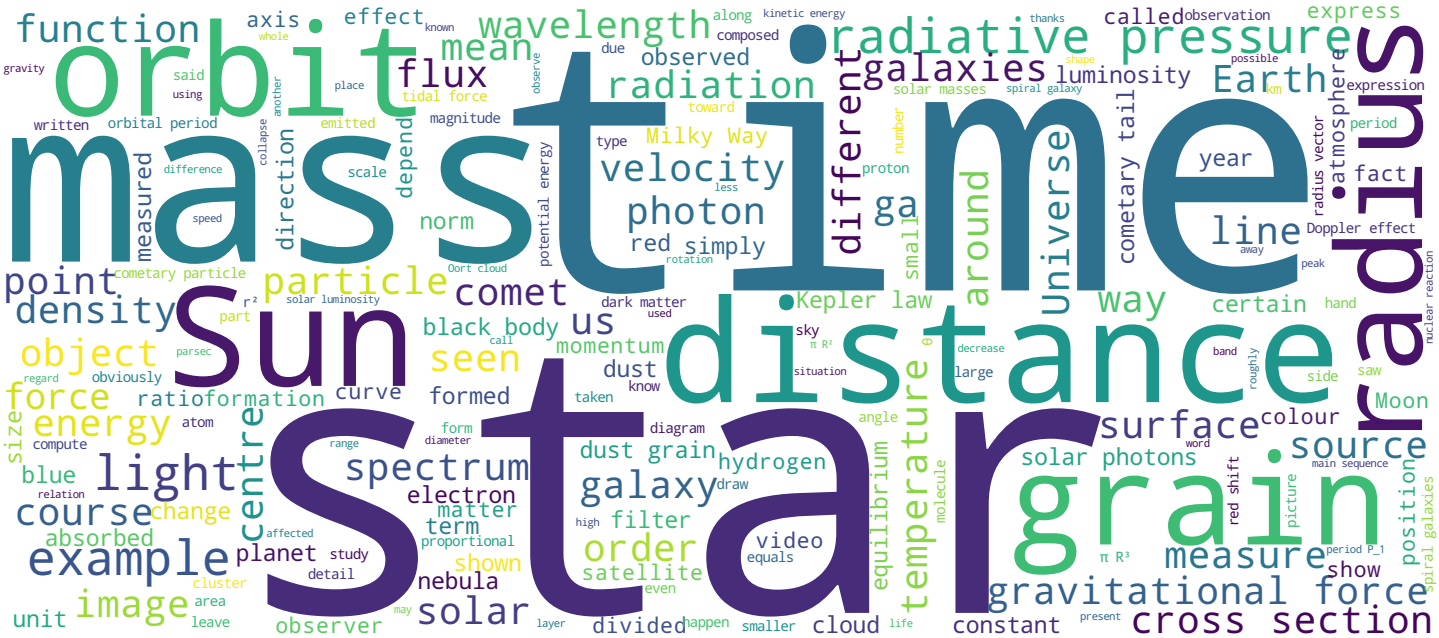
Comet Mc Naught seen from Chile

Image: ESO/Sebastian Deiries

Comets

Introduction to Astrophysics; Chapter 4.2

Frédéric Courbin



In this video we will see with more details what a comet is. They are very small bodies with a diameter not much larger than a few kilometres and composed of 80% of water ice as well as organic compounds such as carbon, hydrogen, oxygen and nitrogen. Comets come from a large spherical cloud at the limit of the solar system, known as the Oort Cloud, named after the Dutch astronomer who first suggested its existence. The spherical geometry of the cloud and its supposed size of the order of 100'000 astronomical units, that is, 100'000 times the size of the Earth orbit, are deduced from the fact that the orbits of comets have sometimes an extreme eccentricity, so they are extremely elongated. They have sometimes very long orbital periods up to several centuries, such as the Halley comet with a period of 76 years, and the orbital inclinations are distributed almost randomly. In other words, comets come randomly from all directions. At the distance of the Oort cloud, the gravitational forces from stars other than the Sun are not negligible any more, so that from time to time, a small gravitational perturbation caused by stars in the Milky Way are able to pull a comet out of the cloud and through it toward the Sun.

