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Monte Carlo Simulations of Stellar Planet Capture and Orbital Perturbations in Rogue Star – Solar System Interactions

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Abstract

Monte Carlo simulations have been performed on gravitational trajectories of objects within the Solar System when a rogue star passes through it. One result is that there is a 4.0 ± 0.1 percent likelihood of Earth being captured by a rogue star under the conditions that the star has one solar mass, an initial velocity magnitude randomly selected within ± 40 percent Earth's orbital speed, spherically isotropic distant starting positions, and randomly selected initial velocity direction that would cause the star to have an impact parameter within 7 AU of the Sun. Thus, showing an alternative to the expected demise of the Earth when the Sun becomes a red giant billions of years into the future. It is observed that the eccentricity increases for planets remaining bound to their parent star after such encounters. This result is consistent with the scenario that observed, unexpectedly high, eccentricities of extra-solar planetary orbits reflect encounters with rogue star-like objects. Furthermore, the likelihood of extra-solar planets being ejected from their original star system, from such encounters, increases with larger semi-major axes.

Keywords: Dynamics, Earth, Extra-solar Planets, Planetary Capture

1. Introduction and Motivation

The ultimate fate of Earth is seemingly bleak looking billions of years into the future when the Sun's internal dynamics cause it to shift off the main sequence of an HR diagram. The Sun will grow in size shifting the habitable zone of the Solar System out beyond Jupiter (Cain, 2016). The Sun will reach its maximum size as a red giant in about 7.6 billion years (Appell, 2008). Its exact size and the orbital radius of the Earth, at this time, are debated but the Earth will not be in the habitable zone and is likely to be engulfed and vaporized inside the Sun (Schroder & Smith, 2008). Thus, causing Neil deGrasse Tyson to quip "*In 5-billion yrs the Sun will expand & engulf our orbit as the charred ember that was once Earth vaporizes. Have a nice day*." (Tyson, 2013)

There is another potential fate which may not be so bleak. It is improbable, yet possible, that a rogue star could pass sufficiently close to our Solar System, and in just the right way, to cause the Earth to be gravitationally transferred, or slingshot, into a stable orbit within the habitable zone around the rogue star. Research results presented herein are based upon computer simulations showing how the planets within our Solar System get perturbed as a rogue star, having one solar mass, passes through it.

The Milky Way galaxy is expected to collide with Andromeda galaxy in about 4 billion years just about the time the Sun moves off the main sequence (Harrington & Villard, 2012). Andromeda galaxy has about one trillion stars and is about 220×10^3 light-years in diameter (Wikipedia, 2015). It is approaching the Milky Way galaxy at about 112,000 m/s (Drake, 2014).

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Just from ray geometry, the projected areal density of stars is approximately $1.3x10^{-7}\,\frac{stars}{AU^2}$. Statistically, this implies one star will pass within 1,540 AU of the Sun during the collision and the likelihood of it passing within 7 AU of the Sun is much lower.

Another way in which our Solar System could encounter another star, in a shorter time span, would be a close pass of a star that is currently nearby. A recent study (Bailer-Jones, 2014), by Dr. Coryn Bailer-Jones at the Max Planck Institute for Astronomy, examined the motion of 50,000 nearby stars in our galaxy for potential close passes to the Sun. The star Hip 85605 was found to have a 90 percent probability of coming between 0.04 and 0.2 pc between 240,000 and 470,000 years from now. This is too far away to significantly perturb planetary orbits in our Solar System but could pose a danger to the Earth by perturbing comets in the Oort cloud causing them to get injected into the inner Solar System. It is indicative that several stars may pass nearby within the next 1 billion years.

Research involving the Hubble Space Telescope has examined Abell 2744 and found approximately 200 billion rogue stars in this vicinity drifting between galaxies (Montes & Trujillo, 2014). Indeed, another research paper (Zemcov, et al., 2014) in 2014 claimed that as many as half the stars in the entire universe live outside of galaxies as rogue stars (Williams, 2014).

2. Experimental Design

The start of all simulations is based upon the positions and velocities of objects in the Solar System on June 20, 2020, at 21:44:00 (UT) as given by Starry Night™ Pro software (version 6.3.3). This date and time was arbitrarily chosen and was extracted from the software on May 29, 2015, at 4pm. Yet, the starting position of the rogue star was shifted to randomize the location of Earth in its orbit about the Sun when the rogue star reaches this vicinity. The origin of the coordinate system is centered on the position of the Sun at this time before any interactions with the rogue star. This origin remains fixed in space even as the Sun is allowed to shift. A Cartesian coordinate system was assigned with the ***x*** and ***y***-directions in the plane of the ecliptic.

