frac{45ckE}{512a^2(1 - e^2)^3}(5 + 7 \cos 2i) \sin^2 i \sin 2\omega + \ldots \quad (2)
\]

\[
\frac{di}{dt} = \frac{45ckE}{1054a^2(1 - e^2)^4}(5 + 7 \cos 2i) \sin 2i \sin 2\omega + \ldots \quad (3)
\]

\[
\frac{d\Omega}{dt} = -\frac{3Ck}{4a^2(1 - e^2)^2} \cos i + \ldots \quad (4)
\]

\[
\frac{d\omega}{dt} = \frac{3Ck}{4a^2(1 - e^2)^2}(3 + 5 \cos 2i) + \ldots \quad (5)
\]

In these equations \( e \) is the orbit eccentricity, \( i \) is the orbit plane inclination relative to the ecliptic, \( \Omega \) is the angle of the orbit’s ascending node, \( \omega \) is the argument of perihelion, and \( a \) is the semimajor axis. The constants \( C \) and \( E \) are the quadrupole and octopole strengths equal to 0.116 and 52, respectively (Gallardo et al., 2012), and \( k \) is the Gaussian constant = \( \sqrt{GM} = 2\pi \) in units where time is measured in years, distances in AU, and masses in solar units. We assume that the Hamiltonian is approximately only a function of the actions, which will be true if the Kozai harmonic, present in Eqs. (2) and (3), circulates rapidly, in which case \( e \) and \( i \) are approximately constant. The precession period is then found from Eq. (5), \( d\omega/dt = 2\pi/T_\omega \), or

\[
T_\omega \approx \frac{16(1 - e^2)^2a^2}{3C(3 + 5 \cos 2i)} \quad (6)
\]

In the Planet X model the precession period = 2 × 27 Myr = 54 Myr is fixed. The required semimajor axis is then given by

\[
a \approx \frac{3CT_\omega(3 + 5 \cos 2i)}{16(1 - e^2)^2} \quad (7)
\]

Equation (7) predicts a unique relation between \( i, e, \) and \( a \), though for a given \( T_\omega \) period the required semimajor axis is fairly insensitive to \( e \) and \( i \). If showers at perihelion dominate then the eccentricity is \( \leq 0.5 \), while for aphelion showers there is no limitation on the eccentricity of the orbit other than that the perihelion point not get too close to Neptune’s orbit (Matese and Whitmire,
The required inclination needs to be \( \geq 25^\circ \) in order that comets can be directly scattered into the spheres of influence of Jupiter and Saturn, as required by the duration of the shower in the inner solar system. Though the 27 Myr extinction period is highly regular, the duration or width of the shower is less well constrained.

Gallardo, et al. (2012) investigated Kozai dynamics as applied to trans-Neptunian bodies, considering both non-resonant and mean motion resonances. We focus on their Fig. 2, panels (e) - (h), which give the non-resonant curves of \( q \) and \( i \) versus \( \omega \) for \( a = 100 \) AU and various values of the constant \( H = \sqrt{1 - e^2} \cos i \) from 0.1 to 0.7. Because of the symmetries, \( \omega \) and \( i \) are shown only to 180\(^\circ\) and 90\(^\circ\), respectively. Inspection of these figures show that for a given \( q \geq 50 \) AU (Kuiper Cliff), corresponding to approximately constant/equilibrium inclinations in the range of 36\(^\circ\) – 83\(^\circ\), neither the perhelia, eccentricities or inclinations vary by more than a few percent as \( \omega \) takes on all values in its circulation. Modest increases of \( H \geq 0.7 \) and/or \( a \geq 100 \) AU would allow values of \( i \) down to 25\(^\circ\), which is the dynamical scattering limit of the Planet X model.

For \( a = 100 \) AU, values of \( q \leq 50 \) AU would be incompatible with the cold classical Kuiper belt which has an inclination dispersion of \( \approx 5^\circ \) (Brown 2001).

