Effects of a Rogue Star on Earth's Climate

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with Richard McGehee
University of Minnesota

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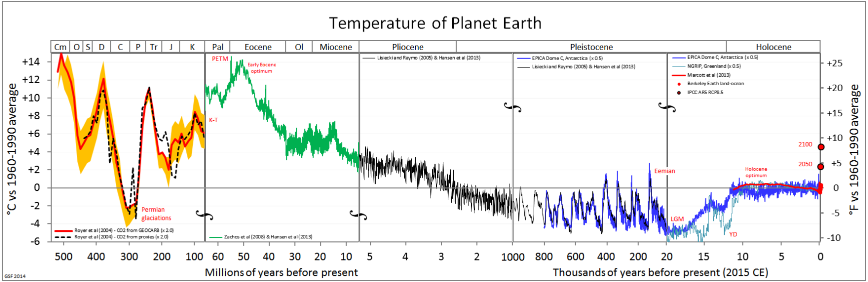
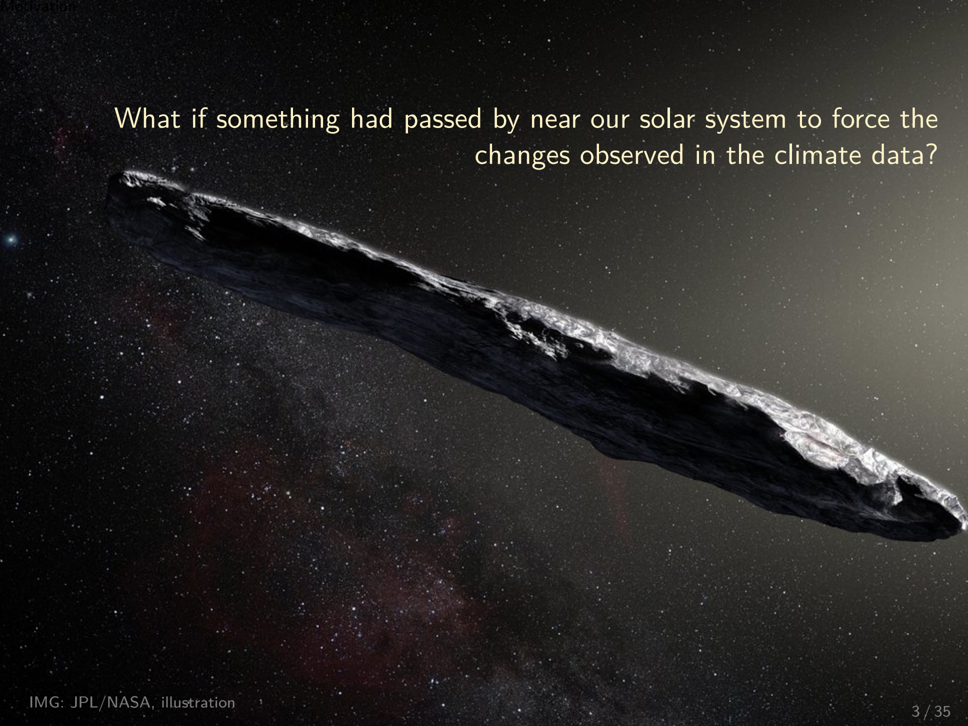
May 22, 2019

Climate Record



Global average temperature estimates for the last 540 My. This shows estimates of global average surface air temperature over the 540 My of the Phanerozoic Eon, since the first major proliferation of complex life forms on our planet. Because many proxy temperature reconstructions indicate local, not global, temperature – or ocean, not air, temperature – substantial approximation may be involved in deriving these global temperature estimates. As a result, the relativities of some of the plotted estimates are approximate, particularly the early ones. Credit: Glen Fergus.

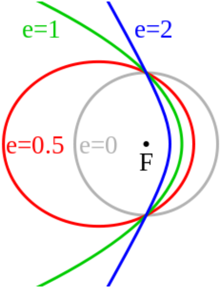
What if something had passed by near our solar system to force the changes observed in the climate data?



IMG: JPL/NASA, illustration

Milankovitch Cycles

eccentricity



eccentricity img: https://kids.kiddle.co/Orbital_eccentricity

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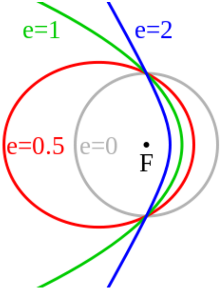
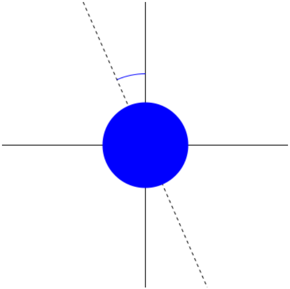
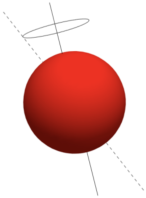


obliquity



precession



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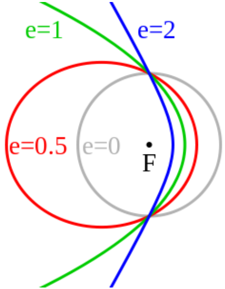

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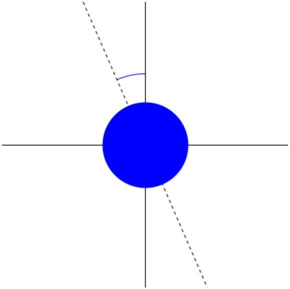

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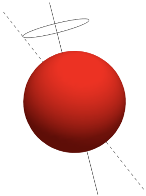

Milankovitch cycles affect our climate because the amount of insolation varies according to the cycles of these three elements.

