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# The Gravitational Assist

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**Abstract.** The goal of this paper is to present basic facts about gravitational assist which is used for interplanetary flights of spacecrafts. A short description of missions that used this technique is given. The table of all important flyby dates, altitudes of closest approaches is also included.

## Introduction

Although astronomy is a very interesting part of physics, at high schools is represented only by a few topics like Kepler's Laws, a brief description of the Solar System, the solar and lunar eclipse, Moon phases, etc. The goal of author's Thesis is to bring additional very interesting topics to high schools: gravitational effects like the gravitational assist, tides, the perihelion precession of planets, etc. Everything should be explained in the form understandable to high school students. In this paper, we will present selected results of our study of the gravitational assist (GA).

When a spacecraft flies past a much more massive body—for example a planet (but it can be a moon as well), the planet acts on the spacecraft via its gravitational force and changes the spacecraft's velocity relative to the Sun. The velocity is a vector so the change can be in direction and also in magnitude and the change can be positive (the spacecraft is accelerated) or negative (the spacecraft is decelerated)—it depends on the way how the spacecraft flies past the planet—if it is in the front of the planet, the spacecraft looses speed, if it is behind the planet, the spacecraft gains speed. How can this be possible?

Because the Law of energy conservation but the choice of the frame of reference is very important here. The change in magnitude of velocity related to the planet is none, the magnitude changes only when it is related to the Sun. During derivation this change in magnitude of velocity is very important the frame of reference so students will work with different frames of reference which is not so much practising at high schools. The change in magnitude of velocity is maybe not clear—where the spacecraft gets or looses the energy? From the planet that slows down or speeds up but it is so massive with respect to the spacecraft that we don't measure any change in planet's movement. This circumstance can be very well derived from the Law of conservation of linear momentum:

$$\frac{\Delta W}{\Delta v} = \frac{m}{M} \approx 10^{-21} \text{ or less,}$$

where $\Delta W$ ($\Delta v$), is the change of planet's (spacecraft's) velocity related to the Sun, $M$ ($m$) is the mass of the planet (spacecraft). The conservation of energy can be simply written as $\Delta E_s = -\Delta E_p$, where $\Delta E_s$ ($\Delta E_p$) is the change in spacecraft's (planet's) kinetic energy related to the Sun.

A short overview of planetary missions which used the GA is enclosed.

## Famous examples—missions to other planets

**Pioneer 10** was the first mission to another planet that used the GA. Launched on March 2, 1972, Pioneer 10 was the first spacecraft that travelled through the asteroid belt and the first spacecraft that made direct observations and obtained close-up images of Jupiter. The closest approach to Jupiter happened on December 3, 1973 so this is the date of the first planetary GA. Pioneer's last, very weak signal was received on January 23, 2003. Pioneer 10 heads towards