The simulation follows 14 objects. These include all the planets in the Solar System, Earth's Moon, dwarf planet Pluto, the Sun, and 3 rogue objects. These 3 rogue objects consists of one Sun-like star (i.e. rogue star) with two Earth-like planets (i.e. rogue planets) orbiting this rogue star. Rogue planets one and two were assigned circular orbits with orbital radii 1 AU and 1.4 AU, respectively. The gravitational influence of all other celestial objects have been omitted.

The simulations were developed in C++ code using Microsoft Visual C++ 2010 Express. The dynamical evolution of the Solar System was determined using a numerical analysis algorithm with small time increments of 600 seconds. This algorithm minimizes differences which arise between the real, continuously varying forces and the simulation which uses small time steps containing discontinuous force changes. The algorithm flowchart is shown in figure 1. Figures 2 and 3 show that the simulation has good agreement for the first orbit of all the planets in the Solar System. The data in these figures have no rogue star influencing their orbits. The simulation changes the force vector 52,500 times per year at a time increment of 600 seconds. Even for a time duration of 165 years as shown by the simulated orbital path of Neptune in fig. 3, which corresponds to $8.67x10^6$ time increments, the agreement with Starry Night is good.

$$\vec{F}_i = \sum_j \vec{F}(\vec{x}_i, \vec{x}_j, t)$$

$$\downarrow$$

$$\vec{a}_i = \frac{\vec{F}_i}{m_i},\ \vec{v}_i = \vec{v}_o + \vec{a}_i \Delta t$$

$$\downarrow$$

$$\Delta\vec{x}_i = \vec{v}_i(\Delta t) + 0.5\vec{a}_i(\Delta t)^2$$

$$\downarrow$$

$$\vec{F}_i' = \sum_j \vec{F}(\vec{x}_i + \Delta\vec{x}, \vec{x}_j + \Delta\vec{x}_j, t + \Delta t)$$

$$\downarrow$$

$$(\vec{F}_{ave})_i = \frac{\vec{F}_i + \vec{F}_i'}{2}$$

$$\downarrow$$

$$(\vec{a}_{ave})_i = \frac{(\vec{F}_{ave})_i}{m_i}$$

$$\downarrow$$

$$(\Delta\vec{x}_{actual})_i \approx \vec{v}_i(\Delta t) + 0.5(\vec{a}_{ave})_i(\Delta t)^2$$

$$\downarrow$$

$$\vec{x}_i + (\Delta\vec{x}_{actual})_i \rightarrow \vec{x}_i,\ t + \Delta t \rightarrow t$$

Figure 1. Numerical analysis algorithm flowchart. The summation is over the gravitational interactions between the objects in the simulation. Standard kinematic equations were used.

The total energy and total angular momentum of the Solar System as a function of time remained constant to within five ten-thousandths of a percent over the span of 140 years of simulating the Solar System without the influence of a rogue star. To further examine the influence of changing the time increments, a single rogue star - Solar System interaction was run twice under the same starting conditions except one had 600-second time increments and the other 100-second increments. The simulation tracked the interactions over 144 years with the rogue star coming to within 0.76 AU of the Sun on the 72nd year. A 25 ten-thousandths of a percent difference in magnitude of the ending velocity of the rogue star was observed. A similar difference was observed with the ending velocity of the Sun under these two different conditions. These observations provide strong evidence that the simulation is performing well and is accurate.

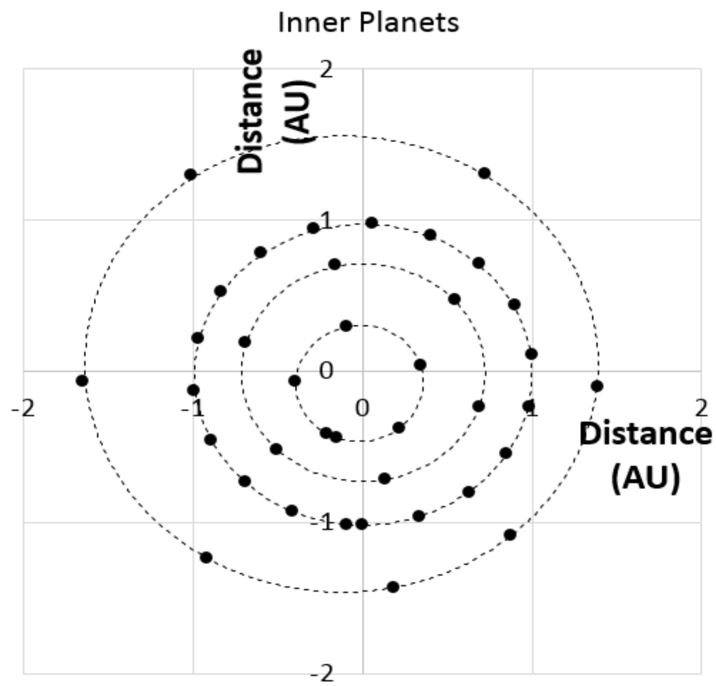

Figure 2. Comparison of simulation orbital position with Starry Night position, projected onto the ecliptic, for one complete orbital period for each planet. This figure shows the Terrestrial planets with the inner circle being Mercury and the outer one Mars.