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Milankovitch Cycles

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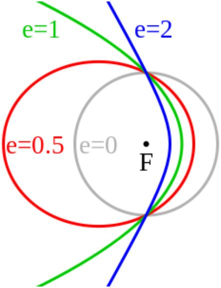

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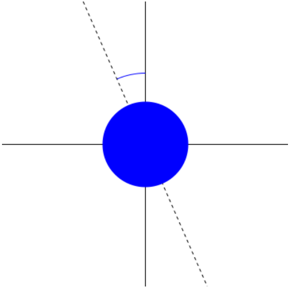

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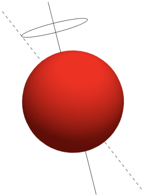

Milankovitch cycles affect our climate because the amount of insolation varies according to the cycles of these three elements.

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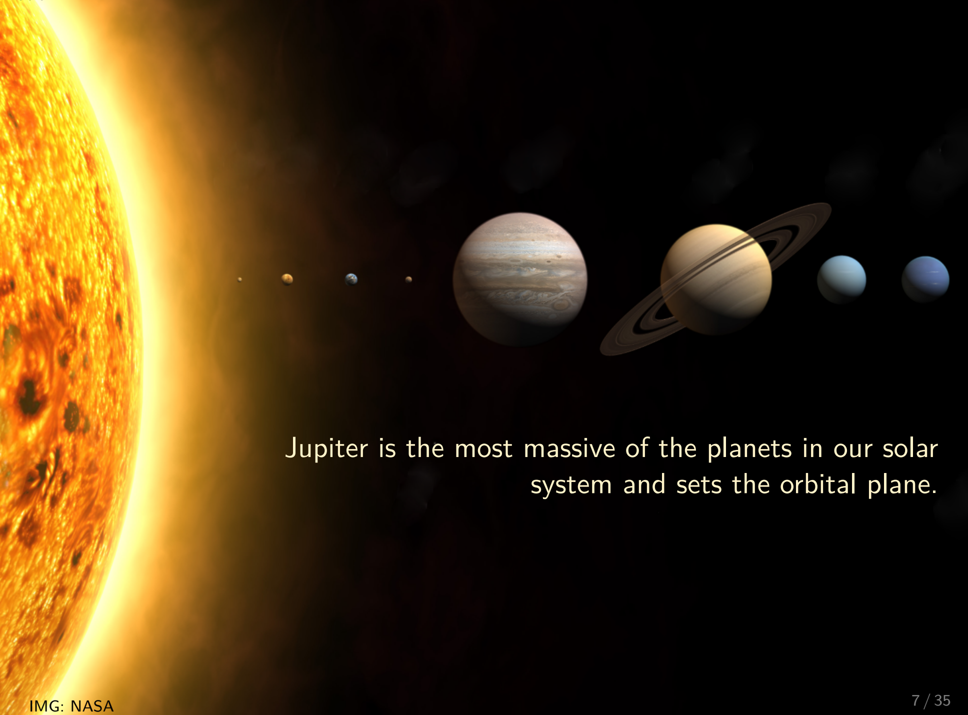
Based on results from the Gaia telescope's 2^{nd} data release from 04/2018, an estimated 694 stars will possibly approach the Solar System to less than 16 light-years over the next 15 million years.

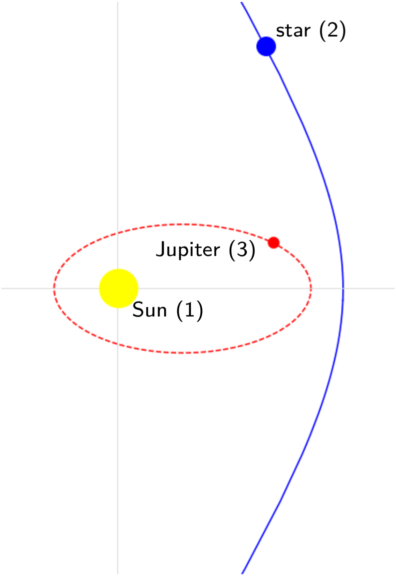
IMG: NASA



Jupiter is the most massive of the planets in our solar system and sets the orbital plane.

