11. Genda H, Abe Y *Icarus* **164** 149 (2003)
12. Pepin R O *Icarus* **92** 2 (1991)
13. Pepin R O *Icarus* **126** 148 (1997)
14. Hunten D M *Science* **259** 915 (1993)
15. Bogard D D et al. *Space Sci. Rev.* **96** 425 (2001)
16. Carr M H *Water on Mars* (New York: Oxford Univ. Press, 1996)
17. Donahue T M *Icarus* **66** 195 (1986)
18. de Bergh C et al. *Science* **251** 547 (1991)
19. Meier R et al. *Science* **168** 731 (1988)
20. Zelenyĭ L M et al. *Usp. Fiz. Nauk* **175** 643 (2005) [*Phys. Usp.* **48** 615 (2005)]
21. Sagan C, Mullen G *Science* **177** 52 (1972)
22. Moroz V I *Fizika Planety Mars* (Physics of the Planet Mars) (Moscow: Nauka, 1978)
23. Mukhin L M, Moroz V I *Pisma Astron. Zh.* **3** 78 (1977) [*Sov. Astron. Lett.* **3** 39 (1977)]
24. Moroz V I, Mukhin L M *Kosmich. Issled.* **15** 901 (1978) [*Cosmic Res.* **15** 774 (1978)]
25. Kasting J F, Ackerman T P *Science* **234** 1383 (1986)
26. Ingersoll A P *J. Atmos. Sci.* **26** 1191 (1969)
27. Marov M Ya, Gal'tsev A P, Shari V P *Astron. Vestn.* **19** (1) 15 (1985) [*Solar Syst. Res.* **19** 9 (1885)]
28. Pollack J B et al. *Icarus* **103** 1 (1993)
29. Afanasenko T S, Rodin A V *Astron. Vestn.* (2005) (in press)
30. Moroz V I, Huntress W T, Shevalev I L *Kosmich. Issled.* **40** 451 (2002) [*Cosmic Res.* **40** 419 (2002)]
31. Moroz V I *Space Sci. Rev.* **29** 3 (1981)
32. Hunten D M et al. (Eds) *Venus* (Tucson, Ariz.: Univ. of Arizona Press, 1983)
33. Bougher S W, Hunten D M, Phillips R J (Eds) *Venus II* (Tucson, Ariz.: The Univ. of Arizona Press, 1997)
34. Marov M Ya, Grinspoon D H *The Planet Venus* (New Haven: Yale Univ. Press, 1998)
35. Carlson R W et al. *Science* **253** 1541 (1991)
36. Golitsyn G S *Icarus* **13** 1 (1970)
37. Spinrad H, Münch G, Kaplan L D *Astrophys. J.* **137** 1319 (1963)
38. Moroz V I *Astron. Zh.* **41** 350 (1964) [*Sov. Astron Rep.* **8** 273 (1964)]
39. Kieffer H H et al. (Eds) *Mars* (Tucson, Ariz.: Univ. of Arizona Press, 1992)
40. Korablev O I et al. *Icarus* **102** 76 (1993)
41. Rodin A V, Korablev O I, Moroz V I *Icarus* **125** 212 (1997)
42. Smith M D *Icarus* **167** 148 (2004)
43. Smith D E et al. *J. Geophys. Res.* **106** (E10) 23689 (2001)
44. Acuna M H et al. *Science* **284** 790 (1999)
45. Boynton W V et al. *Space Sci. Rev.* **110** 37 (2004)
46. Mitrofanov I et al. *Science* **297** 78 (2002)
47. Tillman J E *J. Geophys. Res.* **93** 9433 (1988)
48. Mitrofanov I G et al. *Science* **300** 2081 (2003)
49. Clancy R T et al. *Icarus* **122** 36 (1996)
50. Rodin A V, private communication (2003)
51. Richardson M I, Wilson R J *J. Geophys. Res.* **107** (E5) 7 (2002)
52. Ksanfomality L V *Astron. Vestn.* **37** 307 (2003) [*Solar Syst. Res.* **37** 397 (2003)]
53. Squyres S W, Kasting J F *Science* **265** 744 (1994)
54. Owen T et al. *Science* **240** 1767 (1988)
55. Head J W et al. *Nature* **426** 797 (2003)
56. Morris R V et al. *Science* **305** 833 (2004)
57. Korablev O I et al. *Proc. SPIE* **4818** 261 (2002)
58. Zasova L V et al. *Kosmich. Issled.* (2005) (in press)
59. Bertaux J-L et al. *Science* **307** 566 (2005)
60. Hansen G et al. *Planet. Space Sci.* (2005) (in press)
61. Bertaux J-L et al., in *35th Lunar and Planetary Science Conf., Leaque City, Texas, USA, March 15–19, 2004*, Abstract 2178
62. Bibring J-P et al. *Nature* **428** 627 (2004)
63. Byrne S, Ingersoll A P *Geophys. Res. Lett.* **30** (13) 29 (2003)
64. Bibring J-P et al. *Science* **307** 1576 (2005)
65. Langevin Y et al. *Science* **307** 1581 (2005)
66. Formisano V et al. *Science* **306** 1758 (2004)
67. Krasnopolsky V A, Maillard J P, Owen T C *Icarus* **172** 537 (2004)
68. Mumma M J et al. *Am. Astron. Soc. DPS Meeting* **36** 26.02 (2004)
69. Max M D, Clifford S M *J. Geophys. Res.* **105** (E2) 4165 (2000)