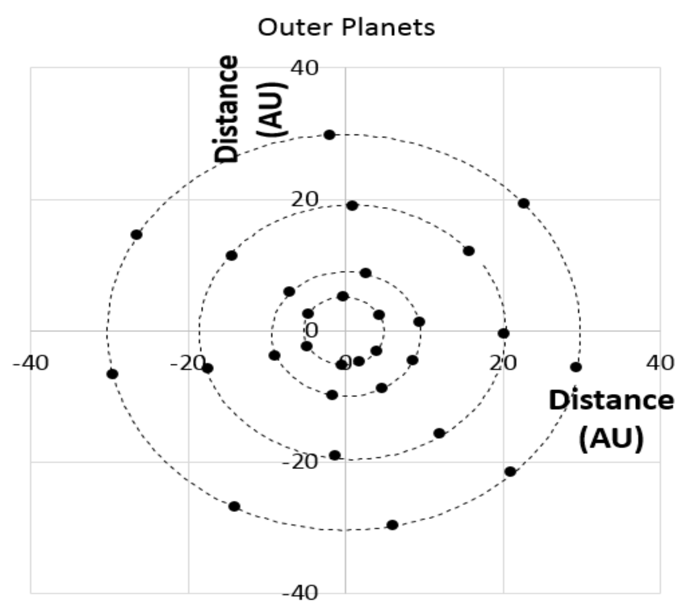

Figure 3. Comparison of simulation orbital position with Starry Night position, projected onto the ecliptic, for one complete orbital period for each planet. This figure shows the Jovian planets with the inner circle being Jupiter and the outer one Neptune.

Due to the long range nature of gravity, simulating the influence of a rogue star on the objects in the Solar System requires a starting position sufficiently far away. When the rogue star is at a distance of 450 AU away from the sun, its force on Earth is 4.9 millionths the force of the Sun. The simulation was run once to examine the gravitational influence between the rogue star and Sun at separation distances between 10,000 AU and 450 AU. The rogue star approached the Sun with an initial speed of 29,200 m/s. During this interaction interval, the Sun shifted 2.25 AU from its original position. It also produced a 65.3 m/s shift in relative velocity between the two objects.

This yielded a 0.2 percent change in relative velocity over a time duration of 1,550 years. The omission of long-range interactions at distances greater than 450 AU are not viewed as appreciably changing the general statistical results presented herein.

Any physical collision between two objects are tagged and treated as a 100 percent inelastic collision. The product of the collision is then continued on in the simulation as a single object with a mass equal to the sum of the objects that collided.

The trajectory of the rogue star approach to the Solar System is determined by two points. The inside point has a randomly selected 3-dimensional location constrained to have a distance from the origin less than 7 AU. Likewise, the outside point has a randomly selected 3-dimensional location constrained to have a distance from the origin between 7 and 14 AU. The rogue star initial direction is collinear with the direction from an outside point towards an inside point. The boundary radius determines the *maximum distance of closest approach* for straight-line trajectories of the rogue star.