IMG: NASA

Hyperbolic Restricted 3-Body Problem



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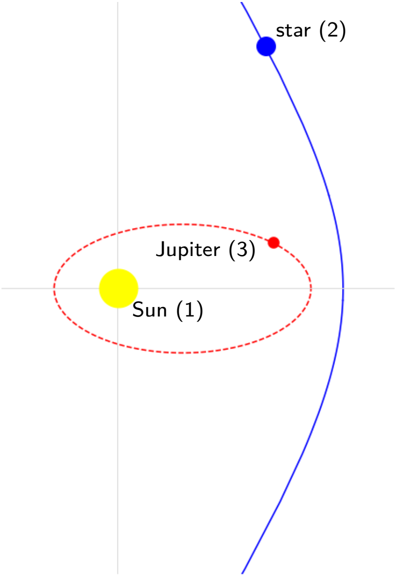
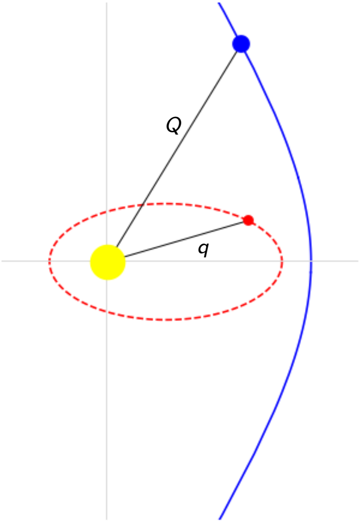


$$\begin{cases} \ddot{x}_1 &= -Gm_2 \dfrac{x_1 - x_2}{|x_1 - x_2|^3} \\ \ddot{x}_2 &= -Gm_1 \dfrac{x_2 - x_1}{|x_2 - x_1|^3} \\ \ddot{x}_3 &= -Gm_1 \dfrac{x_3 - x_1}{|x_3 - x_1|^3} - Gm_2 \dfrac{x_3 - x_2}{|x_3 - x_2|^3} \end{cases}$$

Hyperbolic Restricted 3-Body Problem



Let $Q = x_2 - x_1$ and $q = x_3 - x_1$, then...

$$\begin{cases} \ddot{Q} &= -\dfrac{(m_1 + m_2)\, Q}{|Q|^3} \\ \ddot{q} &= -\dfrac{m_1\, q}{|q|^3} - \dfrac{m_2\,(q - Q)}{|q - Q|^3} - \dfrac{m_2\, Q}{|Q|^3} \end{cases}$$

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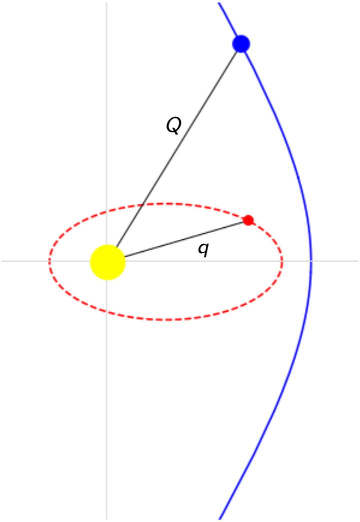

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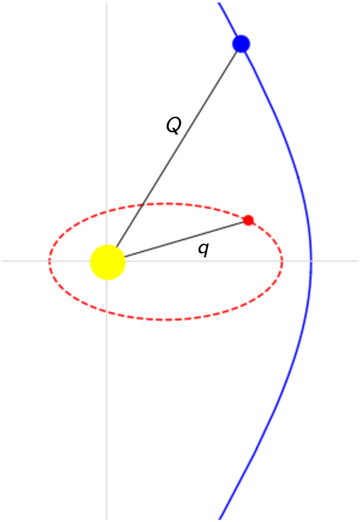

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This is the Kepler problem!

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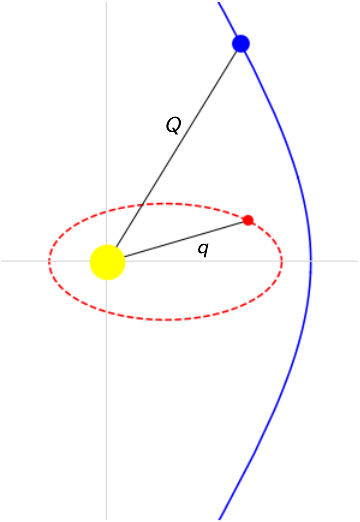

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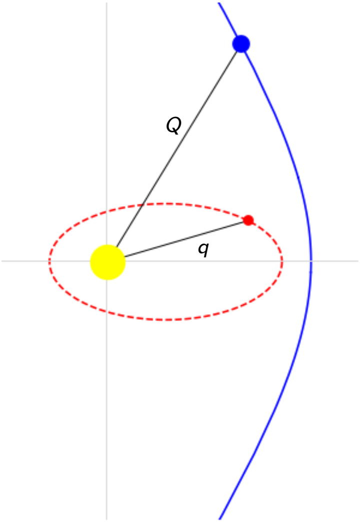

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Perturbation from the Kepler problem.

