The Solar System 2003

A scenario for the movie about planetary systems, vers. Jul 2nd 2007.

The Solar System — a tiny part of the Universe, a vast, almost empty space. It is an alien environment for a human — without atmosphere, without solid land underfoot.

A starry sky in the ecliptic coordinates. The Sun (⊙) moves to the center of the field of view.

The Sun, planets and their moons, asteroids and comets are a kind of small islands, where mass is concentrated. Smaller bodies — meteoroids, interplanetary dust and gas or particles of radiation — photons, also do belong to the Solar System.

A mutual attraction, a gravitational force acts among all of them and governs their motion. The Sun is by far the most massive, therefore other bodies orbit around it. The closer to the Sun a body is, the higher its orbital speed is.

Orbital trajectories of planets, an astaroid and a comet are painted with titles; the camera moves from the S ecliptic pole to the N pole, successive zoom on the inner planets.

The farthest planet is Neptune and then other follow: Uranus, Saturn, Jupiter, Mars, Earth, Venus and Mercury. The mean distance between the Sun and the Earth, so called *Astronomical Unit*, is 150 million km. The light travels this distance in 8 minutes 20 seconds. The diameter of the Earth is only 13,000 km.

A big zoom-in on the Earth (⊕) and Moon (☾), a necessary slow-down of time.

Planets and moons do not shine with their own visible light, they only reflect a part of the sunlight. The Sun is, on the other hand, a star and as such it radiates by the entire surface to all directions.

Rotation of the camera, such that the dark hemisphere of ⊕ and radiating ⊙ would be visible.

Sometimes one can see radiation reflected from the smallest particles of interplanetary **dust** — this phenomenon is called the *zodiacal light*.

The spring sky with the zodiacal light.

Meteoroids, stony fragments from fractions of milimetre upto a few metres in diameter, can be easily observed at the moment, when they hit the air surrounding our planet. Particles move with a relative velocity of about 50 km/s. They begin to heat themselves by a friction of air 150 km above the Earths surface. A warm and shining column of ionized air, which we see on the sky, is called a *meteor*, folkly speaking a “shooting star”.

A meteor and bolide flying on the winter sky.

Several times per year, for example around the 12^{th} of August or the 18^{th} of November, the Earth travels through the streams of cometary meteoroids, what causes a *meteor stream* on the sky.

A fish-eye camera watching Perseids.

Larger and harder meteoroids can "survive" the flight through the atmosphere and they fall on the ground as *meteorites*.

A photography of a meteorite.

A meteor and bolide flying on the sky, a photography of a meteorite.

Bigger bodies are **asteroids**. They typically have an irregular shape and they consist of stony material. There orbit about one million asteroids larger than 1 km in the main belt between Mars and Jupiter.

A cut on rotating textured asteroids, titles under all following bodies.

Small **moons** of planets, like Phobos or Amalthea, are very similar to asteroids.

A smooth passage over the small moons.

Big moons are comparable to small planets: Jupiters moon Ganymede is even larger than Mercury. Bodies with diameters above 1,000 km already have more regular, spherical or elliptical shape.

A zoom-out and passage over big moons (Io, Europa, Ganymede, Callisto, Titan, Triton, the Moon) and planets Pluto and Mercury.

The four planets closest to the Sun — Mercury, Venus, Earth and Mars — are called **Earth-type or terrestrial planets**. They are relatively similar to each other: they comprise mainly of stony material, they have a solid surface and, except Mercury, they are covered by a thin layer of gases — an atmosphere. The most common chemical elements in the Earths body are iron, oxygen, silicon and magnesium.

An enlargement of the FOV on the four terrestrial planets and then successive passage towards giant planets.

The outer planets Uranus and Neptune are **ice giants**. Their substantial parts are ices of water, methane, and ammonia or a mixture of hydrogen, helium and rock.

Quickly rotating Uranus and Neptune.

Jupiter and Saturn are **gaseous giants**. We call them Jupiter-type planets also. Their relatively small cores probably consist of rock and ice, the extended mantles are made of metallic and molecular hydrogen and helium.

All giant planets have *rings* (even thought only rings of Saturn are easily observable) and numerous families of regular and irregular moons.

Saturn with rings and Jupiter. Change of the FOV, such that all planets would be visible together.

The Sun. An incandescent gaseous sphere, with a surface temperature of approximately $6,000\,^{\circ}\mathrm{C}$. There is a hidden natural thermonuclear reactor inside, in which nuclei of hydrogen atoms are transformed to nuclei of helium atoms and photons and neutrinos are emitted at the same time. This source of energy has operated already for four and half billion years.

Sunspots and eruptions are prominent demonstrations of changes on the Sun. Both of them are induced by a strong *magnetic field*, that affects motion of solar material — electrically conductive ionized gases, it means *plasma*.