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# A ‘wild surmise’ [1]: first results from the Huygens probe into Titan's atmosphere

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## 1. Introduction

On January 14, 2005, a dream that first captured our imaginations in 1982 was brilliantly realized: a European-built probe delivered by an American orbiter landed safely on the surface of Saturn's giant satellite Titan after a seven-year journey from Earth. Obviously, it is too soon to know everything that the extensive data set acquired by the probe will reveal. This brief and preliminary report summarizes the reasons Titan was chosen for such intensive study and gives some of the highlights that the various experiment teams have presented after the first weeks of analysis.

## 2. Why Titan?

Titan stood out as a goal for intense exploration because of its thick, intriguing atmosphere. The first hint that an atmosphere was present came from visual observations of limb darkening reported by the keen-eyed Catalonian observer Comas y Sola [1], and was established beyond doubt by G P Kuiper's [2] observations of absorption bands of methane in Titan's spectrum. However, it was the Voyager flyby in 1980 that did establish this satellite as a prime target for exploration by demonstrating that the atmosphere was mostly nitrogen, had a surface pressure of 1.5 bars, and harbored an active photochemistry that produced numerous organic molecules in the upper atmosphere, leading to dense layers of smog. Among the products of this photochemistry was HCN, an important compound in the reactions expected to precede the origin of life on Earth.

The photochemical smog prevented the Voyager cameras from seeing the satellite's surface. Titan, being bigger than Mercury, has the consequently largest unexplored surface in the solar system. This surface was expected to include drifts of precipitated aerosols and lakes, seas, and rivers of liquid hydrocarbons, participating in the equivalent of a hydrologic cycle. The photochemical destruction of methane meant that there must be an internal source to replace it, and therefore the surface might have fissures, geysers, or possibly even volcanoes to enable this degassing to occur. Unless, of course, we just happened to come on the scene when the last relic of an earlier much larger consignment of methane was about to disappear. At 1.9 gm cm$^{-3}$, the density of Titan indicated it was composed of 50% rock and 50% ice by mass, just like its similar-size cousins in the Jupiter system, Ganymede and Callisto. The rock should contain potassium, and the radioactive isotope of that element produces $^{40}$Ar , as it does on

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[1] The title comes from the sonnet by John Keats: "On First Looking into Chapman's Homer". Professor David Southwood, ESA Chief Scientist, read this passage with great feeling at the Press Conference celebrating the success of the Huygens mission. Southwood suggested that we were suddenly seeing a new world, like the European discoverers of the Pacific Ocean in Keats's poem.

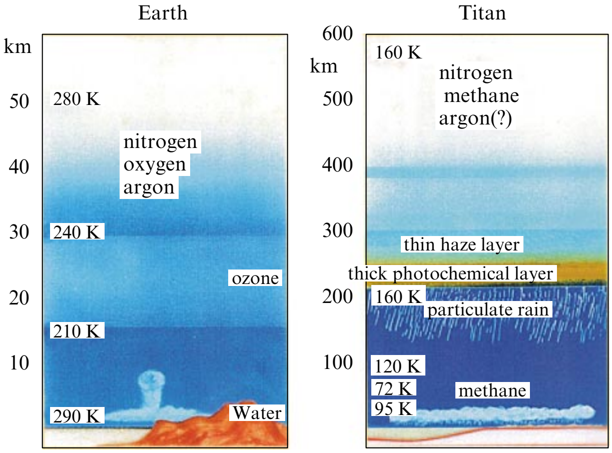

**Figure 1.** Comparison of the atmospheres of Earth and Titan. Both atmospheres are dominated by nitrogen and contain radioactive argon (we can now remove the question mark regarding the presence of argon in the atmosphere of Titan!). But the role of water is played on Titan by methane, and a dense haze due to photochemical reactions covers the surface.