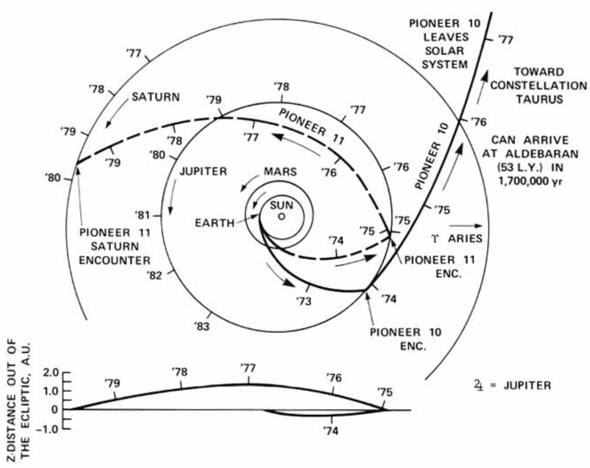


**Figure 1.** Pioneers' trajectory—taken from NASA page [7].

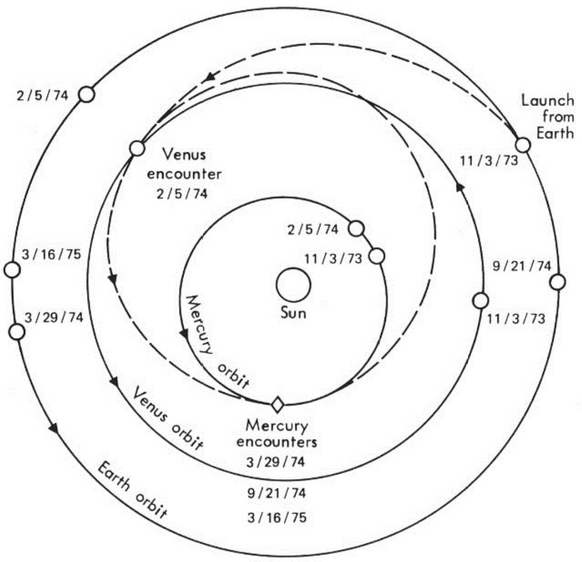


**Figure 2.** Mariner trajectory—taken from NASA page [7].

the star Aldebaran which is about 65 light years away and it would take Pioneer over 2 million years to reach it [7].

The second application of the GA was **Mariner 10**—a mission to Mercury. It was the first use of the GA to reach one planet by using the gravity of another planet. It was launched in 1973 (hereafter accurate dates can be found in Table 1), travelled to Venus and at Venus lost some of its speed to continue to Mercury (no conventional rocket would allow the needed speed loss, so without the GA it wasn't possible to reach Mercury). At Mercury during the first flyby there was another GA which allowed the second encounter with Mercury and during this second Mercury flyby was the third GA which enabled a third Mercury encounter [5].

**Pioneer 11**, launched in 1973, made first direct observations of Saturn. It was originally intended to visit only Jupiter as a precursor to Voyagers. Nevertheless there was the opportunity to make the GA at Jupiter and continue to Saturn. During the closest approach to Jupiter, Pioneer 11 performed the GA which caused the turn almost 180° (see Figure 1) and in 1979 encountered Saturn. The Pioneer 11 mission ended on September 30, 1995 when the last transmission from the spacecraft was received. The spacecraft heads toward the constellation of Aquila (The Eagle) [2], [7].

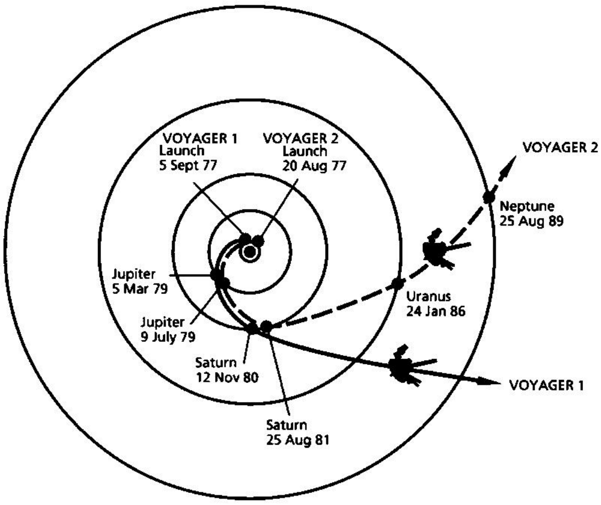


**Figure 3.** Voyagers' trajectory—taken from NASA page [8].

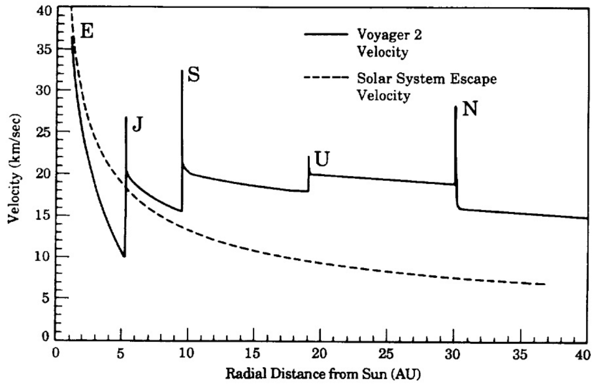


**Figure 4.** Voyager 2 velocity relative to the Sun—taken from [2].

**Voyager 1** was launched in 1977 and was designed to conduct close-up studies of Jupiter and Saturn, Saturn's rings and larger moons of these two planets. It reached Saturn thanks to the Jupiter's GA . Its trajectory was designed to send the spacecraft closely past the large moon Titan. Flying "under" Saturn, Voyager 1 was lofted above the ecliptic at a 35° angle [2].