A further zoom-out on the Sun.

The most extended objects in the Solar System can be **comets**. Their icy–stony cores are tiny (they are a few kilometres in diameter), but when they come near the Sun, ice starts to sublimate and escaping gas and dragged dust create a coma and a tail. Their light hydrogen envelopes may reach a size of upto 100 million km.

Cometary tails are always directed approximately away from the Sun. Molecules of gas and dust grains interact with the radiation and *solar wind* — a stream of charged particles, which spread from the Sun to the interplanetary space with a velocity of about $500\,\mathrm{km/s}$.

The last shot on a big comet with a tail.

A cut. Detailed animations of individual planets follow.

Mercury, the first planet, gets the most solar radiation energy. There is a temperature over $300\,^{\circ}\mathrm{C}$ on the illuminated hemisphere, but the reverse hemisphere cools quickly downto $-200\,^{\circ}\mathrm{C}$. The surface is covered by *impact craters*, which were formed by collisions with asteroids and comets. A big part of the surface has never been observed by a space probe.

Rotating Mercury with one hemisphere gray.

Venus is covered by a dense atmosphere (the pressure on the surface is 90 times higher than on the Earth). Regardless it orbits the Sun twice farther than Mercury and it reflects two thirds of solar radiation, there is an unprecedented temperature 460 °C. The reason is a strong *greenhouse effect* — carbon dioxide in the atmosphere transmits the visible solar radiation towards the surface but it absorbs the infrared radiation radiated from the surface and that way impedes its cooling.

Venus covered by dull opaque athmosphere. Possibly an UV image with percetible bands.

Radars were able to look below the opaque atmosphere — they detected a surface characterized by fractures and volcanos. It is possible to deduce, from the number of impact craters, that the volcanic activity reformed the most of the surface of Venus 700 to 500 million years ago.

A dissolution of clouds, a display of the surface by radar. Possibly a change on an elevation map.

The third planet from the Sun is **the Earth**. It has a suitable size and distance from the Sun, so there may exist not only ice or water vapour but also liquid water on the surface — one of the assumptions for creation of life. The primordial air was completely converted by the activity of live organisms and it contains mostly nitrogen and oxygen today.

The slowly rotating Earth with a cloud cover. Possibly an image without any clouds (illuminated by ambient light) and an animation of seasonal changes from SeaWIFS spacecraft.

The Earth differs from the rest of planets also by the *plate tectonics* — its crust is cracked to individual plates, that can move on the top of the mantle. The ocean floors originate by volcanic eruptions in oceanic ridges and they dissolve by the subduction below other plates. New mountains are folded during collisions of the plates. This may be important for the life on the dry land, because the erosion otherwise would clear all mountains and the entire surface of the Earth would be covered by ocean.

A change of the texture on an elevation map, markings of tectonic plates, a map of the ocean floor age. Possibly an animation of changing continents (Scotese, 2000).

The Earth is followed by **the Moon**. It also has importance for the terrestrial life: it causes, together with the Sun, changes of the low and high tide by tidal forces. The Moon also stabilizes the rotation axis of the Earth on the long term and thus prevents sudden and extreme changes of climate.

We can observe only one hemisphere of the Moon from the Earth, because the Moon rotates around its axis with exactly the same period, as it orbits around the Earth. Such phenomenon is called a *synchronous rotation*.

A map of the Moon with a bump-mapping. A comparsion of the near and far side (a description in a subtitle).

The Moon formed approximately 4.45 billion years ago, when a Mars-sized body collided with the Proto-Earth. A huge amount of fragments was generated by the collision, most of which falled back on the Earth, but a part of them formed a disk around the Earth. The disk acreted very quickly, probably in a few weeks, into one satellite — our Moon.

An image of the Moon-origin impact (only the first, simpler phase). A possible animation from SPH simulations.

Small bodies, like asteroids, can also appear in the neighborhood of the Earth. On average, one asteroid larger than 100 m collides with the Earth every 1,000 years. A collision with a 10-km asteroid, which happens once per a few 10 million years, can cooperate in the course of large extinction of animal and plant species. The best known example is the extinction of dinosaurs 65 million years ago.

The near-Earth asteroid (6349) Golevka, followed by the camera, diring a close encounter between the Moon and Earth. Possibly a display of an impact on the Yucatan peninsula.

Mars. The planet distinctive by its red colour, which is caused by iron oxides.

Slowly rotating planets Mars.

The elevation map and distribution of impact craters on the surface suggest, that the north hemisphere could be covered by ocean 3 billion years ago.

A change of the texture on an elevation map, then on a hypothetic image of the ancient ocean and back on the photographic surface with a bump-mapping.