Notes

Summary

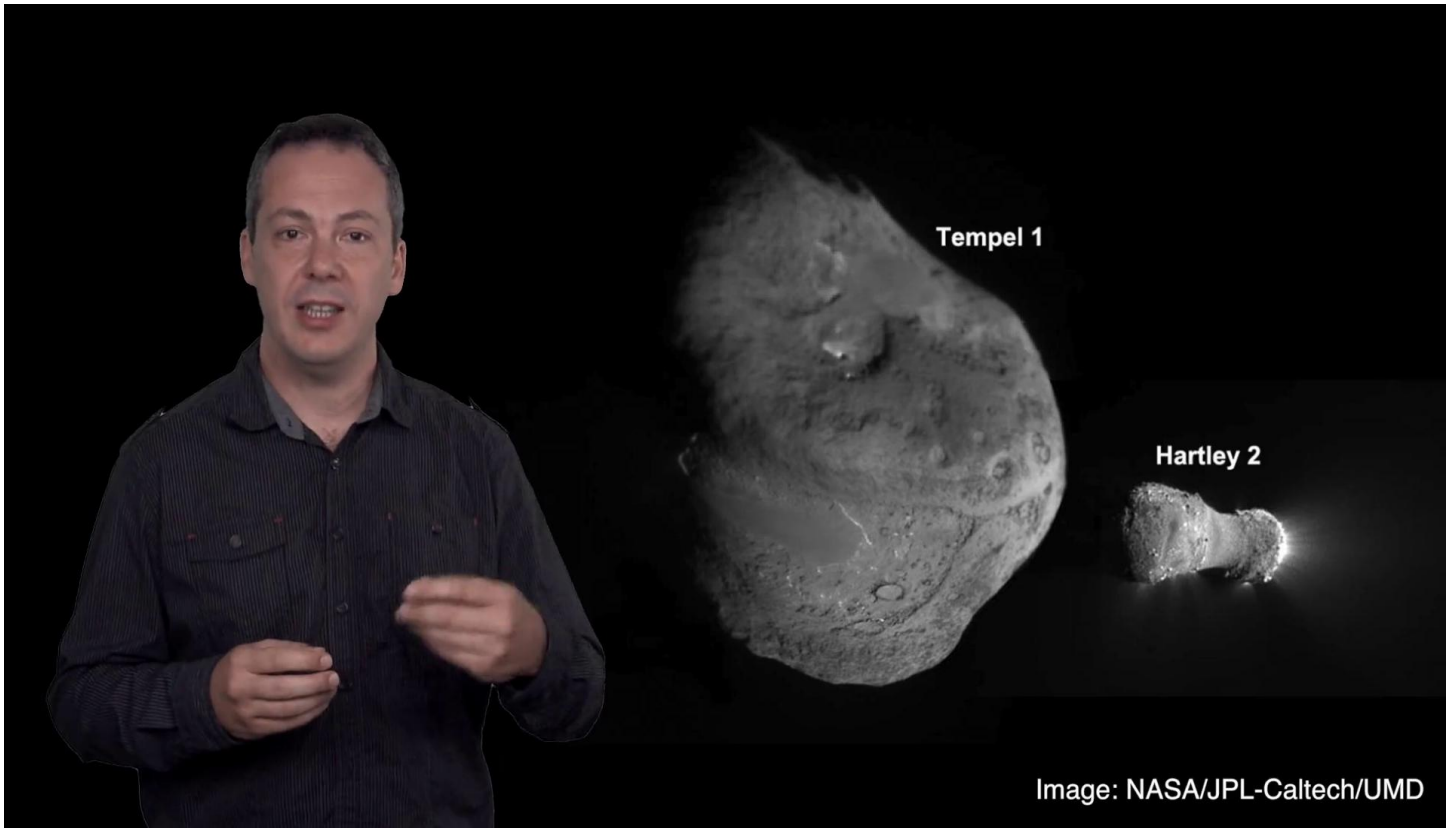
0m 06s

In some way, the Oort cloud is a natural reservoir of comets created at the same time as the solar system. This is why the study of comets is so essential. They consist in genuine fossils of our solar system composed of the primordial matter that formed the planets and that may be at the origin of life.

Notes

Summary

1m 21s



Here are two cometary nuclei visited by the NASA mission Deep Impact. Left is Tempel 1 with a diameter of 7.6 km and right is Hartley 2 with a very small nucleus of 2.2 km wide. When a comet approaches the Sun, the surface of the nucleus melts and matter is ejected to form large and diffuse tails such as here with the comet Hale-Bopp.