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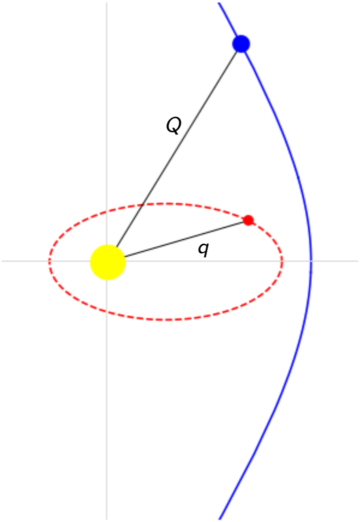

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- Q describes the relative motion of our two stars (hyperbolic)

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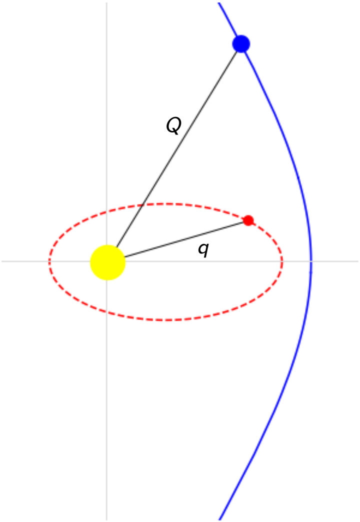

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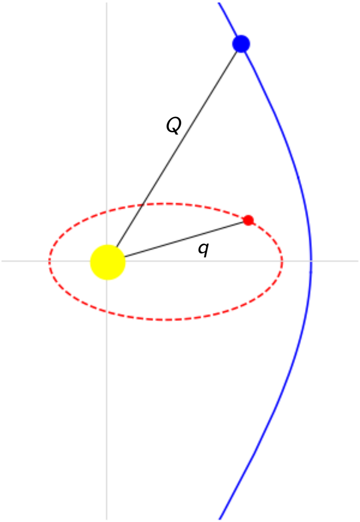

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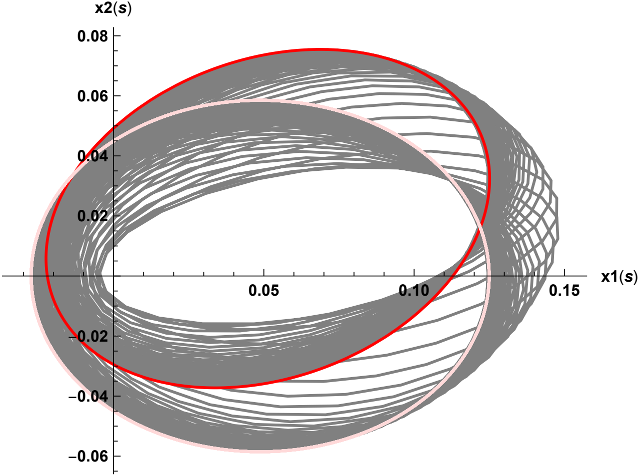
Perturbation from the Kepler problem.

- Q describes the relative motion of our two stars (hyperbolic)
- We can plug Q into the second equation, which describes the motion of Jupiter
- Use Levi-Civita regularization to deal with collisions

Observed Motion

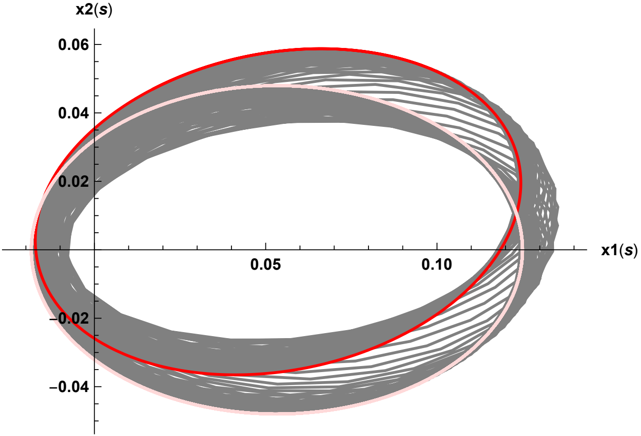
$m_1 = 0.5$ (Sun), $m_2 = 0.5$ (passing star)



The light red path is the original orbit the planet was on before the star passed by, and the right path is the final orbit.

