Gravitational slingshot

FizziQ activity · Middle school · 40-55 min

Scan to open in FizziQ

A probe flies past a moving Saturn in the online FizziQ Web orbits simulation; middle school students compute its speed before and after to explain gravity assist.

Learning objectives

- Configure a flyby of a massive moving planet by a probe in the Orbits and Gravitation simulation
- Compute the speed magnitude of a probe in the spreadsheet using V_x = DIF x / DIF t, V_y = DIF y / DIF t and V = square root of ($V_x^2 + V_y^2$)
- Observe experimentally that the probe is accelerated when passing behind the planet and decelerated when passing in front
- Understand the principle of the gravitational slingshot used by Voyager, Cassini and Juno spacecraft
- Qualitatively explain the energy transfer between planet and probe during the flyby

Instruments and sensors

FizziQ Web simulation (Orbits and Gravitation)

Materials

- Computer, tablet or smartphone with FizziQ Web
- FizziQ experiment notebook
- Note: the protocol remains adaptable to any comparable orbital mechanics simulation software.

Protocol

1. Open the Orbits and Gravitation simulation in FizziQ Web (Experiment → Simulations → Orbits and gravitation).
2. Set the distance scale to 10,000 km/pixel and the time scale to 1 hour per frame. Cancel any centering by clicking the X button in the Centering area to observe motion in a fixed reference frame (heliocentric frame).
3. Configure body 1 as a moving Saturn: select "Saturn" on the mass slider (95 M⊕), speed 10 km/s (Saturn's real orbital speed around the Sun), initial angle 0° (horizontal motion to the right). Place it in the centre-left of the screen.
4. Configure body 2 as a space probe: select "Space probe" on the mass slider, speed 10 km/s, initial angle 90° (vertical downward motion). Choose a contrasting colour to track it easily.
5. Test 1 — Passage BEHIND Saturn: drag the probe to the upper right, at about x = +600,000 km relative to Saturn's initial position and y = -1,500,000 km above. The probe descends while Saturn moves rightward: they cross with the probe passing behind Saturn (on the right, where Saturn just was).
6. Click REC to start recording and launch the simulation. Observe the trajectory: the probe is attracted from behind, deflected by Saturn, then exits towards the bottom-right with a visibly higher speed than at arrival. This is the gravitational slingshot's accelerating effect.
7. Click REC again to stop recording. The columns t (days), x_2 (m), y_2 (m) are automatically exported to the experiment notebook.
8. In the experiment notebook, add three computed quantities: V_x with formula = DIF (x_2,t), V_y with formula = DIF (y_2,t), and V with formula = SQRT (V_x^2 + V_y^2). The V quantity gives the probe's speed magnitude at each instant.
9. Plot V versus time. Read the initial value (close to 10 km/s, the starting speed) and the final value after the

flyby. Note the gain: V_final > V_initial, typically V_final around 15 to 20 km/s. Save a screenshot using the IMG button.

10. Test 2 — Passage IN FRONT of Saturn: stop the simulation to reset. Keep all other settings identical, but drag the probe further left, at about x = -300,000 km relative to Saturn's initial position and y = -1,500,000 km above. This time the probe and Saturn cross with the probe passing in front of Saturn (on the left, where Saturn is heading).

11. Start a new REC recording. Observe the trajectory: the probe arrives facing Saturn which is advancing, is slowed and deflected to the left, then exits with a lower speed than at arrival.

12. Stop REC. Recompute V_x, V_y and V in the spreadsheet, then plot V(t). This time, V_final is lower than V_initial, typically around 5 to 7 km/s: the slingshot has slowed the probe.

13. Fill in a 5-column table: Test, Crossing position (in front or behind), V_initial (km/s), V_final (km/s), Variation (km/s). Conclude that the simple choice of the probe's starting position radically changes the result: a flyby behind the planet accelerates the probe, a flyby in front decelerates it.

14. Bonus — repeat test 1 but replacing Saturn with Earth (1 M⊕) at the same position and speed. Observe that the speed gain is much smaller: the slingshot effect strongly depends on the gravitational assist planet's mass.

Expected results

Test 1 (passing behind Saturn): the probe arrives at 10 km/s, is attracted by Saturn moving rightward, and visibly leaves faster, with a final speed typically between 15 and 20 km/s depending on the approach distance. On the V(t) graph plotted in the experiment notebook, speed shows a peak at closest approach, then settles at a higher value than the initial one. Test 2 (passing in front of Saturn): the probe arrives at 10 km/s but this time Saturn's trajectory opposes its motion. The probe is slowed and exits with a final speed of 5 to 7 km/s. On V(t), the final speed is below the initial speed. The exact gain or loss depends on the approach distance and flyby geometry, and can theoretically reach 2 × 10 = 20 km/s in absolute value (theoretical maximum for a planet at 10 km/s). When replacing Saturn with Earth (1 M⊕) as a variant, the effect is greatly reduced: the planet's mass strongly conditions the slingshot's amplitude.

Questions

- Why is the probe accelerated when passing behind the planet and decelerated when passing in front?
- Where does the extra energy gained by the probe in test 1 come from? Why doesn't Saturn appear to slow down?
- What would happen if Saturn were stationary instead of moving at 10 km/s?
- Why is the slingshot effect much greater with Saturn than with Earth at the same planetary speed?
- Why do space agencies favour Jupiter and Saturn for gravity-assist manoeuvres?

Going further

- Modify Saturn's speed (5, 15, 20 km/s) while keeping the same configuration and observe how the probe's speed gain varies proportionally
- Replace Saturn with Jupiter (318 M⊕) at the same position and speed, and observe an even larger speed gain due to its greater mass
- Modify the probe's vertical starting position to bring it closer or farther from Saturn during the flyby, and observe how the approach distance changes the magnitude of gain or loss
- Reverse the probe's direction of motion (angle 270° instead of 90°, i.e. upward) while keeping Saturn moving rightward, and observe a new slingshot geometry
- Reproduce Voyager 2's historic flyby of Saturn in 1981, which gained speed to reach Uranus and then Neptune