Notes

Summary

1m 43s

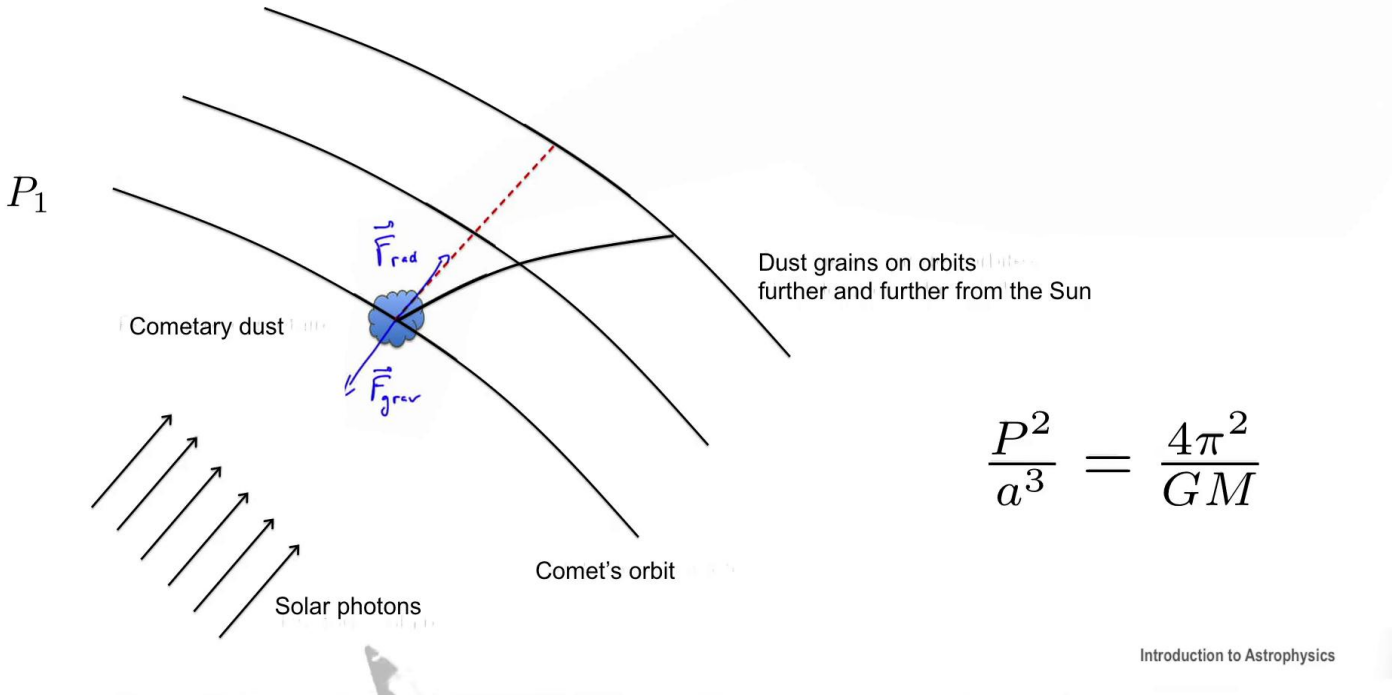
You see here the blue ionised tail, composed of gas, and the other one, more diffuse, composed of dust spreads here with a greyish colour. We will see in more details in this video how cometary tails are formed.

Notes

Summary

2m 07s

Solar Light and Cometary Dust



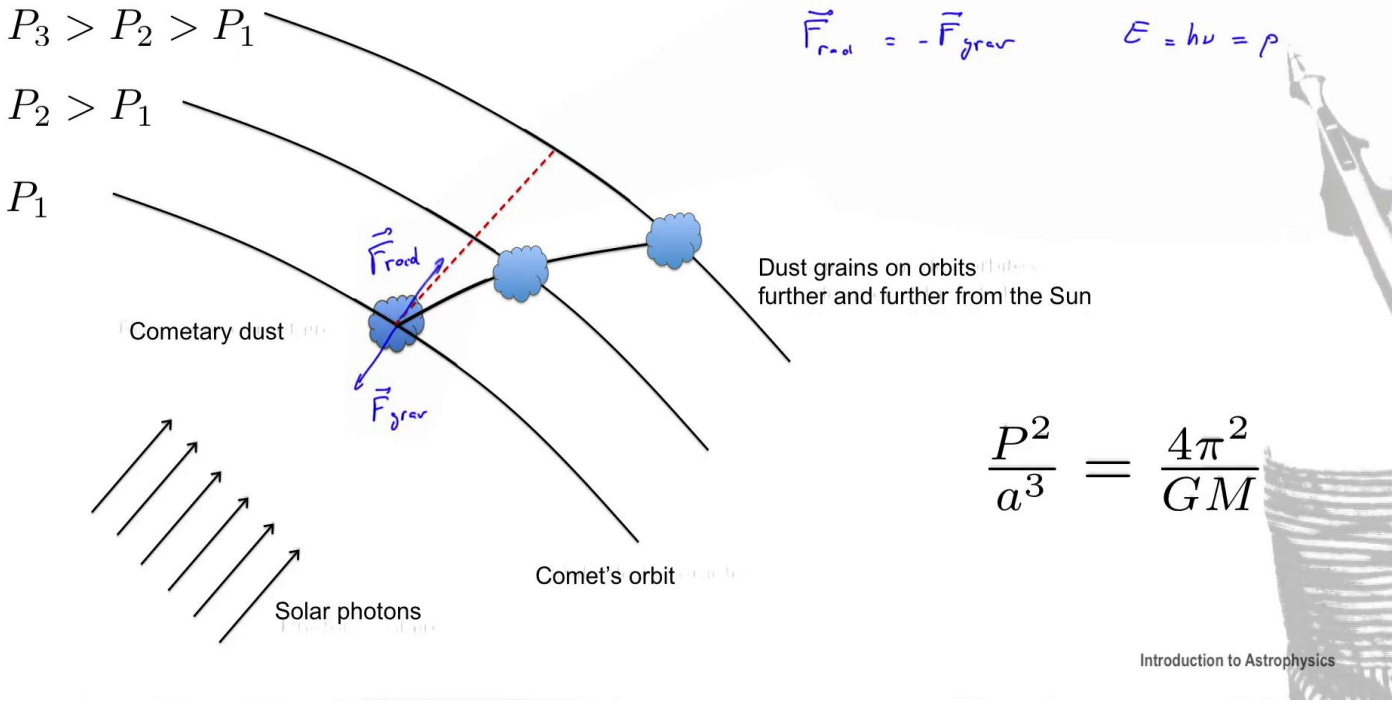
Let us have a look at how cometary tails are formed. We consider a cometary particle at the surface of the comet, on a orbit with a period P_1 at a given distance of the Sun. Following the third Kepler's law with the period P here, divided by the distance to the Sun a there. And M here is the mass of the Sun. We have a competition between two forces. On the one hand, is the gravitational force acting on this grain and on the other hand is the radiative pressure. Lets call the force created by this radiative pressure F rad The dust grain is at equilibrium between the two forces. It has a given mass, a given cross section and therefore a given size. There is an opposition between the radiative pressure caused by solar photons collected on its cross section and the gravitational force which also depends on the size of the grain through its density. The effect of the radiation is proportional to R^2, the particle cross section, and the mass is proportional to 4/3 de πR^3 where R is the radius of the grain. Obviously, as soon as the radiative pressure exceeds the gravitational force, the grain is ejected of the surface of the comet and leaves then radially with regard to the Sun.