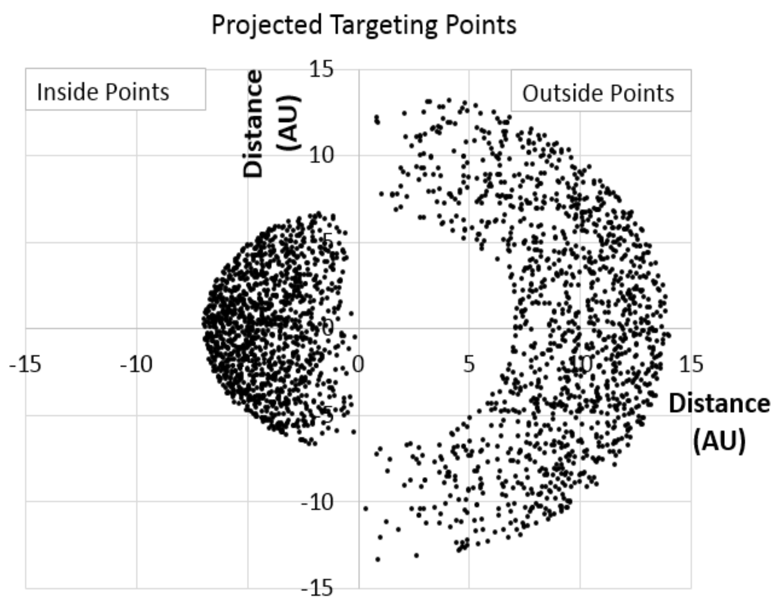

Figure 4. Projected rogue-star initial directional points for 1,303 randomly-selected simulations wrapped around the □-axis. Each data point on the right-side of the figure connects with a point on the left-side.

The randomization sequence of the simulation was:

- Randomly assign, within limits, the directional vector for the rogue star.
- Randomly assign, within limits, the initial velocity magnitude of the rogue star.
- Randomly shift, within limits, the rogue star starting position so that Earth is randomly located in its orbit around the Sun when the rogue star makes its closest approach to the Sun.
- Randomly assign the orientation of the initial rogue planet orbital plane around rogue star. Assumes both rogue planets have the same initial orbital plane.
- Randomly assign rogue planet initial locations in their orbit around rogue star. They each have an initial orbital radius and velocity that is fixed and consistent with their initial circular orbits.
- Begin looping over time steps, following the flowchart in figure 1, and continue until rogue star is 450 AU away from the origin and moving away from it.

The initial rogue star velocity magnitude was constrained to be within ± 40 percent the orbital velocity of Earth. Earth transfers are expected to be exceedingly rare as the initial rogue star velocity exceeds twice the orbital speed of Earth about the Sun - without extremely convoluted Earth trajectories.

3. Results

A total of 57,400 rogue star gravitational collisions with the Solar System were processed. This analysis will examine the statistics, and specific simulation events, within three main scenarios: (1) Earth is transferred to a bound orbit around the rogue star. (2) Earth gets ejected from both the rogue star and Sun. (3) Earth remains in a bound orbit about the Sun where its orbital parameters get perturbed.

Earth physically contacting and colliding with another object being simulated, is a further detail examined within these three main scenarios. For instance, it is possible for the Earth to physically collide with the Moon and have the combined mass go into orbit around the rogue star.

A key quantity in these simulations was the distance of closest approach that the rogue star would have with the Sun from a straight-line trajectory of the initial velocity of the star. This is the *impact parameter* and is denoted as R_c. In general, the position and velocity of all the objects at the start of the simulation determines the dynamical interactions that result. The initial position and velocity vectors of the Sun, rogue star, and Earth primarily control the probability of Earth being gravitationally transferred to a stable orbit around a rogue star.

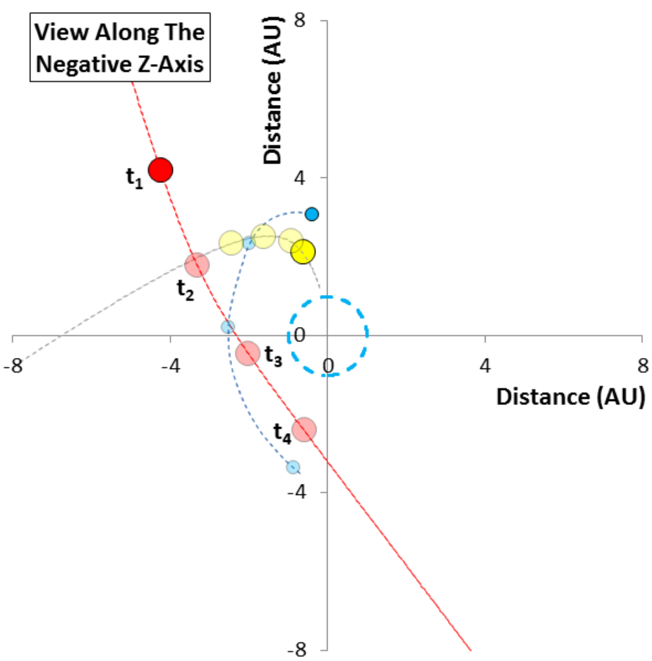

Figure 5. Time-lapsed positions, for a specific simulation, showing Earth (blue), Sun (yellow), and a rogue star (red) as Earth gets transferred to a stable orbit around a rogue star with all trajectories remaining mostly in the ecliptic plane. The dashed curves are the trajectories of the objects. Time starts at t_1 and advances to t_4. The time steps have equal durations.