**Discussion**

Inserting \( e = 0.5 \) and \( i = 25^\circ(35^\circ) \) into Eq. (7) gives \( a = 108(100) \) AU, \( q = 54(50) \) AU and \( Q = 162(150) \) AU. These aphelia are less than the 200 - 300 AU near circular, low inclination orbits assumed by Trujillo and Sheppard in most of their simulations but, as noted above, they acknowledged that their masses and orbits are not unique in maintaining the clustering about \( \omega = 0 \). In their simulations the planet masses included the super-Earth range of \( 2 - 15 \) M\(_{\oplus} \) at 200 - 300 AU. In their illustration they used a 5 M\(_{\oplus} \) planet at 210 AU. They assumed that with a very low albedo such planets could have remained undetected in prior full sky surveys, presumably even near the ecliptic. In the Planet X model the conservative mass limit was given as \( 1 - 15 \) M\(_{\oplus} \) (Matese and Whitmire, 1986a), though assuming Planet X itself created the gap the range given was 3 - 8 M\(_{\oplus} \). However, as noted above, and in our paper, if the Kuiper Cliff is primordial a mass as low as 1 M\(_{\oplus} \) is possible, based solely on the scattering dynamics. A low albedo planet with a mass near the lower end of the range with inclination \( \geq 25^\circ \) and currently near aphelion might likewise have escaped detection in past full sky surveys.

Tombaugh’s full sky survey that discovered Pluto is still relevant beyond the ecliptic and certain other limited deep field studied regions. His full sky search was sensitive to \( \approx 15^\text{th} \) magnitude. The visual magnitude of Pluto at the time of discovery was \( \approx 14.5 \). The reflected flux of Planet X at Earth relative to that of Pluto is \( \propto (A_X/A_P)(M_X/M_P)^{4}(r_P/r_X)^4 \), where \( A \) is albedo, \( r \) is the heliocentric distances, equal densities are assumed, and the Earth-sun distance is neglected. Inserting Pluto’s mass = \( 2.2 \times 10^{-3} \) M\(_{\oplus} \), \( M_X = 2 \) M\(_{\oplus} \), \( r_P = 35 \) AU and \( r_X = Q = 150 \) AU gives a relative reflected flux = 0.278. This
is 1.4 magnitudes dimmer than Pluto, or \( \approx 16 \)th magnitude, assuming equal albedos. Pluto’s average albedo is 0.58. If Planet X has a low albedo of say 0.05 then the relative reflected flux would be further reduced to 0.024, making it about 4 magnitudes dimmer than Pluto, or magnitude 18.5. A planet of visual magnitude 16 - 18.5 currently located well out of the ecliptic could have been missed in Tombaugh’s full sky survey and other subsequent limited-field optical surveys. Luhman (2014) does not give WISE full sky mid-IR limits for rock/ice trans-Neptunian planets.

Lykawka and Mukai (2007) argued that a trans-Neptunian planet of mass up to 1 \( M_\oplus \) can explain the architecture of the Kuiper belt. Some features like the Kuiper Cliff at \( \sim 50 \) AU were explained by the planet prior to outer-planet-migration. The planet subsequently evolved to its present orbit, \( a \geq 100 \) AU and \( i = 20^\circ - 40^\circ \). In this analysis the planet is predicted to have \( q \geq 70 - 80 \) AU and they used this result to rule out several trans-Neptunian planet predictions, including the Planet X model considered here. However, even if this constraint on \( q \) is correct, the Planet X model can still accommodate it. For example setting \( i = 25^\circ \) and \( e = 0.2(0.1) \) in Eq. (7) gives \( a = 93.5(91.6) \) AU and \( q = 74.8(82.4) \) AU.

Bromley & Kenyon (2014) modeled the fate of planets scattered by more massive planets as the scattered planet interacted with a proto-planetary disk. Various planet masses and disk models were studied. Scattered planets with masses \( \geq 5 \) \( M_\oplus \) tended to be circularized by the disk while planets of mass \( \leq 2 \) \( M_\oplus \) maintained their original scattered eccentricity and inclination. These authors note that a remote planet in the solar system at \( \sim 100 \) AU is plausible and might explain the \( \omega \) clustering.

In response to the papers by Trujillo & Sheppard (2014) and de la Fuente Marcos & de la Fuente Marcos (2014), Iorio (2014) argued that a super-Earth planet at 250 AU would induce precessions in the known planets’ orbits that are incompatible with observations. However, the proper approach to this problem requires integrations with and without the hypothesized planet (Hogg et al., 1991; C. de la Fuente Marcos, personal communication; S. Tremaine, personal communication). It is problematic to base conclusions on residuals from a best fit model with many parameters that don’t include the unknown planet (Hogg et al., 1991). That is, Iorio’s approach doesn’t account for the equivalence between the effects of a new planet and other adjustable parameters in the fit. Further, the limits found by Iorio are an order of magnitude more restrictive than earlier constraints (Tremaine 1990; Hogg et al., 1991; Zakamska and Tremaine, 2005) even though the ephemerides are not that much better (S. Tremaine, personal communication).