Notes

Summary

2m 26s

Solar Light and Cometary Dust



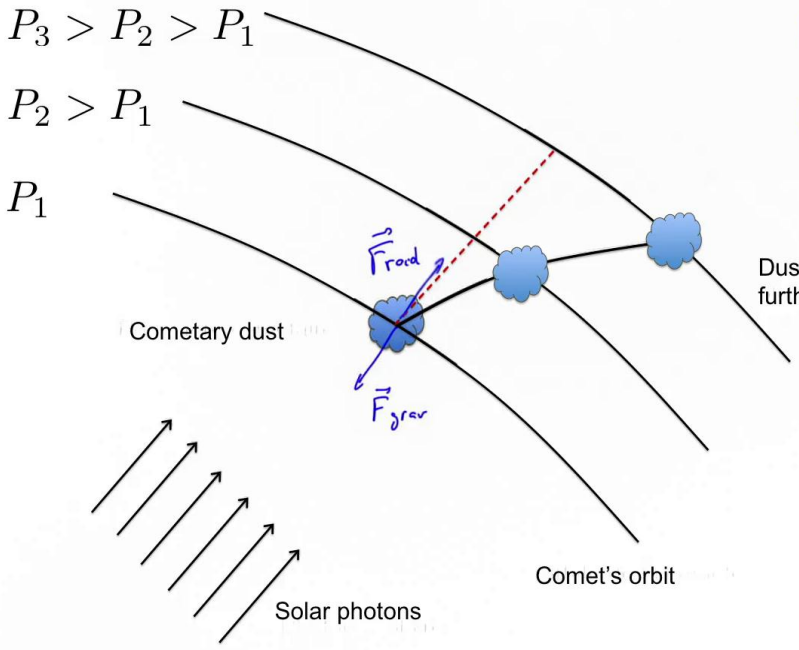
When this happens, the grain reaches another orbit with another orbital radius. We see here the change of orbit. We push the grain, so it leaves to another orbit with a period larger than the orbital period of the comet. Therefore the grain drifts behind the comet. And now for an even larger orbit. By simply writing the third Kepler's law we see that the orbital period gets larger when the radius increases. A grain with some momentum given by the solar photons is pushed over time to orbits of greater radii and therefore of greater periods. We have thus the formation of a curved cometary tail. But there is more. We can also have grains much smaller in size and as such much lighter, such as molecules for example. Molecules are immediately ejected outside of the orbit. Therefore the grains do not have time to change orbit in such a continuous way. They are directly swept by the solar wind. We were saying that there is an opposition between the gravitational force and the radiative pressure, as well as an equilibrium between the two forces. Let us write this equilibrium. How do we express the radiative pressure? Each photon has a given energy E = hν and a given momentum p.