**Voyager 2** was launched in 1977 and was designed for the same aim as its twin spacecraft Voyager 1. But there was the possibility to encounter also Uranus and Neptune. The flight time to Neptune thanks to three GAs was reduced from 30 years to 12 years only. The Neptune flyby design put Voyager close by Neptune's moon Triton rather than attained more speed—see Figure 4. Such layout of Jupiter, Saturn, Uranus and Neptune occurs about every 175 years. Voyager 2 is still the only spacecraft which has visited Uranus and Neptune [7].

For both Voyagers more than 10 000 trajectories were studied before choosing the particular two mentioned above. Current distances of both spacecrafts from the Sun and the Earth can be found on NASA page [8]: Voyager 1 is now (June 2011) more than 117 AU far from the Sun and it is the most distant human-made object in space (until February 17, 1998 it was Pioneer 10). Voyagers are now in the heliosheath—the outermost layer of the heliosphere, where the solar wind is slowed down by the pressure of interstellar gas. The mission was renamed to Voyager Interstellar Mission.

The **Galileo** probe was launched in 1989, it was the first mission to explore Jupiter and its moons in more detail than any previous spacecraft. There were used three GAs: one with Venus and two with the Earth (so the Earth is also used for the GA). On October 29, 1991

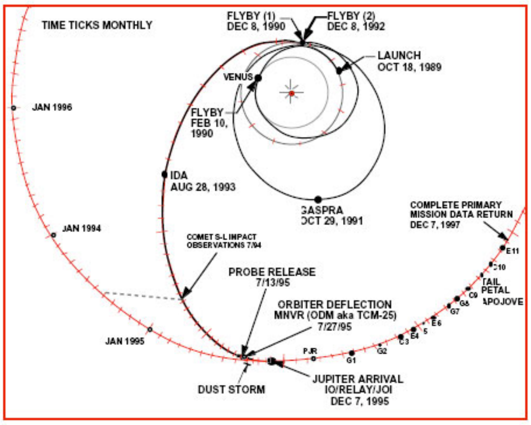


**Figure 5.** Galileo trajectory—taken from NASA page [7].

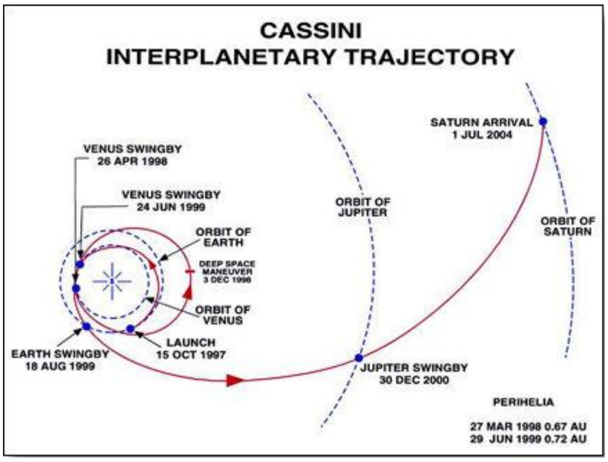


**Figure 6.** Cassini trajectory—taken from NASA page [9].

Galileo made the first close approach (1 600 km distance) to an asteroid Gaspra. On a second pass through the asteroid belt, Galileo discovered a miniature moon orbiting asteroid Ida. This tiny body was named Dactyl. The spacecraft arrived to Jupiter on December 7, 1995. The Galileo mission ended on September 21, 2003 during its direct impact into the Jupiter's dense atmosphere. A list of close encounters with Jupiter's moons can be found in a Fact Sheet [7] about Galileo (and we have to realize that during each encounter with Jupiter's moon occured the GA).