Earth, Mars, and Venus. Thus, we expected to find this argon in Titan's atmosphere once we got inside it, because it is virtually impossible to detect by remote sensing.

All of these features are summarized in Fig. 1, which compares Titan with Earth. These are the only two worlds in our solar system with thick, $N_2$ atmospheres, and we naturally wonder if there is any deep, underlying similarity between the two.

## 3. The origin of atmospheres

Planetary atmospheres consist of volatile compounds of abundant elements. For small bodies like Titan and Earth, this means that we expect to find compounds of carbon, nitrogen, and oxygen, plus the primordial noble gases neon, argon, krypton, and xenon. The noble gases would be occluded, adsorbed, or otherwise trapped in the small solid bodies, called planetesimals, that formed the planets. Krypton and xenon are hardly abundant, but their high atomic weights and chemical inertness virtually guarantee that they will remain in an atmosphere, once degassed.

Earth's atmosphere is clearly an anomaly, even discounting the biogenic oxygen: there is too much nitrogen! Carbon is more abundant than nitrogen in the universe, and carbon in the interstellar medium — and hence the solar nebula — is mainly in the form of carbon grains or organic compounds. Nitrogen, by contrast, is mainly present as $N_2$, a highly volatile gas. Unless the carbon is converted to $CH_4$ and CO before planetesimals form, it would be much easier for them to capture this element than to capture nitrogen. Accordingly, we expect meteorites and comets to show an excess of C/N and indeed they do, exhibiting ratios more than 5 times the cosmic value. Thus, it is not surprising to find atmospheres dominated by carbon in the form of $CO_2$ on Venus and Mars. What happened to the carbon on Earth and Titan?

On Earth, carbon dioxide dissolved in water and formed carbonate rocks — aided and abetted by abundant marine life. If we extracted all of the $CO_2$ that is locked up in limestone, we would suddenly have an atmosphere of 70 bars that was over 95% $CO_2$ . We would look just like Venus!

What about Titan? Surely some of the missing carbon is present as deposits of organic compounds on the satellite's surface. The aerosols produced by Titan's photochemistry must precipitate out and could in principle form a global layer some 100 – 200 m deep [3]. However, if Titan started out with the same value of C/H that we find in comets, meteorites, and terrestrial planet atmospheres, this is not enough! There must be a huge supply of carbon still within the satellite.

## 4. Preliminary Huygens results

### 4.1 The surface of Titan

Surely the most striking result from the Huygens mission was the image of fluvial channels obtained by the Descent Imager (Fig. 2). This showed that one of our central ideas about Titan was indeed correct: liquid hydrocarbons must course over its surface. Why hydrocarbons? Because of Titan's low surface temperature, liquid water is out of the question and no other cosmically abundant fluid is compatible with the satellite's low surface temperature (94 K). The early work on Titan's photochemistry suggested that ethane ($C_2H_6$) would be the dominant end product [3, 4], leading to the suggestion that Titan might be covered with a global ocean of $C_2H_6$ [5]. This extreme model was abandoned when first radar [6] and then near IR observations [7 – 10] showed that the surface of Titan was nonhomogeneous. Nevertheless, ethane still seemed likely to be the most abundant fluid on the surface. Accordingly, the darkest regions glimpsed by ground-based observations that penetrated the ubiquitous hazes that hid the surface from view in visible light were tentatively thought to be seas of ethane.