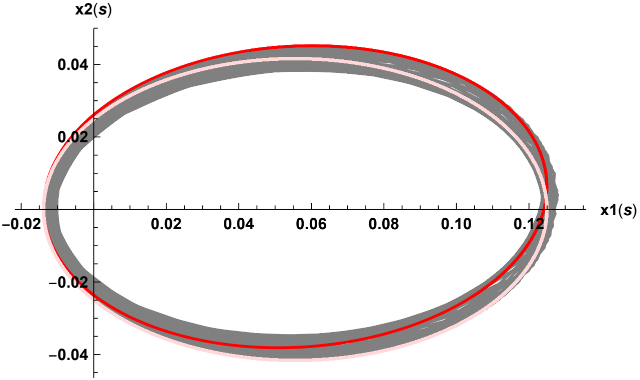
Observed Motion

$m_1 = 0.7, m_2 = 0.3$



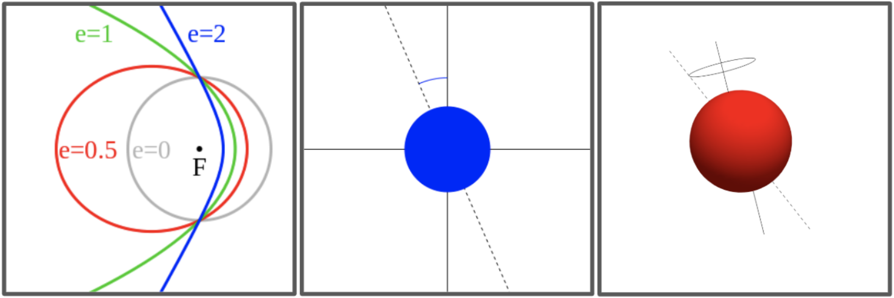
Observed Motion

$m_1 = 0.9, m_2 = 0.1$



Orbital Elements

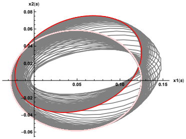
We want to observe how the orbital elements are changed from these perturbations in motion.

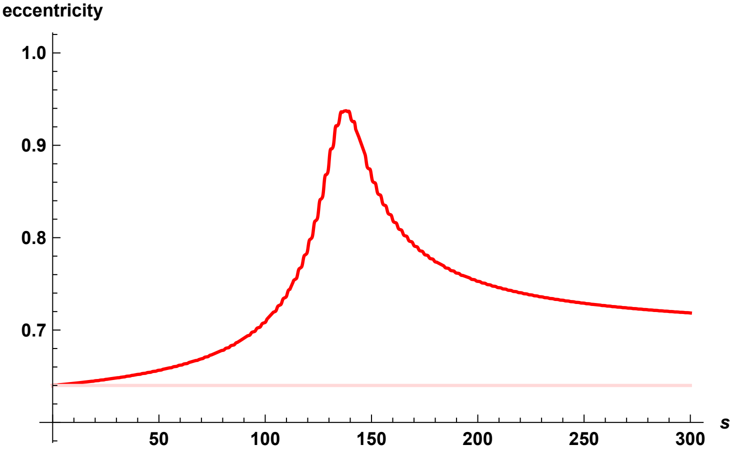


Orbital elements often studied in climate mathematics: eccentricity (left), obliquity or axial tilt (middle), and precession (right). Once again, the eccentricity image is from `https://kids.kiddle.co/Orbital_eccentricity`.

Eccentricity

$m_1 = 0.5,\ m_2 = 0.5$





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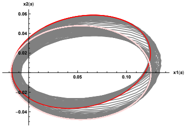

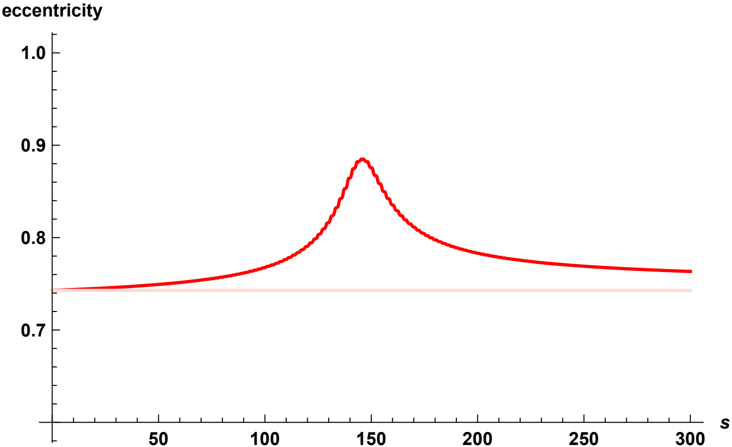

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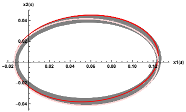

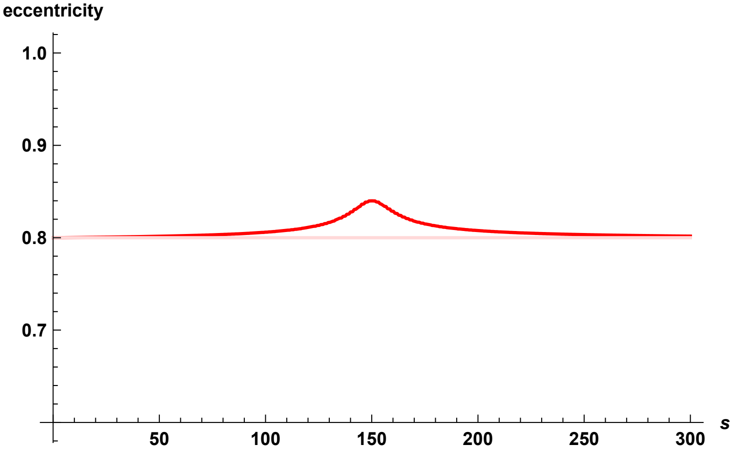

Eccentricity (e) and Semi-Major Axis (a)

$$\text{mean annual solar intensity} = \frac{\overbrace{K}^{\text{solar output}} \quad a^2}{\sqrt{1 - e^2}}$$