**Ulysses** was a joint mission of the European Space Agency (ESA) and the National Aeronautics Space Administration (NASA) which studied the heliosphere—the region of space influenced by the Sun and its magnetic field—from a unique polar orbit. It was launched in 1990 and thanks to the Jupiter's GA the spacecraft was deflected out of the ecliptic plane into its present high inclination polar orbit about the Sun with an inclination to the ecliptic by 80°. Ulysses orbited the Sun three times before the fuel had started to freeze and the mission ended on June 30, 2009. After all Ulysses is still orbiting the Sun so it became a man-made "comet" [6], [7].

**Cassini-Huygens** was launched in 1997 and it was the first mission to explore the Saturn's System. The mission was extended until September 2017 and renamed to Cassini Solstice Mission. On July 1, 2004 Cassini-Huygens arrived to Saturn after 4 succesfull encounters with Venus (two encounters), the Earth and Jupiter. On NASA page [9] can be found the current position of the probe, a list of all encounters with Saturn's moons and also information about next flyby.

**Table 1.** A complete list of planetary missions which used the GA with a planet. $\Delta v$ is the change in magnitude of the planet's velocity relative to the Sun. Some data are missing because they are probably not available, dates are in format dd-mm-yyyy, given altitudes are from planets' surfaces (or from clouds—sometimes it is not clear in References).

| Probe's name | Launch date | Flyby | Flyby date | $\frac{\Delta v}{\mathrm{km \cdot s^{-1}}}$ | $\frac{\text{Altitude}}{\text{km}}$ | References |
|---|---|---|---|---|---|---|
| Pioneer 10 | 02-03-1972 | Jupiter | 03-12-1973 | + 15,3 | 130 000 | [4], [7] |
| Pioneer 11 | 05-04-1973 | Jupiter | 02-12-1974 | | 43 000 | [7] |
| | | Saturn | 01-09-1979 | | 21 000 | |
| Mariner 10 | 03-11-1973 | Venus | 05-02-1974 | < 0 | 5 768 | [7] |
| | | Mercury 1 | 29-03-1974 | | 703 | |
| | | Mercury 2 | 21-09-1974 | | 48 069 | |
| | | Mercury 3 | 16-03-1975 | | 327 | |
| Voyager 1 | 05-09-1977 | Jupiter | 05-03-1979 | + 16 | 277 500 | [2], [7] |
| | | Saturn | 12-11-1980 | | 124 000 | |
| Voyager 2 | 20-08-1977 | Jupiter | 09-07-1979 | + 10 | 650 500 | [2], [7] |
| | | Saturn | 25-08-1981 | + 5 | 100 800 | |
| | | Uranus | 24-01-1986 | + 2 | 81 500 | |
| | | Neptune | 25-08-1989 | − 3 | 5 000 | |
| Galileo | 18-10-1989 | Venus | 10-02-1990 | | 16 000 | [7] |
| | | Earth 1 | 08-12-1990 | | 960 | |
| | | Earth 2 | 08-12-1992 | | 303 | |
| Ulysses | 06-10-1990 | Jupiter | 08-02-1992 | | 376 000 | [3] |
| Cassini-Huygens | 15-10-1997 | Venus 1 | 26-04-1998 | + 3,7 | 337 | [9] |
| | | Venus 2 | 24-06-1999 | + 3,1 | 598 | |
| | | Earth | 18-08-1999 | + 4,1 | 1 166 | |
| | | Jupiter | 30-12-2000 | + 2,1 | 9 721 846 | |
| Messenger | 03-08-2004 | Earth | 02-08-2005 | | 2 348 | [10] |
| | | Venus 1 | 24-10-2006 | | 2 987 | |
| | | Venus 2 | 05-06-2007 | | 338 | |
| | | Mercury 1 | 14-01-2008 | | 200 | |
| | | Mercury 2 | 06-10-2008 | | 200 | |
| | | Mercury 3 | 29-09-2009 | | 228 | |
| New Horizons | 19-01-2006 | Jupiter | 28-02-2007 | + 3,8 | 2 300 000 | [1], [7] |

The second mission (after Mariner 10) to explore Mercury was **Messenger**. Messenger became the first spacecraft to orbit Mercury. It was launched in 2004 (more than 30 years after Mariner 10) and made 6 planetary flybys: one with the Earth, two with Venus and three with Mercury. The Mercury orbit insertion took place on March 18, 2011. The end of nominal mission is planned on March 18, 2012.