Notes

Summary

3m 51s

Solar Light and Cometary Dust



$\vec{F}_{rad} = -\vec{F}_{grav}$

$\vec{F}_{rad} = \frac{\mathcal{E}}{c}\sigma_g$

$\mathcal{E} = h\nu = pc$

$p = \frac{\mathcal{E}}{c}$

σ_g : section efficace

Dust grains on orbits further and further from the Sun

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM}$$

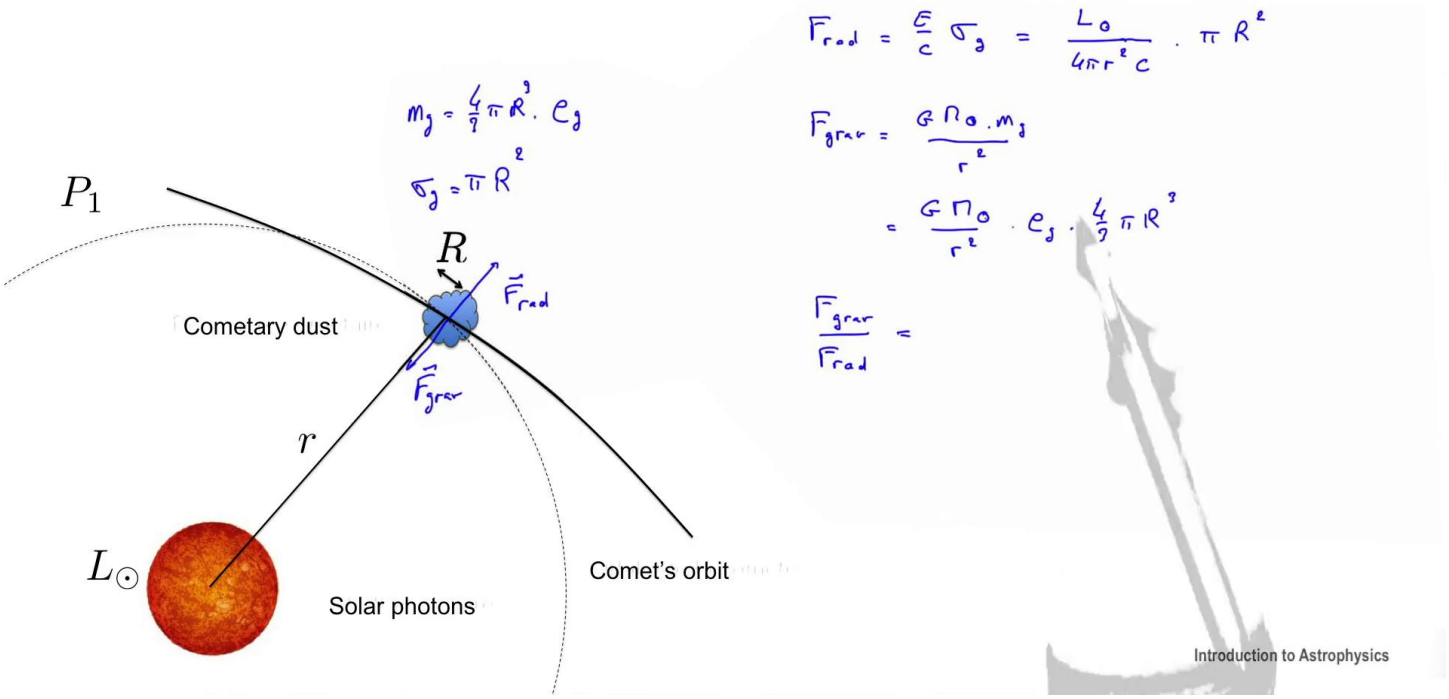
Introduction to Astrophysics

Its energy can be expressed as a function of the momentum. The momentum p associated to each photon is equal to its energy divided by the speed of light c. The radiative pressure F_rad can be written as E/c since each time a photon is absorbed by the dust grain or the molecule on the comet it gains momentum equals to E/c. That is, the momentum change of the dust grain is E/c, which is a force. Of course not all photons are absorbed by the cometary particle. Only the photons with an appropriate impact parameter are absorbed. This impact parameter is simply the grain cross section, namely σ_g.