This was simulation event 1186. The dashed blue-circle is the original orbit of Earth about the Sun. Object sizes are not drawn to scale.

From an energetic viewpoint, the highest likelihood of transfer will occur when the rogue star is in a configuration that, when it passes near Earth, will boost Earth's velocity with respect to the Sun and reduce its velocity with respect to the rogue star. This typically happens in a slingshot fashion where Earth slips behind the motion of the rogue star while the star gets deflected by the Sun as shown in fig. 5. Figure 6 indicates the likelihood of Earth being transferred or ejected increases with decreasing velocity of the rogue star for the range examined.

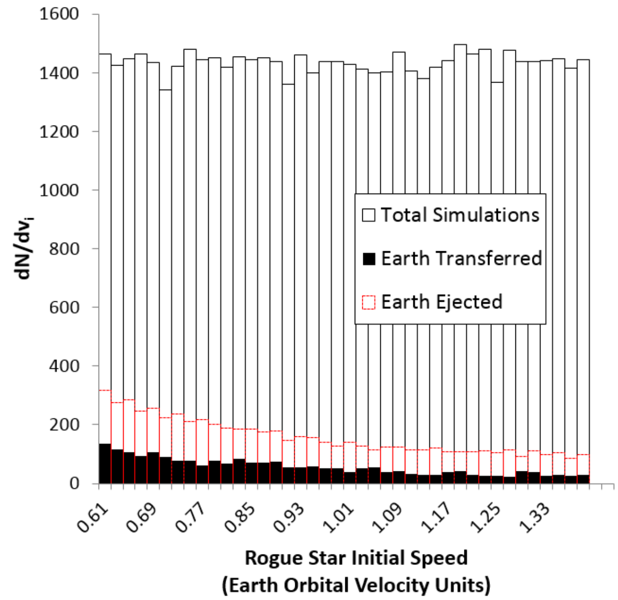

Figure 6. Shows the number of simulations as a function of the initial velocity of the rogue star under different ending circumstances. The simulations have been constrained to only those events in which the rogue star has an impact parameter less than 7 AU.

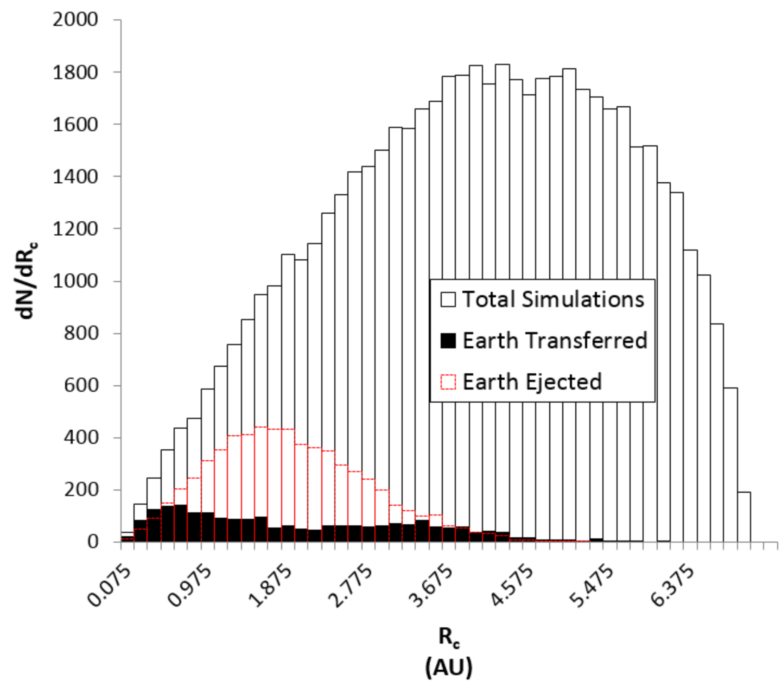

Figure 7. Shows the number of simulations as a function of the impact parameter under different Earth transfer results.

Figures 6 and 7 show the distribution of rogue star velocities and R_c, respectively. For all simulations, the direction of approach is random and R_c is restricted to be between 0 and 7 AU.

Two subsets of the simulations are superimposed in these two figures. One subset are simulations in which the Earth gets ejected. Such that, the speed imparted onto Earth exceeds its escape velocity for both the Sun and rogue star.

The other subsets are simulations in which Earth gets transferred into a bound orbit around the rogue star. These two subsets of simulations exclude any simulations in which Earth physically collides with another object.

