Solar system could go haywire before the Sun dies

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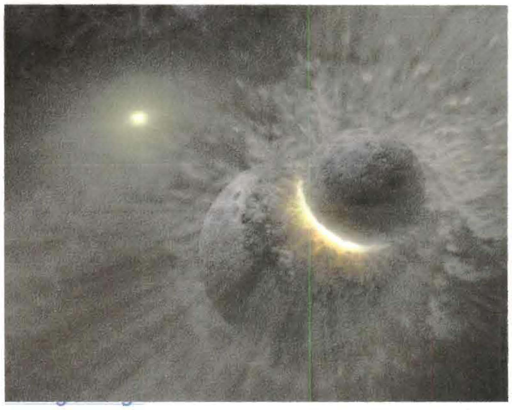
How will life on Earth end? The answer, of course, is unknown, but two new studies suggest a collision with Mercury or Mars could doom life long before the Sun swells into a red giant and bakes the planet to a crisp in about 5 billion years.



A catastrophic collision with Mercury or Mars may be in Earth's future (Illustration: NASA/JPL-Caltech)

The studies suggest that the solar system's planets will continue to orbit the Sun stably for at least 40 million years. But after that, they show there is a small but not insignificant chance that things could go terribly awry.

On human timescales, the solar system seems to move as regularly as clockwork. But Isaac Newton realised three centuries ago that the gravitational tugs the planets exert on each other can potentially nudge them out of their orbits over time.

Predicting what will happen is extremely challenging because so many bodies are involved. Even small errors in the observed positions of the planets today can translate into huge uncertainties in projections of the future. Because of this, astronomers can only say for sure that the solar system will remain stable for the next 40 million years.

Although no one can say for sure what will happen beyond that, new calculations are now providing a rough guide to the more distant future. These suggest that there is a 1 to 2% chance that Mercury's orbit will get seriously out of whack within the next 5 billion years.

This would tend to destabilise the whole inner solar system and could lead to a catastrophic collision between Earth and either Mercury or Mars, wiping out any life still present at that time.

In the case of a smash-up with Mars, for example, "all life gets extinguished immediately, and Earth glows at the temperature of a red giant star for about 1000 years", says Gregory Laughlin, a co-author of one of the studies at the University of California in Santa Cruz, US.

Highly eccentric

Jacques Laskar of the Observatoire de Paris in France authored the other study. He ran 1001 computer simulations of the solar system over time, each with slightly different starting conditions for the planets based on the range of uncertainties in the observations.

In 1 to 2% of the cases, Mercury's orbit became very elongated over time due to gravitational tugs by Jupiter. In these cases, its orbit reached an "eccentricity" of 0.6 or more (an eccentricity of 0 means the orbit is a perfect circle, while 1 is the maximum possible elongation).

Putting Mercury into such an elongated orbit increases the interactions between Mercury, Venus, Mars and Earth. Previous simulations by Laskar have suggested this can throw the whole solar system into disarray, a scenario confirmed in simulations by Laughlin and Konstantin Batygin, also of UCSC.

'All bets are off'

"Once Mercury's eccentricity gets up above about 0.6, then it's getting close to crossing Venus's orbit," Laughlin told **New Scientist**. "Once you get orbit crossings, you sort of transition from the orderly yet chaotic configuration that the solar system is in currently to a much more violently chaotic situation. Then all bets are off – a lot of bad things can happen."

Mercury and Mars tend to get thrown around the most when the solar system destabilises, because at 6 and 11% of Earth's mass, respectively, they are relatively easy to move. It is harder to budge Venus, on the other hand, because it has 82% of Earth's mass.

In one of Batygin and Laughlin's simulations, Mercury was thrown into the Sun 1.3 billion years from now. In another, Mars was flung out of the solar system after 820 million years, then 40 million years later Mercury and Venus collided.

Lava ocean

These were the disasters that happened to occur in the limited number of simulations that Batygin and Laughlin carried out. But Laughlin says there are many other ways for the solar system to unravel.

"You open yourself up to a huge number of possible disasters that can occur," he told **New Scientist**. "In each case, the gory details are completely different."

Direst for Earth is the possibility of a collision with a wayward Mercury or Mars.

A fair bit is known about what Mars could do to Earth. Many scientists think a Mars-sized object bashed into Earth in the early solar system, throwing out debris that eventually formed the Moon.