The relics of running water are erosion shapes in numerous valleys. The largest of all is Vallis Marineris, 4,000 km long, 7 km deep.

A big detail of the area of Vallis Marineris, the camera follows the valley on always rotating Mars, the shadows change. Possibly an animation of a high-resolution block.

The valley drained water from the Tharsis region. The Tharsis is of volcanic origin and one can find here the biggest volcanos in the Solar System — for example Olympus Mons, 27 km high and with the base 600 km in diameter.

Again the shot on the whole Mars and zoom-in on Olympus Mons. Possibly a fly-around the volcano.

Mars is rather a calm planet from the geological point of view for the last two billion years. Weak wind in the light atmosphere plays with small sand grains, seasonal changes lead to the regular growing of polar caps in winter and to their shrinking in summer.

An enlargement on whole Mars.

We can find the asteroid number **(243) Ida**, for example, on an orbit between Mars and Jupiter. This 50-km asteroid belongs to the Koronis family, what is possible to recognize by similar orbits and similar colors of its members. These asteroids made up a single body, which was however shattered by a huge impact. The current moon of Ida — one-kilometre Dactyl — was formed that way.

Slowly rotating Ida and moon Dactyl orbiting around it. Possibly an animation of asteroid families.

Jupiter has the mass higher than all other planets and smaller bodies of the Solar System together. It radiates twice as much energy, as it receives from the Sun. The source is evidently a slight shrinkage of the planet and a transformation of the rotational energy to heat. There is an enormous storm, called the *Great Red Spot*, observed for a few hundreds of years in the atmosphere of Jupiter.

Qickly rotating Jupiter with GRS, a shadow of a moon transiting the disc of the planet.

Probably the most interesting Jupiters moons, out of tens, are *Io and Europa*. Tides of Jupiter are so strong on Io, that they deform the whole moon and heat its interior to a temperature of a few thousand degrees Celsius. It produces never-ending volcanic activity on the surface. The volcanos erupt sulfur to a height of a few hundred kilometres and reshape the surface with unbelievable rate.

A translation of the camera towards Io, Jupiter is visible in the background. An animation of a volcano with an ejection of the material (an "umbrella").

Europa is, on contrary, a very smooth moon, covered by water ice. But the structure of ruptures and magnetometric measurements prove the existence of sub-surface liquid ocean.

Synchronously rotating Europa. Possibly a detail of the ruptures or the inner structure.

Saturn became famous by beauty of its bright *rings*. Regardless they have radius over 100,000 km, they are at most a few hundred metres thick. They look as a series of thousands of differently bright and differently transparent ringlets, but in reality they are composed of individual icy–stony fragments with a typical size of 10 cm. "Spaces" and other structures in the rings are caused by gravitational perturbations of small moons orbiting directly inside the rings or out of them. The moon Mimas is responsible for the most prominent *Cassini division*.

A flight around Saturn, a roll-in of a still image of the ring structure, a dissolution of the image and againg a view on Saturn. The fly continues through the plane of the rings from the north to the south (the non-illuminated side), a quick rotation of the camera on Mimas.

Uranus is almost not visible on the sky with the naked eye. It was discovered by chance using a telescope, by William Herschel in 1781. The rotation axis of Uranus is interesting — it lies almost in the plane of orbit and Uranus exposes in turn the north and the south pole towards the Sun.

Relatively monotonous rotating Uranus, subsequently the rotation axis appears, marked as a thin cylinder.

The discovery of **Neptune** was one of the greatest triumphs of the celestial mechanics in the 19^{th} century. Adams and Le Verrier calculated the position of the unknown planet from the observed perturbations of Uranuses orbit, and Galle then indeed found it on the sky. We observe wind with a velocity of hundreds kilometres per second in the upper layers of the atmosphere, likewise on other giant planets. Spots and storms, which are probably the demonstration of the internal heat source, appear on Neptune, similarly as on Jupiter and Saturn (but not on Uranus).

Neptune with a prominent spot and a big moon Triton.

No space probe has yet visited **Pluto and Charon**. The best ground-based telescopes resolve only a few bright and dark areas on them.

An animation of Pluto and Charon, a synchronous rotation around the common centre of mass.

However, hundreds of other bodies were discovered behind Neptune, moving on similar orbits as Pluto or even farther. The whole population is called the **Kuiper belt**. They are icy bodies, often very dark, reflecting only about 4 % of solar radiation. The equilibrium temperature on their surfaces is only a few tens of degrees above the absolute zero (it is −273 °C).

A zoom-out of the shot on the 1 000 AU big Kuiper belt, displayed as a slightly transparent object with a shape of widening disc.