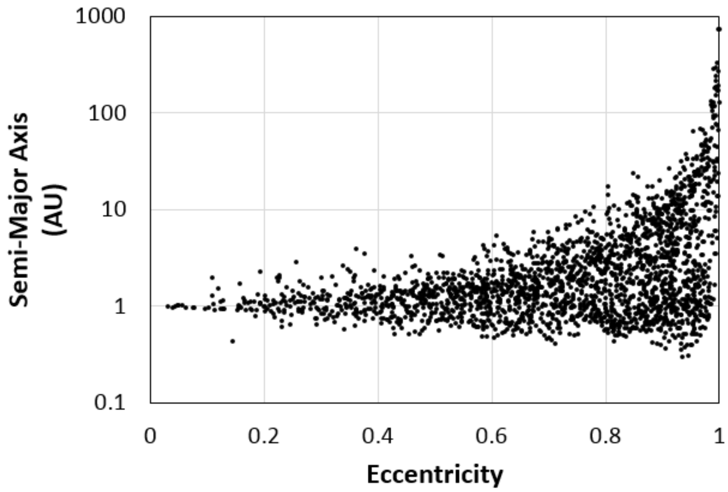

Figure 8. Orbital parameters of Earth after it was transferred to an orbit around the rogue star.

A notable pattern arises in the conditions that promote Earth transfers. At the point in time of closest approach of the rogue star to the Sun, the angle between the velocity vector of Earth with respect to the Sun and the velocity vector of the rogue star with respect to the stationary origin peaks at 45 degrees. It is an asymmetric distribution about this peak having a FWHM of 46 degrees.

These statistics show 4.0 ± 0.1 percent of such simulations result in Earth being transferred to a bound-orbit around the rogue star where the Earth does not physically collide with any other objects for the duration of the simulation which runs for about 70 years after the closest approach of the rogue star to the Sun. [Only 1.6 ± 0.2 percent of simulations result in Earth being transferred and the Moon remains in orbit around Earth.] And 11.0 ± 0.2 percent of encounters result in Earth being ejected all together and not colliding with any other objects. These ejections cause Earth to become un-bound from both the Sun and the rogue star and set adrift into the interstellar medium.

The long-term stability of all the planets and Pluto was examined by determining the new orbital perihelion and aphelion for all objects that were bound to either the rogue star or Sun at the end of the simulation. The Earth was considered in a stable orbit around the rogue star insofar as its orbit comes no closer than 0.2 AU to the orbit of another planet (or Pluto) based solely upon the radial distances of orbits and the Moon is either ejected or gets transferred and remains in orbit around Earth. There were 83 simulations which satisfied these conditions corresponding to 0.14 ± 0.05 percent of all simulations. However, it is possible that unstable planetary orbits, other than Earth, can eventually disrupt Earth's orbit. About sixty percent of Earth transfers resulted in the Moon breaking away from Earth and orbiting the rogue star. The closer the Earth passes by the Sun and/or rogue star, the more likely this break away will happen.
None of these 83 simulations occurred in which either of the rogue planets kept bound orbits around the rogue star. Such a scenario may still be possible but the probability is less than 0.0017 of a percent based on all the simulations processed.

For the bleakest of Earth futures, there was a 0.30 ± 0.02 percent likelihood of the Earth physically colliding with the Sun or rogue star. The Moon colliding with Earth posed a high danger with a 2.20 ± 0.12 percent likelihood for the duration of the simulation. Earth never collided with another planet during the simulations.

The rogue star and Sun have a collision for 0.207 ± 0.008 percent of the simulations. The Earth remains in orbit around the two coalesced stars for 85 ± 2 percent of such collisions without, itself, experiencing a collision. All the statistical inaccuracies were determined by randomly dividing the entire set of simulations into two subsets. The difference between the percentages for each subset is considered the inaccuracy.

Even when the Earth remained bound to the Sun after the rogue star passed through the Solar System, its orbit got significantly perturbed. Of these interactions, the average, new eccentricity of the Earth is 0.2129 ± 0.0015 compared to the old one of 0.0167. The average, new semi-major axis is 1.82 ± 0.03 AU. This implies, on average, the new perihelion and aphelion of Earth's orbit will be 1.43 AU and 2.21 AU, respectively.

Some interesting scenarios can be seen within the simulations in which the Earth remains bound to the Sun. One simulation imparted to the Earth an eccentricity of 0.9988 and a semi-major axis of 326 AU. This is an extreme, comet-like orbit with a perihelion of 0.39 AU and aphelion of 652 AU. In another simulation, the Earth obtained an eccentricity of 0.196 and semi-major axis of 0.49 AU, thus, producing a Mercury-like orbit. Likewise, one can examine the simulations which result in Earth getting transferred to a stable orbit around the rogue star. The most Earth-like orbit had an eccentricity of 0.129 and semi-major axis of 0.936 AU. This corresponds to a perihelion and aphelion of 0.82 AU and 1.06 AU, respectively.