This now seems highly unlikely. The gas chromatography mass spectrometer (GCMS) on Huygens showed that ethane is not the dominant hydrocarbon on Titan's surface. Instead,

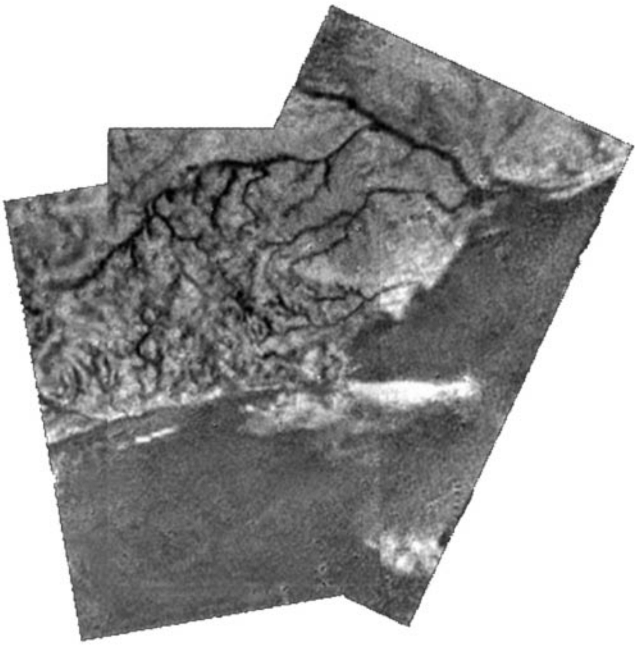

**Figure 2.** River beds on the surface of Titan. The 'rocks' cut by the rivers are not the true rocks but water ice at the temperature 94 K. River beds were formed by the flow of liquid methane, precipitated from aerosols and seen as the dark channel bottom.

methane plays that role. Indeed, after landing, the GCMS detected a sudden surge in the abundance of methane, indicating release of gas, presumably as a result of vaporization of liquid methane on or very near the surface, in response to the heated inlet of the GCMS. This increase in the abundance of methane continued to appear for the approximately one hour over which data were transmitted from Titan's surface, decreasing slightly toward the very end of the transmission. The abundance of nitrogen remained constant throughout this period, maintaining the level it had reached upon impact.

Thus, the current picture is that those intriguing channels were cut by liquid methane, and seas or lakes, if they exist, also consist of this fluid. Indeed, methane must play the same role as water on Earth, going through the cycle of precipitation, run-off, collection, evaporation, condensation, precipitation, etc. anticipated from ground-based work.

At the surface, the GCMS also found evidence of HCN, $C_2H_2$, and other simple compounds, the most complex being benzene, all of which have been detected in Titan's stratosphere, where they are made by photochemistry. We have not yet found evidence of the more complex species we expected to be present on the basis of the thick smog layers, which are thought to be composed of polymers and large organic molecules such a PAHS [11]. The analysis of the relevant data continues.

The Descent Imager and Spectrometer experiment that revealed the intriguing channels also showed that the opacity of Titan's haze layers was considerably greater than had been expected. This result explains why the imaging system on the Cassini orbiter has not been able to provide crisp images of the satellite's surface, even working at its longest wavelength near 1 μm. As the mission goes forward, we will need to rely on results from the visual and infrared mapping spectrometer and especially the radar experiment on the orbiter to provide our best coverage of Titan's surface.

Sensors in the surface science package on the Huygens probe have shown that the surface has a consistency similar to wet sand. 'Mud' is another familiar terrestrial substance often invoked as a model for the material on which the probe landed. This mud should be composed of compacted deposits of the organic aerosols that have precipitated from the atmosphere and been dampened by precipitating or condensing methane. That model would be consistent with the surge of methane gas detected by the GCMS after landing, including the detection of benzene and other organics, presumably vaporized by the heated inlet.

### 4.2 The atmosphere of Titan

An even greater surprise was the absence of detectable amounts of the heavy noble gases, argon, krypton, and xenon. These gases have been found on Venus, Earth, Mars, and Jupiter, and in meteorites. Laboratory experiments indicate that they can be trapped in forming ice, either by adsorption, if temperatures are below 100 K, or perhaps as clathrate hydrates, if the ice forms in the crystalline state at higher temperatures but is then cooled to the low values at which clathrates are stable [12]. Titan has produced a nitrogen atmosphere that has 10 times the mass, per gram of planet, as our own. The absence of detectable primordial noble gases demonstrates that this nitrogen must have come from compounds such as $NH_3$ rather than $N_2$, a clarification that was one of the goals of the mission [13]. The reason is that trapping $N_2$ in the solid materials that formed Titan — specifically the icy component — would have inevitably resulted in the trapping of heavy noble gases as well. Instead, compounds such as $NH_3$ must have evaporated, and photodissociation produced today's $N_2$ [14].