Earth was heated to thousands of degrees by the impact, with an ocean of lava covering its surface. A future replay of that event would be disastrous, Laughlin says.

But there is a 98 to 99% chance that the solar system will still be running like clockwork 5 billion years from now. Says Laughlin: "The glass is 98% full or 2% empty."

Journal references: Laskar, *Icarus* (in press); Batygin & Laughlin, *Astrophysical Journal* (in press)

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Weblinks

Laskar abstract
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Batygin & Laughlin abstract
http://arxiv.org/abs/0804.1946

Jacques Laskar, Observatoire de Paris
http://www.imcce.fr/Equipes/ASD/person/Laskar/Laskar.html

Gregory Laughlin, Lick Observatory
http://www.ucolick.org/~laugh/

ENERGY OF ORBITS

$\boxed{Q}$

What are the two major contributions to the Earth's orbital energy?

Kinetic energy $\boxed{K = \frac{1}{2} m v^2}$

Gravitational potential energy

Since the gravitational force is a central force

Energy is conserved & we can define a potential energy.

What is the work involved in pushing a planet away from the Sun?

Vector notation

$$\Delta U = \int_{\vec{r}_i}^{\vec{r}_f} \vec{F} \cdot d\vec{r}$$

Using gravitational force law

~~#~~ &

fact that $\vec{F}$ and $\vec{r}$ are in same direction

$$\Delta U = \int_{r_i}^{r_f} \frac{GMm}{r^2} \, dr$$

Integrating, we find that

$$U_f - U_i = -GMm\left(\frac{1}{r_f} - \frac{1}{r_i}\right)$$

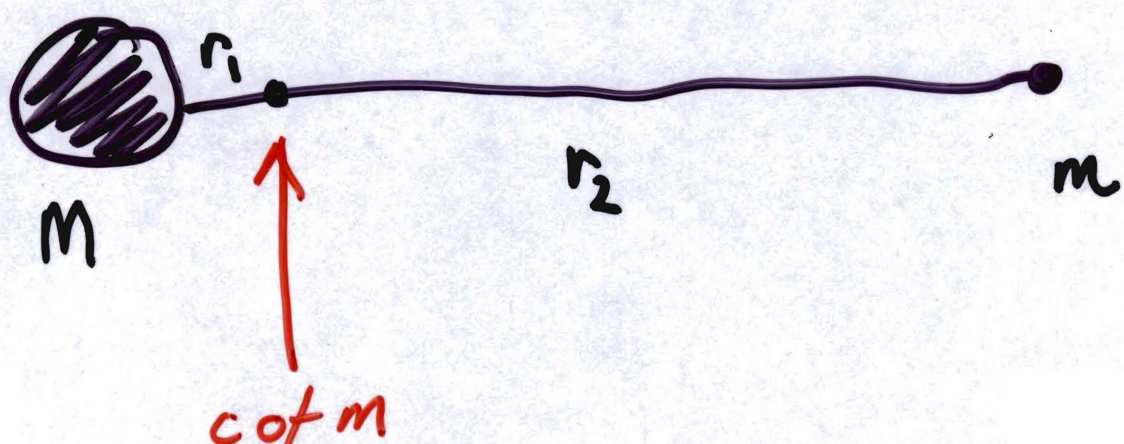
Pushing all the way to ∞ and <u>defining</u> $U(\infty) = 0$

$$\boxed{U = -\frac{GMm}{r}}$$

Now we use the conservation of energy ($K + U = \text{const}$)

So total energy $= K + U$

Looking at an asteroid in orbit around the Sun



Total energy of the system

$$E_{tot} = \frac{1}{2} M v_{Sun}^2 + \frac{1}{2} m v_{asteroid}^2 - \frac{GMm}{(r_1 + r_2)}$$

Define $r_1 + r_2 = r$

$v_{asteroid} = v$

$\boxed{Q}$ We can ignore the term for the Sun's k.e. here. Why?

$$\text{velocity} = \frac{2\pi r}{P}$$ P is period (same for both)

$$\frac{\text{k.e. (Sun)}}{\text{k.e. (asteroid)}} = \frac{M v_\odot^2}{m v^2}$$

$$\frac{v_\odot}{v} = \frac{r_1}{r_2} \quad \text{and} \quad \frac{r_1}{r_2} = \frac{m}{M}$$

(center of mass)