3.1 Earth Transfer Box

One can examine in more detail the initial configuration of the rogue star which results in Earth being transferred. In particular, one can examine, for a given mass and velocity vector of the rogue star, how sensitive the end results are to varying the initial position of the rogue star at its starting point in the simulation which is around 450 AU away from the sun. This will be called the *Earth Transfer Box*. Such that, if a rogue star, having a known mass and velocity vector, is positioned inside this box at a particular time, the Earth will get transferred. (The allowable variation in position, yet still getting transferred, is approximated to a rectangular shape.)

The approximate dimensions of this box were analyzed for event 1186. (Same event as shown in fig. 5.) Each of the three rectangular starting position coordinates were varied separately to determine the boundary in which the Earth no longer gets transferred. It is a relatively small box considering it is determined at a distance of 450 AU away from the origin. Roughly, the position needs to be determined to better than 0.4 percent accuracy at a distance of 450 AU from the Sun, assuming precisely known mass and velocity, for one to be confident the Earth will get transferred for this event.

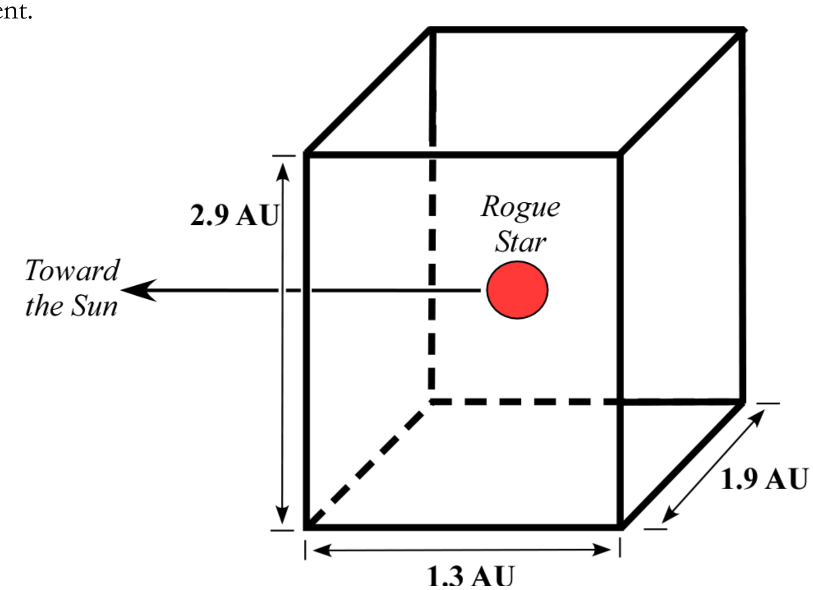

Figure. 9. Earth transfer box for simulation number 1186 at the starting position which is 450.5 AU away from the origin. Its mass is set to 1M$_\odot$ and, at this location, it has a velocity of 37,565 m/s.

Similarly, the velocity in the *x*, *y*, and *z*-directions can vary by 1.0, 0.5, and 27 percent respectively, and still cause the Earth to get transferred assuming high precision in knowing the mass and position.

Lastly, the mass of the rogue star can change by 61 percent and still cause an Earth transfer for this event assuming high precision in position and velocity. Shifting these variables, all while maintaining an Earth transfer, can still lead to dramatic changes in the resulting Earth orbit around the rogue star.

4. Implications

The average observed eccentricity of exoplanets, as of August 11, 2016, is 0.172. This average is from 928 exoplanets listed in The Extrasolar Planets Encyclopedia (Exoplanet, 2016) in which an eccentricity has been determined. The prevalence of large eccentricities for exoplanets are significantly higher than would be expected considering systematic biases and current theories of solar system formation. Phil Armitage, of the University of Colorado, indicates "*This is surprising because massive planets would form in nearly circular orbits, and interactions with a gas disk would tend to keep the eccentricity low*." (Schirber, 2005)

These simulations have found that rogue stars passing near a planetary system significantly shift planetary eccentricities to higher values. The third column in Table I shows a marked increase in eccentricities with increasing semi-major axes.

The hypothesis that observed exoplanet large eccentricities are caused by close encounters with rogue, star-like objects is consistent with the results of this research. Star-like meaning that the rogue object has a mass similar to the Sun.

The fourth column in Table I indicates that as the semi-major axis increases, the probability of the planet remaining bound to its parent star dramatically decreases. This pattern is consistent with the hypothesis that planets with an original, large semi-major axis, in a star system that has experienced an encounter with a rogue star-like object, are missing having been ejected by the encounter.