There is a spherical **Oort cloud** also around the inner Solar System. It is not observable directly, but we infer its existence by new long-periodic comets, which reach the inner part of the Solar System evenly from all directions.

A zoom-out on the Oort cloud (a transparent sligtly emitting hollow sphere)

There is an area farther away, where the gravity of foreign stars starts to dominate…

An increase of the distance of the camera, such that the neighbour stars are visible; some of them are described by subtitles.

Apart from the eight planets in the Solar System, there is also known a few hundreds of **extrasolar planets**, which orbit foreign stars. Contemporary astronomical instruments do not allow to observe these distant planets directly, but their properties are calculated from photometric and astrometric measurements of the mother stars. The most of extrasolar planets, discovered up to now, are bigger than Jupiter and they orbit in the distance less than the Earth orbits around the Sun.

Possibly a detail on a single star, which moves a little bit, because it is affected by a close massive planet, and dwindle during its transits. A further detail could show a giant planet relatively close to the mother star.

There exist hundreds of billions of stars in our Galaxy.

A big zoom-out on the whole Galaxy.

There are tens of billions of galaxies in the entire observable universe...

The last zoom-out on the local group of galaxies and an unbelivable shot on the whole universe with clusters of galaxies.

What is the past and the future of the Solar System?

We know, from the analysis of the decay of radioactive elements in primitive meteorites, that these meteorites solified 4.56 billion years ago. The Sun formed at the same time and the complete planetary system did also.

Possible an image of an ordinary chondrite.

Stars, even whole star clusters, arise from *interstellar gas–dust clouds* (with a main component molecular hydrogen). There sets in a *gravitational collapse*, a strong increase of the density, in their coolest parts, when the temperature is only a few degrees above the absolute zero. Then the pressure and temperature become high and thermonuclear reactions are ignited. That is the time of a star birth. A *flat disk* from the remaining matter forms around it.

A motion of the camera over a still image of the Great Nebula in Orion (M 42).

Collisions, which lead to a consequent coalescens of small bodies to bigger ones, happen frequently in the disk. Finally, only a few large bodies remain, in which the most of the mass is concentrated. We call this process the *accretion*.

A shot on the inner part of the protoplanery disc with arising terrestrial planets.

Embryos of planets, planetesimals, are then heated by radioactive decay of unstable elements. The mentioned collisions support the heating also. Larger bodies are partly or completely melted, what sets up their spherical shape. A core arises from heavier rocks by *differentiation*, lighter elements remain in a mantel and a crust.

A demonstration of the differentiation on a cut of a planet.

There may arise cores of giant planets in greater distances from the Sun, because there are enough icy planetesimals, which cannot exist in the proximity of the Sun. As soon as the mass of the core exceeds the particular critical value, it starts to acrete surrounding gas and the mass of the planet increases many times.

An outer part of the disc with a jovian planet.

Finally, strong ultraviolet radiation and star wind cause, that the mother nebula heats and blows up to the surroundings space. The Solar System thus gains almost the present look.

The complete process of the creation spans approximately 100 million years.

Again M 42 nebula.

As we know from observations of other stars and from models of star evolution, the Sun will calmly shine for about 6 billion years. Then the reserves of hydrogen in the core will be exhausted, the whole interior will be "rebuild" and the Sun will change to a *red giant*. The inner planets may be completely destroyed. The red giant will explode as a nova in later phases, it will expand its envelope, what will be observable as a *planetary nebula* for a short time. Only a naked cooling core — a *white dwarf* — will remain from the Sun.

The evolution of the Sun: a slow increase of the radius and luminosity, a change on the red giant and white dwarf (Schaller aj., 1992). Possibly an image of a planetary nebula.

There is still a lot of open questions in the exploration of planetary systems. What can we await in the forthcoming years?

Cassini probe will explore Saturn and its moon system in detail, the exploration of Mars will continue for example by Mars Express and Mars Exploration Rover, Mercury will be mapped by Messenger and BepiColombo probes, New Horizons probe will be sent to Pluto. Stardust probe should bring samples of dust from the comet Wild 2, Hayabusha should obtain a piece from the near-Earth asteroid Itokawa, Dawn interplanetary probe will become an orbiter of the asteroids Vesta and Ceres.

Cassini probe near Saturn. Possibly shots of the other cosmic probes and their targets.

We probably will discover hundreds of other extrasolar planets, some of them as small as our Earth. Future big space telescopes will allow to obtain spectra of their atmospheres. If we find spectral lines appertaining to nitrogen and oxygen molecules, we can hope, that there may exist biosphere on distant planets.

An image of a hypothetical extrasolar planet with a biosphere.

However, thousands of another, surprising discoveries cannot be predicted...

Short quick titles rolling on the screen, ©.