Notes

Summary

5m 38s

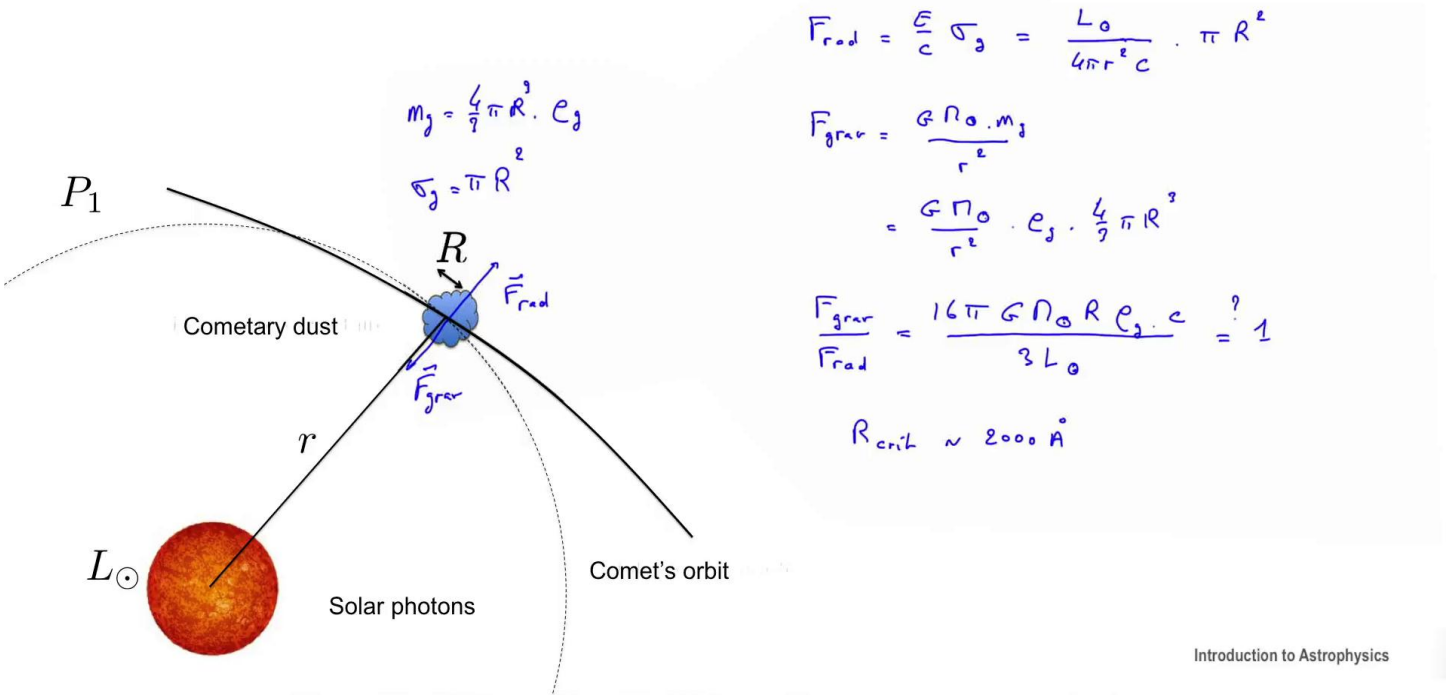


Let us now compute the different forces. We have first the gravitational force here and the radiative pressure. The grain has a given cross section : σ_g = π R². The mass of the grain is : 4/3 π R³ ρ_g where ρ_g is its density. Let us now express the different forces. The norm of the radiative pressure F_rad is E/c * σ_g. Now E is the solar energy received by the grain, so it is simply the solar luminosity L over 4 π r² We have obviously the factor c here and the cross section of the grain, π R² Note the upper case R. Then we have the gravitational force. It is the gravitational force exerted by the Sun on the grain : it is G M, where M is the mass of the Sun, it is G M, where M is the mass of the Sun, times m_g the mass of the grain that we expressed here, divided by the distance between the two bodies, r² With the density expressed previously here. The gravitational force can also be written as : G M / r² times ρ_g the grain density, times 4/3 π R³, the cube of the grain radius. We can now compute the ratio between the norm of the gravitational force and the norm of the radiative pressure force.

Notes

Summary

6m 42s



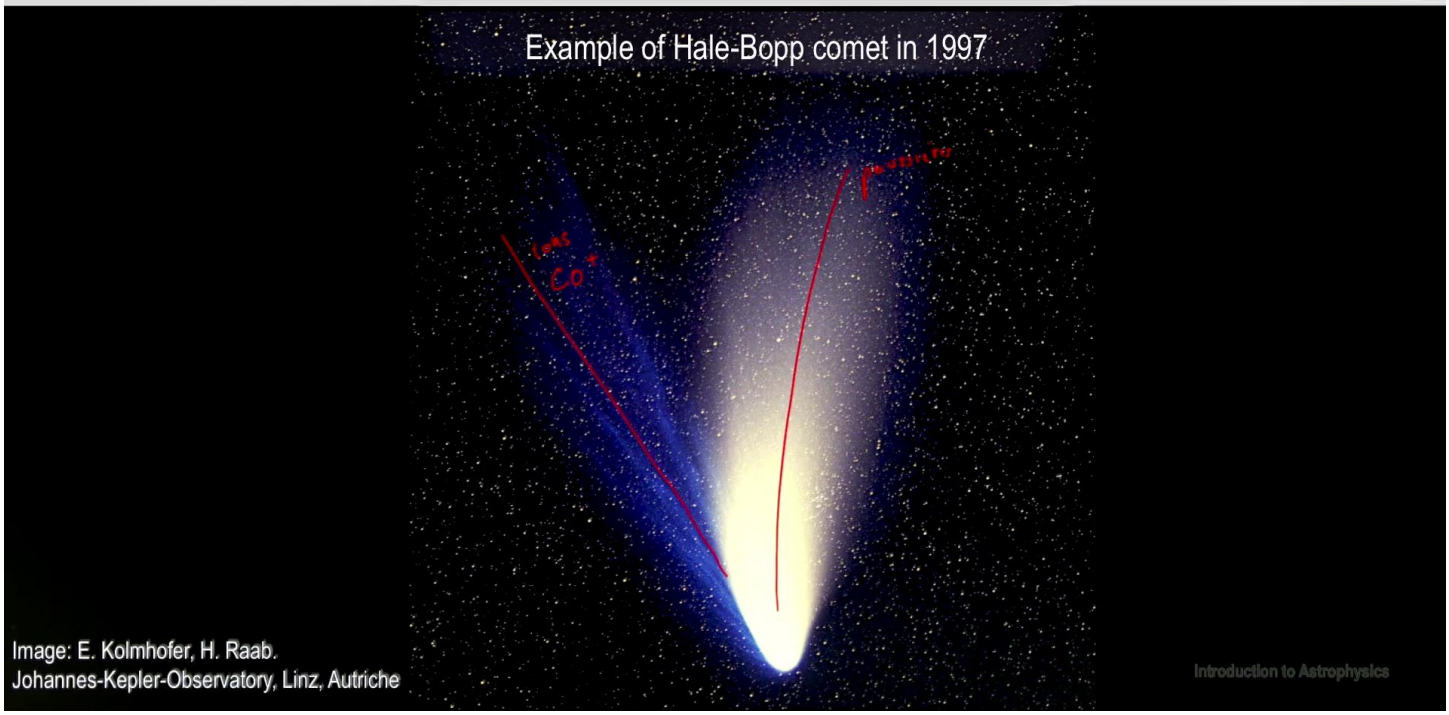
If we rearrange all these terms, we find the ratio to be : 16 π G times the mass of the Sun times R the radius of the grain, times its density and the speed of light, over 3 times the solar luminosity. We have simply expressed the ratio by rearranging the terms as functions of the quantities that we previously defined here. We are of course interested in knowing whether there is an equilibrium or not. We can for example deduce the radius of the grain that ensures equilibrium. We can define a critical radius for which a typical cometary dust is of roughly 2000 angströms. This is the maximum radius of a dust grain under which the grain remains bound to the comet. We saw that the mass of the grain is of the order of R^3 while the cross section is of the order of R^2. When the grain gets too big, it becomes too heavy in regards to its cross section and cannot leave the surface of the comet anymore. In such a case, the solar photons are not able to eject the grain from the surface of the comet anymore.