Table I. Eccentricities and Probabilities

Planet	$e_{original}$	$\langle e \rangle_{new}$	$\langle P \rangle$
Mercury	0.206	0.22700+/-0.00002	82.23+/-0.08
Venus	0.0068	0.1171+/-0.0006	80.36+/-0.04
Earth	0.0167	0.218+/-0.002	83.7+/-0.1
Mars	0.0934	0.314+/-0.002	71.4+/-0.3
Jupiter	0.0484	0.587+/-0.002	39.2+/-0.5
Saturn	0.0542	0.670+/-0.003	24.5+/-0.4
Uranus	0.0472	0.723+/-0.007	12.6+/-0.2
Neptune	0.0086	0.725+/-0.005	7.1+/-0.2

Third column is the average, new eccentricity for the planet when the planet remains bound to the Sun after the rogue star interaction. The fourth column is the average percent probability, in any given simulation, that the planet will remain bound to the Sun.

5. Summary

Observations of exoplanet eccentricities, together with the results from this research, are consistent with the hypothesis that many star systems have been perturbed by a close encounter with a rogue, star-like object passing near them. It is conceivable that these star-like objects are the long sought after Dark Matter MACHOs (Massive Compact Halo Objects). This research also shows an alternative, long-term future for Earth – an alternative to its inevitable demise when the Sun moves into its red giant phase several billion years hence. There is a low, yet non-zero, probability for the Earth to become gravitationally transferred to an orbit around a rogue star that passes near the Sun.

Two recent studies have examined the prospects of planets being captured into our Solar System from encounters with rogue stars. One of them looks at the prospects that a theorized Planet 9, in our Solar System, was gravitationally captured. But this only looked at rogue star and Sun encounters with closest approaches on the order of 150 AU so as to not significantly disturb other orbits in the Solar System (Mustill, Raymond, & Davies, 2016). The other study indicated that it was possible that Sedna and 2012 VP_{113} were captured by our Solar System from a rogue star that passed by at about a distance of 340 AU and had a mass of 1.8 $M_{\odot}$ (Jilkova, Zwart, Pijloo, & Hammer, 2015).

The average speed of stars in the Andromeda galaxy, when Andromeda collides with our galaxy, is 3.8 times faster than the orbital speed of the Earth.

This will significantly decrease the probability of an Earth transfer for any of these stars. If our civilization still exists on Earth long into the future, and a rogue star happens to pass-by the Sun, our best option may be to use spaceships to colonize the rogue planets that are likely to remain in orbit around the rogue star after the encounter. The percent probability in these simulations that rogue planet one and two remain bound to the rogue star after encountering the Sun is 76.94 ± 0.01 and 63.7 ± 0.1, respectively. In these simulations, both rogue planets began in the habitable zone around the rogue star. So, there is a chance that these planets are already occupied by lifeforms, perhaps, intelligent life. Arguably, this would create the most profound ethical dilemma in all eternity for our civilization – immigrate to (or invasion of) the rogue planet or face certain annihilation when our Sun becomes a red giant. Of course, Earth may get invaded if it faces a better future than the rogue planets.

5.1 Description of Two Select Earth Transfer Simulations

Accompanying this paper are animated sequences showing the three-dimensional time evolution of two simulations [*Insert URL links here for animated sequences*]. In simulation number 44084, Earth gets transferred into a stable orbit around the rogue star and the angle between the normal to the new ecliptic plane and Earth's rotation axis is 71°. The daylight cycles on Earth would become dramatically different. The Moon is still in orbit around Earth but was perturbed into a higher eccentricity. In this event, the new perihelion and aphelion for Earth is 0.82 AU and 1.42 AU, respectively. The Earth had a distance of closest approach to the Sun of 0.35 AU and the rogue star of 0.39 AU in this trajectory.

The more interesting simulation is number 1186. For this one, Earth and Moon get transferred where the Earth has similar orbital dynamics around the rogue star as it had around the Sun. The new perihelion and aphelion for Earth is 0.83 AU and 1.14 AU, respectively. However, the neighborhood has become crowded since the two rogue planets remain orbiting the rogue star and have an orbital plane approximately perpendicular to that of Earth's. This is the same simulation shown in figure 5. Alas, this orbit for Earth is unstable due to its proximity to that of one of the rogue planets. The daylight cycles do not change much for Earth. Interestingly, Mars stayed with the Sun and was perturbed into an orbit having an eccentricity and semi-major axis of 0.39 and 1.3 AU, respectively.

Acknowledgements

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