How to explain this? The simplest explanation seems to be that Titan's icy planetesimals formed in a warm environment ($T > 75$ K), in which case the noble gases would not have been trapped, either as clathrates or by adsorption. In this case, $CH_4$ and CO would not be trapped either, but $CO_2$ and $NH_3$ would condense as ices together with $H_2O$. Then $CH_4$ could be made in the interior as serpentinzation released the hydrogen from water and carbon combined with the hydrogen through a kind of Fischer – Tropsch reaction and through reduction of carbon grains. Some methane might also have been produced through the heating of macro molecular carbon brought onto Titan by the planetesimals that formed the satellite. CO could then be produced by OH attacking $CH_4$, as was suggested in [15].

### 4.3 Isotopes

Although the primordial noble gases were not detected, $^{40}$Ar produced by the decay of radioactive $^{40}$K is clearly present. It was discovered by the ion-neutral mass-spectrometer on the Cassini orbiter as it passed through Titan's upper atmosphere [16] and confirmed by the GCMS on the Huygens probe. This gas was expected because the rocky composition of half of Titan's mass must include potassium. The amount detected is less than the maximum amount that could be produced by that mass of rock [17, 18], which may simply indicate the difficulty in getting the gas out to the surface. This inhibition of degassing may also explain the absence of more $CH_4$ in the atmosphere.

Ground-based observations revealed a huge fractionation (by a factor $\sim 4$) of the nitrogen isotopes in HCN, suggesting the escape of a massive early atmosphere. However, both Cassini – Huygens mass spectrometers found that the fractionation compared to the terrestrial value is mush less in $N_2$, the main nitrogen reservoir. Because the terrestrial value appears to represent the value in nitrogen compounds — especially $NH_3$ — in the solar nebula [19], it seems the right standard to use for comparisons with other values. The result is that we expect the loss of approximately 5 times the present mass of the atmosphere over geologic time.

This is consistent with the depletion of $^{16}$O in CO [19], which is somewhat surprising in view of the influx of O as $H_2O$ from outside Titan's atmosphere [20].

In contrast to these large depletions of light isotopes, $^{12}C/^{13}C$ appears to be within $\sim 10\%$ of the terrestrial value [16]. This result especially underlines the need for a source of the $CH_4$ in Titan's atmosphere. As stated above, $CH_4$ is continually being destroyed by photochemistry in Titan's upper atmosphere, such that the present complement will disappear in about $20 \times 10^6$ years [3]. If the methane we see today is a remnant of a much larger fraction that is just now about to disappear completely, the carbon in the $CH_4$ would show the same kind of isotopic fractionation that we see in the nitrogen and oxygen. Since it doesn't, the methane must be continually replaced. Together with the presence of $^{40}$Ar in Titan's atmosphere, the requirement of a source for methane means that Titan must still be geologically active in some way. Future observations from orbit — either imaging or spectroscopy — may provide concrete evidence of this activity.

## 5. Conclusions

As stressed in the introduction, we are still in the early days of analyzing the data that we have in hand from Cassini – Huygens and we anticipate much more data to be coming in as the mission progresses over the next three years. Yet we can already see that Titan is a fascinating world in its own right, with the potential to provide some valuable perspectives on the origin and evolution of our own planet's atmosphere.

Any attempt to extend these perspectives to the problem of the origin of life on Earth must confront the intense cold on Titan and the consequent absence of water in both the liquid and vapor states. Thus, not only is there no chance for aqueous solution chemistry (Darwin's famous 'warm little pond') but there is no readily available reservoir of oxygen, a key element in terrestrial biochemistry. Nevertheless, our ability to understand the organic chemistry that does exist on Titan will surely help us to unravel some of the reactions that took place on the early Earth before life began.