So $$\frac{\text{k.e. } \odot}{\text{k.e. (asteroid)}} = \frac{M}{m} \cdot \frac{m^2}{M^2}$$

$$= \frac{m}{M} \ll 1$$

So $E_{tot} = \frac{1}{2} m v^2 - \frac{GMm}{r}$

For a circular orbit

$$v = \frac{2\pi r}{P}$$

Kepler's 3rd law in full form :

$$\boxed{P^2 = \frac{4\pi^2 r^3}{GM}}$$ ($a \leftrightarrow r$ here)

So $v^2 = \frac{4\pi^2 r^2}{P^2} = \frac{GM}{r}$

and kinetic energy $= \frac{1}{2} m v^2 = \frac{GmM}{2r}$

(same formula applies for ellipse $\bar{c}$ semi-major axis $a \leftrightarrow r$)

We can now simplify formula for total energy

$$E_{tot} = \frac{1}{2} m v^2 - \frac{GMm}{r}$$

$$= \frac{GMm}{2r} - \frac{GMm}{r}$$

$$\boxed{E_{tot} = -\frac{GMm}{2r}}$$

E_{tot} -ve $\Rightarrow$ bound

Formula holds for any bound orbit, using a (semi-major axis) for r.

$\rightarrow$ E_{tot} depends only on a, not eccentricity

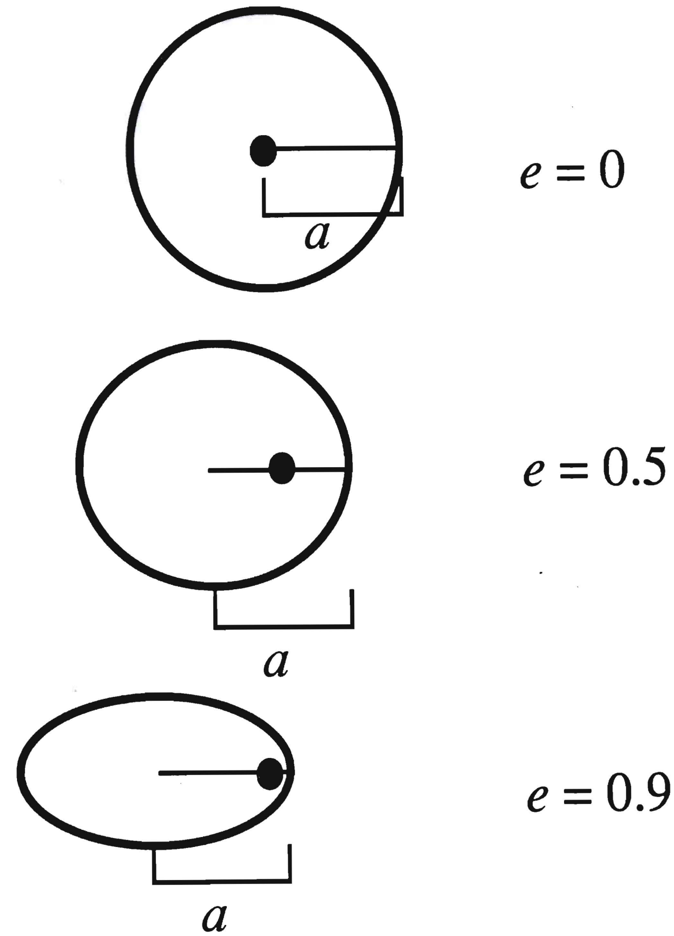


FIGURE 9.7 Three orbits, with the same semimajor axis but different eccentricities, have the same amount of orbital energy.

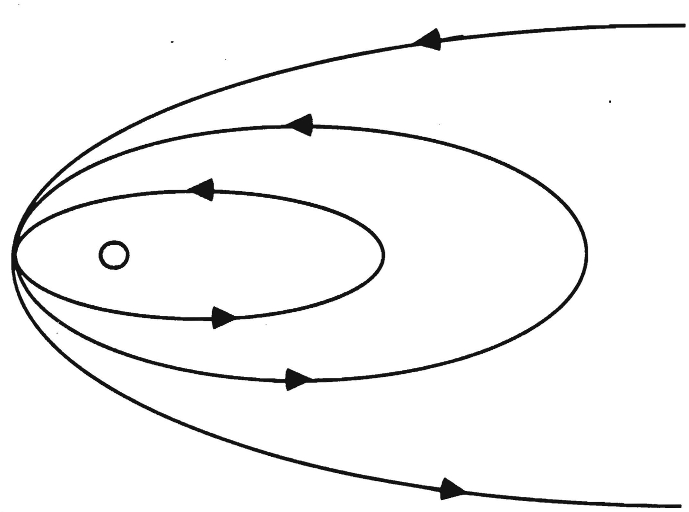


FIGURE 9.8 Closed orbits are in the shape of ellipses; as the energy increases, the orbit stretches out towards infinity until the orbit is a parabola and the body escapes.