In addition to the highly regular 27 Myr period an even stronger 62 Myr period has also been identified in the fossil record (Rohde & Muller, 2005; Melott & Bambach, 2007, 2013, 2014). One astronomical idea to explain this longer period is an increase in the cosmic ray flux as the solar system oscillates to high northern galactic latitudes (Lieberman and Melott, 2012). Another possibility is that a similar Planet X model-like mechanism is at work involving a second planet. However, the dynamics of such a system cannot be addressed using the
limited approximations of the present analysis since planet-planet interactions may dominate the precession frequencies. Alternatively, a more complete dynamical analysis including resonances with the giant planets might conceivably lead to a single planet explaining both periods.

Conclusion

With modest restrictions on inclination and eccentricity the Planet X model, as originally presented, is shown to be consistent with the regularity of the fossil extinction period, in contrast to the Nemesis model. Recent observational and theoretical studies suggest that a trans-Neptunian planet is more plausible today than when the model was first proposed. Although Trujillo & Sheppard (2014) acknowledged that their simulated orbits and masses were not unique, further numerical studies are needed to investigate the phase space of orbital parameters and masses capable of maintaining the ω clustering of detached TNO’s around ω = 0. Of special interest is a planet of a few Earth-masses, semimajor axis ~ 100 AU, in an orbit with moderate eccentricity and inclination ≥ 25°.

Acknowledgments

I thank Carlos de la Fuente Marcos and Scott Tremaine for comments on dynamical limits applied to trans-Neptunian planets and John Matese and Chad Trujillo for other helpful comments. I also thank an anonymous referee for a critical review and suggestions that significantly improved the manuscript.

References

Bromley, B.C., Kenyon, S.J., 2014, ApJ, 796, 141
Brown, M.E., 2001, Astron. J., 121, 2804
Davis M., Hut P., Muller R. A., 1984, Nat, 308, 715
de la Fuente Marcos, C., de la Fuente Marcos, R., 2014, MNRAS, 443, L5
de la Fuente Marcos, C., de la Fuente Marcos, R., Aarseth, S. J., 2015, MNRAS, 446, 1867
Gies D. R., Helsel J. W., 2005, ApJ, 626, 844
Gallardo T., Hugo G., Pais P., 2012, Icarus, 220, 392
Hogg, D. W., Quinlan, G. D., Tremaine, S., 1991, Astron. J., 101, 2274
Hut P., 1984, Nature, 311, 638
Kaib, N.A., Roskar, R., Quinn, T., 2011, Icarus, 215(2), 491
Lieberman, B.S., Melott, A.L. 2007 PLoS ONE, 2(8), 759
Iorio, L., 2014, MNRAS Letters, 444, L78
Luhman K. L., 2014, ApJ, 781, 4
Lykawka P. S., Mukai T., 2008, Astron. J., 135, 1161
Matese, J.J., Whitmire, D.P., 1986a, Icarus, 65, 37
Matese, J.J., Whitmire, D.P., 1986b, The Galaxy and the Solar System, 297, Eds. R. Smoluchowski, J. N. Bahcall & M. S. Matthews, U. Arizona Press
Melott, A. L., Bambach, R.K., 2010, MNRAS, 407, L99
Melott, A. L., Bambach, R.K. 2013, ApJ, 773, 6
Melott, A.L., Bamback, R.K., 2014, Paleobiology, 40(2), 177
Napier, W.M, 2015, MNRAS, 448, 27
Rampino, M.R., 2015 MNRAS 448, 1816
Raup D. M., Sepkoski, J.J. Jr., 1984, PNAS USA 81, 801
Roide, R. A., Muller, R.A., 2005, Nature 434, 208
Tremaine, S. 1990, in Baryonic Dark Matter, ed. D. Lynden-Bell & G. Gilmore (Dordrecht: Kluwer), 37
Trujillo, C. A., Sheppard, S.S., 2014, Nature, 507, 471
Whitmire D. P., Jackson A. A., 1984, Nature, 308, 713
Whitmire, D.P., Matese, J.J., 1985 Nature 313, 36
Zakamska, N.L., Tremaine, S., 2005, Astron. J., 130, 1939