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## References

1. Comas Sola J *Astron. Nachr.* **179** 289 (1908)
2. Kuiper G P *Astrophys. J.* **100** 378 (1944)
3. Strobel D F *Planet. Space Sci.* **30** 839 (1982)
4. Yung, Y L, Allen M, Pinto J P *Astrophys. J. Suppl. Ser.* **55** 465 (1984)
5. Lunine J I, Stevenson D J, Yung Y L *Science* **222** 1229 (1983)
6. Muhleman D O et al. *Science* **248** 975 (1990)
7. Griffith C A, Owen T, Wagner R *Icarus* **93** 362 (1991)
8. Lemmon M T, Karkoschka E, Tomasko M *Icarus* **103** 329 (1993)
9. Smith P H et al. *Icarus* **119** 336 (1996)
10. Meier R et al. *Icarus* **145** 462 (2000)
11. Wilson E H, Atreya S K *J. Geophys. Res.* **109** (E6) E06002 (2004)
12. Hersant F, Gautier D, Lunine J I *Planet. Space Sci.* **52** 623 (2004)
13. Owen T, Gautier D *Space Sci. Rev.* **104** 347 (2002)
14. Atreya S K, Donahue T M, Kuhn W R *Science* **201** 611 (1978)
15. Samuelson R E et al. *Nature* **292** 688 (1981)
16. Waite J H et al. *Science* (2005) (in press)
17. Owen T *Planet. Space Sci.* **30** 833 (1982)
18. McKinnon W, private communication from Waite J H et al. (2005)
19. Owen T et al. *Astrophys. J.* **553** L77 (2001)
20. Coustenis A et al. *Astron. Astrophys.* **336** L85 (1998)

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# Small bodies in the solar system and some problems in cosmogony

M Ya Marov

## 1. Introduction

The solar system is our nearby cosmic surroundings, and hence its study is of primary scientific and practical interest. Enormous progress in solar system studies has been made over the last several 'cosmic' decades, and the avalanche of discoveries grows steadily. Television and radio imaging of planets and their satellites, observations of their surfaces and atmospheres at various wavelengths, and studies of circumplanetary space, and studies of comets, asteroids, and meteors have provided rich experimental material. This has led to the revision of many previous concepts. To a large extent, this was made possible because of the elaboration of much more advanced models of natural phenomena using modern computation facilities. The mechanics of cosmic media has developed greatly. Comparative planetology has opened new possibilities in studies of the entire family of celestial bodies. Complex studies of terrestrial planets, Venus and Mars first of all (as the limiting evolutionary models of Earth), in combination with the dynamics of processes in the entire solar system, have founded the basis for a deeper understanding of properties of both our planet and various natural mechanisms [1].

In recent years, planetary cosmogony has been put on a more rigorous scientific foundation. Its impressive successes have been achieved due to the discovery of extrasolar protoplanetary discs and planetary systems. The next important step on this path must be direct studies of extraterrestrial matter, the primordial matter of small celestial bodies first of all, with its transport to Earth. The design of new highly effective space tools is aimed at solving this problem in the nearest future.

Achievements in researching the solar system required a new outlook on many unsolved problems. These include, first and foremost:

(1) the origin and early evolution of the solar system;

(2) revealing reasons for the uniqueness of the solar system, with the properties of the formation of extrasolar planets taken into account;

(3) the study of the properties of Earth's evolution that made it peculiar among the other terrestrial planets;

(4) the origin of volatiles on terrestrial planets, which allowed the formation of an atmosphere, hydrosphere, and, ultimately, a favorable climatic environment for the emergence and development of the terrestrial biosphere.

Clearly, the question of the origin of life, which remains disputable, is connected with the most intriguing directions in studies of the nature of planets, their satellites, and small bodies, including the problem of transportation (migration) of matter in the solar system and its prebiotic evolution. Of primary interest in this respect are Mars, the Jovian satellite Europa, and the Saturnian satellite Titan. In January 2005, a spacecraft landed on Titan under the joint American – European project Cassini – Huygens.

## 2. Small bodies. Definitions and main characteristics

Small bodies of the solar system include asteroids (minor planets), comets, meteoroids, and interplanetary dust. An asteroid is a celestial body of irregular form with a size from $\sim 1000$ km to several meters. They mostly reside in the Main asteroid belt located between the orbits of Mars and Jupiter at distances from 2.2. to 3.2 a.u. Comets are icy bodies $\sim 10-20$ km in size, usually in highly eccentric orbits. Short-period comets inside Pluto's orbit periodically approach the Sun. Meanwhile, the main cometary families, which also include much bigger bodies, reside outside Neptune's orbit in the Edgeworth – Kuiper belt (one distinguishes the belt itself ($\sim 30-50$ a.u.) and an extended disk reaching $\sim 10^3$ a.u.) and in the Oort cloud located at the boundary of the solar system ($\sim 10^4-10^5$ a.u.). Only some