Notes

Summary

8m 57s

Incurved Cometary Tails



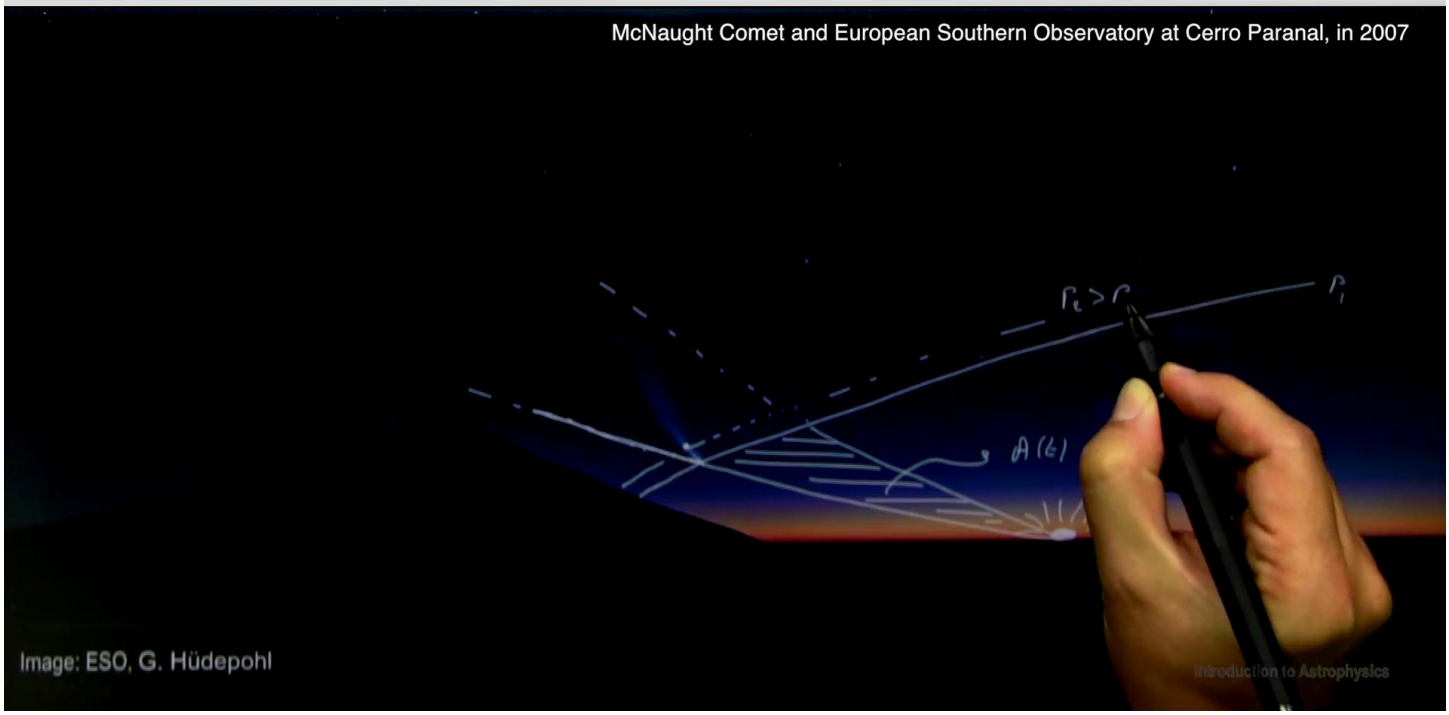
Here is a typical example of the spreading of two cometary tails. There is first a tail of light particules, a tail of ions, that are generally CO+ ions. These particules are extremely light and extremely small so they are ejected directly out of the orbit of the comet by the solar photons. And here is a dust tail. These particles are much heavier. It takes more time to transfer momentum from the solar photons to the cometary particles and therefore to change their orbit. It takes longer to push them away from the orbit of the comet and are affected by Kepler's laws and therefore slowly drift behind the comet.