- For Earth, a is fairly constant and assumed so in models
- If we change e, there will be a change in a as well

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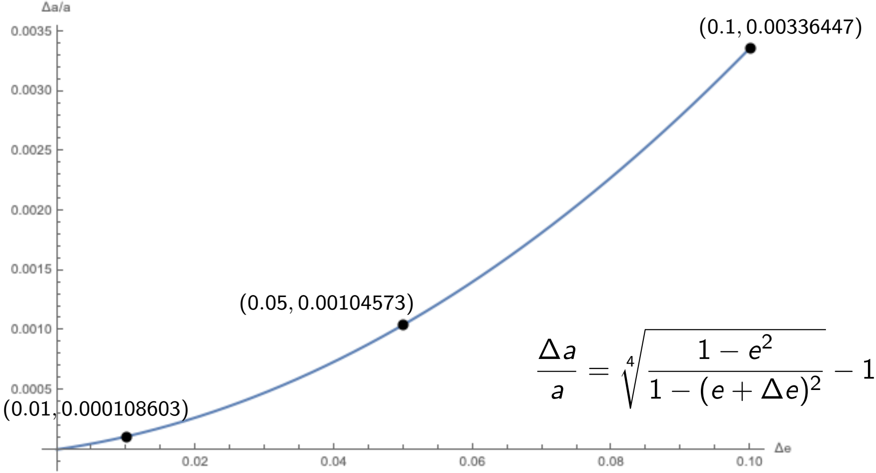
- For Earth, a is fairly constant and assumed so in models
- If we change e, there will be a change in a as well

Assuming the mean annual solar intensity remains constant,

$$\Delta a = a \left(\sqrt[4]{\frac{1 - e^2}{1 - (e + \Delta e)^2}} - 1 \right)$$

Eccentricity (e) and Semi-Major Axis (a)

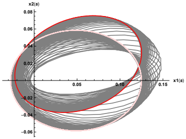


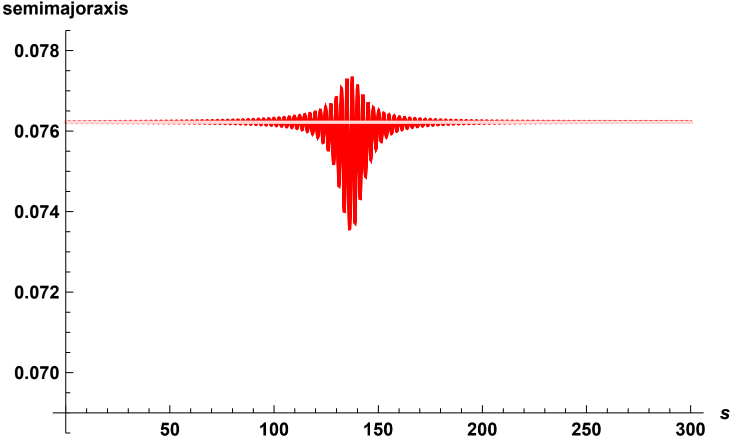
$$\frac{\Delta a}{a} = \sqrt[4]{\frac{1 - e^2}{1 - (e + \Delta e)^2}} - 1$$

Fix $e = 0.0167086$ and $a = 149.60 \times 10^6$ km, the eccentricity and semi-major axis length of Earth's current orbit. $\frac{\Delta a}{a}$ represents the percent change from Earth's semi-major axis length.

Semi-Major Axis

$m_1 = 0.5, \; m_2 = 0.5$





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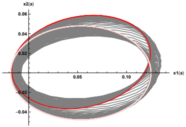