The **New Horizons** probe was launched in 2006, it is the first mission to Pluto and the Kuiper Belt. It used the GA of Jupiter. It should reach Pluto on July 14, 2015.

**Solar Probe Plus** will be the first probe which flies into the Sun's atmosphere (or corona). The launch is scheduled on July 30, 2018 and it will make 7 Venus flybys and approaches the Sun on December 19, 2024. During each Venus encounter its elliptical orbit gets closer to the Sun with the closest approach at 8.5 solar radii. [11]

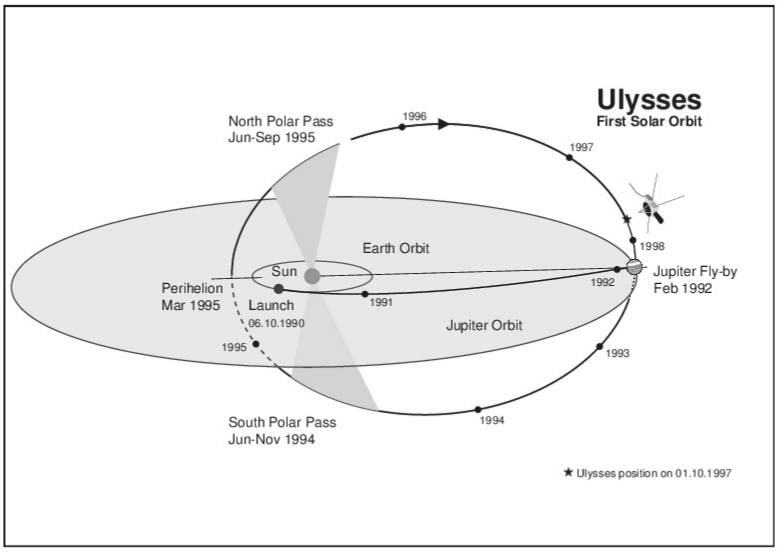


**Figure 7.** Ulysses trajectory—taken from ESA page [6].

## Conclusions

**Practical life**: Today, the GA is a standard technique used in planetary missions which **saves fuel** (GAs from two swingbys of Venus and one of the Earth provided an equivalent of 75 tons of rocket fuel, which was much more than Cassini-Huygens weighed itself—it was lighter than 6 tons, [7]), **shortens travel time** (Voyager 2 travel time to Neptune was shortened from 30 years to 12 years only), **allows reaching Mercury or the Sun** (the spacecraft must slow down) and **allows leaving our Solar System** (see Figure 4). The GA helps to determine masses of planets and moons—the trajectory of Voyager 2 showed that Uranus is about 0.25 % more massive than expected. The telemetry confirmed that behind Neptune is no "*Planet X*"—if there was such a massive planet, the spacecraft's trajectory would be different from the planned one. [3]

**Educational importance**: The GA can be very useful for better understanding of different frames of reference at high schools. It shows to students that physics laws are valid not only on the Earth but also in space. And of course it is very interesting part of physics so it can attract more students to physics—which is in fact the basic purpose of author's Thesis.

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[8] Voyager—The Interstellar Mission: `http://voyager.jpl.nasa.gov/` .
[9] Cassini Solstice Mission: `http://saturn.jpl.nasa.gov/` .
[10] Messenger Web Site: `http://messenger.jhuapl.edu/` .
[11] Solar Probe Plus: A NASA Mission to Touch the Sun: `http://solarprobe.jhuapl.edu/` .