Notes

Summary

10m 18s

Incurved Cometary Tails



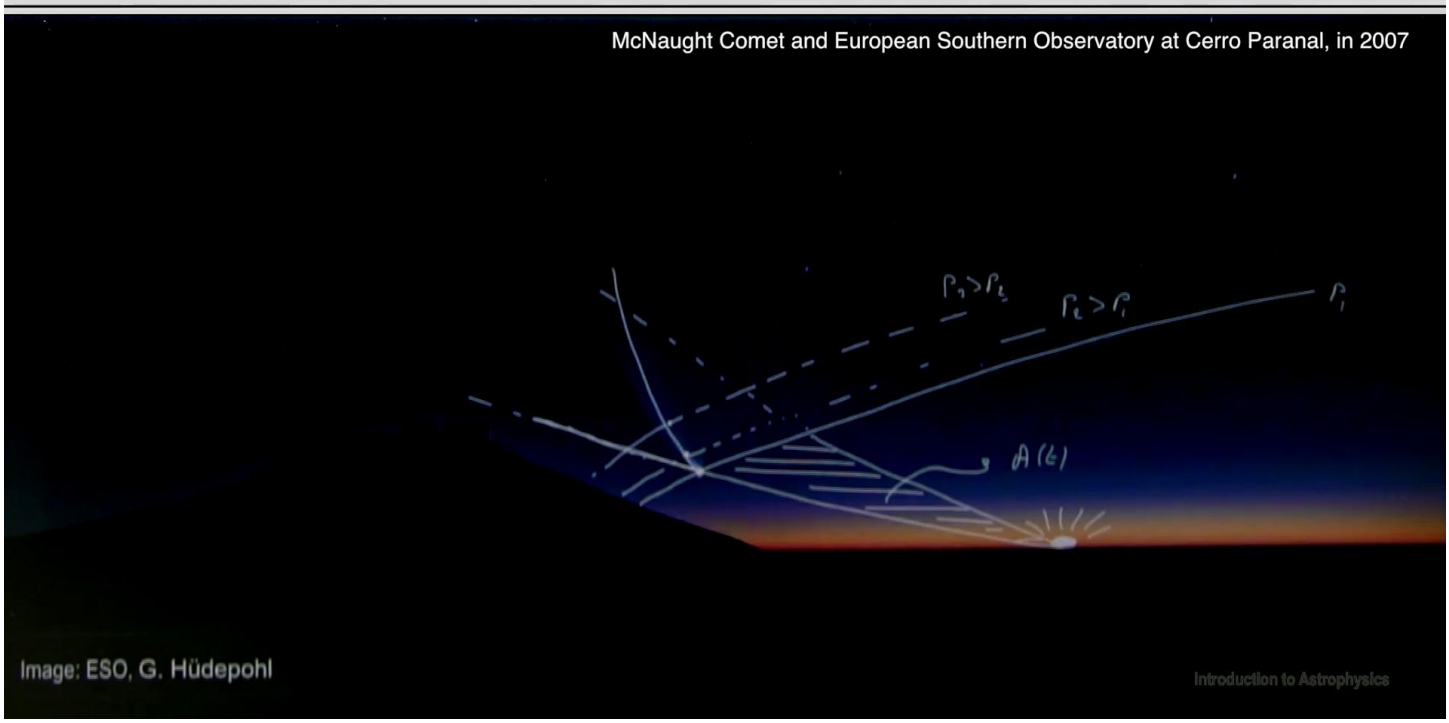
We can see this on another picture. We have here the comet McNaught imaged from the observatory of Cerro Paranal in Chile. This is where the VLT is located, the European « Very Large Telescope » composed of four 8m telescopes in the Andes. This picture is taken just after sunset. I draw the Sun here. Of course the Sun emits photons isotropically. The orbit of the comet around the Sun is roughly like that, or at least we can materialize it in this way. And here are the radius vectors. You remember that these radius vectors sweep out equal areas in equal times. This was the second Kepler's law that we show here as a reminder. Finally we have the solar photons which are produced radially in such a way here. which are produced radially in such a way here. Two cometary tails are formed. The ion tail is in this direction. On this picture it is very thin, we almost cannot see it but the particles are indeed ejected in this direction, radially with respect to the orbit of the comet. The heavier particles are affected more slowly over time by the Sun's radiative pressure. So particles will change their orbit. Here is an orbit with a period P_1 and here a period P_2 greater than P_1.

Notes

Summary

11m 07s

Incurved Cometary Tails



If I add another point on the orbit there, it will have a period P_3 greater than P_2 just like on the slide we showed previously. Since all these orbits have greater and greater periods, the cometary dust grains are delayed with respect to the cometary nucleus which of course stays on the same orbit with a period P_1.

Notes

Summary

12m 41s

We have seen how the solar photons can change the trajectory of cometary particles through the radiative pressure. As many physical phenomena presented during this course, the one we just saw while studying comets manifests itself in several scenarios such as for example the formation and life of stars. We will see that the radiative pressure due to the photons created in thermonuclear reactions in the core of stars prevents them from a gravitational collapse and thus allow them to shine for millions, or even billions of years.

Notes

Summary

13m 05s