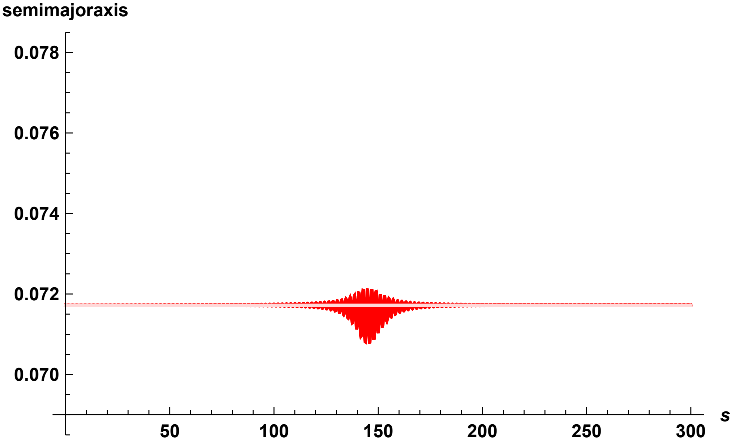

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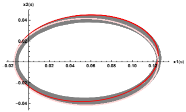
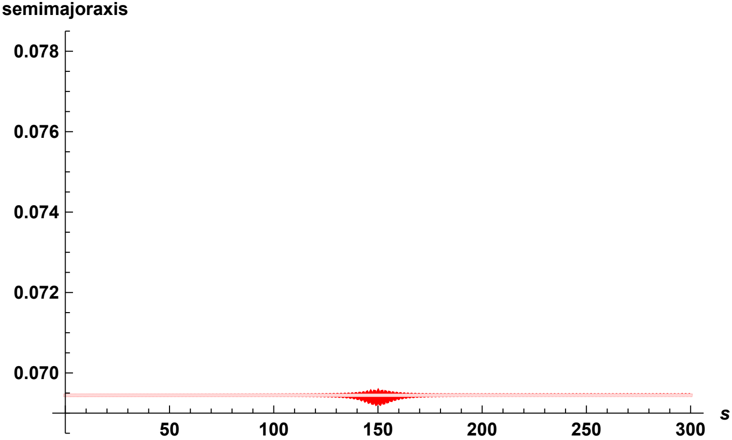
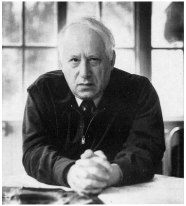




IMG: NASA

How do these changes affect temperature?

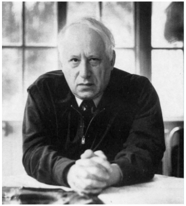
The Budyko-Widiasih Model



The Budyko-Widiasih Model

$$R\frac{\partial T}{\partial t} = \underbrace{Qs(y)\,(1-\alpha(\eta,y))}_{\text{incoming radiation}} - \underbrace{(A+BT(t,y))}_{\text{OLR}} - \underbrace{C\left(T(t,y)-\overline{T}(t)\right)}_{\text{heat transport}}$$

$$\frac{d\eta}{dt} = \varepsilon(T(\eta) - T_c)$$



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$$R\frac{\partial T}{\partial t} = Qs(y)\left(1 - \alpha(\eta, y)\right) - \left(A + BT(t,y)\right) - C\left(T(t,y) - \overline{T}(t)\right)$$
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$$Q = Q(e) = \frac{Q_0}{\sqrt{1 - e^2}}$$

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$$\frac{d\eta}{dt} = \varepsilon(T(\eta) - T_c)$$

$$Q = Q(e) = \frac{Q_0}{\sqrt{1 - e^2}}$$

$$A = 202\,\mathrm{Wm}^{-2}$$
$$B = 1.9\,\mathrm{Wm}^{-2}(^\circ\mathrm{C})^{-1}$$
$$C = 3.04\,\mathrm{Wm}^{-2}(^\circ\mathrm{C})^{-1}$$
$$Q_0 = 342.95$$
$$\alpha(\eta, y) = \begin{cases} \alpha_{H_2O} = 0.32, & y < \eta \\ \alpha_{ice} = 0.64, & y > \eta \end{cases}$$

The Budyko-Widiasih Model

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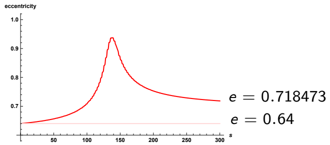
$$\frac{d\eta}{dt} = \varepsilon(T(\eta) - T_c)$$

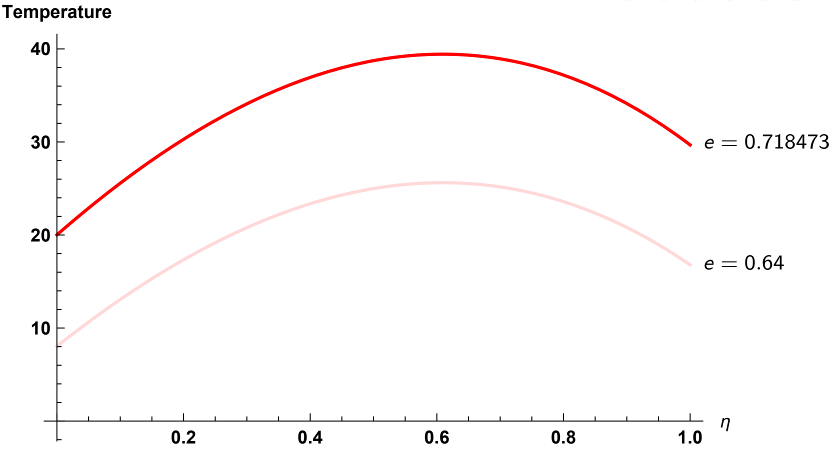
Equilibrium Temperature Profile

$$T^*_\eta(y) = \frac{1}{B+C}\left(Q(e)s(y)\left(1-\alpha(y,\eta)\right) - A + \frac{C}{B}\left(Q(1-\overline{\alpha}(\eta)) - A\right)\right)$$
$$\overline{\alpha}(\eta) = \int_0^\eta \alpha_{H_2O} s(y)\,dy + \int_\eta^1 \alpha_{ice} s(y)\,dy$$