For all bound orbits

$$\frac{1}{2}mv^2 - \frac{GMm}{r} = -\frac{GMm}{2a}$$

present radius

semi-major axis of ellipse

→ mass m cancels : orbit is the same for Jupiter or a matchbox, depends on M (Sun's mass) and a

→ <u>total</u> orbital energy doesn't change but K & U trade off.

General formula for circular velocity

$$v = \sqrt{\frac{GM}{r}}$$

We can use these formulae to work out speed & period of Hubble Space telescope, in its low-earth orbit (600 km from surface)

$$v_c = \sqrt{\frac{G\, m_\oplus}{r}}$$

$$= \sqrt{\left(\frac{6.67 \times 10^{-11} \times 6 \times 10^{24}}{(6378 + 600) \times 10^3}\right)}$$

$$= 7.6 \text{ km/s}$$

$$P = \frac{2\pi r}{v_c} = 96 \text{ min.}$$

Escape velocity

Take a satellite in orbit about the Earth.

If it burns fuel & increases total energy, eventually total energy will be zero and it will no longer be bound to Earth

$$k.e + p.e = 0$$

$$\frac{1}{2} m v^2 - \frac{GMm}{r} = 0$$

$$v^2 = \frac{2GM}{r}$$

or $$v_e = \sqrt{\frac{2GM}{r}}$$

At surface of Earth $v_e = 11$ km/s

Escape velocity from Solar System @ 1 AU is

$$\sqrt{\frac{2 G M_\odot}{1 \text{ AU}}}$$

4.2×10^6 cm/s

$= 4.2\ 10^4$ m/s km/s

42 km/s

Escape velocity from Solar System at surface of Sun is:

For comparison, the Sun's orbital motion about the center of the Galaxy is ~ 220 km/s.

Synchronous satellites

Escape velocity is $\sqrt{2} \times$ circular velocity @ same r.

$\odot^r$ velocity $\quad v_c = \sqrt{\dfrac{GM}{r}}$

Synchronous satellite : takes 1 day to complete orbit, going in same direction as Earth's rotation, so appears fixed above one point

Distance from Earth ?

Kepler's 3rd law $\quad P^2 = \dfrac{4\pi^2 a^3}{G M_{earth}}$.

Period = 1 day = 24 × 3600s

solve for a : $\quad a^3 = \dfrac{P^2 \times G \times M_{earth}}{4\pi^2}$

$$= \frac{(24 \times 3600)^2 \times 6.7 \times 10^{-8} \times 6 \times 10^{27}}{4\pi^2}$$

$a = 4.2 \times 10^9$ cm or 42,000 km

Earth's radius is 6378 km so this is about 35,600 km above surface

Space shuttle orbits about 300 km above surface – what is its period ?

Comets and asteroids : orbits

Comets & asteroids are particularly interesting because of their resemblance to planetesimals : the building blocks of the Solar System

Asteroids are rocky, most are found between Mars & Jupiter

Comets contain mostly ice ; outer Solar System objects with elliptical orbits

$\boxed{Q}$ Do you think it is a coincidence that rocky asteroids are found near the rocky planets, icy comets near gas giants?

A

If asteroids & comets were formed where they spend most of their time (inner solar system for asteroids, outer for comets) we would expect them to reflect conditions there.

Inner solar system too hot for ices to be solid, so asteroids rocky.

$\boxed{Q}$ However, the split between comets & asteroids is less absolute than the terrestrial planet / gas giant division. What else might be going on? Should we toss out the condensation vs. temperature theory we talked about last week?

A We dont need to toss it out, but should recognise that it describes conditions in the early Solar System.

Anything that modifies orbits afterward will mess up these correlations. Resonances with Jupiter have cleared out regions in the asteroid belts because the asteroids there get an extra gravitational kick from Jupiter over & over again.