Equilibrium Temperature Profiles

$m_1 = 0.5, \ m_2 = 0.5$





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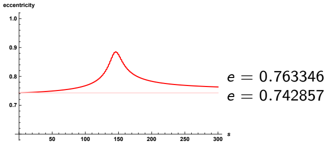
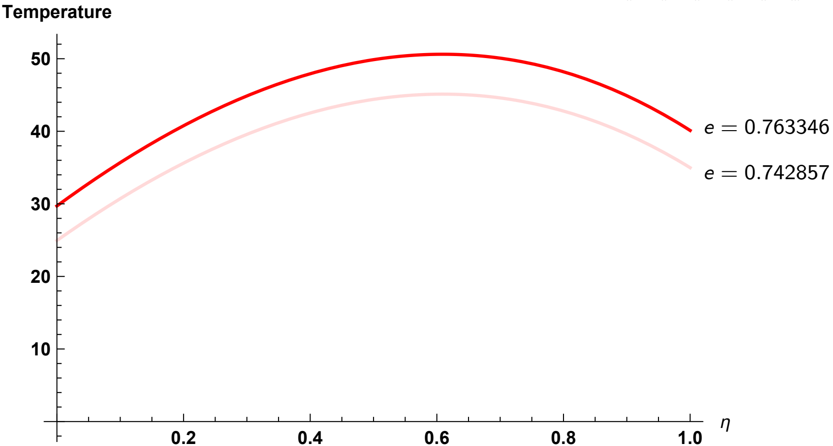
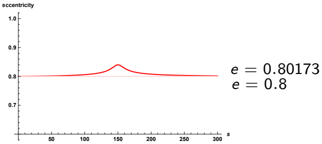
$m_1 = 0.7,\ m_2 = 0.3$

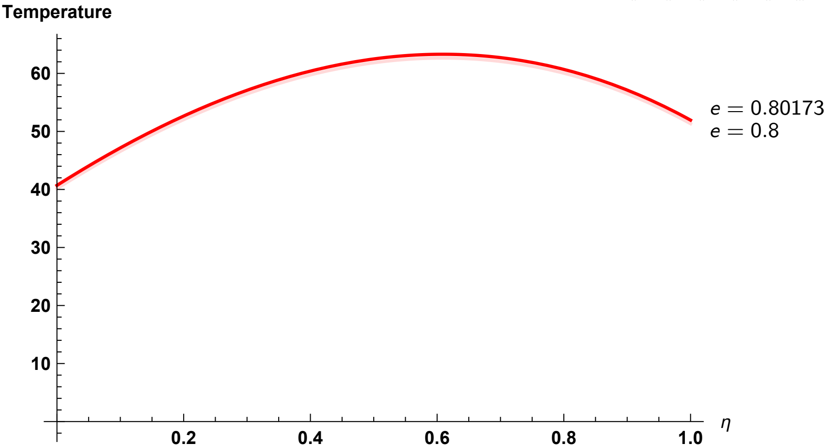




Equilibrium Temperature Profiles

$m_1 = 0.9,\ m_2 = 0.1$





Summary

- Used the HR3BP to model a scenario where a rogue star could pass near our solar system
- Studied its effects in 2D on eccentricity and noticed that it if a passing star was large enough, we could see persistent changes in the eccentricity
- Looked at how those sustained changes resulted in changes in the equilibrium temperature profile of an Earth-like planet

Future Work

- Apply this analysis with initial conditions which reflect the orbits of Jupiter and/or Earth
- Look at how the initial position of the third body changes the system

Thank You!

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Planetary Motion and its Effects on Climate

MS149: Wednesday, May 22nd, 05:00PM

The Snowball Bifurcation on Tidally Influenced Planets
Jade Checlair, University of Chicago

Ice Caps and Ice Belts: The Effects of Obliquity on Ice-Albedo Feedback
Brian Rose, University at Albany

Modeling Martian Climate with Low-Dimensional Energy Balance Models
Gareth Roberts, College of the Holy Cross

Effects of a Rogue Star on Earth's Climate
Harini Chandramouli, University of Minnesota

MS162: Thursday, May 23rd, 08:30AM

The Geological Orrery: Mapping the Chaotic History of the Solar System using Earth's Geological Record
Paul Olsen, Columbia University

Forcing-Induced Transitions in a Paleoclimate Delay Model
Courtney Quinn, University of Exeter

Modeling the Mid Pleistocene Transition in a Budyko-Sellers Type Energy Balance Model using the LR04 Benthic Stack
Somyi Baek, University of Minnesota

A Conceptual Glacial Cycle Model with Diffusive Heat Transport
James Walsh, Oberlin College